

Analysis of Micro-Hole Fabrication in Laser Drilling of Titanium Grade 5

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Abstract: The customer demands on micro component usages have been increased in past some of the decades. So, the development is necessary to achieve desired smaller shape and size of components with high accuracy. In this work, blind-hollow cylindrical micro-hole fabrications of various diameter (0.5 x 0.7 mm, 1 x 1.4 mm and 2 x 2.8 mm) on Titanium grade (Ti6Al4V) were processed by Nd:YAG laser machine. The design of experiment, Analysis of Variance (ANOVA) techniques and effect of process parameters has been implemented to assess performance. The performance characteristics of the blind-hollow cylindrical micro-hole fabrication were evaluated through circularity and Feret's diameter. The laser tuning parameter such as current, pulse frequency and air pressure were considered as input laser parameters.

Keywords: Circularity, Cylindrical micro-hole, Feret's diameter, Heat affected zone, Image processing.

I. INTRODUCTION

All the microcomponent manufacturing industries are increases usages in miniaturization process. The fundamental tool for manufacturing micro-components and parts is micromachining. Laser machining is the one of the micromachining process which is used to produce micro-feature on components. It can be machine conductive and non-conductive materials irrespective of hardness. The main advantage of laser process is the non-contact and energy conversion process and without any force between the tool and workpiece [1]. Laser machining has the ability to make microfeatures in thermoplastic cutting [2], telecommunications, sensing devices [3], printer nozzles, drilling of biomedical catheter, microscribing [4], optical fiber microsensors for vibration detection [5], and biomaterial fluidic-channels [6]. Microchannels are widely applied in biomedical devices to dosage pass ways to the human body, analyzing the DNA structural arrays and cellular cultures. The micro-sized channels on glass, polymeric and ceramics widely

available in the literature than metallic substrate. The channel developed in glass material by laser and machined width and depth of channels modeled [7]. Nieto *et al.* [8] developed the microfluidic application material soda lime glass and the circular cross-sectional microchannels fabricated on glass by Nd:YVO4 nanosecond laser. The obtained channel depth 1.5 mm and diameter 8 mm is unaccepted appearance in size. Therefore, the post-thermal treatments needed to obtain desired shapes. In order to eliminate the post processing issues Li *et al.* [9] fabricated microchannels using water assisted femtosecond laser ablation. They found that desired channel dimensions can be controlled by pulse energy and scanning width. The laser tuning parameters mostly influence the size of microchannels [10, 11 and 12]. Because of unique capabilities of titanium alloys are broadly applied in aerospace industry. Even though advantages in titanium and some limitation issues on manufacturing and high costs. The more attention is focused on feasibility to realize micro feature creating on titanium alloys. The microchannel fabricated on Ti6Al4V processed by CNC machine using microtools. The effects of cooling and lubrication conditions analyzed. The results revealed that left out the positive influences on channel's geometries and surface appearance. In order to reduce the surface roughness of milled features, pulsed laser micropolishing is introduced in this work [13]. The microfeature creates on aluminium and titanium using laser milling [14] and micronotches creates on aluminium and steel using laser [15]. The microfeature and micronotches dimension are depends upon the selection of laser power, pulse frequency, shielded gas pressure and number of passes. The ablation depth is depends on power and frequency of laser pulses. The blind-hollow cylindrical micro-hole fabrication on titanium alloy is not easy to achieve at exact combination of laser parameters to obtain the desired size. In this connection, the present study has been carried to explore the machining limits of Nd:YAG laser for the development of blind-hollow cylindrical micro-hole in real time. It is necessarily felt to reach at the clue for parametric settings that can generate the minimum channel dimensions with best suitable tolerances. Three sets of

blind-hollow cylindrical micro-hole with incremental geometry (cylindrical cross-section) but different dimensions (0.5 x 0.7 mm, 1 x 1.4 mm and 2 x 2.8 mm) have been selected to generate on Ti6Al4V titanium alloy. This study aims to investigate the impact of three very important laser parameters on the quality of blind-hollow cylindrical micro-hole using image processing. Some of the measures to quantify the quality of the blind-hollow cylindrical micro-hole are circularity and Feret's diameter at the entrance. The detailed experimental conditions and results are presented in the subsequent sections.

