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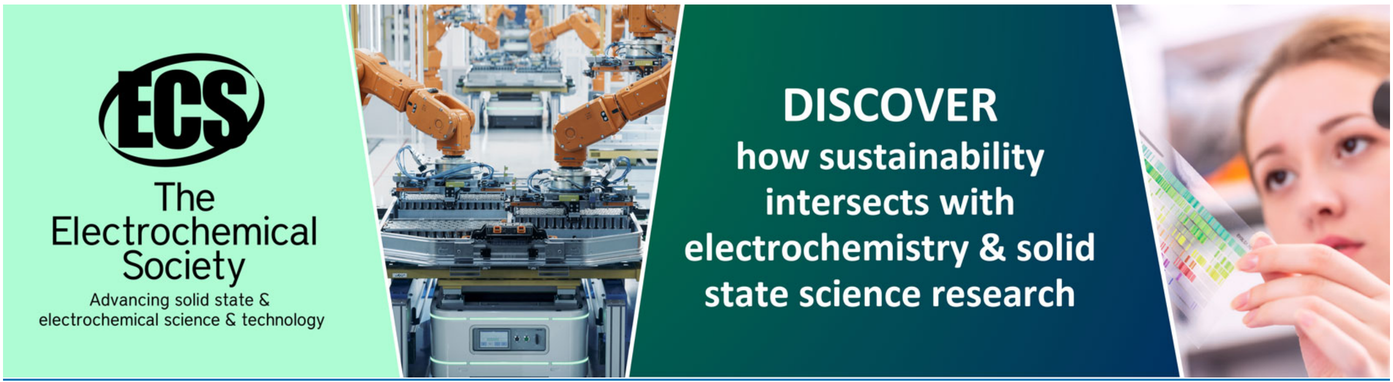

EFFECT OF LASER PROCESS LOOPS ON THE HOLE DIAMETER AND HOLE FORMATION OF LASER MICRO DRILLING ON TC4

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ABSTRACT

Laser micro drilling stands as a precise manufacturing method that employs a focused laser beam to craft accurate, small holes within a diverse array of materials. Its applications span across vital industries like aerospace, medical, and electronics, playing a pivotal role in creating components like fuel injectors, medical implants, and microelectronics. Within this context, a notable challenge emerges in obtaining a refined surface finish during laser micro drilling. This study delves into the impact of a laser loop, a crucial parameter, on the surface quality of TC4, also known as Ti6Al4V—an aerospace staple. Employing a Conventional Fiber Laser with a peak output of 30 W, the experiment meticulously directs the laser beam onto the TC4 surface via a microscope objective lens. The drilling process unfolds in controlled conditions, mitigating external variables such as temperature and humidity. Assessment of drilled hole surfaces transpires through both light and 3D microscopes. Interestingly, holes subjected to higher laser power and increased laser loop rates demonstrate enhanced surface smoothness. In essence, this inquiry demonstrates the substantial influence of laser loop on TC4's surface finish during laser micro drilling. Elevating the laser loop factor leads to heightened surface refinement and diminished roughness in drilled holes. It was found that the diameter entry of the micro-holes was increased by 61% - 89.35% and the diameter exit of the micro-holes also increased by 55.55% - 62.79%. The outcomes of this investigation offer valuable insights for refining the laser micro drilling process to achieve premium surface quality on TC4 and comparable materials. As such, these findings extend guidance for optimal laser loop settings in the realm of laser micro drilling across various materials, benefiting future manufacturing endeavors.

Keywords. Laser Micro Drilling; TC4; 3D measuring laser microscope; Light microscope.

