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ORIGINAL ARTICLE

Combined machining of SiC/Al composites based on blasting erosion arc machining and CNC milling

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Abstract In this study, a combined method is proposed for the machining of SiC/Al matrix composites to achieve high efficiency and better surface quality based on blasting erosion arc machining (BEAM) and computer numerical control (CNC) milling. The combined method consists of two stages. BEAM is adopted in the first stage to achieve a high machining efficiency. During this stage, the negative BEAM is used for improving material removal rate (MRR) while positive BEAM is adopted to reduce roughness of machined surface. In the second stage, CNC milling is utilized to achieve a fine surface. Firstly, in order to perform the combined processing, a special machine tool system is designed. Secondly, machining efficiency of the combined processing is discussed. It is disclosed that in the negative BEAM step, when peak current is 600 A, MRR of 20 vol.% SiC/Al and 50 vol.% SiC/Al composites can be as high as 10,200 and 7500 mm^3/min separately. Thirdly, comparison experiments are designed and surface integrity (e.g., surface topography, surface roughness, heat affect zone, surface hardness, compositions) of each machining stage is analyzed. It is demonstrated that in the CNC milling stage, side effects of BEAM on the workpiece (e.g., rough surface, thick heat affect zone) can be eliminated effectively. The roughness of the machined surface can be lower than Ra 0.5 μm; heat affect zone (HAZ) and debris almost cannot be observed. Finally, a SiC/Al workpiece is machined to demonstrate the advantages of the combined machining of SiC/Al matrix composites.

Keywords Combined · SiC/Al · Efficiency · Surface · BEAM · Milling

1 Introduction

SiC/Al is regarded as one of the most important metal matrix composites [1]. Incorporation of silicon carbide particles enhances the properties like adhesive, abrasive, diffusion wear resistance, thermal properties, hardness, and stiffness [2]. These properties give this material a wider application area, including its use as advanced engineering ceramics, aerospace materials, nuclear energy processing materials, high-performance semiconductor materials, and ballistic protection materials [3]. Among the combinations of the matrix and reinforcements, despite the superior mechanical and thermal properties of SiC/Al MMC, its poor machinability has been the main deterrent to its substitution for metal parts [4].

Traditional machining processes such as turning [5, 6], drilling [7], and grinding [8] can be used for the machining of the SiC/Al. The main problems of the cutting processes are the severe tool wear and high machining costs. For instance, Bhushan studied turning of 15 wt.% (about 12–15 vol.%) SiC/Al composites and found that the optimized material removal rate (MRR) was about 2700 mm^3/min (cutting speed was 90 m/min, feed rate was 0.15 mm/rev, and cutting depth was 0.2 mm) [6]. Especially, when machining

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high-volume fraction SiC/Al composites, the SiC particles make the material much more difficult to cut, which leads to a typically low machining efficiency. For example, Muguthu et al. [9] used an optimization method to find the optimal parameters for the turning 45 wt.% (about 40 vol.%) SiC/Al metal matrix composite using polycrystalline cubic boron nitride (PCBN) and polycrystalline diamond (PCD) tools, and they reported that the MRR was about 1200 mm^3/min with the optimal combination of parameters (cutting speed 40 m/min, feed rate 0.15 mm/rev, depth of cut 0.20 mm) .

Non-traditional machining, such as electric discharge machining (EDM) [10], wire electrical discharge machining (WEDM) [4], and electrochemical machining (ECM) [11], have been adopted for the machining of SiC/Al composites by many researchers. The disadvantage of the non-traditional machining of SiC/Al composites mainly lies on the limited machining efficiency. For instance, Mohan et al. [10] employed a tubular electrode to machine 20 vol.% SiC/Al matrix composites with EDM, and the maximum MRR was only about 60 mm^3/min (peak current 11 A and pulse duration 0.088 ms). Seo et al. [12] conducted EDM drilling of 20 vol.% SiC/Al matrix composites and found that the MRR was about 140 mm^3/min (peak current 100 A and the pulse duration 0.5 ms).

Blasting erosion arc machining (BEAM) [13] is a newly developed machining technology based on hydrodynamic arc breaking mechanism. The principle of the BEAM is described as the following: by performing a strong multi-hole inner flushing, the arc plasma column in the discharge gap will be stretched, elongated, or even broken by the strong hydrodynamic force. When the arcing plasma column breaks, an extremely strong blasting occurs, and the coexisting shockwave blows off the molten material explosively from the molten pool on the workpiece [14]. Xu et al. [15] conducted experiments on the machining nickel-based alloy with BEAM utilizing a bundled electrode and found that a significantly high MRR (up to 14,000 mm^3/min) and low TWR (down to 1%) can be obtained under the peak current of 500 A. Chen et al. [16] studied the processing of titanium alloy with BEAM and machined a blade sample successfully (MRR was higher than 16,800 mm^3/min).

As we know, metal matrix composites are conventionally fabricated using different techniques such as power metallurgy, squeeze casting, and stir casting [17]. Particle reinforced SiC/Al composites are typical SiC/Al composites, the common reinforcement fractions are 20 vol.%, 50 vol.%, etc. 20 vol.% SiC/Al is a kind of low-SiC fraction material while 50 vol.% SiC/Al stands for high-SiC fraction materials. The machining performance of the different SiC fraction composites is generally not the same. Recently, Gu [14] and Chen [18] respectively conducted experiments on the machining of 20 vol.% SiC/Al and 50 vol.% SiC/Al composites. According to their results, although BEAM can be utilized for the machining of SiC/Al composites with high efficiency, the machined surfaces are quite rough, which is not suitable for further finishing processes.

In order to improve machined surface quality, other processes such as cutting methods can be adopted after BEAM. However, BEAM and the following traditional refining processes generally cannot be executed in one machine. Because BEAM is a thermal process while milling belongs to cutting process, the workpiece has to be re-fixed after the first process, which causes a lot of preparation time as well as increasing the costs in the demand of at least two kinds of machine tools.

