Light Metals 2013 *Edited by: Barry Sadler*
TMS (The Minerals, Metals & Materials Society), 2013

INFLUENCE OF MACHINING PARAMETERS ON AL-4.5Cu-TiC IN-SITU METAL MATRIX COMPOSITES

Pradeep Kumar Jha*, Anand Kumar, M M Mahapatra

Department of Mechanical and Industrial Engineering Department
Indian Institute of Technology Roorkee, Uttarakhand- 247 667, India
*Email: pkjhafme@iitr.ernet.in

Keywords: *In-situ* MMCs, Turning, Cutting force, Surface roughness, ANOVA

Abstract

With the advent of large number of composite materials, a systematic study of machining characteristics of these new materials is necessary for their rapid adoption in the actual engineering applications. Al-Cu-TiC metal matrix composite is widely used in aeronautical and automobile industries due to their excellent mechanical and physical properties. However machining of these composites is difficult because of the harder reinforcement particles. This paper presents an experimental investigation on the machinability bahavior of Al-4.5Cu-TiC in-situ cast metal matrix composite reinforced with weight percentage of 10% of Titanium Carbide. The experimental studies were conducted under varying process parameters e.g. cutting speed, feed rate and depth of cut. The optimization of machining parameters was done by designing a full factorial (L_{27}) matrix using Taguchi method. The analysis of variance (ANOVA) is employed to investigate the influence of used parameters on surface roughness Ra.

Introduction

A number of processing routes have been developed for production of aluminium based metal matrix composites like powder metallurgy, liquid metal infiltration, compocasting, squeeze casting method, stir casting and spray decomposition method *etc*. Among these, *in-situ* stir cast route offers more advantages when compared to others conventional routes. Small particles size (1μm to 3μm), greater bonding, high specific strength, high specific stiffness, better wear resistance, good thermodynamic stability, and uniform distribution are the advantages of produced *in-situ* composite materials. Clustering and improper wetting of reinforced particles can be avoided by using *in-situ* stir casting method [1-3]. The major typical application of *in-situ* composite materials serves in the aerospace and automotive sectors include piston, engine block, brake component (discs and rotors), valves, liners, drive shaft [4].

The component produced by composite materials requires a machining process to achieve a required shape with dimensions with requisite tolerance. The machining of composite materials is associated with interaction of hard ceramic reinforced particles with the tool. These characteristics lead to difficulties in machining of composite materials. The cutting force, tool wear, surface finishes are the important indices to assessing the machinability behavior. Hence, the selection of proper cutting tool and machining condition is essential to produce a better finished metal matrix composites product. From the literature review it is observed that much works have been done on machining and machinabilty of *ex-situ* SiC reinforced composites, however reported works related to machining of *in-situ* TiC reinforced composite materials are limited [5]. There is, therefore, a need to investigate the machninability of *in-situ* TiC reinforced composite materials.

N. Muthukrishanan *et al*. [6] reported in their studies on continuous turning of A356/SiCp/10p composite by medium grad polycrystalline diamond (PCD 1500) inserts at various cutting condition. The response parameters of machining such as specific power consumed, surface roughness, and tool wear were considered. It was concluded that the formation of built up edge (BUE) and tool wear was less at lower cutting speed. At higher cutting speed, less consumption of specific power and less tool wear was observed. Quan Yaming *et al.* [7] had investigated the tool wear in machining of SiC reinforced aluminium based metal matrix composites. The material structures and tool wear mechanism were investigated. They stated that the tool life was strongly depended on the volume fraction and size of reinforcement in composites materials. Hooper *et al.* [8] had studied machinability of aluminium metal matrix composite reinforced with SiC particles with polycrystalline diamond (PCD) and conventional tungsten carbide (WB) tools. It was concluded that the PCD tool was more suitable for the MMCs as compared to WB tools. X Ding *et al.* [9] also reported on the superior performance of polycrystalline diamond (PCD) tools in terms tool life over polycrystalline boron carbides (PCBN). It was observed that the formation of BUE tendency was more in PCBN tool as compared PCD tools. L.T.Lin *et al*. [10] had studied the machining of Al356/SiC/20p with polycrystalline diamond (PCD) tools under various cutting speed, feed rate and at constant depth of cut. The tool life data had been analyzed using regression and general form of the Taylor's equation was developed to describe the tool performance for the Al356/SiC/20p composite. The time required to reach the tool wear limit decreased with increases of speed and feed. However, the volume of material removed before reaching the wear limit increased with the higher feed rate. A Manna *et al.* [11] investigated the machining of Al/SiC/20p composite material with uncoated tungsten carbide (WB) K-10 type tools. Analysis of variance was employed to investigate the influence of cutting speed, feed and depth of cut on surface roughness. It was observed that the surface roughness affected by cutting speed, feed rates and depth of cut, while the feed rates and depth of cut affected the maximum peak-to-valley roughness height. M Seeman *et al*. [12] studied the machinability of Al/SiC/20p composite material with uncoated carbide tool (K-10) inserts. Response Surface Methodology (RSM) was employed to investigate the machining parameters including cutting speed, feed rates, depth of cut and machining time on the basis of performance characteristics such as tool flank wear and surface roughness. K. Palanikumar [13] developed a model for surface roughness prediction through response surface method (RSM) for machining of glass fiber reinforced (GFRP) composites. Four factors, five level, central composite rotatable design matrix was employed to carry out the experimental investigation. Analysis of variance was also used to check the validity of the model. E.L. Gallab *et al.* [14] had studied PCD tool performance during high-speed turning of Al/SiC/20p MMC and reported that PCD tools suffered excessive edge chipping and crater wear during the machining of the MMC. From the literature it is observed that the machining of Al based MMC is an important research area but only very few research have been carried out on machining of *in-situ* TiC reinforced composite materials .

