

LASER MICRO DRILLING OF DE LAVAL NOZZLES USING A HYBRID HEXAPOD SYSTEM

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HYBRID HEXAPOD SYSTEM

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We certify that we have read this thesis and that in our opinion it is fully adequate,
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ABSTRACT

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In recent years, miniaturization, one of the most intensely focused topics in science and technology, has enabled the use of macroscale engineered components at the microscale. Although components at this scale are extremely small, they can exhibit complex geometries. Therefore, precise manufacturing setups are required for their production or for processing existing ones. An example of such components is micro de Laval nozzles, which are used in the propulsion systems of micro-satellites.

In this thesis, a novel method is presented for the production of micro de Laval nozzles, in addition to a method that enables drilling on freeform surfaces using a nanosecond laser and performing angled drillings on planar surfaces, all facilitated by a hybrid hexapod. The effects of parameters such as laser power, laser frequency, scan speed, number of loops, and rotation speed on the geometry and morphology of the nozzle were investigated for the method developed for micro de Laval nozzles. Experimental results demonstrated that critical geometric parameters for micro de Laval nozzles, such as throat diameter, outlet diameter, and outlet half angle, meet the requirements specified in the literature. The findings suggest that the developed method has the potential to provide a single-step, cost-effective solution for fabricating micro de Laval nozzles.

In the future, efforts will focus on minimizing the sidewall roughness of the produced nozzles and automating the method for practical applications.

Keywords: Micro De Laval nozzle, hybrid hexapod, nanosecond laser, laser drilling.

ÖZET

HİBRİT HEKZAPOD SİSTEMİ KULLANILARAK LAZER İLE DE LAVAL TİPİ NOZULLERİN İŞLENMESİ

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Son yıllarda bilim ve teknolojinin en çok yoğunlaştığı konulardan biri olan minyatürleşme, makroskobik ölçekli mühendislik bileşenlerinin mikroskobik ölçekte kullanılmasını mümkün kılmıştır. Bu ölçekteki bileşenler oldukça küçük olmalarının yanında karmaşık geometrilere sahip olabilirler. Bu nedenle, bu tür bileşenlerin üretilmesi veya mevcut olanların işlenmesi için hassas imalat kurulumları gereklidir. Mikro uyduların itki sistemlerinde kullanılan mikro de Laval nozülleri bu tür bileşenlere örnek olarak verilebilir.

Bu tezde, hibrit bir hexapod kullanılarak, serbest form yüzeylere sahip bileşenlerin nanosaniye lazer ile delinmesini ve düzlemsel yüzeylere sahip bileşenlerde açılı delme işlemlerinin yapılmasını sağlayan bir yöntem sunulmuştur. Ayrıca, mikro de Laval nozüllerin üretimi için yenilikçi bir yöntem geliştirilmiştir. Mikro de Laval nozüller için geliştirilen yöntemde, lazer gücü, lazer frekansı, tarama hızı, döngü sayısı ve dönüş hızı gibi parametrelerin nozül geometrisi ve morfolojisi üzerindeki etkileri incelenmiştir. Deneysel sonuçlar, mikro de Laval nozüller için kritik olan throat çapı, outlet çapı ve outlet yarı açısı gibi geometrik parametrelerin literatürdeki gereksinimleri karşıladığını göstermiştir. Elde edilen bulgular, geliştirilen yöntemin mikro de Laval nozüllerin tek adımda ve düşük maliyette üretilmesi için potansiyel bir çözüm sunduğunu ortaya koymaktadır.

Gelecekte, pratik uygulamalarda kullanılmak üzere, üretilen nozüllerin yan duvar pürüzlülüğünün en aza indirilmesi ve yöntemin otomasyonu üzerine çalışılması hedeflenmektedir.

Anahtar sözcükler: De Laval nozüülü, hibrit hekzapod, nanosaniye lazer, lazer delme.

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Chapter 1

Introduction

The latest technological advancements in many fields have resulted in the emergence of devices with freeform surfaces. These devices require micrometer- or millimeter-scale machining. Examples include small-scale holes drilled into cooling channels of turbine blades, lubrication channels on bearings and shafts, and friction-reducing holes on biomedical implants [1]. Furthermore, the downsizing of devices actively used in the macro world to micro scales, in other words, miniaturization, has become one of the most actively researched and significant directions of progress in science and technology in recent years [2]. One of the fields that has benefitted from this advancement is aerospace [3, 4]. Micro-satellites, in particular, have been studied and actively developed for years in the aerospace field due to their faster production and cost-effectiveness in space exploration [5, 6]. Naturally, systems of this scale require equally small components. One such component is the micro de Laval nozzle, used in the propulsion systems of micro-satellites.

De Laval nozzles, or Laval nozzles, feature a converging-diverging structure although not limited to a single geometric shape. This design enables de Laval nozzles to transform subsonic flow entering the inlet into supersonic flow at the outlet. In addition to their role in propulsion systems, de Laval nozzles also find application in mixture separation. Mixture separation is a critical process for

isolating toxic or explosive chemicals and increasing their concentration to levels detectable by sensors [7]. Naturally, the realization of these applications requires the manufacturing of such components using a promising microfabrication technique.

Although various manufacturing methods exist for such applications, Laser Micro Machining (LMM) could be highly promising as an alternative to existing methods due to their ability to perform manufacturing processes that are done by those methods regardless of size, material, or geometry [8]. As an example, He et. al. successfully fabricated sub-millimeter converging-diverging type of nozzles using femtosecond laser technology [9]. Moreover, Louwerse et. al. investigated DRIE, sand blasting, and femtosecond laser separately to assess their performance and reported that femtosecond laser is the most promising method among them [10] which could be an evidence that lasers could be a viable option in these applications.

LMM technology offers different kinds of applications in the industry and literature such as drilling [11], polishing [12], texturing [13]. While ultrashort lasers such as femtosecond lasers offer significant advantages in applications requiring very high precision and for development purposes, they require complex and expensive equipment. On the other hand, nanosecond lasers are widely used in the industry and have proven themselves as a mature manufacturing technique for many applications [14]. When combined with a precise positioning system, literature suggests that nanosecond lasers could perform these types of operations on complex geometries as well [15].

