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Study and Analysis of Spiral Micro-grooving Process of Aluminium using Pulsed Fiber Laser

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Abstract

Laser beam micro machining (LBMM) is one of the most widely used non- contact advanced machining process in which a single laser beam is used to produce micro-scale components with required precision and geometrical tolerances. This present paper deals with experimental investigation and analysis of laser spiral micro-grooving process on cylindrical shaped pure aluminium material by using pulsed fiber laser system. In this study, laser beam average power, pulse frequency and axial feed rate are considered asprocess parameters and geometrical dimensions such as micro-groove top width and depth are considered as response parameters. Experimentation has also been performed on the previously formed micro-grooves by defocusing condition of laser beam to obtain definite geometry of micro-groove for obtaining rectangular shaped micro-groove. Microgroove images were taken by using high resolution optical microscope and then analysed the effects of process parameters on the spiral micro-groove dimensions.

Keywords: Spiral micro-grooving, fiber laser, micromachining, aluminium, defocusing, groove top width, groove depth.

1. INTRODUCTION

In recent year, there is urgent need of miniaturized products or parts for diversified applications in the field of biomedical, automotive, aerospace and aircraft, micro electro mechanical systems (MEMS) and military purpose [1-2]. Not only that, these miniaturized products must meet several features such as high precision dimensions and tolerances with required surface characteristics and complex geometries. Thus, there must by some suitable and reliable micromachining technologies utilizing which efficient and effective manufacturing of miniaturized parts can be done. Laser Beam Machining (LBM) has a great potential for micromachining of advanced engineering materials such as metal, high strength and temperature resistant alloys, ceramics, composites etc with the help of various machining processes such as micro-drilling, micro-grooving, micro-milling, micro-turning, micro-marking in present manufacturing industries [3-6]. Not only that, laser micro-forming methods such as micro-bending, micro-welding etc has also been utilizing in present industries for effective manufacturing of micro-components. One of the recently developed and emerging laser micromachining processes is laser micro-turning, where cylindrical micro-parts or components is processed utilizing single laser beam to micro-turn for specific depth and length of work sample [7].

2. SPIRAL MICRO-GROOVING PROCESS

Spiral micro-grooving process by using pulsed fiber laser beam is one of the new novel techniques to produce spiral type micro-groove of required geometry and dimensions on cylindrical shaped micro parts made of various engineering materials. Single laser beam is used for micron level material removal from workpiece surface with high dimensional accuracy and quality finish. In this process, an extremely intense laser beam (collimated, monochromatic and coherent) irradiates on a rotating workpiece for a required length of the cylindrical workpiece. The laser micro-grooving process can be further utilized to develop laser spiral micro-grooving process, where spiral micro-grooves are produced side-by-side on the workpiece surface along the length of sample. The rotational speed and axial movement of work sample is controlled in such a manner that multiple spiral micro-grooves are produced on the workpiece surface without having any overlap between two successive groove widths. As a result of this, a spiral shaped micro-groove is generated on the work sample by keeping a small unmachined gap between two consecutive micro-groove widths. For obtaining desired quality of micro-groove dimensions, spot overlap factor play very important role [8-9]. The laser beam spot diameter which was measured at focused condition as 21 μm. For achieving better quality of spiral micro-groove, the overlap between two successive laser beams (spot overlap) should be as high as possible. In this research work, the values of various process parameters are chosen in such a manner that spot overlap is more than 99% for workpiece rotating speed of 25rpm. In this experiment, a research plan has been designed for performing laser spiral micro-grooving process by using pulsed fiber laser micromachining system. The aim of this work is to study and analysis the effects of laser beam at focused and defocused condition of processing parameters such as average power, pulse frequency, axial feed rate on the geometry of cylindrical aluminium workpiece. These types of micro-grooves and micro- fluidic channels have many applications in electronics as well as in bio-medical applications. Spiral micro-grooving process can be applied for manufacturing of dowel pin which is an essential component for assembly of micro components.

3. EXPERIMENTAL PLANNING

Laser spiral micro-grooving process is carried out on multi-diodes pumped Ytterbium (Yb^{3+}) doped fiber laser machining system of 50 W, made by M/S Sahajanand Laser Technology Limited, Pune, India. Fig. 1 shows the experimental set-up which is used in the present research work. A work holding and rotating system is used to carry out laser spiral micro-grooving operation on cylindrical workpiece. For providing different rotational speed of the cylindrical job, a microprocessor based servo motor drive system is also used. The workpiece holding device is attached with the servo motor which rotates simultaneously.

