In Situ Geometric Measurement of Microchannels on EN31 Steel by Laser Micromachining using Confocal Sensor

A.K.Sahu, F. Iqbal, A Kumar and S.Jha*
Department of Mechanical Engineering
Indian Institute of Technology, Delhi – 110 016, INDIA

Abstract

Laser micromachining is a popular method of fabricating microchannels on wide range of metals and polymers. Microchannels are required for biomedical, biological, chemical, fuel-cell applications for flow of liquids and gases in predefined path for microfluidics and microreactors. In situ measurement of precise geometrical features on fabricated channels is required to avoid systematic errors. In situ measurement requires measuring instrument to be located on processing system itself. The width and depth of microchannels are the most important attributes which greatly influence quality of microchannels. This paper proposes in situ measurement of geometrical features of microchannels fabricated on EN-31 steel by laser micromachining. A confocal sensor is integrated with the laser cutting head to carry out in situ measurement. An infra-red fiber laser source (wavelength: 1064nm) of average power 50W has been used for fabrication of microchannels. Geometrical features (i.e. width, depth), have been measured with confocal sensor and which is further employed to evaluate MRR and surface roughness of the samples. The geometrical features, material removal rate and surface quality of microchannels have been analysed by confocal sensor experimentally and results thus obtained are compared with microscopic images of the samples.

Keywords: Laser Micromachining, Microchannel, In-Situ Measurement, Confocal Sensor.

1. INTRODUCTION

Microfluidics is the science and technology of systems that processes or manipulate small (10^{-9} to 10^{-18} liters) amounts of fluids, using channels with dimensions of tens to hundreds of micrometers. The field of microfluidics has four parents: molecular analysis, biodefence, molecular biology and microelectronics. Microfluidics has seen the rapid development of new methods of fabrication, and of the components such as the microchannels that serve as pipes, and other structures that form valves mixers and pumps that are essential elements of microchemical ‘factories’ on a chip [1]. Microchannel reactors reduce the size of conventional chemical reactors without lowering the throughput. Heat and mass transport limitations slow the observed reaction rates in conventional reactors, but are reduced in microchannel reactors [2].

Laser micromachining (LMM) is a highly precise, fast and force-free technology for fabrication of microchannel on polymers and metals. Laser micromachining using nanosecond pulses has been used by focusing laser beam to a selective portion of material to create a desired feature on the substrate. Laser micromachining involves the fabrication of microfeatures with nanometer (nm) tolerances. In LMM, the feature size depends on beam quality (M^2), wavelength and focusing lens and aperture of lens [3]. It can be used to fabricate 3-D submicron sized structures microchannels, hollow channel used for different application used for microfluidics and microreactors application.

In previous studies many researchers described microchannel fabrication by laser micromachining. Zhou et al. introduced laser micro-milling technique into the fabrication process of microchannel with different geometry and dimensions. The effects of process parameter i.e. scanning speed, laser output power and number of scans on the surface morphology and geometrical dimension of microchannel have been investigated based on SEM observations. It is found that the change of scanning speed and laser output power significantly affected the surface morphology of microchannel. Moreover, the depth of microchannel was increased when the laser output power and number of scans were increased [4]. Qi et al. performed micromachining of microchannel on polycarbonate by CO_2 laser. The influence of process parameter i.e. laser power, moving velocity, scanning time on microchannel quality (depth, width, aspect ratio) was studied. They have found that with high laser power and lower velocity the depth and width of microchannel is more. With higher laser power it would be steady state when laser power increases to 9 W caused by effect of laser power on different direction of microchannels [5]. Teixidor et al. performed ns-pulsed laser micromachining of PMMA based microfluidic channel. They have considered scanning speed and pulse frequency and q switching delay time as parameter and identified effect on MRR and surface quality. They also found when the laser focal objective is closer to the workpiece the width and the depth values become higher. However, when the z-level [6] is above the set level (z=0), the channel depth is not affected by this change. Pulse frequency has almost no influence on both response parameters. The focused beam z-level of (z=0) results in the best microchannel quality. The pulse frequency is the only parameter that improves both outputs (i.e. MRR and quality rating) by obtaining the best results at its highest value (PF = 11 Hz). They have concluded it is not possible to achieve high quality microchannels with high material removal rates at the same time. Slower scanning rate can promote a wider heat affected zone [6].

