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Optimisation of Spindle Speed and Feed Rate for Drilling of Al-SiCp Metal Matrix Composites using ANOVA and Genetic Algorithm

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ABSTRACT:

This paper presents the influence of the spindle speed and feed rate of the drilling on machinability of metal matrix composites (MMC) manufactured using stir casting technique. The drilling of MMC is carried out using Ti-Al-N coated and uncoated solid carbide drills. Analysis of variance technique is used to find the percentage of contribution for each drilling parameters and then regression equations were developed to find the thrust force and torque. The drilling parameters were also optimized using Genetic Algorithm. For the optimum values of spindle speed and feed rate, the tool life in terms of tool wear and number of holes drilled was compared for the cases of coated and uncoated drills. From the analysis, it was inferred that feed rate is the significant factor affecting thrust force and torque. Coated solid carbide drill performed than better than the uncoated carbide drill.

KEYWORDS:

Drilling; Metal matrix composites; Analysis of variance; Genetic algorithm; Tool life

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1. Introduction

Conventional monolithic materials have limitations in achieving good combination of strength, stiffness, toughness and density. To overcome these shortcomings, composites are most promising materials of recent interest. Due to their potentially attractive properties coupled with the inability to operate at high temperatures, metal matrix composites (MMC) compete with super-alloys, ceramics, plastics and re-designed steel parts in several aerospace and automotive applications. Machining composite materials differs significantly in many aspects from machining of conventional metals and their alloys. Composite materials are difficult to machine when compared with conventional metals and their alloys because of their non-homogeneous anisotropic properties and very abrasive components reinforcement. Significant damage to the work piece is introduced and high wear rates of the cutting tools are experienced. The cutting tool materials must be attentively chosen to minimize wear due to the hard abrasive constituents of the reinforcing phase in the composite representing the work material.

Rao et al [1] and Kumar et al [2] have investigated the processing and mechanical properties of aluminium alloy MMC. They have reported that hardness, tensile strength and wear resistance properties have been improved by varying the composition and processing of MMC. The effect of machining parameters on turning of Aluminium alloy MMC on surface quality characteristics of machined parts has been investigated by many researchers [3-7]. Amongst them, Seeman et al [5] and Bhushan et al [6] have studied the tool wear and wear mechanism while machining MMC and then economic machining conditions were obtained. Drilling of hole in composite material is very common process in the assembly of aerospace and automotive composite structures. Unlike metal machining, where there is a vast array of hand books, there are relatively few publications addressing machinability and selection of cutting parameters for machining MMC. The effect of drilling parameters on drilling forces, tool wear, chip formation and drilled-hole quality of aluminium alloy MMC were investigated by few researchers [8-12]. Davim et al [9] have concluded that cutting time has greater influence on tool wear and feed rate on specific cutting pressure and surface roughness. Tsao et al [11] has conducted a set of experiments and concluded that increasing drill hardness decreases the surface roughness of drilled surface for all heat treated conditions. The drilled hole surface quality is strongly dependent on cutting parameters, tool geometry, thrust force and torque.

This paper presents the optimisation of spindle speed and feed rate of the drill on thrust force and torque as drilling performance using analysis of variance (ANOVA) and Genetic Algorithm (GA). MMC specimens are manufactured using stir casting technique. The experimental work involves drilling of MMC using Ti-Al-N coated and un-coated solid carbide drills. For the optimum values of spindle speed and feed rate, the tool life in terms of tool wear and number of holes drilled by coated drill was compared and uncoated drill.

2. MMC specimen preparation

The required quantity (3 kg) of Al6061-T6 aluminium alloy has been placed in the graphite crucible and kept inside the furnace. The alloy is heated in the electrical resistance furnace at 750 ºC using the temperature controller. The temperature of the aluminium alloy has been increased and the melting takes place at 660 ºC. Then, the temperature of the molten is increased and then maintained at 750 ºC. The preheating of the reinforcement particles is carried out in an electrical muffle furnace with a capacity of 3.5 kW power rating with a maximum operating temperature of 1200 ºC. This furnace is capable of melting 5 kg of aluminium in a batch. Fig. 1 shows the melting arrangement. The reinforcement is heated up to a temperature of 750ºC and maintained at this temperature for 30 minutes. The motor-stirrer assembly is lowered such that the stirrer is submerged in the molten metal. Then, the stirrer is rotated at a speed of 500rpm using the speed controller. This creates a vortex on the molten metal surface. The preheated silicon carbide particle (43μm) is uniformly fed through the feeding arrangement as shown in Fig. 2. The feeding and the stirring are simultaneously carried out until the calculated preheated reinforcement is fed into the molten metal.

