Experimental Investigation of Microchannel Milling on Zirconia (ZrO_2) by Using Pulsed Fiber Laser

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Abstract

Laser beam micro-milling is one of the significant microfabrication techniques in which laser beam is employed to remove material from difficult-to-machine materials especially alumina, zirconia, aluminum nitride, titanium alloy etc. In the present paper, an attempt has been made to carry out experimental investigation into generation of micro-channel utilizing laser micro-milling process on flat zirconia (ZrO_2) ceramics using pulsed fiber laser system. Micro-channels were fabricated utilizing laser micro-milling scanning strategies for each layer of scan. Process parameters for the present study considered are laser power, pulse frequency, laser scanning speed, transverse feed and number of laser scan. For obtaining the desired dimensions of micro-channels as well as surface quality machined at various parametric combinations, one factor at a time experimental strategy was utilized.Micro-channel width and surface roughness were considered as performance measures of the present experimentation.Microscopic images of machined surface were also analysedfor qualitative assessment of this novel process.

Keywords:Microchannel, laser micro-milling, fiber laser, zirconia, micromachining.

1. INTRODUCTION

Now-a-days, there is an increasing trend toward miniaturization and micromachining becomes animportant activity in the fabrication of micro parts in the micro manufacturing as well as micro-assembly industries.There are many non-traditional machining processes which are successfully applied in the industries for microfabricationof various macro as well as micro-components with specific geometrical dimensions and surface conditions. Electro discharge machining (EDM) [1], laser beam machining (LBM)[2], electron beam machining (EBM), ion beam machining (IBM) electrochemical machining (ECM), ultrasonic machining (USM) [3], abrasive jet machining, water jet machining, abrasive water jetmachining have been already applied toobtain the desired miniaturized product made of wide variety of materials.Laser beam machining is one of the most promising non-conventional machining processes for machining of engineering materials [4, 5].The high energy density laser beam is focused on the surface of workpiece and the thermal energy of laser beam is absorbed which heats and transforms the work volume into molten-vaporized or chemically changed state that can easily be removed by flow of high pressurized assist gas jet associated with the acceleration and ejection of molten material from the laser focused zone [6].Laser beam micro-milling (LBMM) is widely used for microfabricationof advanced materials due to its several competent advantages offered in terms of design flexibility, sharp feature control, high aspect ratio, no tooling cost or associated wear costs and precision cutting of simple or complex parts. It is also well suited for surface treatments as well as machining 3D micro-features on a variety of materials irrespective of its hardness, melting point and other thermo-physical properties [7]. Laser micro-milling of the zirconia (ZrO_2) material has considerable advantageous over the conventional machining processes in terms of its high mechanical strength and fracture toughness. Micro-channels are widely used in various engineering applications including micro-channel heat exchangers, micro-channel coolers, micro-channel heat pipes, and micro-channel pulsating heat devices which are used in various fields like aerospace, automotive, cooling of gas turbine blades, cryogenic systems, bioengineering etc.

Microchannel can be produced by both the conventional and nonconventional techniques. But every manufacturingprocess has its own limitations.In this process, a single laser beam is used to produce micro-channel on zirconia (ZrO_2) material by removingmaterial with the help of high intense laser beam for a desired length of the square shaped workpiece. During the experiment, it has been found that two major factors involved for achieving better quality micro-channel. They are spot overlap and circumferential overlap.These overlap factors have significant effects on laser micro-milling process characteristics like width, surface roughness (Ra) etc. Spot overlap is defined as overlap between two consecutive laser beam spots on the workpiece surface. The relationship between spot overlap with other process parameters is describes in equation (1).

$$Spot\ Overlap = (1 - \frac{v}{D \times f}) \times 100\% \qquad (1)$$

In thisequation, v, D and f represent scanning speed (mm/s), laser spot diameter (mm) and pulse frequency of laser beam (Hz) respectively.The second important factor in the laser micro-milling process is transverse overlap. It is the measure of surface contour produced along the length of the workpiece. The relationship between the transverse overlap and other process parameters are described in equation (2), where D, D_T are laser beam spot diameter (mm)and transverse feed (mm) respectively.In this experiment, the values of the various process parameters are chosen in such a way that these two overlap factors are more than 85% which provide confirmation of better quality micro-channel.

$$Transverse\ overlap = (1 - \frac{D}{D_T}) \times 100\% \qquad (2)$$

2.EXPERIMENTAL PLANNING

In the present experimental study, laser beam micro-channel millingoperation has been performed onflat Zirconia (ZrO_2) workpiece by using multi-diodes pumped Ytterbium (Yb^{3+}) doped fiber laser of 50 W, made by M/S Sahajanand Laser Technology Limited, Pune, India. Fig. 1 shows the photographic view of the fiber laser machining system which is used during the research work. Table 1 shows the detailed specifications of the multi diode pump fiber laser set-up.