Maccioni et al. did laser ablation by Nd-YVO4 laser source on Ni alloy polished surface to fabricate microstructure in high vacuum (10^{-7}torr).They have considered process parameter i.e. laser fluence, Q switch working frequency and scan rate. Both morphological and structural surface modifications have been

---

*Author to whom correspondence should be made, Email: suniljha@mech.iitd.ac.in investigated by Field Effect Scanning Electron Microscopy, EDX and micro profilometer 2D. EDX analysis shows in ablated channel oxygen is absent. They also fabricated master type for microfluidic in Ni alloy having 50 µm channel length. [7]. Ibrahim et al. investigate the micro-milling performance of the AISI H13 with different process parameters namely laser power, scan speed, frequency, and fill spacing using 30W fiber laser marking machine and found optimal operation conditions for minimum surface roughness and maximum milling depth. The highest percentage contribution for SR and depth was observed at scan speed, which is 60.12% and 51.3% respectively. The milling depth increased with the decrease of scan speed and fill spacing. The surface roughness decreases with decrease in the laser power and frequency [8].

Consequently, few research studies were reported on use of nanosecond pulsed laser micromachining with near-infrared (NIR) wavelength of 1064 nm for microchannel but there is no study available of in situ geometrical measurement of microchannel. In situ measurement able to measure 3D surfaces without removing the part from the machine tool because mounting and un-mounting the part leads to systematic errors and geometrical deviations. A non-contact optical sensor can be incorporated in system to achieve in situ measurement of surface roughness [9]. The chromatic confocal sensor such as the one used [10, 11] is light, compact and easily mounted on the laser cutting head tool fulfilling the need for in situ measurement system for laser micromachining process. The workpiece is initially scanned using confocal sensor and plotted using confocal sensor data to find out geometrical features and surface roughness of flat workpiece. En31 widely used in automobile, aircraft component and having good property like strength, high melting point and hardness. Therefore, the main objective of this study is In situ measurement of geometrical features of microchannels fabricated on EN-31 steel by laser micromachining. Geometrical features (i.e. width, depth), have been measured with confocal sensor and the confocal sensor is further employed to evaluate MRR and surface roughness of the samples. The results thus obtained are compared with microscopic 3-d images data of the samples for width and depth.

2. EXPERIMENTAL SETUP

A laser micromachining system containing a fiber laser source (SPI lasers) of near infrared wavelength 1064nm operated in pulsed mode was used for fabrication of microchannel. The expanded and collimated beam was guided by optics and focused onto a workpiece of EN-31 sample in a small spot size. Workpiece of 50×50×10 mm placed horizontally on motorized stage. As the stage translates while keeping the laser spot stationary. The scanning speed is controlled by software with a scanning speed 1-3 mm/s. In order to focus laser beam on workpiece sample, the stage height can be adjusted relative to focus position. The accuracy of height adjustment is 10 µm. All the experiments were performed in assist gas as air at a pressure of 5 bar. Length of microchannel fabricated is 30 mm each. For in-situ measurement the chromatic confocal sensor being light in weight and compact in size is used with the laser cutting head to avoid error of measurement. A system schematic of the laser micromachining setup is shown in Fig 1(a). Laser source and confocal sensor specification mentioned in table 1 and 2 respectively. Total 6 microchannels have been fabricated with scanning speed 1, 2, 3 mm/sec and with number of scans 1 and 2.