II. MATERIALS AND METHODS

A CNC Nd:YAG laser system (Lasertec 40 by DMG Mori Sieki) was used in all the experiments. It is continuous wave pulsed laser with 1064 nm wavelength capable of generating train of pulses with 10 μ m pulse duration following the Gaussian mode. The average and maximum power ranges from 10 to 100 W, respectively. The available beam spot diameters are 30 and 80 μ m that can generate the average laser intensities of 42.441 and 5.968 kW/mm², respectively for both diameters. The system is equipped with a CNC controlled worktable movable in three transverse directions (X, Y, and Z) and galvanometer head containing the optical lens (s) assembly. The galvanometer head has the capability of focusing the laser spot on the targeted substrate. For large movements (>65 mm) the table executes linear motion while for minor movements up to 65 mm the galvanometer adjusts the lenses' positions according to focal distance and depth of cut. Rectangle cross-sectional sheets (100 x 35 x 3 mm) of Ti6Al4V (supplied by Sai Titanium Pvt. Ltd, Chennai) were used to ablate the various sized hollow micro hole. The chemical composition is supplied in Table I. The specimen was initially grinded and flattened to ensure the flat surface for uniform focal distance. Three different sizes of hollow micro hole were designed to explore the possibility of micromachining on titanium alloy. The Computer Aided Design (CAD) of each channel was realized on the machine's

supplied design software (LaserSoft 3D). After the geometrical CAD development (Fig. 1), a full fledge coded programming file gets generated and transfers to the machining unit. The D1 represents inner diameter and D2 represents the outer diameter. It is necessary to have a match of parameters of the programming file and the machine parameters. Importance of these includes laser current, pulse frequency and air pressure. The laser process parameter is shown in Table II. Thus, 27 blind cylindrical hollow microholes were machined with 0.5 mm constant depth of cut and the microscopic images (Fig. 2) of the microholes are captured using optical microscope. Table III shows the values of circularity and Feret's diameter. Circularity quantifies the perfection in the rim of microholes. In this experiment, circularity and Feret's diameter (ratio of major axis diameter to the minor axis diameter) of the blind hollow microholes were measured and compared using an image-processing tool (image J), in which the value of circularity (C) is calculated using $C = 4\pi A/P^2$, where A is the area of the circle, and P is the perimeter of the circle. If the value of circularity is closer to 1, then it is perfect circle and vice versa.

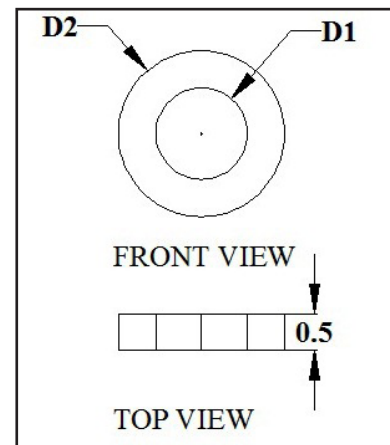


Fig. 1: 2D Sectional View Representation of Computer Aided Design

TABLE I. CHEMICAL COMPOSITION OF Ti6Al4V

Elements	Al	V	Fe	O	C	N	Y	Ti	Other
Weight (%)	6.11	4.00	0.18	0.18	0.01	0.01	<0.05	BAL	0.40

TABLE II- LASER PARAMETERS USED IN THIS TEST

Parameters	Symbol	Unit	Levels		
			1	2	3
Current	I	Amp	20	25	30
Pulse Frequency	F	KHz	1	2	3
Air Pressure	P	kg/cm ²	1	2	3

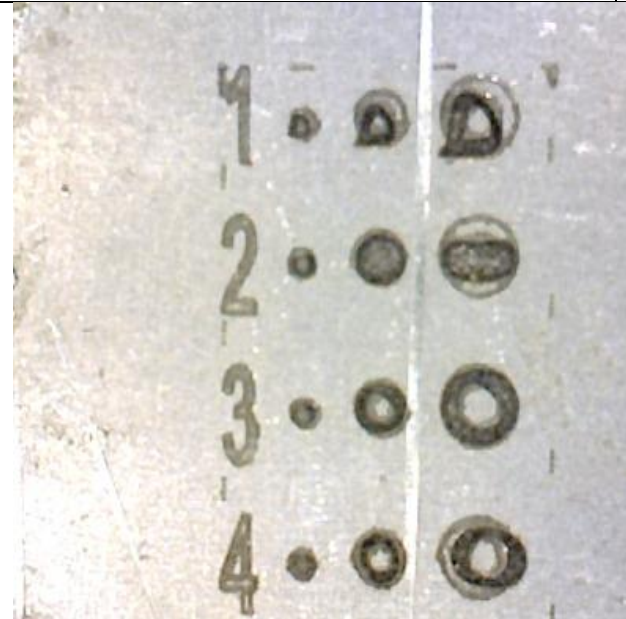




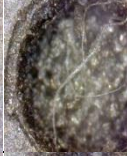
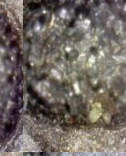