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The laser beam propagates through a f-θ lens of 71 mm of diameter (focus lens).Spot diameter of laser beam at focused condition was measured as 43 µm. The spot overlap values were calculated based on this value. In the present experimentation, assist air jet was utilized as shielding gas. Also, the shielding gas was employed by a nozzle which was kept at the peripheral position of laser beam delivery unit.

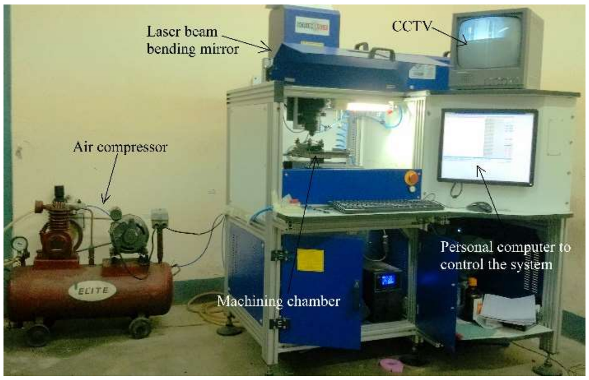

Fig. 1 Photographic view of the multi diode pumped pulsed fiber laser system

Table 1Detailed specifications of fiber laser set-up

Specification	Description
Laser type	Multi Diode Pump Fiber Laser
Wavelength	1064 nm
Pulse Repetition Rate	50-120 kHz
Nominal Average Power	50 W

Experiments have been conducted by utilizing one factor at a time (OFAT) experimental scheme. In this process, a high intense focused laser beam irradiates on a workpiece surface for a desired length. Process parameters which have been selected for conducting the experiments are average power, pulse frequency, scanning speed, number of pass and transverse feed and responses are width and surface roughness of the micro-channel. In table 2 shows the details of various process parameters considered during experimentation.

Table 2 Details of process parameters and ranges

Process parameters	**Values**
Average power	10, 11.25, 12.50, 13.75, 15 W
Pulse frequency	50, 60, 65, 70, 75 kHz
Scanning speed	1, 5, 7, 9, 11 mm/s
No of pass	1
Transverse Feed	0.005 mm

All the experiments were carried out keeping pulse width as 80% of duty cycle and air pressure of nozzle at 4kgf/cm^2. The range of the process parameters were taken after conducting some trial experiments.The dimensions of the micro-channel width was measured by using Olympus STM6-LM optical measuring microscope using 10X magnification.The roughness of the machined surface was measured by MITUTOYO SJ410 roughness measuring instrument. The surface roughness of the top surface ofmicro-channel was measured along the axis of the workpiece.

3. RESULTS AND DISCUSSIONS

The aim of this research work was to investigate the influence of process parameters like laser beam average power, pulse frequency, scanning speed on various responses like width, surface roughness through various graphsand also using optical images of the micro-channels.

3.1.Influence of process parameters on micro-channel width

3.1.1. Effect of laser beam average power on micro-channel width

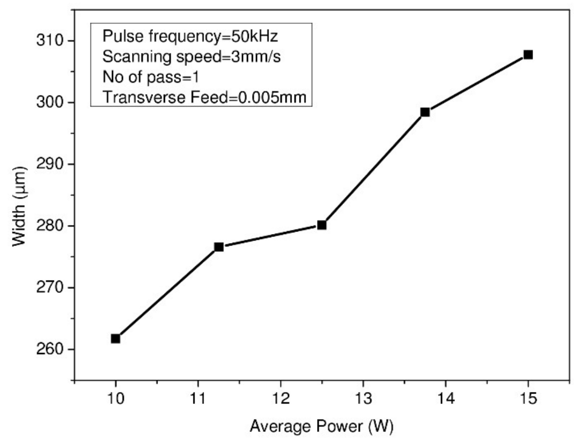

Fig. 3Influence of laser beam average power on micro-channel width

Fig. 3 shows the influence of micro-channel width with the variation of laser average power. The values of the process parameters such as pulse frequency, scanning speed, no of pass and transverse feed were kept at 50 kHz, 3mm/s, 1 and 0.005mm respectively. It is seen from this graph that the value of micro-channel width increases with the increase of laser average power. This is due to the fact that as thelaser beam average power increases, the workpiece surface gets more energy for melting and evaporation which leaded to more material removal rate.

3.1.2. Effect of pulse frequency on micro-channel width

Fig. 4 shows the influence of micro-channel width with the variation of pulse frequency. The values of the process parameters such as laser beam average power, scanning speed, no of pass and transverse feed were kept at 10 W, 3 mm/s, 1 and 0.005 mm respectively. It is observed from this graph that values of micro-channel width decreases with the increase of pulse frequency. Peak power of the laser beam is inversely proportional to pulse frequency. As a result of this lower value of pulse frequency causes more material removal from the surface of the workpiece as compared to higher values of pulse frequency.