Table 1. Laser source specifications

Laser type	Fiber
Avg. power	50 W
Mode	Pulsed
M^2	1.3
Pulse energy	1 mJ
Pulse duration	290ns
Pulse repetition rate	500 kHz
Assist gas	Air(5 bar)
Wavelength	1064nm

Table 2. Confocal sensor specifications

Fiber core dia	50 µm
Light spot dia	6 µm
Probe diameter	27 mm
Probe length	154 mm
Range	300 µm
Resolution (Z)	10 nm
Working distance	6 mm

After laser processing the workpiece moved to below confocal sensor with the help of x-y stage. The confocal sensor is brought closer to the workpiece until it reaches the measuring range, a fine spot of the white light can be seen on the surface to be measured, the workpiece is moved in such a way that it brings the laser beam spot to microchannel as shown in fig 1 (b). Each microchannel scanned with confocal sensor along width five times. The workpiece stops moving after the desired distance is covered to measure and the data acquisition is halted at this point, the acquired data during this path is stored in first column of an MS excel file. Stored excel data stored is then plotted in form of graph and average of multiple passes considered to calculate depth, width and surface roughness. MRR has been calculated based on depth, width and scanning speed. Geometrical parameter of microchannel shown in fig 2. The geometry of channel has been considered as triangular for MRR calculation.

The result of confocal sensor is compared with Leica optical microscope M205A at 160 x and 3-d image of microchannel has been acquired. A image of microchannel fabricated by laser micromachining has been shown in fig 3. The width and depth has been compared with confocal sensor measurement.

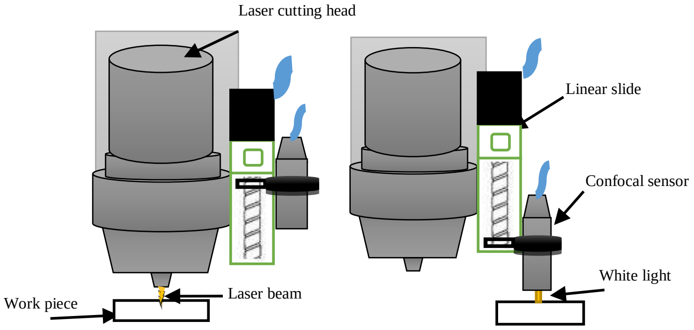

Fig 1. a) Laser Micromachining of workpiece b) Measurement by Confocal sensor

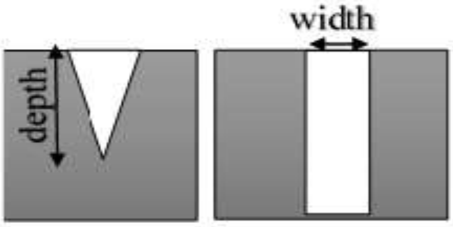

Fig 2. Geometrical features of microchannel

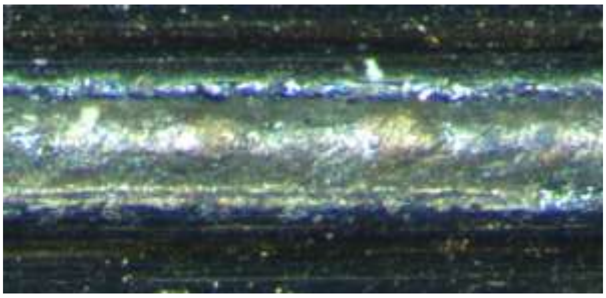

Fig 3. Image of microchannel at 160 X

3. RESULT AND ANALYSIS

The MRR has been calculated based on depth and width of average of five scans of confocal sensor**.** The material removal rate of microchannel varied from 0.004216 to 0.011055 mm^3/s. MRR has been increased significantly when number of scans is varied from 1 to 2. This is due to simultaneous scanning of channel formed in one scan by second scan. At higher scanning speed significant variation in MRR can be seen. It is more than twice when scanning speed 3mm/s in two scans as shown in fig 4. This is due to at high scanning speed material get melted and removed simultaneously by assist gas.