Fig. 1: Melting arrangement

Fig. 2: Stirrer and SiCp feeder arrangement

After the addition of the reinforcement, stirring is continued for 10 minutes at a reduced speed of 100 rpm to make the homogenous composite slurry. The composite slurry is then quickly poured into a mould and allowed to solidify. The solidified casting is removed from the mould and cleaned. Fig. 3 shows the photograph of casted MMC for the size of 210x50x15 mm. The chemical composition of casted Al 6061-T6/SiCp MMC material through testing in Si'Tarc is given in Table 1. The microstructure of MMC specimen was studied using Scanning Electron Microscope (SEM). Specimen was polished before investigating its microstructure. The microstructure of the specimen as obtained at x200 resolution is shown in Fig. 4. The microstructure clearly shows that the SiCp embedded well in the aluminium matrix. The Vickers micro-hardness of casted Al6061/SiCp MMC was evaluated using diamond indenter at an applied load of 100g for a time of 15 seconds and found to be 65 VHN.

Fig. 3: Stir casted MMC material

Table 1: Composition of Al 6061-T6/SiCp elements (in %)

Si	Mn	Ti	Cr	Cu	Zn	Mg	Fe	Al
2.9	0.03	0.055	0.008	0.22	0.1	0.84	0.23	95.617

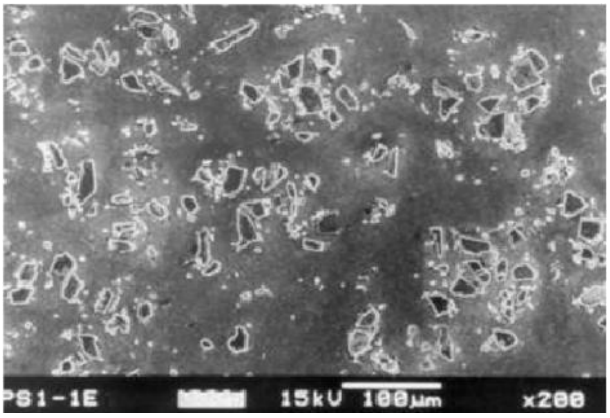

Fig. 4: Microstructure of MMC material

3. Influence of drilling parameters

Fig. 5 shows the effect of feed rate for various spindle speed on thrust force. At low feed rate the thrust force recorded for all the three spindle speeds are almost same. When the feed rate increases the thrust force also increased. This is because of the increase in cross sectional area of the chip. At higher feed rates (0.25 mm/rev) and higher spindle speed, the thrust force recorded was higher. This could be due to impinging of cutting edges on the SiCp at higher spindle speeds in the aluminium matrix composites. When the feed rate was increased from 0.05 mm/rev to higher values, the thrust force has increased. This could be because of reduction in working relief angle. Since the MMC contains highly abrasive SiCp (20%), this may lead to increase in thrust force when the feed rate increased. Apart from increase in cross sectional area of chip, working clearance angle of the drill and abrasive SiCp could be the reason for higher thrust force. Table 2 gives the results of ANOVA for thrust force. The F value for feed rate (186.70) is greater than Fα, which implies that feed rate is the significant factor influencing thrust force which has a percentage of influence of 96.4%. Regardless of tool and work piece, the thrust force is highly dependent on feed rate than the spindle speed [10]. Fig. 6 shows the signal to noise ratio graph for various values of feed rate and spindle speed, from which we can infer that signal to noise ratio is large for a feed rate of 0.05 mm/rev and 2500 rpm which makes it an optimal combination for reduced thrust force.