Experiment Details

In-situ as-cast Al-4.5%Cu-TiC metal matrix composites were fabricated with weight percentage of 10 by stir casting method. The cylindrical bar specimen of 45 mm diameter and 300 mm length were turned on NH-22 self centered three jaw chuck based lathe made by Hindustan Machine Tools (HMT). The uncoated cemented carbide inserts were used for turning of Al-4.5%Cu-10%TiC composites materials. The specification of cemented carbide inserts was ISO coding CNMG 120408 grade H13A and tool holder specification of ISO DCLNR 2525M12. The cemented carbide inserts were rigidly mounted on tool holder. The angles set with inserts and tool holder were at rake angle of - 6^0, clearance angle of 5^0, negative cutting edge inclination angle of - 6^0, approach angle of 95^0, and nose radius of 0.8 mm respectively. A Kistler Pizoelectric Dynamometer Kistler (Type 9257B) loaded with multi charge amplifier of Kistler (Type 5070) was connected with the tool holder. Data acquisition of machnining was carried out by appropriate software (DynaWare Kistler type 2825A-02).The surface roughness (R_a) was measured by Veeco optical profiling system (WYKO NT1100) instrument with the scan length of 50 µm. Data acquisitions system for machined surface was carried out by Vision 32 software. The microstructure of Al-4.5% Cu/10% TiC cast composite material is shown in Figure2. The full factorial machining parameters (control factors) and their levels are presented in Table 1.

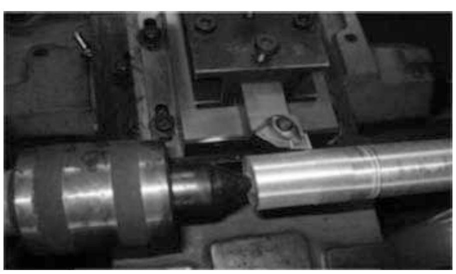

Figure 1. Experimental setup of turning operation

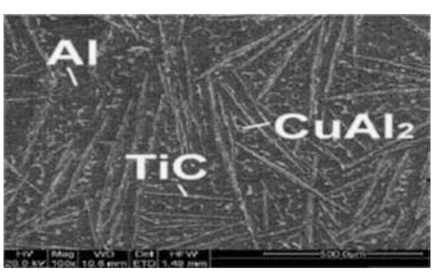

Figure 2. SEM micrograph of Al-4.5%Cu/10%TiC composite material

Mathematical modeling of experimental data

Machining experiment was conducted using the full factorial design matrix as given in Table I. Twenty seven experiments with replication was done and the average experimental data for the full factorial experiment is given in Table II. The responses of the experiment such as cutting force and surface roughness values for the twenty seven experiments are also presented in Table II.