While many different methods can be used as positioning systems, the increasing use of robotic manipulators in various manufacturing methods is becoming more apparent. Examples include drilling, cutting, milling [16], polishing [17], and grinding [18]. Robotic manipulators are fundamentally divided into two categories: serial and parallel robotic manipulators [19]. Serial robots are not used in some applications requiring high precision due to the accumulation of positioning errors at the end-effector and the resulting low load-carrying capacity. In contrast, parallel manipulators distribute the load equally among the legs supporting

the end-effector, thereby preventing the accumulation of positioning errors at the end-effector. An illustrative figure showing serial manipulators with linear and rotational actuators, as well as parallel manipulators, is provided in Figure 1.1. Mechanisms that utilize both types of positioning methods are referred to as hybrid positioning systems [20]. These systems are used in complex applications as they combine the advantages of both mechanisms, allowing precise positioning with higher degrees of freedom [21].

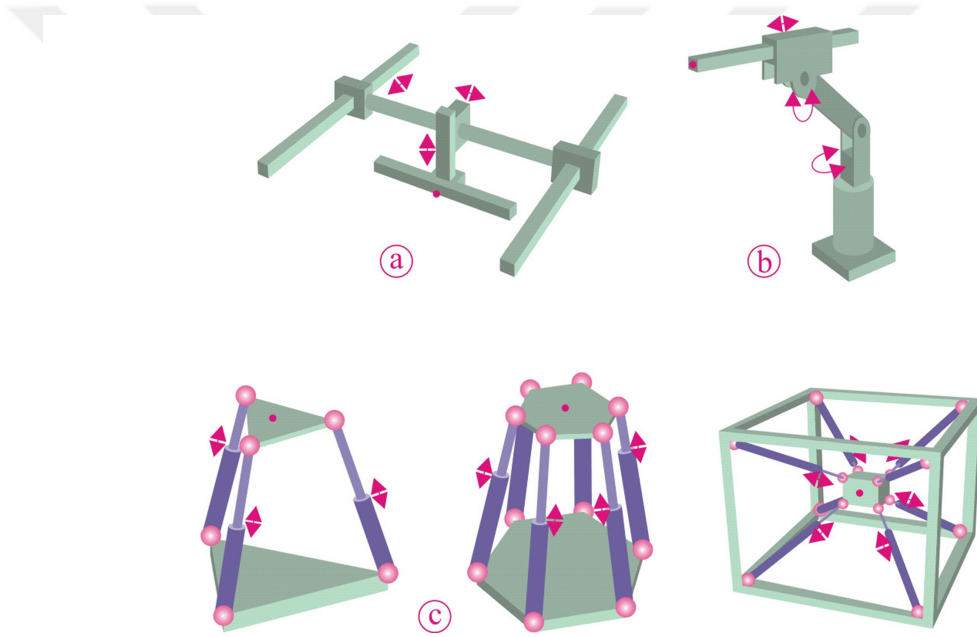


Figure 1.1: a) serial composition with linear joints, b) serial composition with rotational joints, c) parallel compositions [19].

In this thesis, a micromachining setup and a novel method are presented for the fabrication of de Laval type nozzles using a 6-axis hybrid hexapod and a commercial nanosecond laser. The motivation of this thesis is to methodologically demonstrate how a setup established for machining [22] can be utilized for complex operations, such as drilling holes on freeform surfaces at the micro level or angled drilling on flat surfaces, which may not be achievable using conventional methods. Additionally, it aims to present a promising alternative fabrication method for the production of micro de Laval nozzles.

The structure of the thesis will be as follows: first, it will present a review of the literature. Then, the experimental setup used in the work will be given.

Afterwards, the inverse kinematics model of the positioning system (the parallel manipulator) will be given. Subsequently, it will discuss the method used to experimentally determine the workspace of the positioning system and the algorithm employed to express it geometrically. Following this, the thesis will explain how freeform surface modeling, required for trajectory planning, is conducted and will provide examples of some freeform surfaces. Next, it will address the selection of optimal parameters for laser trepan drilling and their correlations. Afterward, the method used for fabricating de Laval nozzles will be detailed, and after discussing the methodology used to automatically fabricate such nozzles will lead the de Laval nozzle fabrication chapter to the results section. In the results and discussion section, the de Laval nozzle outcomes obtained using the methods and correlations given in the previous sections will be presented and the findings will be discussed. Finally, the thesis will conclude with a conclusion and future work section, summarizing the study and discussing potential applications for future exploration.

Chapter 2

Literature Review

2.1 Laser Micro Drilling

As stated in DIN 8580, laser drilling is essentially a laser cutting operation [23]. The objective of laser drilling is to focus the laser beam on a specific point, which results in heating the material to its melting or vaporization temperature and removes the material [24]. When vaporization occurs, a formation called a keyhole is created, which increases absorptivity and allows the hole to deepen further [25]. When this operation is performed on a micro scale, and the resulting hole is smaller than 1 mm, it is referred to as laser micro drilling [9]. Laser drilling offers several advantages over conventional drilling methods. These include being a non-contact process, the ability to accurately determine the location of the hole, the absence of chip formation, achieving high depth-to-diameter aspect ratios in small holes, and the capability to drill holes at challenging entrance angles [24].

Laser micro drilling finds applications in a wide range of industries. Examples include injection nozzles and lubrication holes in the automotive industry, cooling holes, flow control holes, and turbine blades in the aerospace field [26], friction reduction on implant surfaces [27] and micro-tubing in drug delivery systems in the biomedical industry [28], through vias [29] and printed circuit boards [30] in

microelectronics, and micro-filtration [31] in environmental engineering. Laser micro drilling is observed to be applied in many other areas as well.