The values of some process parameters such as laser pulse width at 95% of duty cycle and assist compressed air pressure at 2.5 kgf/cm^{2}were kept constant during experimentation. These constant values were chosen after conducting some trial

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experimentation. In laser spiral micro-grooving process, equation (1) is used for calculating the values of axial feed rate.

$$l_s = F \times t = \frac{60 \times F}{N} \qquad (1)$$

Where l_s is the spacing between two consecutive micro-grooves (pitch), F is axial feed rate in mm/s and N is the rotational speed in rpm of the workpiece. In table 1, Details of various process parameters considered during experimentation.

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

Table 1 Details of process parameters

Process parameters	Values
Average power	35, 37, 40, 42.5, 43, 45 W
Pulse frequency	55, 65, 70, 75, 80, 85 kHz
Workpiece rotating speed	25 rpm
Pulse width	95% of duty cycle
Axial feed rate (25rpm)	=0.083mm/s for pitch 0.2mm =0.125mm/s for pitch 0.3mm =0.167mm/s for pitch 0.4mm

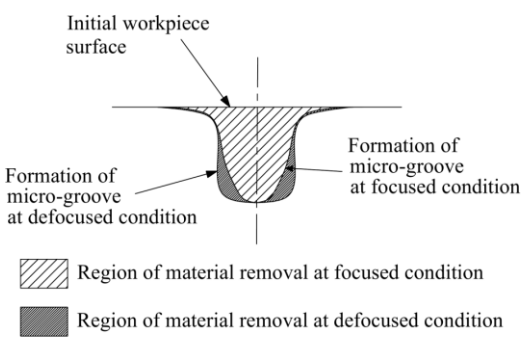

Fig. 2 Schematic representation of generation of micro-groove with sequential laser focused and defocused conditions

For generating rectangular shaped micro-groove, experiments have also been performed by utilizing laser beam at defocusing condition in which laser focused point is set at same condition with respect to workpiece surface. In this situation, laser beam is considered as defocused in respect of micro-groove sidewall and bottom surface. First of all, experiments have been performed to generate spiral shaped micro-groove on the workpiece surface at focused condition then the laser beam is once again set at initial position for conducting micro-groove at defocused condition. The laser beam energy intensity is reduced at defocused condition due to increase of spot diameter of laser beam. Material is removed from both the surfaces i.e. sidewall as well as bottom region to achieve rectangular shape micro-groove from tapered form. The schematic representation of material removal at both laser focused and defocused conditions is shown in Figure 2. Two responses which were considered for defocused condition such as groove top width and groove depth for this experimentation. Various optical microscopes were used for the measurement of the response parameters. Top width was measured by using Leica optical microscope (10X magnification). Micro-groove depth was measured by using Olympus STM6-LM optical measuring microscope (5X magnification).

4. RESULTS AND DISCUSSION

In this section, comparative study of micro-groove geometries at laser focused and defocused conditions have been analysed using various graphs of experimental results and also by using various optical images of micro-grooves which is taken by using optical microscope.

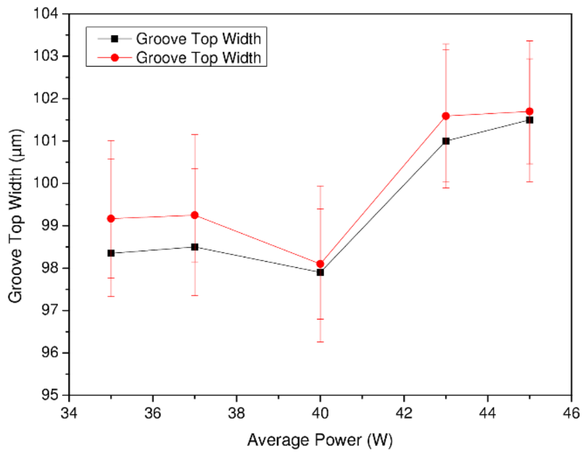

Fig. 3 Comparative results of groove top width with average power at focused and defocused conditions

4.1 Comparative study of groove top width

In this section, comparative study and analysis has been carried out by varying two major process parameters i.e. laser beam average power and pulse frequency of laser focused and defocused spiral micro-grooving process. Maximum value of groove top width was obtained at pitch value of 0.4mm in case of laser focused condition and this value is taken for comparative study and analysis.

4.1.1 Comparative study of groove top width with average power

The variation of laser average power with micro-groove top width value is shown in figure 3. The value of pulse frequency was kept constant at 70 KHz. It is seen from this graph that the value of groove width increases with the increase of laser average power. As the laser average power increases, the material from the laser irradiated zone gets sufficient energy to melt and vaporize. It is also seen from the graph that at all values of average power there is small increase in groove top width at laser defocused condition as compared laser focused machining. This is because of the fact that there is small amount of material is removed from both the surfaces sidewall as well as bottom surface in respect of earlier obtained micro-groove bottom surface at focused condition.