3.1.3. Effect of scanning speed on micro-channel width

Fig. 5 shows the influence of micro-channel width with the variation of scanning speed. The values of the process parameters such as pulse frequency, laser beam average power, no of pass and transverse feed were kept at 65 kHz, 10 W, 3 mm/s, 1 and 0.005 mm respectively. At lower values of the scanning speed, laser beam gets sufficient time for removing the material from the workpiece but with the increase of scanning speed, low value of spot overlapping is occurred on the workpiece surface. As a result of this, with the value of micro-channel width decreases with the increase of scanning speed.

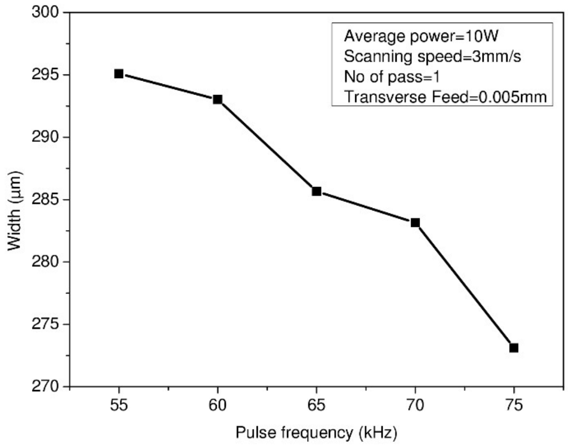

Fig. 4Influence of pulse frequency on micro-channel width

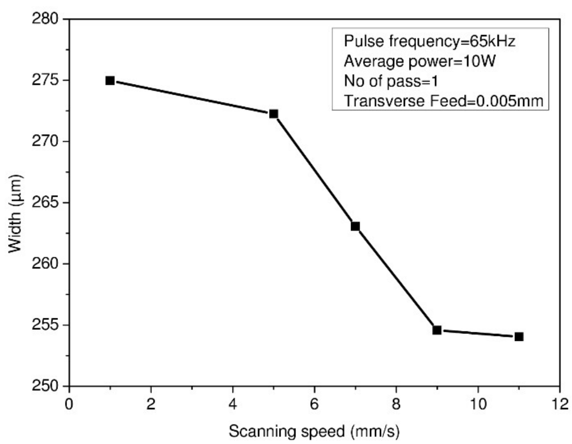

Fig. 5 Influence of scanning speed on micro-channel width

3.2. Influence of process parameters on surface roughness of micro-channel

3.2.1. Effect of laser beam average power on surface roughness of micro-channel

Fig. 6 shows the influence of surface roughness of micro-channel with the variation of average power. The values of the process parameters such as pulse frequency, scanning speed, no of pass and transverse feed were kept at 50 kHz, 3 mm/s, 1 and 0.005 mm respectively. From this plot, it is observed that with the increase of average power, surface roughness also increases. Increase in average power causes linearly increase in laser beam energy. As a result of this the workpiece surface gets more energy to melt and evaporate which leads to more amount of resolidified material on the cutting zone.

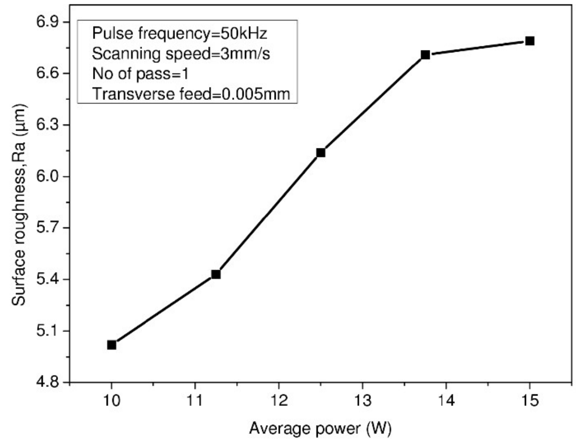

Fig. 6 Influence of laser beam average power on surface roughness of micro-channel