The factors affecting the laser micro drilling process can generally be examined under three main categories: laser-related parameters, material-related parameters, and process-related parameters. Some of the laser-related parameters can be listed as wavelength, pulse duration, pulse energy, intensity, repetition rate, pulse form, polarization, beam position and pulse-to-pulse stability [9]. With a simple laser marking software, it is not possible to modify parameters such as wavelength and polarization. However, parameters like laser power, laser frequency, scanning speed, and pulse distance can be adjusted. Therefore, parameters such as intensity (as it is related to pulse energy, average power, and repetition rate), repetition rate (as it is related to power and pulse area), and pulse distance (as it is related to repetition rate and scanning speed) can be indirectly controlled, even though they cannot be adjusted directly. Another influencing factor is material-related parameters, including surface quality, the microstructure of the material, absorptivity, thermal conductivity, specific heat capacity, melting point, boiling point, and thickness. However, since this study was conducted exclusively on aluminum 2024 alloy, the effects of material-related parameters on drilling quality have not been discussed. Finally, process-related parameters such as focal length, focus position, drilling strategy, and drilling path have been examined. For instance, the drilling strategy was controlled through both the laser marking software and the positioning system. The quality of the resulting hole is generally assessed based on parameters such as geometric accuracy, morphological properties, metallurgical features, and productivity. Examples of geometric accuracy include the hole's circularity, conicity/cylindricity, and aspect ratio. Morphological properties can be represented by surface roughness and surface debris, while metallurgical features include the heat-affected zone and resolidified material. As for productivity, an example is the material removal rate (MRR), defined as the ratio of the material removed to the processing time. In this thesis, geometric accuracy, morphological properties, and productivity are particularly considered as critical categories affecting the quality and efficiency of micro-machining.

To categorize laser drilling methods fundamentally, they can be divided into

four types: single-shot drilling, percussion drilling, trepan drilling, and helical trepan drilling [32, 33]. Single-shot drilling, as the name suggests, involves creating holes by delivering a single laser pulse to the workpiece. For this method to produce a usable hole, the laser pulse must have very high energy levels, which reduces productivity, increases plasma formation, and consequently lowers overall hole quality [34]. Percussion drilling, on the other hand, involves creating holes by delivering multiple laser pulses to the same point. The quality of the holes produced is better compared to single-shot drilling due to the reduction in required peak power, which subsequently reduces the amount of molten material and plasma formation [23]. Unlike percussion drilling, trepan drilling technique enables more accurate and controlled hole shapes by moving either the laser or the workpiece in a specified path. Additionally, trepan drilling enables the drilling of holes in almost any geometric shape. The general representation of these methods is provided in the Figure 2.1. Helical trepan drilling, while essentially a variant of trepan drilling, involves the rotational movement between the workpiece and the laser beam being combined with a continuous elevation of the workpiece.

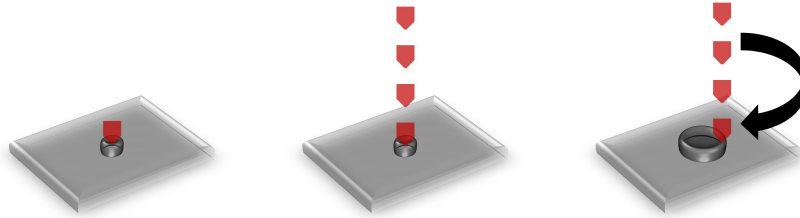


Figure 2.1: Single Shot, Percussion, and Trepan Drilling Methods.

Laser trepan drilling or laser trepanning is a technique particularly used in cutting more accurate circular holes or other complex geometries in a wide range of materials such as metals [35], ceramics [36], and composites [37] in various different disciplines as stated.

2.2 Freeform Surface Machining

Freeform is a term used to classify one or more non-planar, non-quadric surfaces, as opposed to more familiar planar surfaces [38]. An example of freeform surfaces can be seen in Figure 2.2, which depicts turbine blades from aircraft engines. For creating the cooling holes shown here, methods such as mechanical drilling, electrical discharge drilling, electrochemical drilling, and laser drilling are frequently employed [39].

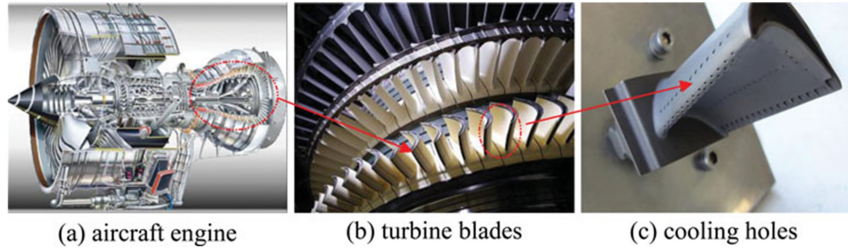


Figure 2.2: Cooling holes on a turbine blade [39].

Although drilling on planar surfaces with laser is relatively straightforward since the laser beam and the surface tangent are perpendicular, this is not the case for complex surfaces. The reason, as explained in the Figure 2.3, is that on complex surfaces, the tangent vector of the drilling point is not perpendicular to the laser beam, making it challenging to achieve the desired hole. As stated in the literature, this process has now become feasible with the emergence of platforms capable of simultaneous positioning [8]. Therefore, to ensure this perpendicularity, an additional positioning system that is capable of simultaneous positioning of the workpiece must be integrated, and positioning must be performed accordingly.