1.INTRODUCTION

Laser micro drilling has a wide range of industrial applications like creating notches in diesel engine, aircraft industry for making holes in the engine for fuel injection, medical industry for drilling polymer-based medical devices, etc. (Pattanayak et al, 2018). Laser Micro Drilling research may be traced back to the early 1960s, when the first laser was invented. Over the last several decades, the research background of Laser Micro Drilling has progressed dramatically, resulting to the development of powerful laser systems and a greater knowledge of the fundamental principles of laser-material interaction. Advanced engineering materials required new development. Smooth side walls, low tapered, inclined hole with less burrs and cracks around the hole are hard to achieve using conventional drilling process. So, it is necessary to laser micro drilling methods to achieve the objectives. The recent advances in the manufacturing technology have led to the development of miniature products in the field of automobile, biomedical implants, biomedicine, aerospace and robotics (Pattanayak et al, 2018). Ti6Al4V are extensively studied due to their excellent mechanical properties such as high strength to weight ratio and high temperature resistant and highly corrosion resistance (Chatterjee et al., 2017). TC4 alloy, also known as Ti-6Al-4V alloy, is a widely used aerospace-grade titanium alloy that is known for its high strength-to-weight ratio and excellent corrosion resistance. However, drilling TC4 alloy is a challenging task due to its high hardness and tendency to form burrs and heat-affected zones. The micro hole drilling by laser ablation is crucial to control material removal rate (MRR), ablation depth, and aspect ratio. Important process parameters include laser pulse width, pulse repetition rate, pulse energy, and the material properties (Nibras H. et al., 2022). Fiber lasers were use in this research, fiber Lasers incorporate some key advantages such as high thermal efficiency and robustness of operation which negates any non-linear environmental effects and Fiber lasers offer flexibility and produce high quality beams (W.Noor et al., 2022). A fibre laser is a laser in which the active gain medium is an optical fibre doper with rare-earth elements such as Ytterbium (Yb). Fibre laser has developed quickly and has the advantages of high flexibility and good beam quality, which being applied in the electrical and automotive industries (Salleh, M.N., 2020). The laser power and gas flow are two of the most critical parameters in laser micro drilling. The laser power determines the amount of energy delivered to the material, which affects the material removal rate, drilling speed and the quality of the drilled hole. The gas flow, on the other hand, is used to cool the material and remove debris from the drilling zone, which affects the material's thermal state, the surface quality and the drilling efficiency. Previous studies have shown that the optimal laser power and gas flow settings vary depending on the material properties, drilling conditions, and the desired drilling results. However, there is a lack of research on the effect of laser power and gas flow on the surface of TC4 during laser micro drilling. This investigation aims to fill this gap by studying the effects of laser power and gas flow on the surface of TC4 during laser micro drilling, in order to understand the optimal laser power and gas flow settings for achieving high-quality drilling results on TC4 alloy.

2.MATERIALS AND METHODS

The substrate material employed for the test specimens consisted of TC4, a titanium alloy renowned for its distinctive properties. TC4, also known as Ti-6Al-4V or Ti64, is an alpha-beta titanium alloy formulated with a composition of 6% aluminum and 4% vanadium. This alloy has garnered significant attention owing to its remarkable strength and hardness, rendering it highly suitable for a diverse array of applications. Notably, the aerospace sector benefits from the use of titanium alloys due to their advantageous attributes, including low density, high strength, toughness, and favorable high-temperature characteristics.

The mechanical attributes of titanium alloys, like TC4, play a pivotal role in determining their performance in aerospace and industrial contexts (Guo et al., 2013). These properties are closely linked to factors such as chemical composition, processing history, and heat treatment protocols, which subsequently influence the range of microstructures present within the material (Peng et al., 2012).

The exceptional blend of qualities exhibited by TC4 positions it as an ideal material for laser micro drilling. Particularly well-suited for aerospace and automotive applications, TC4 offers an impressive strength-to-weight ratio, corrosion resistance, thermal stability, and outstanding machinability. Moreover, its low thermal expansion coefficient and strong absorption coefficient for laser energy contribute to its efficacy in precision laser micro drilling applications.

Table 1. TC4 properties

TC4 Properties	Metric
Density	4.43 g/cc
Thermal conductivity	6.7 W/m/K
Electric resistivity	17.8 Ω/ cm
Melting point	1650 °C

2.1. Machine constant parameter

There are several parameters of the machine that needs to be defined and set constant to avoid extensive variation during the printing process as it may affect the consistency of the printing process. Aside from infill density and raster angle, all other parameters were kept constant. The machine parameters that have been kept constant in this study are shown in Table 2.

Table 2. Parameter that are constant during the laser drilling process.