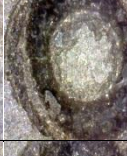
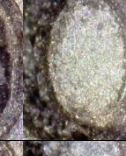
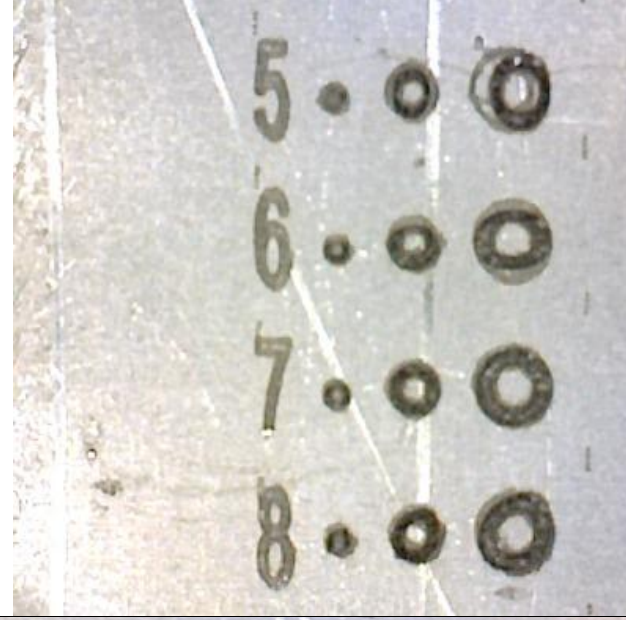

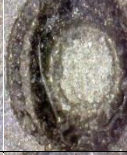


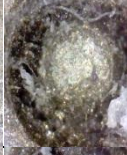





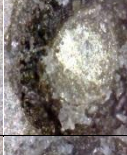

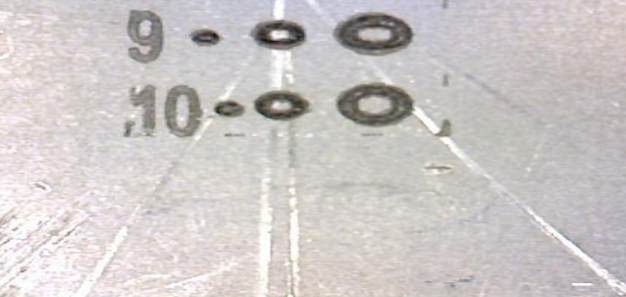

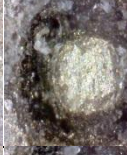



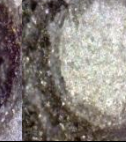
No.		Study 1	Study 2	Study 3
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Fig. 2: Entry Images of Laser Machined Hole

TABLE III: LASER MACHINED CYLINDRICAL HOLLOW MICROHOLE VALUES

Exp no	Process Parameter			Case Study 1				Case Study 2				Case Study 3			
				Inner Diameter		Outer Diameter		Inner Diameter		Outer Diameter		Inner Diameter		Outer Diameter	
	I	F	P	C	F	C	F	C	F	C	F	C	F	C	F
1	1	1	1	0.824	0.581	0.929	1.567	0.83	1.162	0.838	2.162	0.838	2.171	0.848	4.342
2	1	2	2	0.861	0.612	0.971	1.628	0.867	1.224	0.875	2.224	0.875	2.233	0.885	4.466
3	1	3	3	0.855	0.629	0.962	1.661	0.861	1.258	0.869	2.258	0.869	2.267	0.879	4.534
4	2	1	2	0.833	0.635	0.939	1.671	0.839	1.27	0.847	2.27	0.847	2.279	0.857	4.558
5	2	2	3	0.838	0.615	0.945	1.633	0.844	1.23	0.852	2.23	0.852	2.239	0.862	4.478
6	2	3	1	0.822	0.615	0.93	1.631	0.828	1.23	0.836	2.23	0.836	2.239	0.846	4.478
7	3	1	3	0.844	0.639	0.949	1.68	0.85	1.278	0.858	2.278	0.858	2.287	0.868	4.574
8	3	2	1	0.814	0.657	0.918	1.719	0.82	1.314	0.828	2.314	0.828	2.323	0.838	4.646
9	3	3	2	0.791	0.634	0.901	1.672	0.797	1.268	0.805	2.268	0.805	2.277	0.815	4.554

III. RESULTS AND DISCUSSIONS

A. Analysis of Variance

Table IV shows the circularity and Feret’s diameter of inner diameter and outer diameter value of cylindrical hollow micro-hole in case study 1, case study 2 and case study 3 respectively.