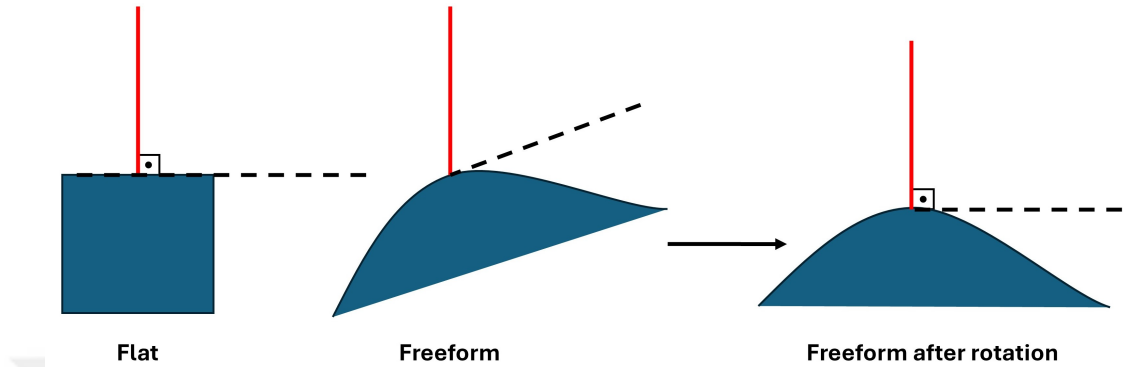


Figure 2.3: Angle between laser beam and surface tangent for flat and freeform surfaces.

There are many examples of robot manipulators being used in manufacturing applications, such as drilling, cutting, milling [16], polishing [17], and grinding [18]. Robot manipulators may be more suitable for some applications than CNC machines [40] and they can be categorized as serial and parallel manipulators [19]. Serial manipulators have an open-loop chain mechanism, while parallel manipulators have a closed-loop mechanism. Due to the accumulation of positional errors at the end effector, serial manipulators are not preferable for high-precision applications. On the contrary, parallel manipulators exhibit better dynamic performance [41]. The combination of serial and parallel manipulators also exists in the literature [20]. Such manipulators are often called “hybrid”.

For a typical machining operation, Computer Aided Manufacturing (CAM) software generates G-codes that generate the locations of the cutter [42]. Therefore, a typical G-Code program contains commands, and the positioning system moves the tool and the part according to these commands; however, in systems where parallel manipulators are used to position the workpiece. The discrete position inputs are used to create a path for the manipulator through various interpolation methods, and a consistent simulation of the manipulator must be designed and tested on a computer before turning the positions into drive commands. It’s possible to obtain path interpolation using mathematical methods such as B-Spline [43] and NURBS [44]. The simulation of the position and the

orientation of the manipulator can be made via inverse kinematic equations [45]. Another critical aspect is analyzing whether the positioning system can execute the generated path. A workspace analysis can be conducted to determine this. The workspace represents the maximum volume that a manipulator can reach. It can be determined experimentally [46] by noting the positions successfully reached by the positioning system or analytically [47] in a similar manner but using equations instead of experiments. Conducting the workspace analysis provides crucial information on whether a part can be processed before actual machining begins.

Another example of a freeform surface can be seen in the knee implant shown in the Figure 2.4. The pocket-like holes observed in this knee implant were created using laser micro drilling alongside with a stewart platform which shows a potential application of laser and parallel manipulator for freeform surface machining [15].

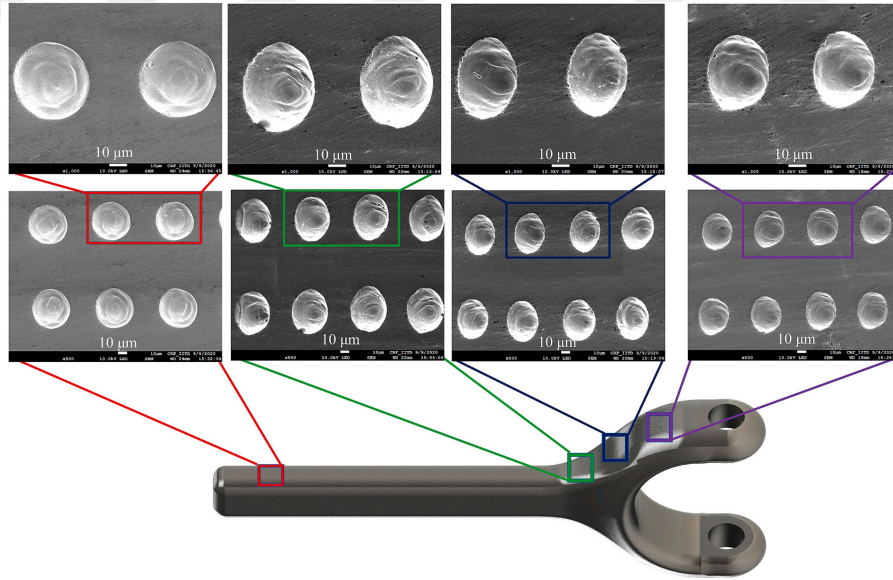


Figure 2.4: Laser drilled pocket-like structures on a knee implant [15].

2.3 Micro De Laval Nozzles

2.3.1 Definition

Nozzles, despite their various geometries, are fundamentally components attached to the end of a propulsion system to accelerate exhaust gases. In 1890, one of the fastest steam turbines of its time was invented using a series of nozzles [48]. This invention, made possible by the use of converging-diverging nozzles, known today as De Laval nozzles, was created by Carl Gustaf Patrick De Laval. Sub-millimeter versions of these kinds of nozzles are named as micro De Laval nozzles.

One of the most significant applications of micro De Laval nozzles today is in satellite propulsion systems, where the gas enters the inlet at subsonic speed and high pressure, reaches the speed of sound at the throat, and is then ejected from the outlet at low pressure and supersonic speed. A typical shape of a De Laval nozzle is shown in the 2.5.

In itself, De Laval nozzles can also have various geometric shapes and sizes depending on different applications and requirements, but they all fundamentally feature a converging-diverging profile. Thus, their main components are the inlet, outlet, and throat. For micro De Laval nozzles, the geometric parameters necessary to achieve the required flow characteristics have been approximately determined in the literature through both numerical simulations and experimental studies [2, 10]. Moreover, many studies have identified the sidewall roughness of these nozzles as the most critical parameter affecting flow performance [2, 49, 50].