Parameters	Constants
Speed	4000 mm/s
Power	80%
Frequency	20kHz
Jump Speed	0.010 mm/s
Min Jump Delay	10 µm
Max Jump Delay	85 µm
Max limit length	10.00 mm

Controlling the depth and quality of the drilled holes depends heavily on the drilling speed. Faster speeds may produce faster result and suitable for the thickness of the material . The material being drilled, the laser power, and the required hole characteristics all affect the ideal speed.

One important factor that directly affects both the size of the drilled hole and the pace of material removal is laser power. Higher power results in faster material removal; nevertheless, overpowering can have unfavorable effects like heat damage or material splattering.

The quantity of laser pulses produced in a given amount of time is determined by the laser frequency. The way that various materials react to different laser frequency varies. To get the best possible absorption and energy transmission to the material, the frequency was set as low as possible to reduce the HAZ.

Jump speed refers to the speed at which the laser beam moves between drilling points. The jump speed was adjusted until it is able to control the build-up of heat and avoid thermal damage. The material has an opportunity to cool significantly between pulses by adding a jump or hold period, which lowers the total heat impacted zone.

2.2. Laser Process

Laser micro drilling is a precision manufacturing technique that uses a focused laser beam to drill small, precise holes in a variety of materials. The process begins with the setup stage, where the material to be drilled is placed on a stage and aligned with the laser beam. The laser beam is then focused to a small spot size using a lens or mirror system. Next, the stage is positioned so that the laser beam is directed at the desired location for the hole. The beam is then scanned over the area to be drilled to ensure proper alignment. Once the alignment is confirmed, the drilling stage begins. The laser beam is activated and directed at the material. As the beam is directed at the material, it melts, vaporizes, or ablates the material to create the hole. The hole size and shape are controlled by adjusting the laser power, beam spot size, and scanning speed. After the drilling is completed, the drilled area is cooled to prevent thermal damage and to minimize distortion of the material. This can be done by blowing cool air over the material, immersing the material in a coolant bath, or using a water-cooled laser head. The final stage is the analysis, where the quality of the hole is checked. This can be done by measuring the hole circularity, checking for the deposition. Laser micro drilling is a complex process that requires precise control of the laser beam and the material being drilled. It is often used in industries such as aerospace, electronics, and medical device manufacturing. The process is repeatable and accurate, with the ability to drill holes as small as a few microns in diameter and with a high degree of precision.

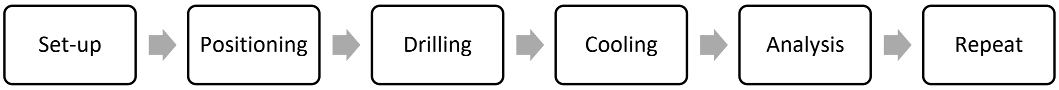

Fig.1. Procedure of experiment.

In this study, the research employed fiber lasers, a category of solid-state lasers where the active gain medium is formed by optical fibers. These fibers, crafted from silicate or phosphate glass, absorb initial light emissions from pump laser diodes and subsequently transform them into laser beams with specific wavelengths. This conversion process hinges on the fiber being doped—meaning that it incorporates rare-earth elements. By varying the doping materials, fiber lasers can produce laser beams spanning a broad spectrum of wavelengths.