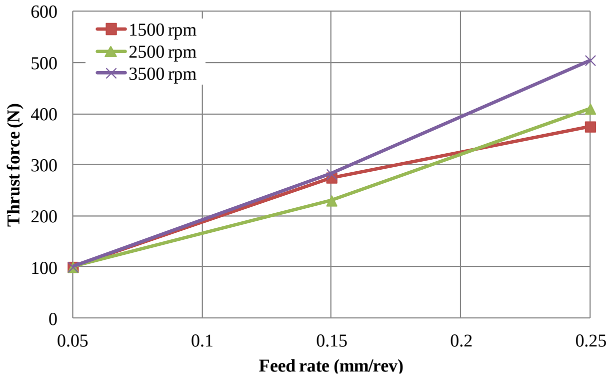

Fig. 5: Effect of feed rate on thrust force for various spindle speeds

Table 2: ANOVA for thrust force

Source	Feed rate (mm/rev)	Spindle speed (rpm)	Error
Sum of Squares	205.711	4.119	2.204
Degree of Freedom	2	2	4
Variance	112.856	2.059	0.551
F Test	186.70	3.74	-
F(α=0.05)	6.94	6.94	-
% Contribution	96.4%	3.017%	1.5%

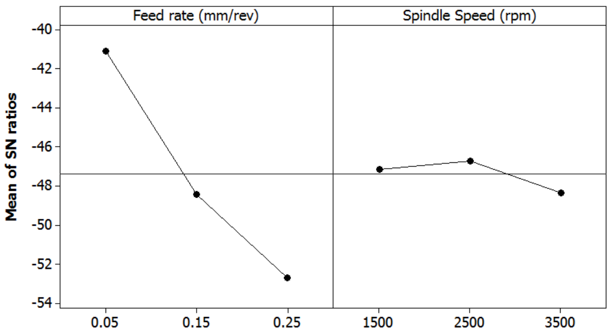

Fig. 6: Signal to noise ratio graph for thrust force

Fig. 7 shows the effect of feed rate on torque for various spindle speed. The torque increases with increase in feed rate for a constant spindle speed. For a spindle speed of 1500 rpm and high feed rate of 0.25 mm/rev, the torque has decreased. This can be attributed to the heterogeneous property of the material. The thrust force and torque has increased for feed rate of 0.15 mm/rev and spindle speed of 1500 rpm. This could be due to localized SiCp distribution. In case of torque, a proper trend can't be established with respect to the spindle speed and feed rate. This is due to the interaction effect of feed rate and spindle speed and anisotropic property of work material. The results of ANOVA for the torque are shown in Table 3. The F value of feed rate (9.49) is greater than Fα which implies that the feed rate is the significant factor influencing torque with the percentage of contribution as 73.5%. The percentage of error is 25.99% which is due to the interaction effect of drilling parameters. From Fig. 8, it is seen that signal to noise ratio value is large for the feed rate of 0.05 mm/rev and spindle speed of 2500 rpm which becomes the optimal combination for reduced torque.

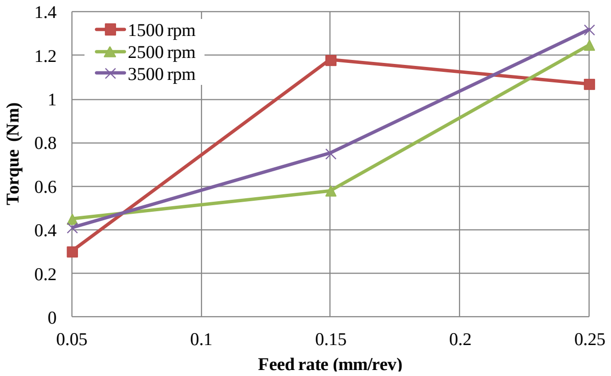

Fig. 7: Effect of feed rate on torque for various spindle speeds

Table 3: ANOVA for torque

Source	Feed rate (mm/rev)	Spindle speed (rpm)	Error
Sum of Squares	155.671	0.887	32.820
Degree of Freedom	2	2	4
Variance	77.8356	0.4433	8.2051
F Test	9.49	0.05	-
F(α=0.05)	6.94	6.94	-
% Contribution	73.5%	0.55%	25.99%