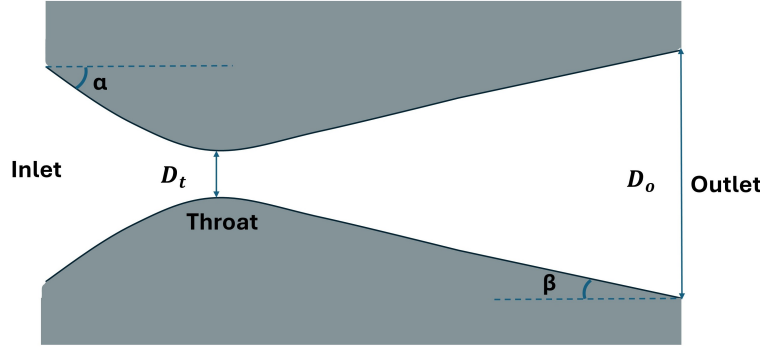


Figure 2.5: Key parameters of a de Laval nozzle. D_t and D_o are throat and outlet diameters, respectively.

2.3.2 Fabrication Methods

In the literature, numerous methods have been proposed for the fabrication of micro-scale nozzles. Each of these methods has its own advantages and disadvantages. The most suitable method is determined by achieving a balance between geometric precision, surface quality, and cost efficiency. Therefore, a comprehensive literature review is necessary to assess whether the method proposed in this thesis meets these criteria. There are examples of producing micro nozzles by bonding silicon wafers that are etched with Deep Reactive Ion Etching (DRIE) using the fusion bonding method [51, 52]; Huh et al. utilized wet etching on glass [53]; Chu et al. applied mechanical micromachining [54]; Cai et al. used micro drilling [49]; Zhang et al. adopted co-fired ceramic technology [55]; Cheah et al. implemented gel casting and sintering methods [56]; and Tong et al. and Li et al. successfully fabricated micro nozzles using Electro Discharge Machining (EDM) [57, 58]. These studies resulted in various types of micro nozzles designed for different purposes.

If the mentioned methods are to be examined individually, in the approach proposed by London et al. and similarly by Ayon et al., six separate silicon wafers were first etched using the DRIE method to form the layers of the micro nozzle. These layers were then bonded together using fusion bonding to create the micro

nozzle. The layer-by-layer two-dimensional etching of the nozzle provided an advantage in adjusting its geometric parameters, resulting in a nozzle with a 1:15 throat-to-outlet ratio. However, this method's reliance on silicon, a material that is easier to etch compared to metals and widely used in the semiconductor industry, allows for better control over the manufacturing process parameters. Due to this, the method proposed here may not be considered a universally applicable method.

The reason behind Huh et al. using glass as the nozzle material is explained as taking advantage of the thermal insulation properties of glass. In this study, the nozzle was also fabricated layer by layer. First, a film mask of the nozzle profile was created for each layer, chrome masks were produced using photolithography, the glass was exposed to UV light, heat-treated, wet-etched with hydrofluoric acid, polished, and finally bonded together using thermal bonding. Although this method allowed for the production of nozzles with high throat-to-outlet ratios due to the convenience of layer-by-layer two-dimensional etching, the equipment required for such an application is extensive, and the fabrication process involves numerous intermediate steps. On the other hand, Low-temperature co-fired ceramic (LTCC) tape technology, while enabling the fabrication of micro nozzles without the need for expensive equipment and complex fabrication steps and providing higher performance compared to silicon-based micro nozzles, has faced various constraints regarding the maximum temperature the materials can withstand [56].

Chu et al. successfully fabricated micro nozzles on Aluminum 6061 T6 material using a flat-end mill for roughing and a ball-end mill tool for finishing. In this application, the smallest tool diameters ranged from 100–500 μm for the flat-end mill and were 200 μm for the ball-end mill. The nozzles produced in this study had throat diameters of 0.5 mm and 1 mm. Although the nozzles were successfully fabricated, the total machining time of 2 hours and 30 minutes indicates that the process duration is significantly long. Similarly, on another aluminum alloy, Cai et al. produced micro nozzles using a 1 mm flat-end mill for roughing and a 0.8 mm ball-end mill for finishing. In this study, the divergent section of

the nozzle was first machined using milling, followed by a drilling operation extending downward from the throat. Finally, the converging section was machined via milling, resulting in the successful fabrication of a micro nozzle. Although the nozzle produced in this study had a 1 mm throat diameter, this work also demonstrates that when attempting to fabricate micro nozzles using mechanical micromachining, factors such as machining time, tool diameter, tool material, and the inclusion of multiple positioning steps in the process must be considered.

In another study, Li et al. successfully fabricated micro nozzles using micro-EDM with ZrB₂-SiC-graphite material. However, similar to other methods, this was achieved only through multiple positioning steps: first, the rough inlet of the micro nozzle was created using a 400 μm electrode, followed by the completion of the converging section with a 150 μm electrode. The workpiece was then rotated 180 degrees to process the outlet, which was similarly machined first with a 400 μm electrode and then with a 150 μm electrode. This resulted in a micro nozzle with a 200 μm throat diameter and 1200 μm inlet and outlet diameters. As with previous methods, multiple intermediate positioning steps were used in this approach, and constraints related to the electrode diameter, similar to the tool diameter in mechanical micromachining, were also observed.

To summarize the literature review presented in this chapter, it can be understood from the studies that the use of lasers holds potential as a viable option for operations requiring high precision, such as freeform surface machining and micro nozzle fabrication. When the methods previously used for micro nozzle fabrication are examined, it is evident that each has certain aspects that need improvement. These can be summarized as follows:

1. Nozzles fabricated through layer-by-layer etching using DRIE or chemicals like HF involve numerous intermediate steps and require complex setups, including specialized environments such as clean rooms. Moreover, the individually fabricated layers in these methods need to be meticulously bonded together. Additionally, they are subject to certain material constraints.

2. Nozzles fabricated using methods like micro milling or micro-EDM require

multiple intermediate positioning steps and are subject to geometric constraints based on the diameter of the tool or electrode used. Additionally, these intermediate positioning steps can potentially compromise the symmetry of the fabricated micro nozzle. Moreover, these methods typically involve an initial rough machining process followed by a finishing step.