Aim at realizing high-efficiency machining with good surface quality and limited preparation time, the combined processing method is proposed. This combined process is achieved by combining BEAM and CNC milling. The principle of the combined processing method was introduced firstly. And then, a special machining system and an exchangeable BEAM flushing device were designed. Secondly, comparison experiments were conducted on two typical volume fraction (20 and 50 vol.%) SiC/Al composites and machined surface quality was analyzed. Finally, a SiC/Al workpiece sample was machined with the combined machining to demonstrate the applicability of this novel processing.

2 The combined machining method

2.1 Schematic of the combined machining

The combined processing is an enhanced material removal process that has a better machining ability by combining at last two effects of the processes. Figure 1 shows

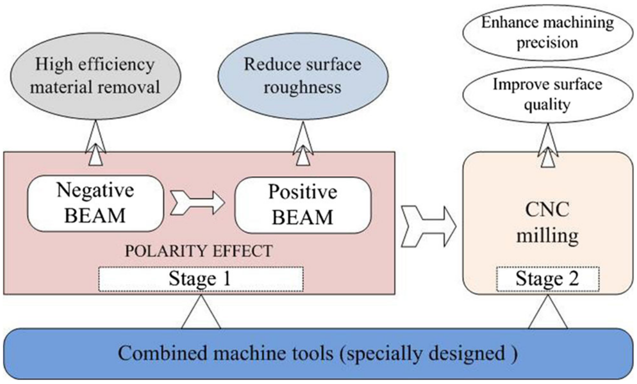

Fig. 1 Compositions of the combined processing

the schematic of the combined machining. The combined processing consists of two stages: BEAM and CNC milling.

Stage 1: High-efficiency machining with BEAM.

The main purpose of stage 1 is to achieve high-efficiency machining of SiC/Al composites based on the BEAM. BEAM is a thermal process which removes workpicec material with arc discharge. When adopting BEAM for the machining of difficult-to-cut materials, e.g., titanium alloy, the specific energy efficiency (divide MRR by current) can be over ten times of the EDM processing [16].

It is known that polarity effects [15] exist in BEAM, that is, machining with different polarities appear different machining efficiencies and surface characters. Generally, negative BEAM can achieve higher machining efficiency and rougher machined surface, while in positive BEAM, machined surfaces are smoother but machining efficiency is lower. Based on polarity effects, stage 1 contains two kinds of machining polarity, negative BEAM and positive BEAM. Negative BEAM is designed to realize high-efficiency material removal while positive BEAM is adopted to reduce surface roughness.

Stage 2: Refining surface quality with CNC milling.

It is noted that although the machining efficiency of BEAM is very high, machined surfaces are quite rough. Even after adopting positive BEAM, the surfaces are still too rough to meet finishing or semi-finishing demands. Besides, the heavy-tool electrode wear in the BEAM will enlarge the machining error. Consequently, CNC milling is adopted in stage 2 to achieve machining precision and surface quality.

Since stage 2 is milling process, a CNC milling machine will be competent. However, stage 1 is BEAM processing, which requires high interior flushing and electricity supply. In order to integrate stage 1 and stage 2 into a same machine tool to reduce non-machining time, a combined machine tool needs to be specially designed.

2.2 Machining system design

BEAM and CNC milling are quite different machining methods, they remove material based on totally different mechanisms. In order to perform combined machining, a machine tool is specially designed. Design principle of the combined machine tool is shown in Fig. 2. The machining system is designed and modified based on a five-axis CNC milling center. Originally, the CNC milling machine is competent for milling but did not contain systems that are necessary for BEAM. Consequently, a pulse generator, a gap condition detection system, and a replaceable BEAM flushing device are necessary.