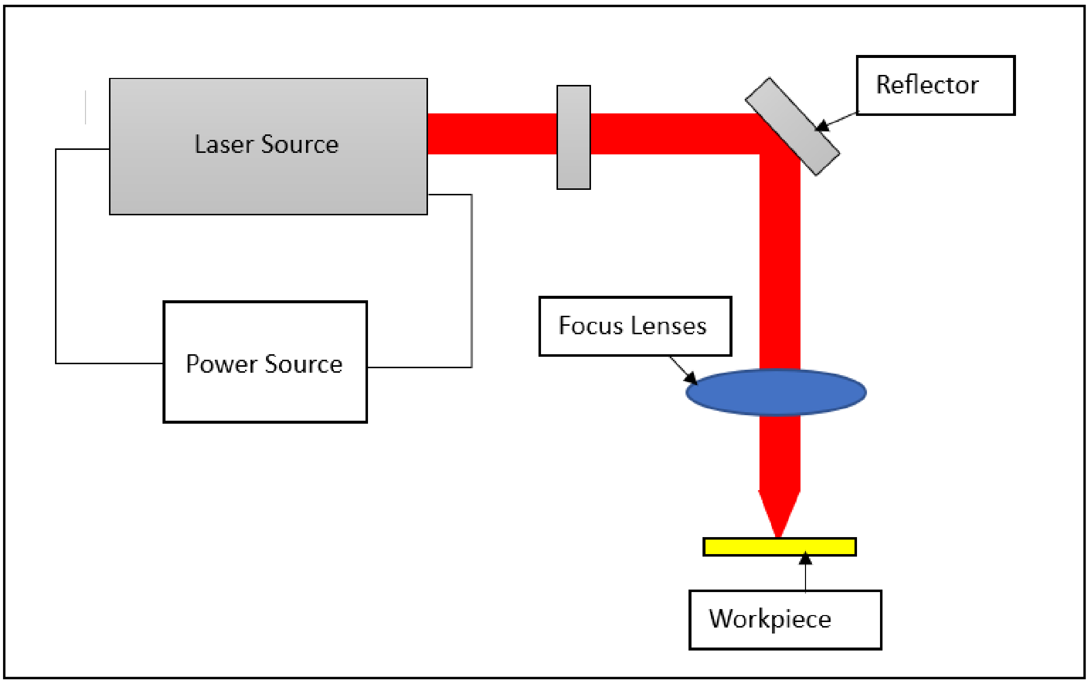

Fig 2. Schematic diagram of the laser system

The functionality of a typical fiber laser relies on the principle of stimulated emission of radiation. The fundamental components of such a system include a gain medium, pump source, resonator, and output coupler. In practice, an optical fiber enriched with rare-earth ions like erbium, ytterbium, or neodymium frequently serves as the gain medium. Through this arrangement, a standard fiber laser generates a coherent and focused laser beam, which can operate either continuously or in pulsed mode, contingent on the specific configuration and operational parameters of the laser system.

3.ANALYSIS OF THE EXPERIMENT

The OLS5000 3D measuring laser microscope stands as an advanced instrument renowned for its ability to accurately assess a diverse range of materials and structures. Functioning by scanning laser light across a sample's surface, this microscope generates magnified images that highlight intricate micro-scale details and provides measurements of surface attributes like roughness, steps, and more. This precision is further elevated by the incorporation of 4K scanning technology and custom-designed optics tailored specifically for the LEXT OLS5000 microscope. In tandem with a scanning TC4, the OLS5000 could potentially deliver even more meticulous and comprehensive readings. A scanning TC4, in essence, acts as a scanning probe microscope, employing a minute tip to traverse a material's surface, thereby offering extensive insights into its structure and properties. By employing a laser beam to create minuscule perforations, often measuring less than 100 micrometers, this technique serves various purposes such as establishing fluid flow channels or penetrating delicate layers. To enhance compatibility with the LEXT OLS5000 microscope, new optical components have been developed, including a 10X lens designed for a 405 nm wavelength light source and a long working distance objective lens. These optics effectively minimize aberrations, facilitating precise measurements across the entire field of view.

Integrating 4K scanning technology, which boasts a resolution of 4,096 pixels in the X direction (four times greater than its predecessor), markedly enhances resolution and the reliability of shape measurements. This translates to a twofold enhancement in the signal-to-noise ratio, enabling the identification of nearly vertical slopes and minute steps without necessitating image correction. Bolstered by a data recording speed quadruple that of its forerunner, the microscope employs the PEAK algorithm, ensuring swift and accurate readings at both low and high magnifications. Simultaneously, the inclusion of Smart Scan II and analytical templates streamlines the workflow from data acquisition to reporting, rendering the microscope accessible to users of all levels of expertise—activated by a simple press of the start button. These attributes collectively contribute to a user-friendly experience, even for those less familiar with the technology.