3. In addition to requiring complex processes, all other methods necessitate different process designs for varying nozzle designs. For instance, in layer-by-layer fabricated micro nozzles, any design change requires altering the mask used for each layer and adjusting the production accordingly. Similarly, in mechanically fabricated micro nozzles, each new design entails meticulously planned new tool-paths. Furthermore, these methods are often not adaptable to different materials, requiring the process to be tailored for each specific material.

2.4 Research Question and Objective

The aim of this thesis is to explore whether it is possible to develop a fabrication method for micro de Laval nozzles using a commercially available nanosecond laser that addresses some of the constraints and drawbacks identified in existing techniques. Specifically, this research investigates whether a cost-effective method can be developed that eliminates the need for layer-by-layer processing, enables the fabrication in a single positioning step, avoids the necessity of customized process planning for varying designs, and overcomes geometric and material limitations.

Chapter 3

Experimental Setup

This chapter will discuss the components of the experimental setup used in this study. The chapter consists of four sections: first, the positioning system; second, the nanosecond laser; third, the devices used for measurements; and finally, the software used to control all these systems. A breakdown of the experimental setup is provided in Figure 3.1 and a breakdown of the components is given in Figure 3.2.

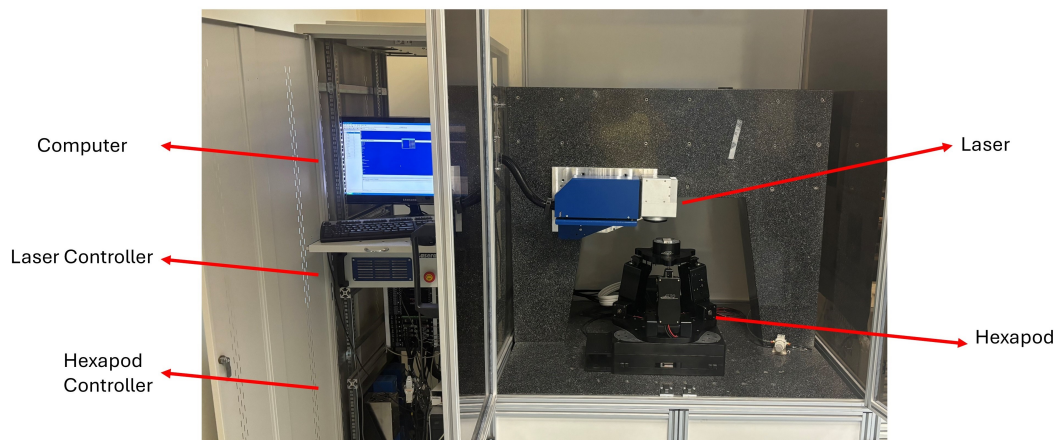


Figure 3.1: Experimental Setup.

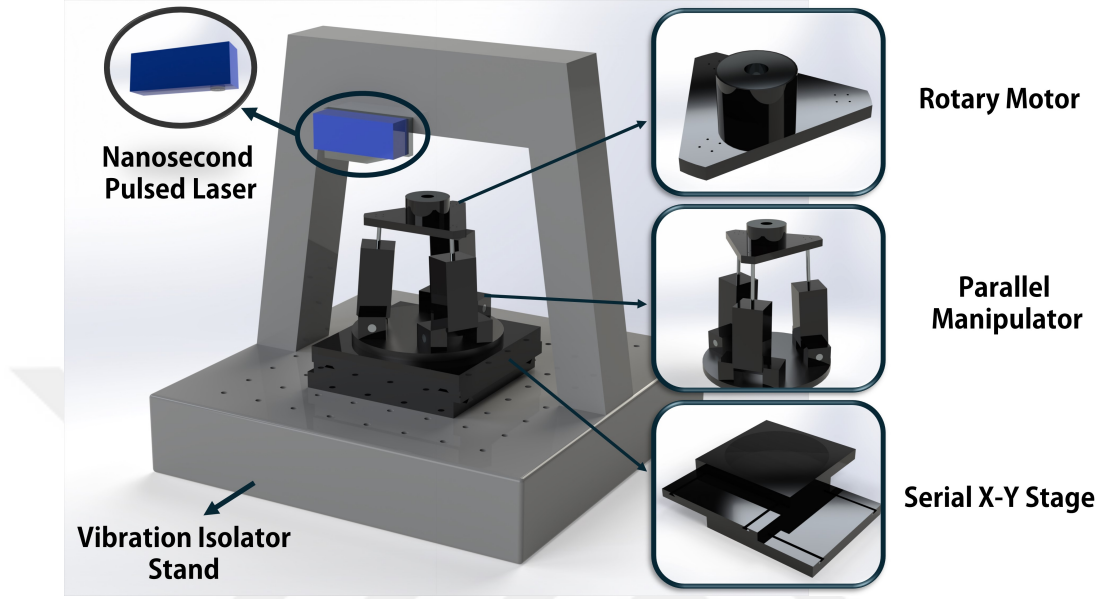


Figure 3.2: Experimental Setup Breakdown.

3.1 6-Axis Hybrid Hexapod

As stated, the positioning system used in this study is referred to in the literature as a hybrid hexapod. It is called "hybrid" because it combines the characteristics of robots with both parallel and serial kinematic chains. To begin with the parallel manipulator component, it is a system with 3 degrees of freedom, consisting of rotational, prismatic, and spherical joints, which is why such parallel manipulators are referred to as 3-RPS. This parallel manipulator is mounted on a planar stage with 2 degrees of freedom, allowing it to move freely in the x-y axes. Finally, a rotary motor is positioned on top of the parallel manipulator, enabling the end-effector to rotate around the z-axis. When combined, these components create a positioning system capable of free movement across 6 axes. The system's specifications are provided in Table 3.1.