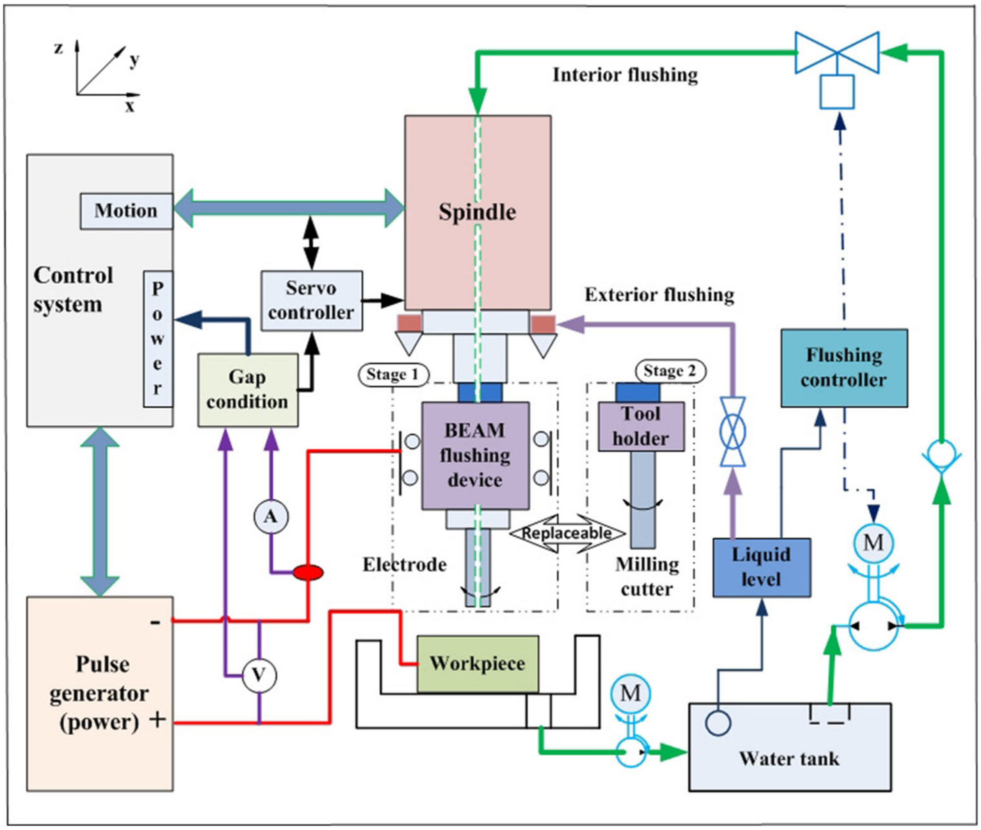

Fig. 2 Design principle of the combined machine tool

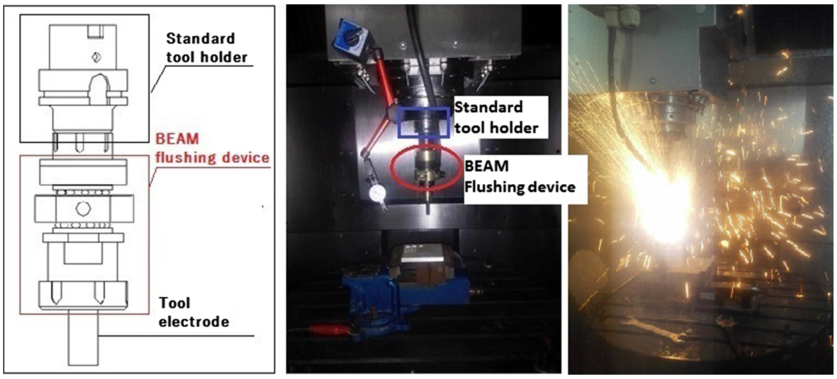

Fig. 3 BEAM flushing device

The pulse generator supplies high-energy pulse to conduct arc discharge. Current, voltage, pulse duration, and pulse interval are the main parameters which affect machining performance of BEAM. During machining, current and voltage can be monitored with gap condition detection system (including Rogowski coil, conversion unit, and oscilloscope). Besides, the design of flushing is to supply high-pressure dielectric to form fluid dynamics-based arc break.

The setup of BEAM flushing device is shown in Fig. 3.

Main design parameters of the BEAM is listed in Table 1.

Flushing is necessary both for BEAM and milling, while BEAM needs interior flushing and the CNC milling needs exterior flushing. So both interior and exterior flushing are supported in the machine tool. One pipe supplies high-pressure fluid through motorized spindle to BEAM flushing device and another pipe supplies water-based working fluid to exterior nozzles for milling. When the machining system conducts BEAM, exterior flushing is shut off. On the contrary, interior flushing will be shut off in the milling processing.

In stage 1, BEAM is conducted and the cylinder tool electrode feeds in milling mode; tool electrode is fixed on a flushing device. Negative BEAM can be switched to positive BEAM by reversing the polarity of the power. While in stage 2, flushing device used for BEAM is removed and a milling cutter is fixed on the spindle with a standard tool holder.

3 Machining efficiency

The combined processing contains totally three machining steps (negative BEAM, positive BEAM, and milling). The total MRR of the combined machining (M_{com}) is calculated by

$$M_{\mathrm{com}} = \left(M_{\mathrm{ne}} \times t_{\mathrm{ne}} + M_{\mathrm{po}} \times t_{\mathrm{po}} + M_{\mathrm{mi}} \times t_{\mathrm{mi}}\right) / \left(t_{\mathrm{ne}} + t_{\mathrm{po}} + t_{\mathrm{mi}}\right) \tag{1}$$

where M_{ne} ,M_{po}, and M_{mi} are the MRR of negative BEAM, positive BEAM, and milling respectively; and t_{ne} ,t_{po}, and t_{mi} are the corresponding machining time in the combined processing.

In the combined processing, negative BEAM is positioned to achieve high machining efficiency, positive BEAM is adopted to reduce surface roughness, and the milling is performed as semi-finishing or finishing machining. Most of bulk material removal depends on negative BEAM, while positive BEAM and milling are utilized to perform small allowance machining. Compared to t_{ne}, t_{po}, and t_{mi} are small; consequently, the MRR of the combined processing is mainly determined by MRR of the negative BEAM.

Gu and Chen [14, 18] studied the performance of machining 20 vol.% and 50 vol.% SiC/Al matrix composites with BEAM. According to their reports, MRR of machining SiC/Al is mainly effected by current (I_{p}), pulse duration (t_{on}), and pulse interval (t_{off}), as shown in Fig. 4.

It can be concluded that MRR of negative BEAM increases with peak current and pulse duration, but declines with the elongation of pulse interval. Therefore, in order to increase the machining efficiency, higher peak current, longer pulse duration, and shorter pulse interval should be applied. According to optimization results reported by Gu and Chen, when peak current is 600 A, the MRR of 20 vol.% and 50 vol.% SiC/Al composites can be as high as 10,200 and 7500 mm^3/min separately. Some typical machining parameters are listed in Table 2.

Table 1 Design parameters for BEAM flushing device

Current I_{p} (A)	Pulse duration t_{on} (ms)	Pulse interval t_{off} (ms)	Spindle speed s (rpm)	Flushing pressure p (MPa)
100–1000	0.5–10	0–10	$\geq$ 1000	$\geq$ 1.0