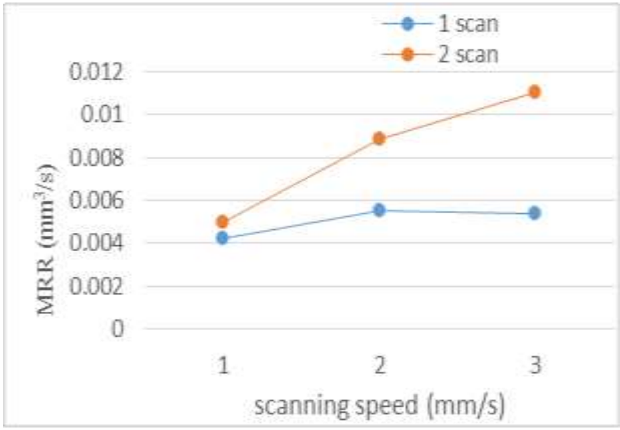

Fig 4. Effect of scanning speed on MRR

Surface roughness (R$_a$) has been calculated based on average of five scans of confocal sensor. The R$_a$ varied between 11.2 to 1.4 µm. By incresing number of scan of laser micromachining more material get melted so R$_a$ increases as shown in fig 5. At higher scanning speed R$_a$ is better.

4. COMPARISON OF MEASUREMENT OF CONFOCAL SENSOR AND MICROSCOPE

Microchannel width on top of surface has been varied from 131 µm to 105 µm when in situ in measuered by confocal sensor. Similarly when 3d image of microscope analyzed for width it varied between 127 µm to 99 µm. Both of measurennt is come closer. Fig 6 showing width interaction with scanning speed and measurement value by confocal sensor and microscopic 3d image. It is clear from graph there is not much variation in width measurementin width.

Width is more at low scannign speed. It is due to laser beam get more interaction time on surface of workpiece and by increasing number of scan it increases.

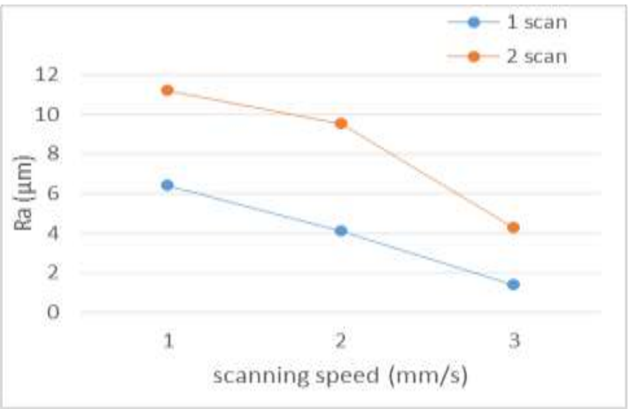

Fig 5. Effect of scanning speed on surface roughness (R$_a$)

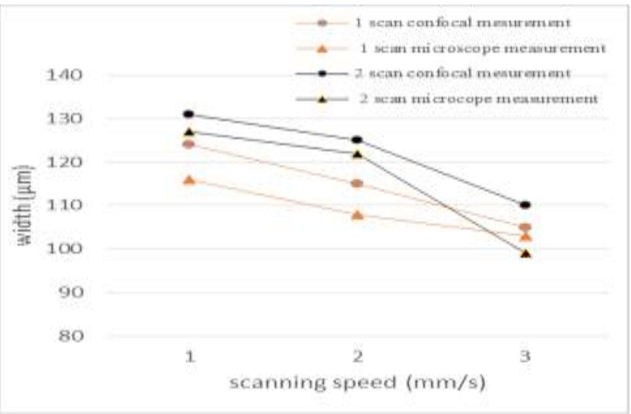

Fig 6. Comparison of measurement of width by confocal sensor and microscope

Microchannel depth varied from 76 µm to 34 µm when in situ measured by confocal sensor. Similarly when 3-d image of microscope analyzed for depth it varied between 63 µm to 28 µm. This difference because of white light of confocal sensor could reach to significant depth of microcahnnel at high frequency but 3-d images of microscope unable to process higher depth. Fig 7 showing width interaction with scanning speed and measurement value by confocal sensor and microscopic 3d image.

Depth of microcahnnel decreases by increasing in scanning speed because laser beam energy unable to melt at higher depth. If number of scans increases it increases significantly.