Table I. Process parameters (control factors) for turning operation

Sl. No.	Parameters	Unit	Level 1	Level 2	Level 3
1	Cutting Speed	mm/min	40	80	120
2	Feed	mm/rev	0.12	0.24	0.36
3	Depth of Cut	mm	0.5	0.75	1.00

Table II. Turning conditions and machining responses of MMC

Sl. No.	Cutting Speed (m/min)	Feed (mm/rev.)	Depth of Cut (mm)	Cutting force, F_z (N)	Surface roughness R_a (µm)
1	1	1	1	47.22	2.670
2	1	1	2	84.68	3.140
3	1	1	3	119.35	3.590
4	1	2	1	108.82	3.094
5	1	2	2	149.75	3.571
6	1	2	3	189.67	4.023
7	1	3	1	182.35	3.510
8	1	3	2	224.56	3.890
9	1	3	3	256.85	4.340
10	2	1	1	45.67	1.960
11	2	1	2	87.59	2.460
12	2	1	3	126.56	2.935
13	2	2	1	119.62	2.391
14	2	2	2	153.55	2.780
15	2	2	3	184.22	3.120
16	2	3	1	191.81	2.560
17	2	3	2	226.34	2.970
18	2	3	3	267.65	3.699
19	3	1	1	42.04	1.380
20	3	1	2	75.97	1.792
21	3	1	3	116.89	2.296
22	3	2	1	107.68	1.895
23	3	2	2	140.09	2.260
24	3	2	3	177.66	2.734
25	3	3	1	169.87	2.430
26	3	3	2	208.54	2.934
27	3	3	3	322.39	3.294

The full factorial experimental data was used for building the mathematical model for the turning operation of Al-4.5%Cu/10%TiC composite. Analysis of Variance (ANOVA) was used to investigate the effect of the control factors on the responses such as cutting force and resulting surface roughness. ANOVA is a method of apportioning variability of an output to various inputs. Table III& IV shows the results of ANOVA analysis from MINITAB 13.1 software [15]. The purpose of the analysis of variance was to investigate which machining parameters that significantly affect the performance characteristics such as cutting force and resulting surface roughness. Initially the experimental data was analyzed using the ANOVA. Table III and Table IV, shows the ANOVA for responses such as cutting force, F_z and surface roughness, R_a respectively. From Table III the significance of control factors such as cutting speed (V), feed (F) and depth of cut (DOC) and their interactions were summarized in terms of "P" value. As indicated from Table III, the "P" values of feed (F) and depth of cut (DOC) are less than 0.05 indicating significance in the regression relation. The "P" value for other terms in Table III such as for cutting speed and interactions is more than 0.05, indicating their non-significance in the regression relation. This is also exhibited in the main effect plots for cutting force, F_z in Figure III.

Table III. Analysis of Variance for cutting force, F_z

Source	DF	Seq SS	Adj SS	Adj MS	F	P
F	2	94857.6	94857.6	47428.8	204.9	0.00
DOC	2	31032.7	31032.7	5516.4	67.04	0.00
V	2	123.7	123.7	61.8	0.27	0.77
F*DOC	4	932.2	932.2	233.1	1.01	0.46
F*V	4	395.2	395.2	98.8	0.43	0.79
DOC*V	4	926.6	926.6	231.7	1.00	0.46
Error	8	1851.7	1851.7	231.5		
Total	26	130119.8				

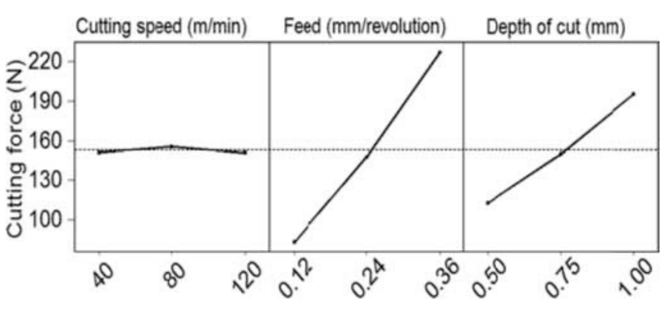

Figure 3. Main effects plot data means for cutting force F_z (N)

Based on the ANOVA Table 3 and the main effect plot for the cutting force, F_z in Figure 3, the regression equation is developed for predicting the cutting force and given in equation 1.