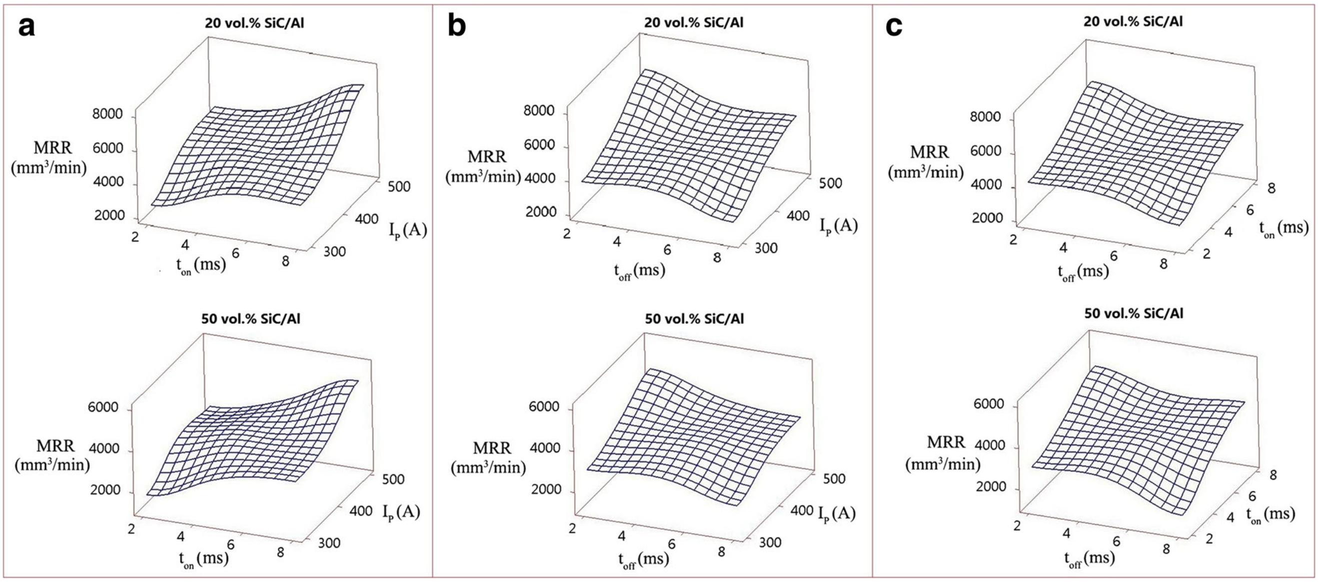

Fig. 4 MRR vs current and pulse duration (**a**), current and pulse interval (**b**), and pulse duration and pulse interval (**c**)[14, 18]

Table 2 Typical machining parameters of BEAM

20 vol.% SiC/Al				50 vol.% SiC/Al			
I_p (A)	t_{on} (ms)	t_{off} (ms)	MRR (mm^3/min)	I_p (A)	t_{on} (ms)	t_{off} (ms)	MRR (mm^3/min)
400	5	5	4670	400	5	5	3600
500	8	2	8400	500	8	2	6000
600	10	1	10,200	600	8	1	7500

Table 3 Experimental parameters

Parameters	Stage 1	Stage 2
Tool diameter (mm)	20	8
Discharge parameters	I_p = 500 A, t_{on} = 8 ms, t_{off} = 2 ms	/
Spindle speed (rpm)	1000	3000
Cutting depth (mm)	3	0.5
Feeding rate (mm/min)	Negative BEAM 140 (20 vol.% SiC/Al) 100 (50 vol.% SiC/Al) Positive BEAM 85 (20 vol.% SiC/Al) 60 (50 vol.% SiC/Al)	100 (20 vol.% SiC/Al) 50 (50 vol.% SiC/Al)

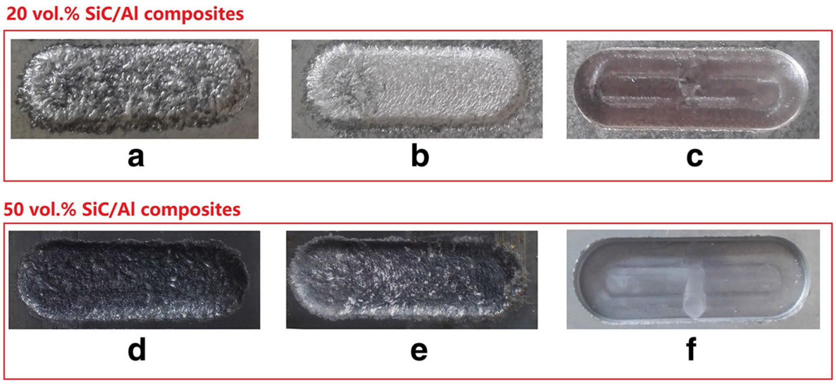

Fig. 5 Machined surface comparison **a** negative BEAM-20 vol.% SiC/Al; **b** positive BEAM-20 vol.% SiC/Al; **c** milling-20 vol.% SiC/Al; **d** negative BEAM-50 vol.% SiC/Al; **e** positive BEAM-50 vol.% SiC/Al; **f** milling-50 vol.% SiC/Al

4 Surface integrity analysis

Surface integrity of the combined processing was tested. Machining parameters are listed in Table 3. In stage 1, peak current 500 A, pulse duration 8 ms, and pulse interval 2 ms were selected as the machining parameters. The cylinder (ϕ 20 mm) tool electrode was made of graphite with 12 flushing holes (ϕ 2 mm) and the flushing pressure was 1.0 MPa. The machined groove was 20 mm wide, 60 mm long, and 3 mm deep. In stage 2, a PCD milling cutter (ϕ 8 mm) was chosen as the cutting tool, the spindle speed was set 3000 rpm, cutting depth was 0.5 mm, and machined allowance was 1 mm.

The surfaces was observed by a scanning electron microscope (SEM, type: JEOL JSM-7800F Prime) and the section view was observed by metallomicroscope (Axio Imager A1m). And the surface roughness was measured by Mitutoyo SJ-210. The discharge craters of 20 vol.% and 50 vol.% SiC/Al composites were observed with a confocal microscopy (type: ZEISS LSM700). Besides, the surface compositions were analyzed by energy-dispersive spectrometer (EDS, type: Thermo NORAN 7).

4.1 Surface roughness

Machined surfaces of 20 vol.% and 50 vol.% SiC/Al composites at different stages are shown in Fig. 5. It is obvious that the surface roughness is reduced after positive BEAM. Especially after milling, metallic luster appears.

The roughness of machined surfaces are measured and the average value is listed in Table 4. It indicates that surfaces in BEAM stage is far from satisfaction. For example, the average roughness of machining 20 vol.% SiC/Al composites with negative BEAM can be higher than Ra 25 μm. While adopting positive BEAM, it can be reduced to Ra 11.31 μm, which is still much rough. However, the average roughness of both 20 vol.% SiC/Al and 50 vol.% SiC/Al composites can be less than Ra 0.5 μm after milling.