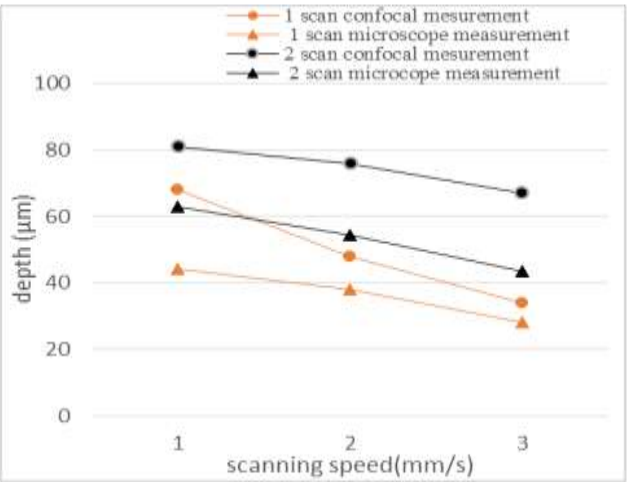

Fig 7. Comparison of measurement of depth by confocal sensor and microscope

5. CONCLUSION

In this study in situ geometrical measurement of microchannel has been performed by confocal sensor on EN-31and parameter i.e. scanning speed and number of scans effect has been studied. Also geometrical parameter measured by confocal sensor and microscope 3d image has been a comared. Results indicated following conclusions:

- Confocal sensor can be intgrated with laser micromachining system for In situ measurement of geometrical parameters and surface roghness.
- The MRR and surface roughness (R_a) for all experiment have significantly depends on scanning speed and number of scans.
- Confocal sensor and microscope both can be emplyed for width measurement but for depth measurement microscopic 3d image have limitation due to image processing and confocal sensor white light can easily scan higher depth at higher frequency. So it more reliable.
- Higher deviation found in measurement of depth as compared to width due to image processing capability limitation of microscope and it takes images at 10 micron of step and combine them. But resolution of confocal sensor is 10 nm. So significant variation shown in depth measurement.

References

[1] G. M. Whitesides, “The origins and the future of microfluidics,” nature vol. 442, no. July, 2006.

[2] A. Y. Tonkovich, J. L. Zilka, M. J. Lamont, Y. Wang, and R. S. Wegeng, “Microchannel reactors for fuel processing applications . I. Water gas shift reactor,” vol. 54, pp. 2947–2951, 1999.

[3] Ronald D. Schaeffer “Fundamentals Of Laser Micromachining” Taylor & Francis Group, Llc CRC Press Is An Imprint Of Taylor & Francis Group, Page 49,2012

[4] W. Zhou et al., “Laser micro-milling of microchannel on copper sheet as catalyst support used in microreactor for hydrogen production,” Int. J. Hydrogen Energy, vol. 39, no. 10, pp. 4884–4894, 2014.

[5] H. Qi, T. Chen, L. Yao, and T. Zuo, “Micromachining of microchannel on the polycarbonate substrate with CO2 laser direct-writing ablation,” Opt. Lasers Eng., vol. 47, no. 5, pp. 594–598, 2009.

[6] D. Teixidor, T. Thepsonthi, J. Ciurana, and T. Özel, “Nanosecond pulsed laser micromachining of PMMA-based microfluidic channels,” J. Manuf. Process., vol. 14, no. 4, pp. 435–442, 2012.

[7] G. Maccioni et al., “Study of micro-structured master fabrication on Nickel alloy by DPSS laser ablation technique laser ablation technique,” Proceedings of the Fifth International WLT-Conference on Lasers in Manufacturing 2009 Munich.

[8] I. E. Saklakoglu and S. Kasman, “Investigation of micro-milling process parameters for surface roughness and milling depth,” Int. J. Adv. Manuf. Technol., vol. 54, no. 5–8, pp. 567–578, 2011.

[9] Y. Quinsat and C. Tournier, “In situ non-contact measurements of surface roughness,” *Precis. Eng.*, vol. 36, no. 1, pp. 97–103, 2012.

[10] Minoni U, Cavalli F. “Surface quality control device for on-line applications” Measurement. Aug 31; 41(7):774-82 2008.

[11] F. Iqbal, Z. Alam, D. A. Khan, and S. Jha, “Localized finishing by ball end magnetorheological finishing process using integrated confocal sensor for in-situ surface roughness measurement” Paper No: (0019) – 39th MATADOR Conference 2017.