Parameter	Data	Unit
Travel Range (Z)	55	nm
Travel Range (Pitch and Roll)	± 20	deg
Bi-Directional Linear Repeatability	± 100	nm
Angular Repeatability	~ 0.5	arc-sec
Linear Z-Axis Resolution	5	nm
Pitch and Roll Resolution	~ 0.02	arc-sec
Max Velocity	0.2	m/sec
Max Angular Velocity	90	deg/sec
Max Payload Capacity	10	kg

Table 3.1: Properties of the Hybrid Hexapod.

3.2 Nanosecond Fiber Laser

As previously mentioned, a q-switched nanosecond fiber laser was used to perform the machining operations. The laser is commercially available and has a peak power of 20 watts. This makes it a cost-effective option for microfabrication processes. The specifications of the laser are provided in Table 3.2.

Parameter	Data	Unit
Central Wavelength	1064 ± 4	nm
Peak Power	20	W
Energy Per Pulse	0.5~0.6	mJ
Pulse Width	80~120	ns
Frequency Tunable Range	22.7-79.4	kHz
Beam Quality	< 1.4	M2
Beam Diameter	6~8	mm

Table 3.2: Properties of the Nanosecond Laser.

3.3 Measurements

Two different microscopes were used for measurements: an optical microscope and a laser microscope, specifically the Keyence VHX-1000 and VKX-100 models, respectively. The optical microscope was utilized for basic geometric measurements and imaging, while the laser microscope was employed for more precise measurements, such as roughness evaluation, and for generating 3D representations of the measurements.

3.4 Software

Three main software were utilized in this work. Power PMAC (Programmable Multi-Axis Controller), to control the hybrid hexapod positioning system. Power PMAC provided precise motion control, enabling accurate manipulation of the end-effector across six degrees of freedom. Its advanced programming capabilities allowed for customized motion trajectories, essential for the complex operations required. Furthermore, among many different move commands, it includes a B-Spline based move mode called SPLINE which aligns with the freeform surface modeling strategy that will be presented in this work. EzCad2, to control the laser system. EzCad2 software facilitated the configuration and execution of some of the laser parameters such as power, frequency, and speed. Keyence Analysis Application, to analyze the results obtained from VKX 100 microscope. It supported both 2D and 3D data processing and noise filtering, enabling detailed and precise evaluation of parameters such as surface roughness, dimensions, and geometric characteristics.

Chapter 4

Laser Micro Drilling on Freeform Surfaces

In this section, the laser micro drilling experiments and their results, conducted using the experimental setup detailed in previous sections, will be discussed. Initially, the parameter study performed for blind holes created using the trepanning method will be explained, focusing solely on the nanosecond laser parameters, independent of the hexapod's effects which was primarily conducted to determine the correct laser parameters for drilling holes in 2024 aluminum. Subsequently, using the optimized laser parameters obtained from this study, the results of holes drilled perpendicular to tangent vectors at various points on a sinusoidal surface, as described in the previous section, will be presented and the results will be discussed.

4.1 Strategy

LMM using a hybrid manipulator is a challenging task from many perspectives, including finding the complex kinematics of the manipulator, modeling the complex geometry, finding the workspace, and trajectory planning. The methodology

used in this work can be broken down into six categories as given in Figure 4.1 as follows: (1) Design a complex geometry using SOLIDWORKS and take the CAD file in IGES format. (2) Read the data using MATLAB IGES Toolbox and extract the NURBS surfaces. There are certain types of entities included in an IGES file. To extract the NURBS surfaces or curves for further analysis, write an external code that searches for them. (3) Model the surface of the complex geometry using MATLAB NURBS Toolbox. This is essential for tiling the surface and finding the normal vectors of the tiles where the holes will be drilled. (4) Find the necessary position inputs by using the normal vectors of the tiles and the kinematic equations. (5) Check if the hexapod can achieve the necessary position inputs from its experimentally found workspace. (6) Write the position inputs in PPMAC (Power – Programmable Multi-Axis Controller) format and give as the input to the hexapod and execute the operation.

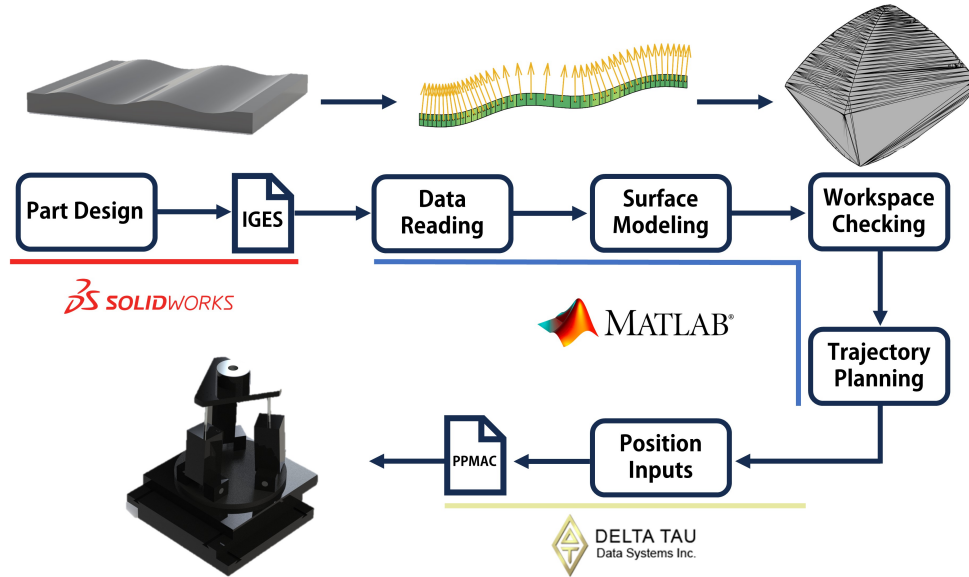


Figure 4.1: Drilling strategy workflow.