4.2 Surface topography and composition

SEM observation of machined surface is shown in Fig. 6. Micro cracks and craters can be found on the BEAM-machined surfaces. Under high discharge energy (e.g., 500-A current) conditions, materials are heated in discharge durations and then cooled by dielectric rapidly in the pulse interval (less than several milliseconds). Dramatic temperature fluctuations are very easy to cause cracks and craters.

Panels e and f in Fig. 6 respectively show the SEM observation of 20 vol.% and 50 vol.% SiC/Al composite surfaces that machined by milling. It can be found that cracks and craters generated in BEAM stage can by eliminated by CNC milling effectively.

Surface composition is measured with energy-dispersive spectrometer (EDS). Three measuring areas were selected for each machining condition and results are listed in Table 5. In both BEAM stage and milling stage, the machined surface contains O (oxygen) element, which

Table 4 Surface roughness comparison

Step	20 vol. % SiC/Al		50 vol.% SiC/Al	
	Ra (μm)	Standard deviation	Ra (μm)	Standard deviation
Negative BEAM	> 25	/	15.15	2.7
Positive BEAM	11.31	1.07	10.78	0.71
Milling	0.36	0.0.9	0.24	0.12

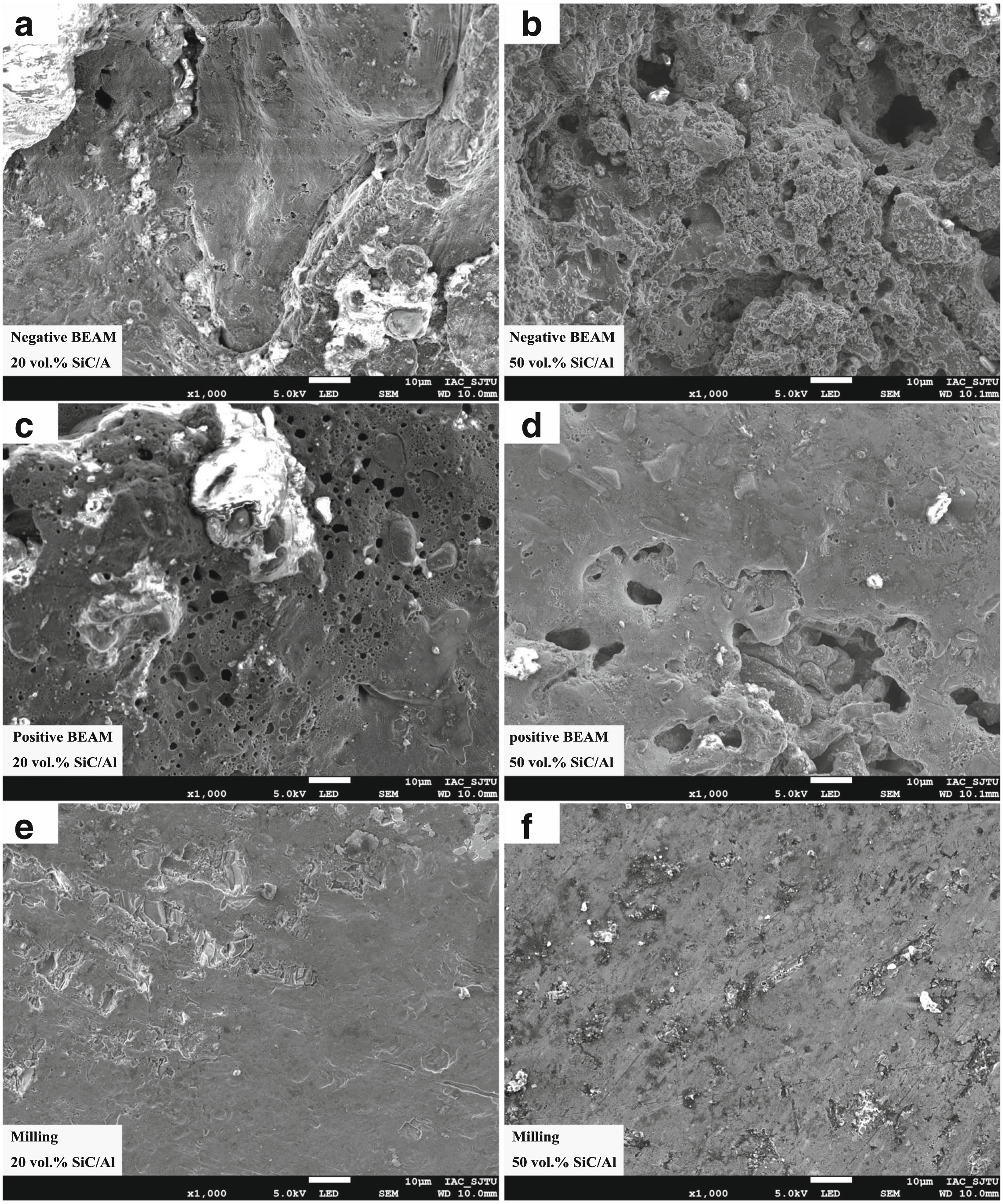

Fig. 6 SEM observation on machined surfaces

indicates that the wokepiece material is oxidized to a certain extent. The difference is higher scale of O element can be found in BEAM stage (especially in negative BEAM step).

After milling, percentage of O element is much low and Al element becomes high. It can be demonstrated that oxidized surface of negative BEAM can be improved by positive BEAM and then cut by milling.