4.RESULTS AND DISCUSSION

The experimental setup included a laser drilling machine with a high-powered laser and a light microscope with sufficient magnification capabilities. Using Titanium, TC4 with thickness 0.2 mm. The laser parameters, such as power, pulse duration, and frequency, were optimized based on the material properties. Using magnification 10 × 0.5, the analysis begins with measuring the dimensions of the laser-drilled holes. This includes measuring the diameter of the holes. These measurements can be obtained by carefully examining the drilled samples under a light microscope equipped with appropriate measuring tools. The light microscope enables for the identification and characterization of numerous faults or irregularities that may occur during the laser drilling process during the study. This involves looking for spatter, debris, or burrs surrounding the drilled holes. Any evidence of heat degradation or structural changes in the material surrounding the drilled area might also be explored. Argon gas were used in laser drilling processes due to its unique properties.

Sample	Mark Loop	Drilled Hole (Top view)			$d_{entryavg}$	Std Dev
		Hole 1	Hole 2	Hole 3		
1	2(0.03)	90.07	91.58	90.22	110.62	0.83
2	4(0.0.06)	115.58	117.20	115.23	116.00	1.05
3	20(0.30)	120.06	121.55	120.50	120.70	0.77
4	32(0.48)	125.87	124.02	121.52	123.80	2.18
5	35(0.53)	125.01	123.22	125.79	124.67	1.32
6	40(0.60)	145.85	140.32	147.89	144.69	3.92
7	50(0.75)	157.18	153.23	155.78	155.40	2.00
8	60(0.90)	158.73	155.02	159.06	157.60	2.24
9	80(1.2)	156.36	158.32	159.60	158.09	1.63
10	90(1.35)	159.85	162.40	160.24	160.83	1.37

Table 3. Diameter of drilled hole from top view

Sample	Laser Loop	Drilled Hole (Bottom view)			$d_{exitavg}$	Std Dev
		Hole 1	Hole 2	Hole 3		
1	2(0.03)	-	-	-	-	-
2	4(0.0.06)	-	-	-	-	-
3	20(0.30)	-	-	-	-	-
4	32(0.48)	-	-	-	-	-
5	35(0.53)	92.97	93.78	90.60	92.45	1.65
6	40(0.60)	98.30	96.23	97.12	97.22	1.04
7	50(0.75)	98.99	101.67	99.54	100.07	1.42
8	60(0.90)	105.80	103.69	107.45	105.65	1.88
9	80(1.2)	108.08	101.23	112.32	107.21	3.46
10	90(1.35)	115.79	112.20	111.06	113.02	2.47

Table 4. Diameter of drilled hole from bottom view

Mark Loop	$d_{entryavg}$	$d_{exitavg}$	d_{ratio}
50	155.40	100.07	64.39
60	157.60	105.65	67.03
80	158.09	107.21	67.81
90	160.83	113.02	70.27