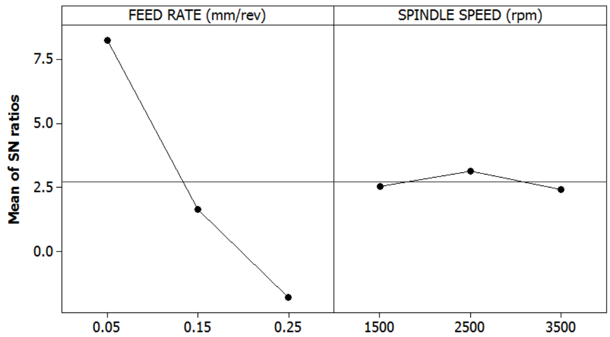

Fig. 8: Signal to noise ratio graph for torque

4. Optimisation of drilling parameters

The objective of optimisation is to minimize the thrust force (*TF*) and torque (*T*) as a function of feed rate (*f*) and spindle speed (*s*) through multiple nonlinear regression analysis as,

$$TF \ or \ T = b_0 + b_1 f + b_2 s + b_3 fs + b_4 f^2 + b_5 s^2 \quad (1)$$

The units of *f* and *s* are mm/rev and rpm respectively. Table 4 shows the coefficients b_0 to b_5 for the *TF* and *T* objective functions. The regression analysis coefficients of correlation (R2) are 0.9921 and 0.829 for *TF* and *T* respectively. GA is employed for the experimental results using MATLAB Version 2014b and the optimal combination of process parameters was obtained. The best fitness graphs using genetic algorithm for thrust force and torque are shown in Fig. 9 and Fig. 10 respectively. The best fitness obtained for thrust force is 117.4964 N and for torque is 0.40699 Nm. Their corresponding optimal combination of feed rate and spindle speed is shown in Table 5.

Table 4: Coefficients of regression analysis equations for TF & T

Coeff.	TF (N)	T (Nm)
b_0	276.04	0.739
b_1	528.41	4.3151
b_2	-0.17993	-4.656×10^{-4}
b_3	3.2055	3.265×10^{-4}
b_4	904.52	-3.3206
b_5	3.1605×10^{-5}	8.2201×10^{-8}

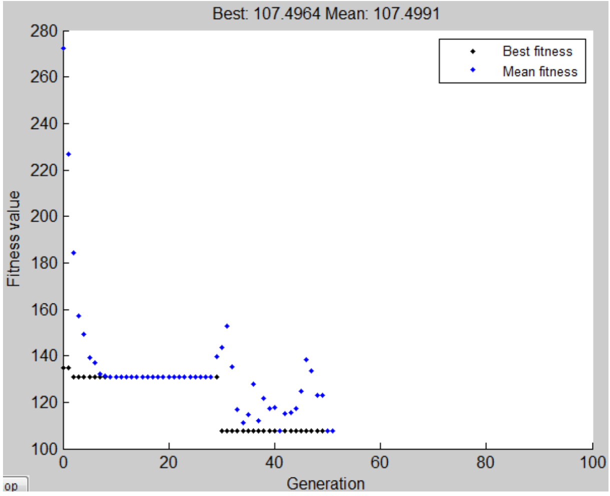

Fig. 9: Genetic algorithm plot for thrust force

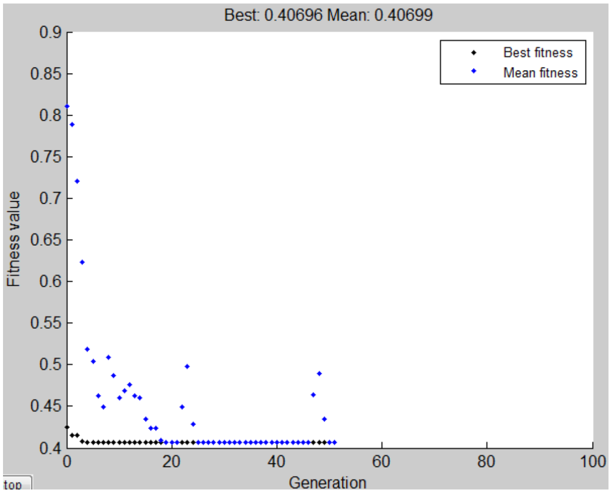

Fig. 10: Genetic algorithm plot for torque

Table 5: Optimum drilling parameters from GA

Optimum values	Feed rate (mm/rev)	Spindle speed (rpm)
TF = 117.496 N	0.0502	2633.43
T = 0.40699 Nm	0.0512	2445.66