4.1.2 Comparative study of groove top width with pulse frequency

Figure 4 shows the comparative graph of micro-groove top width with the variation of pulse frequency. The value of average power was kept constant at 42.5 W. It is observed from the graph that the values of micro-groove width have decreasing trend with the increase of pulse frequency. With the increase of pulse frequency values, the peak power of laser beam decreases. As a result of this less amount of material is removed from top surface of material. It is also shown from the graph that values of micro-groove top width again increases for all values of pulse frequency at defocusing of laser beam compared to focused micro-grooving process. The increase in groove top width at defocused laser beam is due to removal of small amount of material from sidewall surface of micro-groove at lower value of pulse frequency. Peak power of the laser beam is more at lower value of pulse frequency and due to defocusing of laser in respect of micro-groove bottom surface, material is removed from bottom surface of micro-groove also. However, at higher value of pulse frequency, there is less increase in peak power and as a result of this the amount of material removal is less compared to higher setting of pulse frequency.

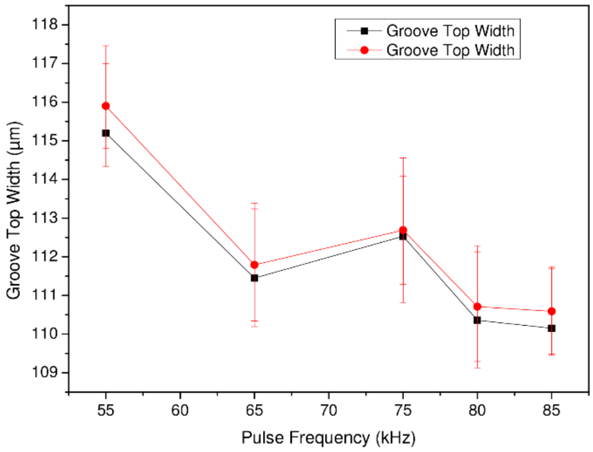

Fig. 4 Comparative results of groove top width with pulse frequency at focused and defocused conditions

4.2 Comparative study of groove depth

In this section, the comparative study and analysis is carried out by varying micro-groove depth for laser focused and defocused machining when the two major process parameters i.e. laser average power and pulse frequency were varied. For this study pitch value of 0.2 mm was only considered as at this pitch value, maximum value of groove depth was obtained.

*4.2.1 Comparative study of groove depth with average power*Figure 5 shows the variation in micro-groove depth at both focusing conditions as well as defocusing conditions when average power is varying. The value of pulse frequency was kept constant at 70 kHz. It is observed from this graph that laser average power has great effect on micro-groove depth. It is observed from this plot that the value of groove depth increases rapidly with the increase of average power of laser beam. With the increase of laser beam average power, peak power also increases. As a result of this, the material at the laser irradiated zone gets more energy to melt and vaporize the material from the workpiece. It is also shown from this figure that, the depth in defocused condition micro-grooving process has increased slightly more as compared to micro-groove depth obtained by laser focused condition. There is a very small change in depth for lower value of average power. However, at higher value of average power there is significant increase in micro-groove depth and this is because of the fact that more amount of material is removed from groove bottom area at higher average power.

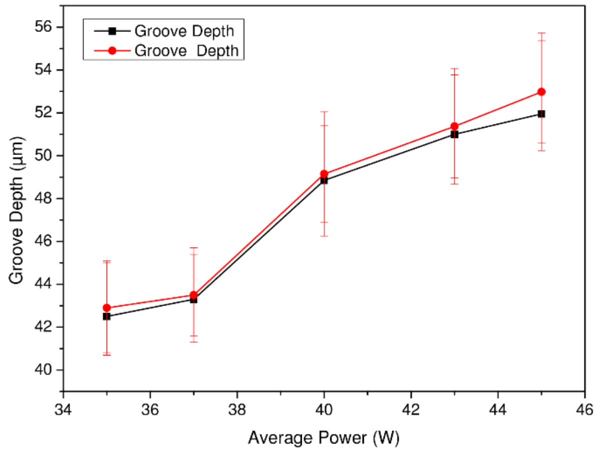

Fig. 5 Comparative results of groove depth with average power at focused and defocused conditions

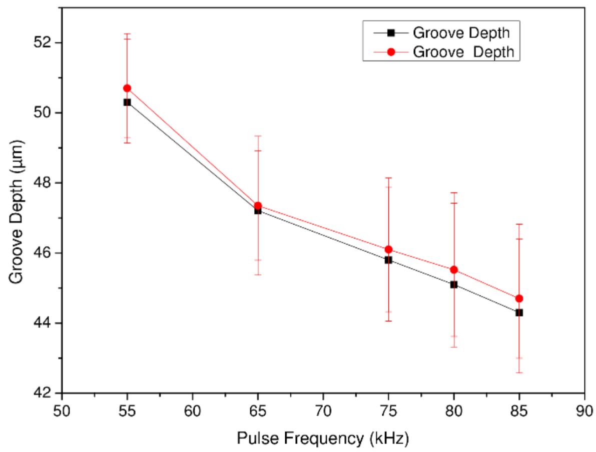

Fig. 6 Comparative results of groove depth with pulse frequency at focused and defocused conditions