Table 5. Diameter of drilled hole from bottom view

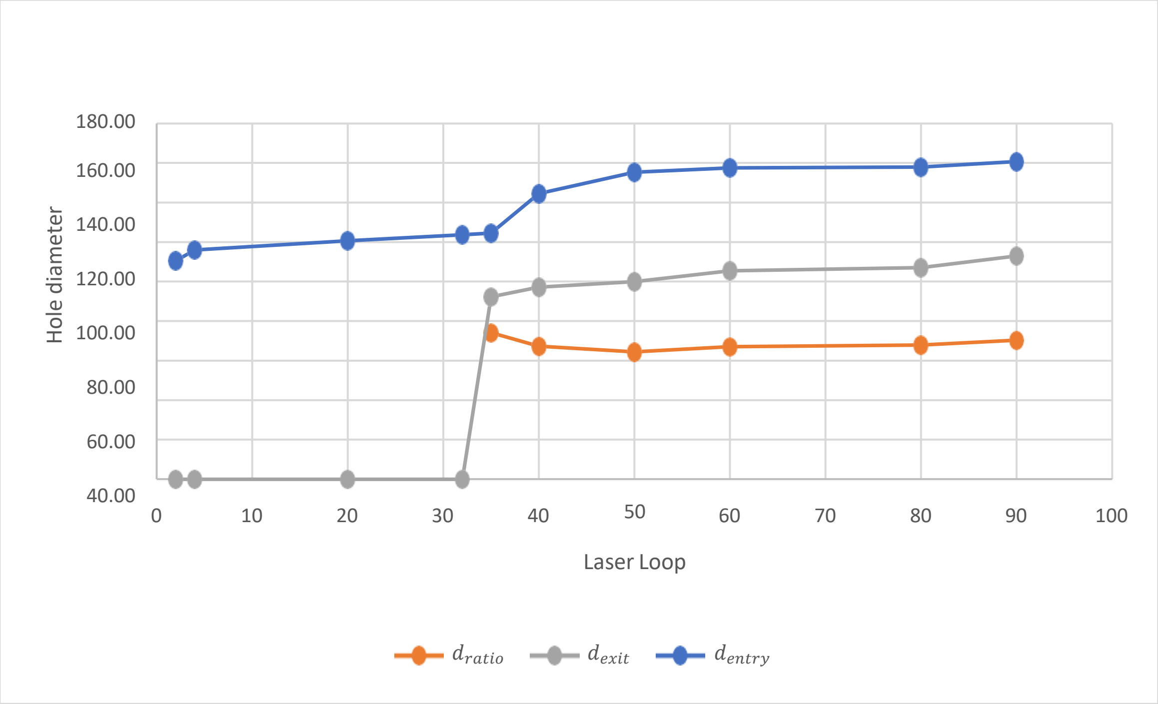

Fig 3. Laser loop against hole's ratio

From the graph we can conclude that the hole's ratio is exponentially increase as the laser loop increase. Meanwhile the entry and exit diameter increases as the loop increase.

The laser loop affects the material removal efficiency during laser drilling. At higher loop, the laser pulses are delivered more frequently, leading to a higher rate of material removal per unit of time. This can result in faster drilling speeds and larger hole diameters, as the material is ablated more aggressively. On the other hand, lower loop may yield finer drilling but with slow material removal rates. Finding the optimal loop involves striking a balance between drilling speed and hole quality, considering the specific requirements of the application. Factors such as laser power, frequency, and material properties should be considered in conjunction with the loop. The specific requirements and constraints of the drilling application should also be taken into account. By finding the right balance between drilling speed, hole quality, heat effects, and material response, the optimal loop was identified.

Laser micro drilling hole formation is a complex process involving the interaction of a high-energy laser beam and the material which is TC4 with thickness 200 microns. The laser energy is focused at the focal point, causing localized heating and vaporization and, eventually, the development of a hole. Because of the material's characteristics and the laser wavelength, the laser beam is typically absorbed by the material's surface. The absorbed energy is transformed into heat, boosting the material's temperature and ablate the surface of the material forming hole.

Sample	Laser loop			
	2(0.03)	4(0.0.06)	20(0.30)	32(0.48)
1	34.56	53.52	87.56	172.62
2	30.69	48.3	92.61	167.59
3	29.8	46.86	96.98	160.67
Average	31.6	49.56	92.38	166.96
STD	2.53	3.50	4.71	5.99