Tool life study was conducted using coated N20 drill and uncoated K20 drill for the optimal combination feed rate of 0.05 mm/rev and spindle speed of 2500 rpm that was obtained from ANOVA. The flank wear was measured for drilling of every five holes for both the drills. While drilling particulate MMC, it was seen that abrasion is the primary mode of tool wear. Abrasive wear involves the removal of tool material by scoring action of hard phase inclusions in the chip. The predominant wear develops on the flank face of the tool in drilling SiCp reinforced aluminium composite. When drilling MMC, the thrust force increases with the flank wear of the drills. The torque is not sensitive to the increase in tool wear [8]. In case of N20 drill, the tool wear was 0.15 mm after 5 holes and a maximum wear was 0.41 mm after 15 holes were drilled. This is due to high volume fraction of SiCp in the MMC work piece. The entry burr was formed for all holes after drilling the eighth hole. This is due to excessive tool wear and the tool became weak for the drilling action to take place and hence resulted in entry burr. Microscope images of the tool crack and flank wear for N20 drill is shown in Fig. 11 and Fig. 12. In case of K20 drill, the tool wear rate was faster than N20 drill and the tool broke by the time twelfth hole was drilled. The wear was 0.48 mm by the time tenth hole was drilled. The K20 drill was broken due to excessive tool wear.

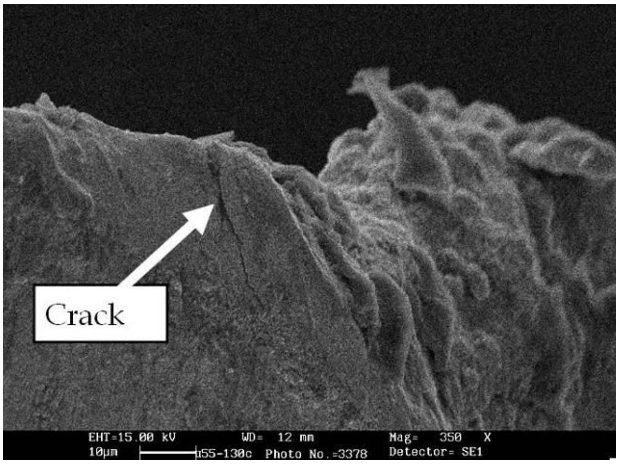

Fig. 11: Microscope view of coated N20 drill showing cracks

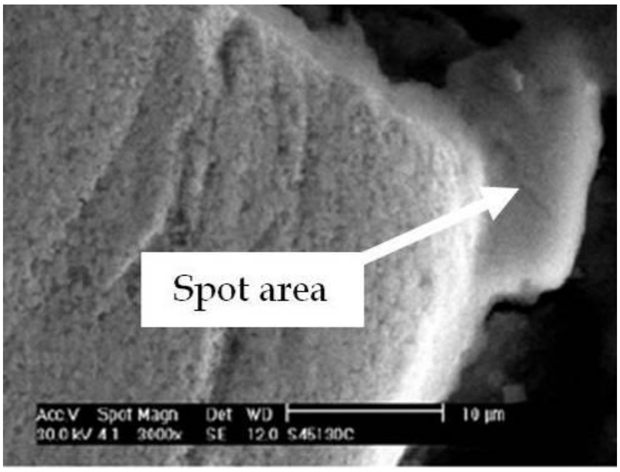

Fig. 12: Microscope view of coated N20 drill showing flank wear

5. Conclusions

The influence of the spindle speed and feed rate of the drilling on machinability of MMC manufactured using stir casting technique was detailed through experimental work and statistical analysis. Based on the presented results, the following can be concluded:

- The thrust force was highly dependent on feed rate when compared to the spindle speed.
- Interaction effects of feed rate and spindle speed were predominant in torque.
- Optimal combinations of drilling parameters for thrust force and torque obtained using ANOVA and GA were found to be in good agreement.

- Coated drill performed better than uncoated one.
- Burr height increased for an increase in feed rate.
- The primary mode of tool wear was abrasion which involved the removal of tool material by scoring action of hard phase inclusions in the chip.

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