4.2.2 Comparative study of groove depth with pulse frequency

Figure 6 shows the comparative variation in micro-groove depth with the increase in pulse frequency at focused and defocused condition of micro-grooving process. The value of laser average power was kept constant at 42.5 W during the experiment. It is observed from the graph that the values of micro-groove depth decrease rapidly with the increase of pulse frequency. With the increase of pulse frequency, the peak power of the laser beam decreases. As a result of this, less amount of material is removed from the workpiece surface and ultimately reduces the overall values of micro-groove depth. It is also shown from the comparative plot that with the increase in pulse frequency, the values of micro-groove depth are decreasing rapidly and this is mainly due to decrease in laser peak power which cannot provide sufficient laser energy onto the laser irradiated zone to remove material by melting and vaporization. However, it is also observed from the same plot that due to defocused condition some additional amount of material is removed which causes increase in the micro-groove depth compared to focused condition machining.

5. STUDY OF OPTICAL MICROSCOPIC IMAGES

In Figure 7, comparative study and analysis of optical microscopic images of micro-grooves obtained from focused and defocused spiral micro-grooving process are shown at two machining parametric settings i.e. average power at42.5W and pulse frequency at 85 kHz, pitch value at 0.4 mm and average power at 35 W and pulse frequency at 70 kHz, pitch value at 0.4 mm. The measured values of micro-groove top width and micro-groove depth are also shown in the figure. By comparing the values of micro-groove geometrical dimensions as shown in Figure 7 and also by qualitative observation and analysis, it is concluded that the process parameters i.e. laser average power and pulse frequency have great influence on micro-groove geometrical dimensions. Thus, proper controlling these process parameters are required to achieve dimensional micro-groove with specific value of spacing between two successive microgrooves.

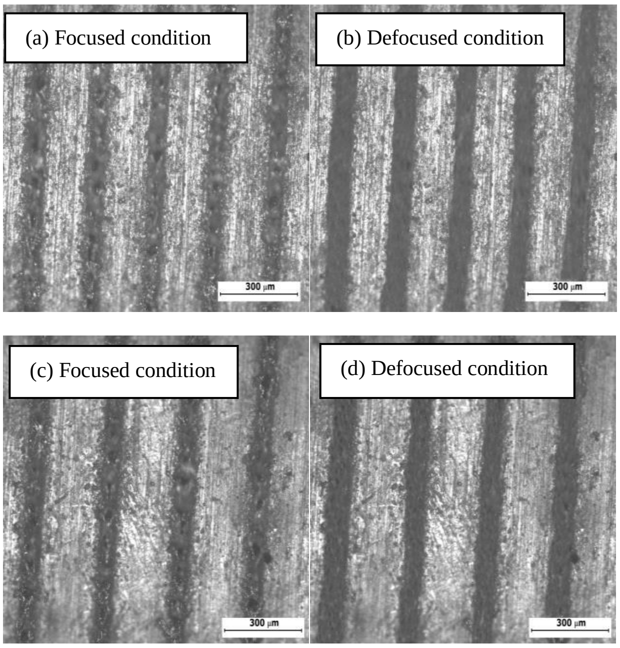

Fig. 7 Optical microscopic images of spiral micro-grooves machined at parametric settings of (a) and (b) average power at 42.5W and pulse frequency at 85 kHz, pitch value of 0.4 mm, (c) and (d) average power at 35 W and pulse frequency at 70kHz, pitch value at 0.2 mm

6. CONCLUSIONS

Fiber laser micro-machining system has a great potential for fabrication of spiral micro-groove on commercially pure aluminium material. In this experimental investigation, 50 W ytterbium doped fiber laser system has been utilized to produce spiral micro-groove on aluminium material of 7mm diameter. The results show that the process parameters have significant effects on geometrical dimensions of spiral micro-groove. It has been also observed that the axial feed rate values considered for the experiment, have significant effect on dimensional spacing between two consecutive micro-groove widths. Thus, by proper controlling predominant process parameters and pitch values by utilizing novel strategy of laser defocusing condition, required shape and geometry of micro-groove can be obtained. Groove top width is achieved as 115.9 µm at parametric combination of average power at 42.5 W, pulse frequency at 55 kHz and at pitch value of 0.4mm. Groove depth is achieved as 52.98 µm at parametric combination of average power at 45 W, pulse frequency at 70 kHz and at pitch value of0.2mm.

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