4.3 Surface hardness

Machined surface hardness is shown in Fig. 7. Compared to base material, the hardness of 20 vol.% SiC/Al increases. This is because characteristics of 20 vol.% SiC/Al are similar to that of the matrix material (Al). During the machining, the workpiece is heated by the high-temperature arc plasma

Table 5 Surface compositions (measured with EDS)

		20 vol.% SiC/Al				50 vol.% SiC/Al			
		C-K	O-K	Al-K	Si-K	C-K	O-K	Al-K	Si-K
Negative BEAM	Base-pt1	9.11	26.23	51.49	1.74	7.25	31.96	29.64	29.00
	Base-_pt2	9.80	29.78	48.61	11.49	17.19	11.51	36.35	28.61
	Base-_pt3	12.73	23.16	46.53	13.58	16.14	21.61	28.86	30.89
	Average	10.55	26.39	48.88	8.94	13.53	21.69	31.62	29.50
Negative BEAM	Base-pt1	6.17	7.84	64.80	11.62	10.19	16.52	42.57	29.13
	Base-_pt2	2.86	6.54	73.06	9.47	12.37	13.91	33.35	37.86
	Base-_pt3	10.05	9.46	67.92	11.08	7.15	17.99	36.76	30.94
	Average	6.36	7.95	68.59	10.72	9.90	16.14	37.56	32.64
CNC Milling	Base-pt1	3.96	8.00	79.07	7.65	18.04	7.22	46.00	24.56
	Base-_pt2	4.92	3.19	84.57	5.57	19.70	14.61	39.64	24.42
	Base-_pt3	9.46	2.11	76.54	9.22	16.78	18.25	40.34	20.27
	Average	6.11	4.43	80.06	7.48	18.17	13.36	41.99	23.08

and then cooled by the dielectric within several milliseconds. This heating and cooling process brings metal hardening (similar to aging strengthening effect), which leads to a higher hardness. In contrast, because half of the workpiece material of 50 vol.% SiC/Al is SiC and SiC particles are likely to sublimate and decompose at the melting point(about 3000 K) [19, 20], which can cause the decrease of surface hardness. Besides, some reactions [21] (e.g., Aluminum reacts with SiC to form Al_4C_3 and Si) are found during the process which can also destroy the integrity of SiC particles and reduce surface hardness.

During milling stage, the hardness of 20 vol.% SiC/Al becomes near to that of base material, while the hardness of 50 vol.% SiC/Al is still lower than that of base material (because of sublimation and reactions which caused by milling heat).

4.4 Heat affect zone

Cross section view of 20 vol.% and 50 vol.% SiC/Al composite workpieces is shown in Fig. 8. Because of high discharge energy, the heat-affect zone (HAZ) is much thicker in negative BEAM step. Especially, when machining of 50 vol.% SiC/Al composites with high current, HAZ can be almost as thick as 200 μm. Besides, debris can also be found attached to machined surfaces.

Too thick HAZ and too many debris are generally harmful for the following traditional cutting; therefore, positive BEAM can be utilized to remove debris and reduce the thickness of HAZ. For instance, HAZ of 50 vol.% SiC/Al composites can be reduced to 50 μm after positive BEAM. Especially, HAZ and debris almost cannot be discovered after milling.

5 Discussion

In stage 1, BEAM is adopted and very rough surfaces can be observed; the reason lies on the high discharge energy and high temperature of arc plasma. The power of a single pulse discharge can be higher than 2.5 kW when current is 100 A. Power increases with the increasing of current and pulse on time, for example, when current is 500 A, the power in