$$Fz = -116 - 0.0029*cutting\ speed + 604*feed + 166*DOC \quad (1)$$

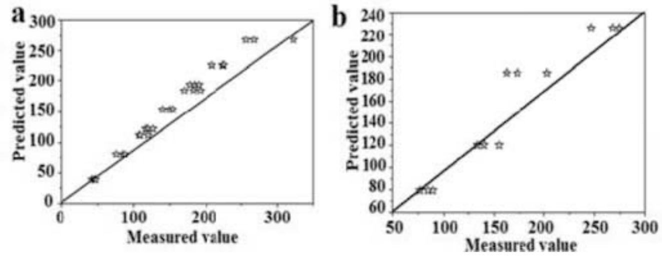

Figure 4. Measured and predicted value of cutting force F_z (N) from the regression equation: (a) For the full factorial experimental data; (b) For the test cases

Measured and predicted value of cutting force F_z (N) from the regression equation(1) for the full factorial experimental data given in Table II and for the test cases are plotted in Figure IV. It can be observed from Figure IV that there is close agreement between the measured and predicted values of cutting forces for the experimental and test cases.

Table IV. Analysis of Variance for surface roughness, R_a

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	2	6.67	6.67	3.37	480.47	0.000
F	2	3.05	3.04	1.53	219.31	0.000
DOC	2	3.68	3.68	1.84	265.26	0.000
V*F	4	0.16	0.16	0.04	5.69	0.018
V*DOC	4	0.01	0.01	0.002	0.22	0.921
F*DOC	4	0.01	0.01	0.003	0.48	0.751
Error	8	0.06	0.06	0.007		
Total	26	13.63				

The data of the surface roughness obtained from the machining of Al-4.5%Cu/10%TiC composite for the twenty seven experiments together with the input control factors presented in Table II were also investigated for the interaction effects of the process variables and ANOVA results are given in Table IV. The significance of control factors such as cutting speed (V), feed (F) and depth of cut (DOC) and their interactions were summarized in terms of "P" value in Table IV. The "P" values of cutting speed (V), feed (F) and depth of cut (DOC) are less than 0.05. The "P" value for other terms in Table IV such as for the interactions is more than 0.05, indicating the non-significance interaction. The main effects of the process variables for surface roughness are presented in Figure 5. From Figure 5 it can be inferred that with increasing the cutting speed the surface roughness of Al-4.5%Cu/10%TiC composite decreases. For example at cutting speed of 120 m/min a surface roughness value of 2.4 µm is achieved. The increasing depth of cut and feed rate have detrimental effects on the surface roughness.

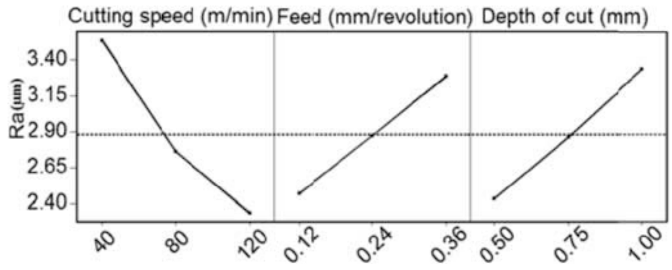

Figure 5. Main effects plot data means for surface roughness, R_a

Based on the ANOVA data and interaction effects of the process variables, the regression equation to predict the surface roughness of Al-4.5%Cu/10%TiC composite is stated in equation (2).

$$R_a = 1.90-0.0150*cutting\ speed +3.43*feed +1.81*DOC \quad (2)$$

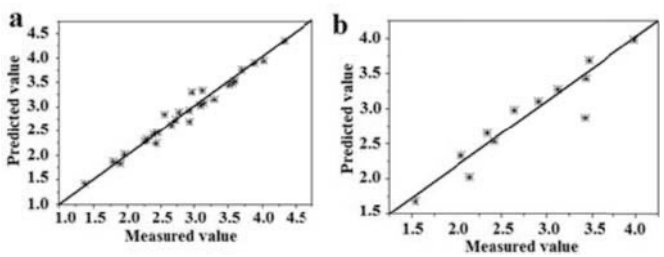

Figure 6. Measured and predicted value of surface roughness, R_a (µm) from the regression equation: (a) For the full factorial experimental data; (b) For the test cases

The regression equation (2) was also tested for a number of test cases, the parameters of which are excluding those of given in Table II. The measured and predicted value of surface roughness, R_a(µm) from the regression equation for the full factorial experimental data and for the test cases are shown in Figure 6. It can be observed from Figure 6 that there is close agreement between the experimental and predicted values of surface roughness, indicating the adequacy of the regression model.