All the case studies the higher contribution percentage is current and followed by air pressure. The influence of pulse frequency on circularity and Feret’s diameter doesn’t affect the quality of microhole. Especially test statistic value of current is much higher than critical value. From this it is evident that current influences circularity more when compared to air pressure both inner and outer diameter.

TABLE IV: ANOVA - CIRCULARITY AND FERET’S DIAMETER OF CASE STUDY 1

Case Study 1							
Circularity - Inner Diameter							
Source	DF	Seq SS	Adj SS	Adj MS	F	P	CP
Current	2	0.001381	0.001381	0.00069	1.46	0.406	37.16
Pulse Frequency	2	0.000362	0.000362	0.000181	0.38	0.723	9.74
Air Pressure	2	0.001029	0.001029	0.000514	1.09	0.479	27.68
Error	2	0.000945	0.000945	0.000472			25.42
Total	8	0.003716					100
Feret’s Diameter - Inner Diameter							
Current	2	0.001971	0.001971	0.000985	1.41	0.415	53.05
Pulse Frequency	2	0.000156	0.000156	7.81E-05	0.11	0.9	4.20
Air Pressure	2	0.000188	0.000188	9.38E-05	0.13	0.882	5.05
Error	2	0.0014	0.0014	0.0007			37.69
Total	8	0.003715					100
Circularity - Outer Diameter							
Current	2	0.001473	0.001473	0.000736	1.56	0.391	39.28
Pulse Frequency	2	0.000283	0.000283	0.000141	0.3	0.77	7.54
Air Pressure	2	0.001047	0.001047	0.000523	1.11	0.475	27.92
Error	2	0.000947	0.000947	0.000473			25.25
Total	8	0.00375					100

Case Study 1							
Feret's Diameter - Outer Diameter							
Current	2	0.007885	0.007885	0.003942	1.45	0.409	53.59
Pulse Frequency	2	0.000691	0.000691	0.000345	0.13	0.888	4.70
Air Pressure	2	0.000686	0.000686	0.000343	0.13	0.888	4.66
Error	2	0.005453	0.005453	0.002726			37.06
Total	8	0.014714					100

IV. MAIN EFFECTS PLOT

Fig. 3 and Fig. 4 shows the effects of laser process parameters on circularity and Feret's diameter of inner diameter value of cylindrical hollow micro-hole in case study 1. In case of circularity against current, it is observed that hole circularity decreases almost linearly with the increase in lamp current.

In case of circularity against pulse frequency, it is observed that hole circularity increases then decreases. The reason is at low lamp current, the circularity first increases then decreases with increase in air pressure.

In case of circularity against air pressure, it is observed that hole circularity increases. Low-assist air pressure removes less heat

from the drilling zone and is also unable to assist the removal of molten material. However, at higher assist air pressures, excess heat is removed rapidly and it also helps to eject molten material from the drilling zone. As a result, variation in circularity due to increase in lamp current is higher when using low air pressure.

In Fig. 4, In case of Feret's diameter against current and air pressure, it is observed that diameter increases almost linearly with the increase in lamp current. This is due to the reason that high lamp current generates high thermal energy, due to which large amount of material gets melted and vaporized instantly from the top surface of work specimen and results in higher diameter at entry.