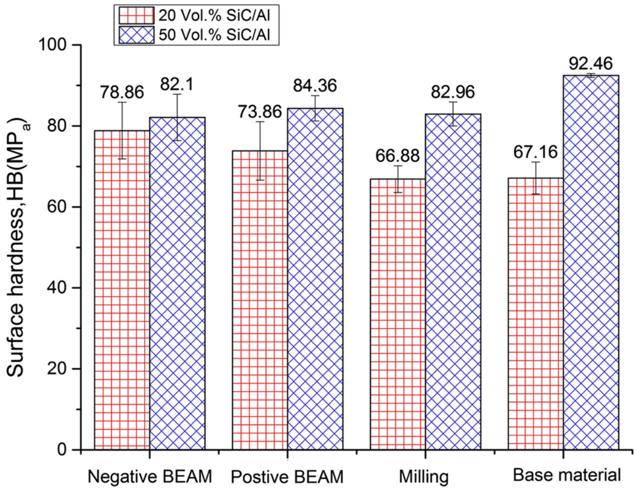

Fig. 7 Hardness of machined surfaces

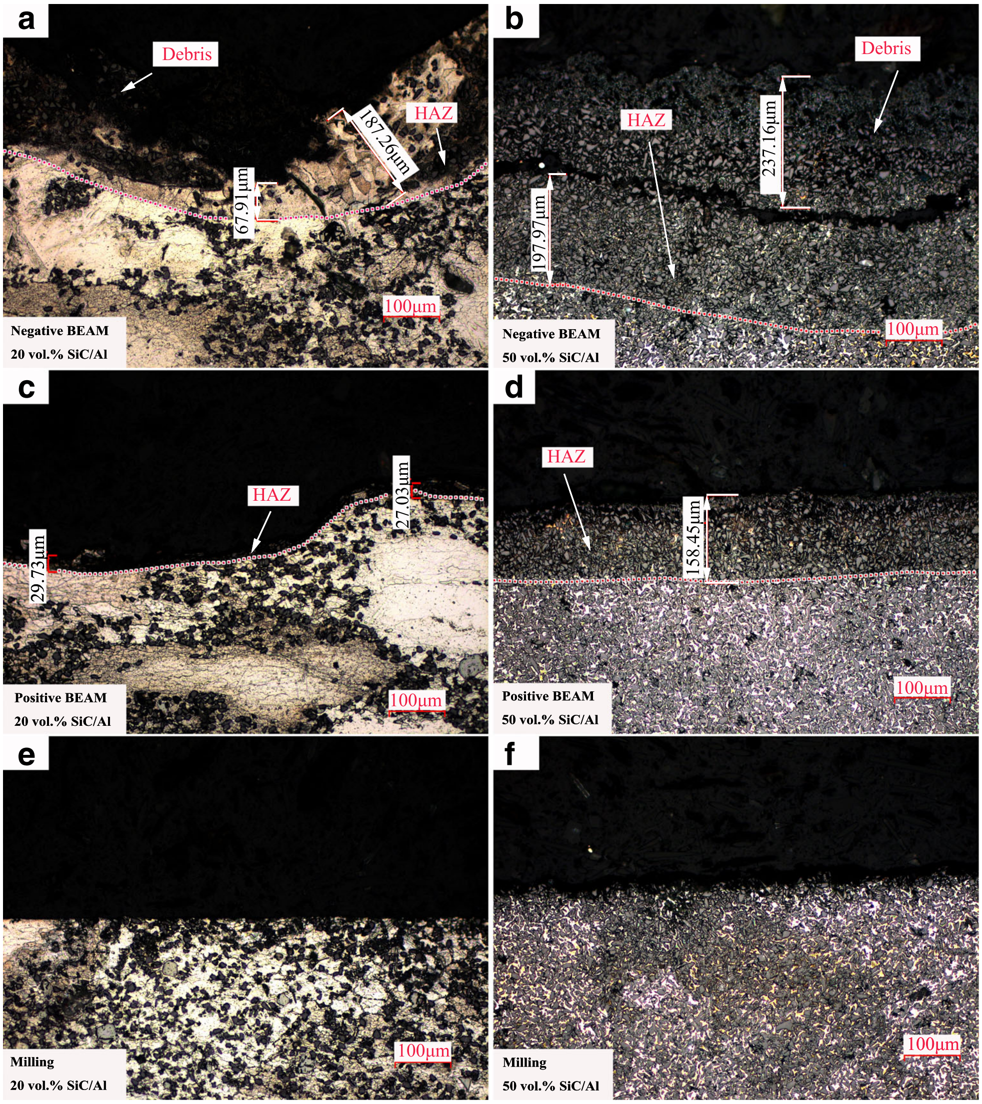

Fig. 8 Metallographic observation of cross section

a single pulse discharge can be as high as 12.5 kW. Consequently, the machining efficiency of BEAM is typically high. However, the side effect of the high discharge power is large discharge craters. The discharge craters can be obviously observed even under small machining parameters. For instance, when current is 100 A and pulse on time is 2 ms, the crater diameter can be larger than 1 mm, and the depth of the crater is greater than 0.2 mm, as shown in Fig. 9. As a result, large discharge craters lead to rough machining surfaces.

After adopting positive BEAM, although surface quality can be improved due to lower energy distribution coefficient

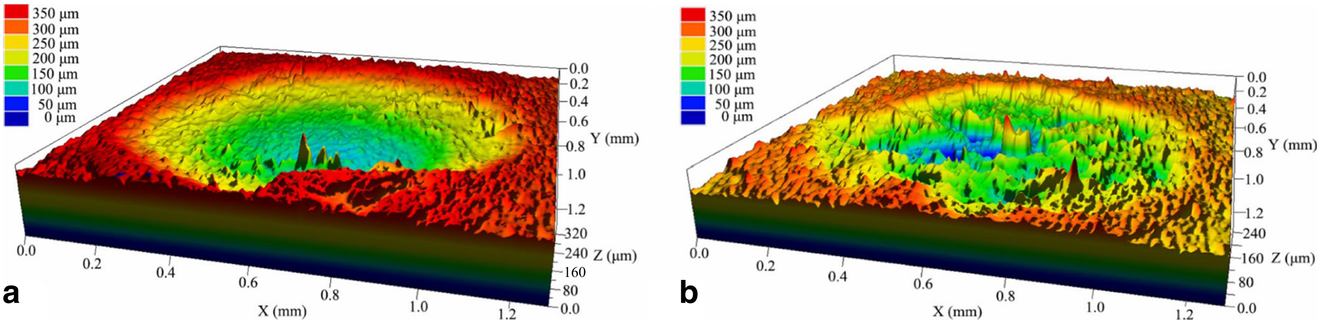

Fig. 9 Discharge caters (100 A). **a** 20 vol.% SiC/Al, and **b** 50 vol.% SiC/Al

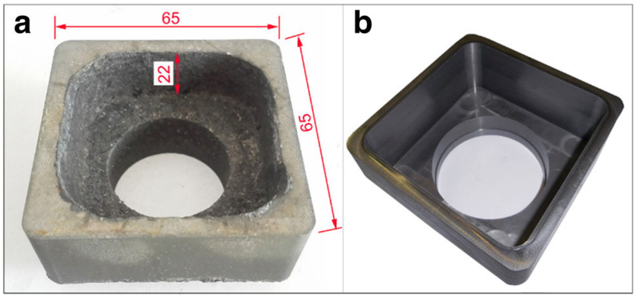

Fig. 10 SiC/Al composites workpiece. **a** Machined with BEAM and **b** machined with milling

(lower energy is distributed to cathode), machined surfaces are still far from satisfaction. And finally, when milling is adopted in stage 2,surfaces are much smoother with high precision.

Further, compared with milling, HAZ thickness of BEAM is much thicker (e.g., near 200 μm, 500 A). BEAM removes workpiece material with high-temperature arc plasma, the temperature of arc plasma can be higher than 10,000 K [22]. Besides, thermal characteristics of SiC are sensitive to temperature, for instance, thermal conductivity of SiC decreases monotonically with the increase of temperature [23]. In discharge process, it is more difficult to transfer discharge heat under lower-thermal conductivity condition, thus, residual heat makes the HAZ of BEAM more thick. When milling SiC/Al, good flushing condition takes away cutting heat and forms thin HAZ.

6 Machining sample

Figure 10 shows a machining sample of SiC/Al matrix composite workpiece, the material of the workpiece is 50 vol.% SiC/Al composites and the dimension of the workpiece is 65 mm × 65 mm × 35 mm. Generally, 50 vol.% SiC/Al is regarded as high-fraction SiC composites which is much more difficult to cut than low fraction (e.g., 20 vol.%) SiC/Al composites. With the combined machining, not only the machining time is reduced more than half of previous cutting processing, but also, machined surfaces are much better. It is demonstrated that the combined processing is available for the machining of SiC/Al matrix composites with high efficiency and good surface quality.