3.2.2. Effect of pulse frequency on surface roughness of micro-channel

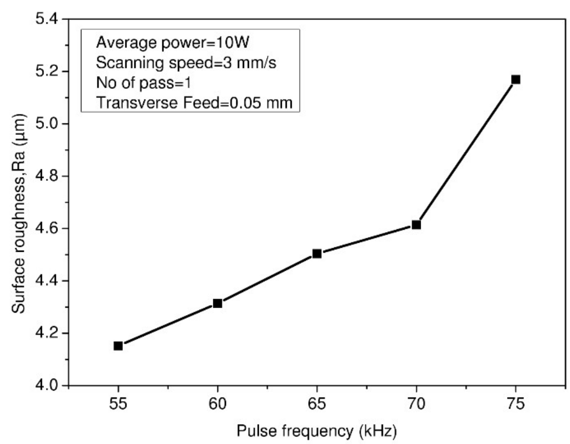

Fig. 7Influence of pulse frequency on surface roughness of micro-channel

Fig. 7 shows the influence of surface roughness of micro-channel with the variation of pulse frequency. The values of the process parameters such as laser beam average power, scanning speed, no of pass and transverse feed were kept at 10 W, 3 mm/s, 1 and 0.005 mm respectively.It is seen form this graph that surface roughness increases linearly with the increase of pulse frequency. As the value of pulse frequency increases, peak power of the laser beam also decreases. At higher value of pulse frequency, the time interval between two successive laser beams is very less and because of this only top surface of the workpiece gets sufficient energy to melt and vaporize instantly.

3.2.3. Effect of scanning speed on surface roughness of micro-channel

Fig. 8 shows the influence of surface roughness of micro-channel with the variation of scanning speed. The values of the process parameters such as pulse frequency, laser beam average power, no of pass and transverse feed were kept at 65 kHz, 10 W, 3 mm/s, 1 and 0.005 mm respectively.It is observed from this graph that there is a great influence of scanning speed on surface roughness. It is seen that value of surface roughness decreases with the increase of scanning speed.The increase of scanning speed results in less interaction duration for laser onto the workpiece surface. Therefore, the depth of crater formed on the workpiece surface is less and in turn, this results in low value of surface roughness.

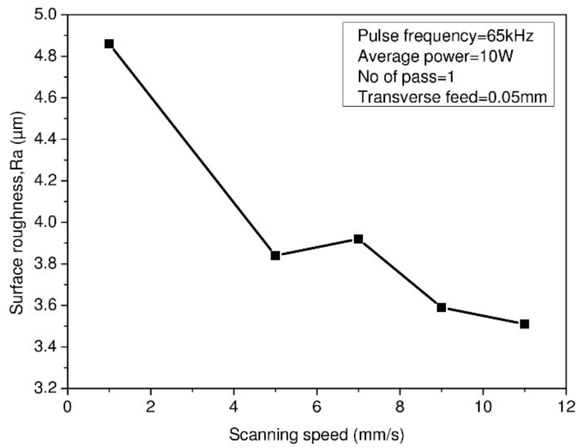

Fig. 8 Influence of scanning speed on surface roughness of micro-channel

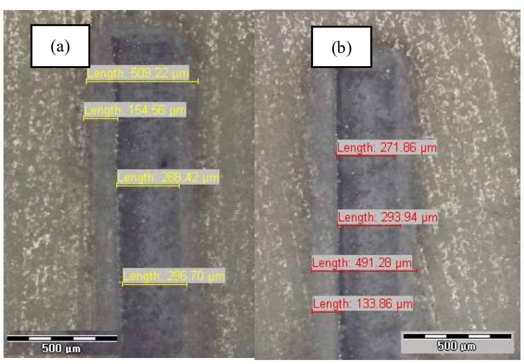

Fig. 9 Optical microscopic images of micro-channel milling on zirconia at parametric settings of (a) average power at 10 W and pulse frequency at 50 kHz, scanning speed of 3 mm/s, transverse feed at 0.005 mm (b) average power at 10 W and pulse frequency at 65kHz, scanning speed of 7 mm/s, transverse feed at 0.005 mm

Fig. 9 shows Optical microscopic images of micro-channel milling on zirconia at parametric settings of a) average power at 10 W, pulse frequency at 50 kHz, scanning speed of 3 mm/s, transverse feed at 0.005 mm (b) average power at 10 W, pulse frequency at 65 kHz, scanning speed of 7 mm/s, transverse feed at 0.005 mm.From these images and results, it can be concluded that there is a significant influence of process parameters on width of the micro-channel.

4. CONCLUSIONS

In this research paper, experimental investigation of micro-channel milling on flat zirconia workpiece surface has been performed at various parametric combination by usingYtterbium doped 50 W fiber laser. From the experimental results, it can be concluded that there is a great influence of process parameters such as laser beam average power (10-15 W), pulse frequency (55-75 kHz) and scanning speed (1-11 mm/s) on responses like micro-channel width and roughness of the base surface.It was found that with increase of average power, micro-channel width and surface roughness increases. Moreover, with increase of pulse frequency, micro-channel width decreasesbut surface roughness increases.The maximum value of width is achieved as 307.74 µm at a parametric combination ofaverage power at 15 W, pulse frequency at 50 kHz, scanning speed at 3 mm/s and transversefeed at 0.005 mm and minimum surface roughness is achieved as 3.51 µm at a parametric combination ofaverage power at 10 W, pulse frequency at 65 kHz, scanning speed at 11 mm/s and transverse feed at 0.005 mm.

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