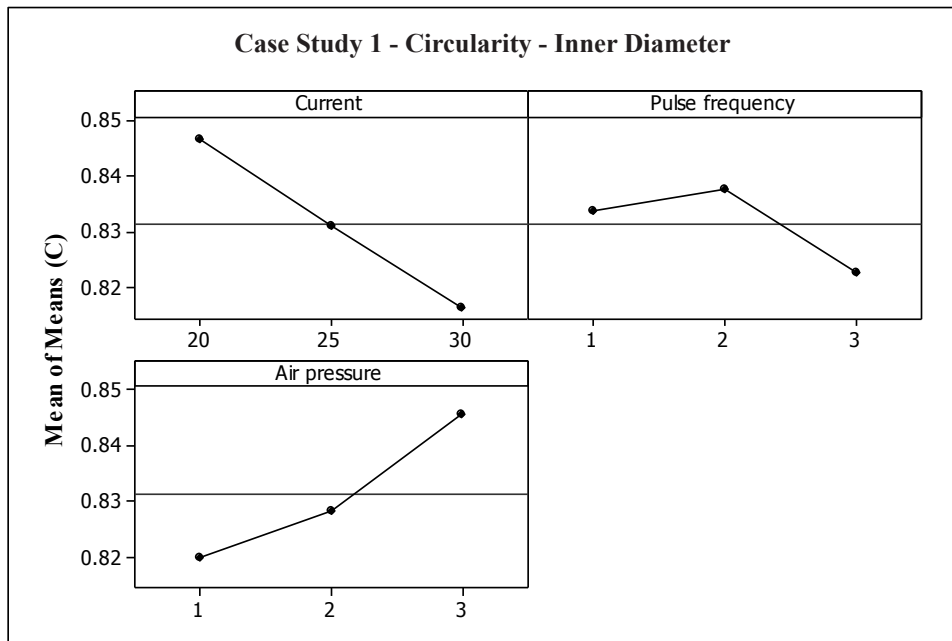


Fig. 3: Main Effects Plot - Circularity - Inner Diameter - Case Study 1

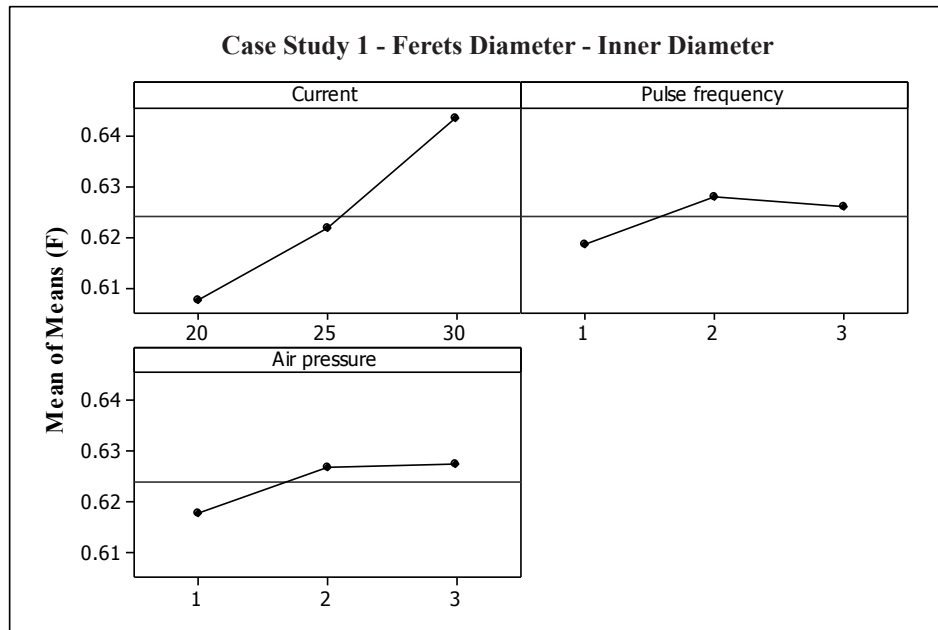


Fig. 4: Main Effects Plot - Feret's Diameter - Inner Diameter - Case Study 1

At some experimental runs, the authors experienced that the heat affected zone obtained in machined surface and irregular dimension in inner and outer diameter of the rim hole. This is called as machined surface defects. Due to machined surface defects, the quality of hollow cylindrical microholes is severely affected. Some of the holes seem to have irregular edges, and these irregularities were due to beam quality and selection of process parameters. A machined surface defect has occurred while machining was done at very low level process parameters. The reason for this is that, at lower current discharge energies, melting efficiency is more, and so more debris particles are formed. Thus, thermal defects and dimensional inaccuracy are formed which leads to continuous debris and machined surface defects. Because of machined surface defects, laser machining becomes unstable, which worsens the quality of the rim of hollow cylindrical microholes.

V. CONCLUSIONS

- Current significantly influences the quality of the edges of holes more when compared to air pressure.
- The process parameter lowers than 20 amp reduce the quality of microholes.
- Current values 20 amp, pulse frequency 2 khz and air pressure 3 kg/cm² for circularity and Current values 30 amp, pulse frequency 2 khz and air pressure 3 kg/cm² for feret's diameter are the optimized values of input parameters for achieving best quality of microholes.
- The Feret's diameter is amazingly showing the effects of current in the quality of the microholes.
- The heat affected zone and dimensional inaccuracy are obtained in machined surface.

- For future work, the data sets obtained can be used to predict the values of circularity and Feret's diameter for the other intervals for the levels of current and air pressure.

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