7 Conclusions

In this work, a combined method for the machining of SiC/Al matrix composites based on blasting erosion arc machining (BEAM) and CNC milling is introduced and the machining performance of the combined machining is studied. The following conclusions are drawn based on the above work:

1) In the BEAM stage, both low-volume fraction and high-volume fraction SiC/Al materials can be removed by negative BEAM efficiently.
2) Positive BEAM can remove debris and reduce the thickness of heat-affected zone after negative BEAM. And in both positive and negative BEAM, cracks and craters can be found on the machined surfaces. However, cracks and craters can be eliminated after milling.
3) In milling stage, side effects (e.g., rough surfaces, thick HAZ) of the BEAM stage can be modified. The roughness of the machined surface can be less than Ra 0.5 μm, heat affect zone and debris almost cannot be discovered.
4) With the design of a special combined machine tool, BEAM and traditional milling can be integrated into a same machine tool to reduce non-machining time. The combined processing can be utilized for the machining of SiC/Al matrix composites with high efficiency and good surface quality.

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References

1. Koczak MJ, Khatri SC, Allison JE, Bader MG (1993) Chapter 16–metal-matrix composites for ground vehicle, aerospace, and industrial applications. Funda Metal-Matrix Compos 297–326
2. Bhushan RK, Kumar S, Das S (2010) Effect of machining parameters on surface roughness and tool wear for 7075 Al alloy SiC composite. Int J Adv Manuf Technol 50(5):459–469
3. Zhang ZH, Wang FC, Luo J, Lee SK, Wang L (2010) Microstructures and mechanical properties of spark plasma sintered Al–SiC composites containing high volume fraction of SiC. Mater Sci Eng A 527(27–28):7235–7240
4. Fard RK, Afza RA, Teimouri R (2013) Experimental investigation, intelligent modeling and multi-characteristics optimization of dry wedm process of Al–SiC metal matrix composite. J Manuf Process 15(4):483–494
5. Karthikeyan R, Ganesan G, Nagarazan RS, Pai BC (2001) A critical study on machining of Al/SiC composites. Materi Manuf Processes 16(16(1)):47–60
6. Bhushan RK (2013) Optimization of cutting parameters for minimizing power consumption and maximizing tool life during machining of Al alloy SiC particle composites. J Clean Prod 39(1):242–254

7. Haq AN, Marimuthu P, Jeyapaul R (2008) Multi response optimization of machining parameters of drilling Al/SiC metal matrix composite using Grey relational analysis in the Taguchi method. Int J Adv Manuf Technol 37(3):250–255
8. Thiagarajan C, Sivaramakrishnan R, Somasundaram S (2011) Experimental evaluation of grinding forces and surface finish in cylindrical grinding of Al/SiC metal matrix composites. Proc Instit Mech Engi Part B J Eng Manuf 225(9):1606–1614
9. Muguthu JN, Dong G, Ikua B (2015) Optimization of machining parameters influencing machinability of Al2124SiCP. 45 J Compos Mater 49(2):217–229
10. Mohan B, Rajadurai A, Satyanarayana KG (2004) Electric discharge machining of Al–SiC metal matrix composites using rotary tube electrode. J Mater Process Technol 153–154(1):978–985
11. Senthilkumar C, Ganesan G, Karthikeyan R (2009) Study of electrochemical machining characteristics of Al/SiCP composites. Int J Adv Manuf Technol 43(3):256–263
12. Seo YW, Kim D, Ramulu M (2006) Electrical discharge machining of functionally graded 15–35 vol % SiCP/Al composites. Mater Manuf Process 21(5):479–487
13. Zhao W, Gu L, Xu H, Li L, Xiang X (2013) A novel high efficiency electrical erosion process—blasting erosion arc machining 621–625
14. Gu L, Chen J, Xu H, Zhao W (2016) Blasting erosion arc machining of 20 vol.% SiC/Al metal matrix composites. Int J Adv Manuf Technol 87(9-12):1–10
15. Xu H, Gu L, Chen J, Hu J, Zhao W (2015) Machining characteristics of nickel-based alloy with positive polarity blasting erosion arc machining. Int J Adv Manuf Technol 79(5):937–947
16. Chen J, Gu L, Xu H, Zhao W (2016) Study on blasting erosion arc machining of Ti–6Al–4V alloy. Int J Adv Manuf Technol 85(9):2819–2829
17. Bhushan RK, Kumar S, Das S (2013) Fabrication and characterization of 7075 Al alloy reinforced with SiC particulates. Int J Adv Manuf Technol 65(5-8):611–624
18. Chen J, Gu L, Zhu Y, Zhao W (2017) High efficiency blasting erosion arc machining of 50 vol. Institut Mech Eng Part B J Eng Manuf 1–9
19. Abbate C, Busatto G, Cova P, Delmonte N, Giuliani F, Iannuzzo F, Sanseverino A, Velardi F (2014) Thermal damage in SiC Schottky diodes induced by Se heavy ions. Microelectron Reliab 54(9-10):2200–2206
20. Bhatnagar M, Baliga BJ (1993) Comparison of 6H-SiC, 3C-SiC, and Si for power devices. IEEE Trans Electron Dev 40(3):645–655
21. Lee JM, Kang SB, Kamio A, Sato T, Tezuka H (1999) Microstructural changes in Al-Cu-Mn alloy reinforced with SiC particles on holding at high temperatures. Mater Trans Jim 40(6):537–545
22. Yang Y, Cho YI, Fridman A, Yang Y, Cho YI, Fridman A (2012) Plasma discharge in liquid: water treatment and applications. Aiche J 59(11):4451–4451
23. Wei R, Song S, Yang K, Cui Y, Peng Y, Chen X, Hu X, Xu X (2013) Thermal conductivity of 4H-SiC single crystals. J Appl Phys 113(5):283