Table 6. Depth of the hole

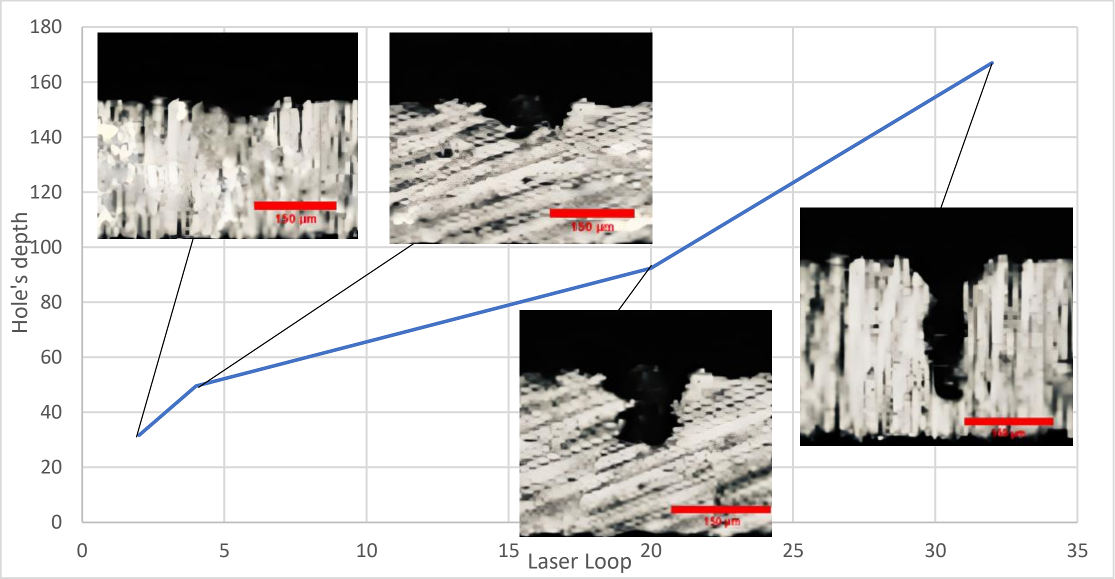

Fig 4. Laser loop against hole depth

Based on the information provided in the graph, it can be inferred that there is a positive correlation between the increase in laser loop and the corresponding increase in hole depth.

The figure above depicts at loop 2 the initial stage of laser ablation, where the laser beambegins to remove the material from the surface. The average depth obtain is 92.38 µm andstandard deviation is 2.53. To minimize spattering and improve the process, argon gas is directed towards the material surface. It was found that the pulse frequency has a significant effect on the hole entrance diameter (Pattanayak et al., 2018).

At loop 4 shows that the material is undergoing removal, leading to the formation of ahole. The average depth increases which is 49.56 µm and standard deviation 3.50. It shows the increase in depth as the loop increase. The diameter of the entry and exit increase as the laser loop increase. The lower peak power and shorter pulse time can reduce hole diameter due to less material removal by less energy in each pulse (Pattanayak et al., 2018).

Then, loop 20 shows the laser ablates and removes the material, resulting in the formationof a progressively deeper hole. The average depth obtain is 31.6 µm and standard deviation is 4.71. Additionally, the surface of the hole wall exhibits visible material deposition.

As the hole becomes deeper at loop 32, an increased amount of material is deposited on the surface of the hole wall. The average depth obtain is 166.96 µm and standard deviationis 5.99. The increase of the standard deviation shows that there are deposition occurs at the bottom of holes before the laser drilled through. This deposition occurs because the laser beam's power prevents a certain amount of material that should have been removedfrom being expelled, leading to its accumulation at the wall surface. When material removal rate increases, adequate flushing may not take place resulting in increase in spatter area (Chatterjee et al., 2018). It was discovered that, at focus point distance, where the diameter of the laser becomes smallest, the photon can produce enough laser energy to melt the metal in short time (Arsyad et al., 2022).

We can conclude that during material removal, material that are remove will be ejected through top hole and near top surface of the hole. Some material also redeposited onto the hole wall surface. After the material are drilled through, the material ejected through the bottom hole and the redeposited material on the wall surface of the hole are ejectedthrough the bottom hole.

5.CONCLUSION

This chapter highlights the conclusion based on experimental results conducted throughout the study. The conclusions summarize the investigation focused on studying the effect of micro drilling loops on the hole entry and exit diameters on TC4. The objective was to analyze effect of micro drilling loops to the hole entry and exit diameters and to investigate the effect laser loop to the formation of hole for micro drilling. The larger the laser loop size, the more laser energy and heat input is distributed across the material's surface. The increased energy deposition causes more material to removed causing the hole diameter to expand. As the holes deepen during the drilling process, material ablation leads to an increased deposition of material on the walls of the holes. However, once the drilling process is completed and the laser has fully drilled through the material, the accumulated material deposition can be effectively expelled through the exit holes and the surface wall become smooth. Increase in laser energy results in increase in thermal input which in turn increase the rate of material removal from the required cross section. During material removal, it can be concluded that the expelled material is primarily ejected through the top hole and near the top surface of the hole. Moreover, a portion of the removed material also undergoes redeposition onto the wall surface of the hole. The increase of the standard deviation at loop 32 shows that there are deposition occurs at the bottom of holes before the laser drilled through. This deposition occurs because the laser beam's power prevents a certain amount of material that should have been removed from being expelled, leading to its accumulation at the wall surface.

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