Conclusion

From the machining experiment it is observed that the *in-situ* Al-4.5%Cu/10%TiC composite is machinable with the use of cemented carbide inserts with appreciable surface roughness and tolerable cutting force. The machining force generated did not lead to detrimental chattering and vibration of the machine tool. It was also observed that the cutting force was directly proportional to feed and depth of cut. The cutting speed had marginal effect on the cutting force. However, the cutting speed was having significant effect on the surface roughness of *in-situ* Al-4.5%Cu/10%TiC composite. The length of removal chips from composite material was longer at higher cutting speed and low depth of cut. Feed and depth cut were having similar effect on both cutting force and surface roughness. The full factorial experimental data was utilized in developing the mathematical model for predicting the machining responses such as cutting force and surface roughness. The regression equations were developed based on the significance of control factors and interactions. Close agreement was observed between the experimental and regression equation predicted values of cutting force and surface roughness.

Reference

1. M.Gupta and M.K. Surappa, "Processing-Microstructure-Mechanical Properties of Al Based Metal Matrix Composites Synthesized Using Casting Route", *Key Engineering Materials*, Part 1, 259 (1995), 104-107.
2. S.Prabu Balasivanandha , L. Karunamoorthy , S. Kathiresan , B. Mohan. "Influence of Stirring Speed and Stirring Time on Distribution of Particles in Cast Metal Matrix Composite". *J.of Materials Processing Technology*, 171(2006), 268-273.
3. Jasmi Hashim,"The Production of the Cast Metal Matrix Composites by a Method of Stir Casting Method", *Journal Teknolgi*, Vol. 35(A) (2001), 9-20.
4. D.B. Miracle"Metal Matrix Composites-From Science and Technological Significance". *Composites Science and Technology*, 65 (2005), 26-2540.
5. A.Mahamani, " Machinability Study of Al-5Cu-TiB2 In-situ Metal Matrix Composites Fabricated by Flux-assisted Synthesis", *Journal of Minerals & Materials Characterization & Engineering*, Vol. 10, No.13(2011),1243-1254.
6. N. Muthukrishnan & M. Murugan & K. Prahlada Rao "Machinability Issues in Turning of Al-SiC (10p) Metal Matrix Composites". *Int J Adv Manuf Technol* , 39(2008), 211–218
7. Quan Yanming, Zhou Zehua, "Tool Wear and its Mechanism for Cutting SiC Particle-Reinforced Aluminium Matrix Composites". *Journal of Materials Processing Technology*, 100 (2000), 194-199.
8. R.M. Hooper, J.L. Henshall, A. Llopfer, "The Wear of Polycrystalline Diamond Tools Used in the Cutting of Metal Matrix Composites". *Int J Refract Met Hard mater* 17(1999), 103–109.
9. X. Ding, W.Y.H. Liew, X.D. Liu "Evaluation of Machining Performance of MMC with PCBN and PCD Tools". *Wear* 259 (2005) 1225–1234.
10. J.T. Lin, D. Bhattacharyya, and C. Lane "Machinability of a Silicon Carbide Reinforced Aluminium Metal Matrix Composite". *Wear* 181-183 (1995) 883-888.
11. A. Manna, B. Bhattacharyya, "Investigation for Optimal Parametric Combination for Achieving Better Surface Finish during Turning of Al /SiC-MMC". *Int J Adv Manuf Technol* 23(2004), 658–665.
12. M. Seeman & G. Ganesan & R. Karthikeyan & A. Velayudham "Study on Tool Wear and Surface Roughness in Machining of Particulate Aluminum Metal Matrix Composite-Response Surface Methodology Approach". *Int J Adv Manuf Technol*, 48(2010), 613–624.
13. K.Palanikumar, "Modeling and Analysis for Surface Roughness in Machining Glass Fibre Reinforced Plastics using Response Surface Methodology". *Mater Des* 28(2007), 2611-2618.
14. El-Gallab M, M.Sklad, "Machining of Al/SiC Particulate Metal-Matrix Composites part I & II", *J Mater Process Technol* 83(1998), (151–158):277–285.
15. Minitab Inc User manual of MINITAB Statistical Software. Release 13.31 (2000) State College PA 16801 USA.