4.1.1 Inverse Kinematics

This section outlines the overall structure of the manipulator, the reference frames used, inverse kinematic equations, and the positioning simulation made in MATLAB. The inverse kinematic equations for the 3-RPS part of the hexapod were

determined to find the joint and limb values needed for a given end effector position and orientation. These equations identify independent parameters and facilitate movement when inputting data. They also allow us to pre-check the system's orientations for complex geometries and ensure alignment between the laser beam and surface normal vectors.

4.1.1.1 Overall Structure of the Manipulator and Reference Frames

The type of manipulator that is used in this work is called a hybrid manipulator which has 6 degrees of freedom. A hybrid manipulator is a combination of serial and parallel kinematic structures where the serial part is composed of two sliding stages, which provide a planar movement to the platform. On the other hand, the parallel part is composed of three limbs, which have revolute, prismatic, and spherical joints that provide the setup to move on yaw, pitch, and roll axes to the end-effector and allows it to elevate. A 3-RPS manipulator is composed of 3 revolute, prismatic, and spherical joints. In Figure 4.2a, spherical joints are given in blue, prismatic joints are given in red, and revolute joints are given in green. Two reference frames, one being an inertial reference frame (o -xyz) and the other one is the moving reference frame (c -xyz) in Figure 4.2b. In a 3-RPS parallel manipulator, it is assumed that both the points $B_1B_2B_3$ and $A_1A_2A_3$ make equilateral triangles.

4.1.1.2 Position Analysis

Positions of points A_1, A_2, A_3 and B_1, B_2, B_3 can be expressed in their respective reference frames, $o - xyz$ and $c - xyz$, as:

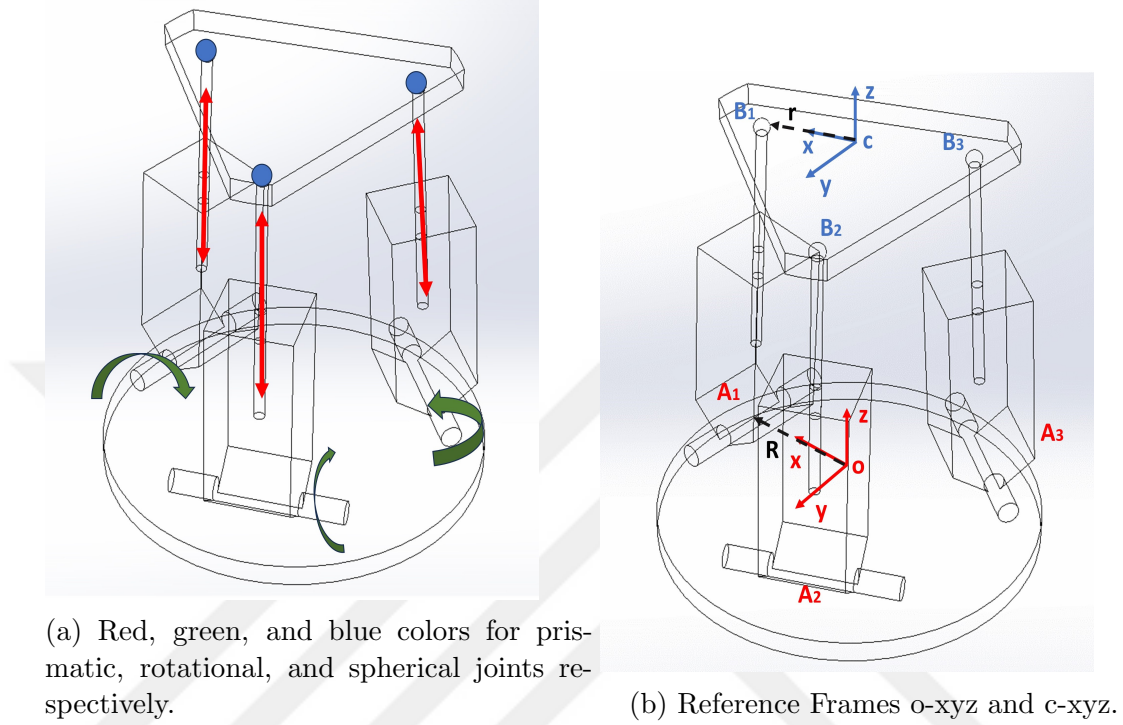


Figure 4.2: Reference Frames and Joint Types

$$A_1/o = \begin{bmatrix} R \\ 0 \\ 0 \end{bmatrix}, \quad A_2/o = \begin{bmatrix} -\frac{R}{2} \\ -\frac{\sqrt{3}R}{2} \\ 0 \end{bmatrix}, \quad A_3/o = \begin{bmatrix} -\frac{R}{2} \\ \frac{\sqrt{3}R}{2} \\ 0 \end{bmatrix}, \quad (4.1)$$

$$B_1/c = \begin{bmatrix} r \\ 0 \\ 0 \end{bmatrix}, \quad B_2/c = \begin{bmatrix} -\frac{r}{2} \\ -\frac{\sqrt{3}r}{2} \\ 0 \end{bmatrix}, \quad B_3/c = \begin{bmatrix} -\frac{r}{2} \\ \frac{\sqrt{3}r}{2} \\ 0 \end{bmatrix}, \quad (4.2)$$

where R and r are the distances of points A_1 and B_1 measured from the origins of the coordinate frames $o - xyz$ and $c - xyz$, respectively. A_i/o represents the position of the joints A_i in the inertial reference frame $o - xyz$, and B_i/c represents the position of the joints B_i in the moving reference frame $c - xyz$.

To find the position of points B_1/c , B_2/c , and B_3/c in the $o - xyz$ reference frame, a coordinate transformation can be applied:

$$\begin{bmatrix} B_{ix} \\ B_{iy} \\ B_{iz} \end{bmatrix} / o = \text{Rot} \begin{bmatrix} B_{ix} \\ B_{iy} \\ B_{iz} \end{bmatrix} / c + \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix}, \quad (4.3)$$

where Rot is the rotation matrix given by:

$$\text{Rot} = \begin{bmatrix} \cos \alpha \cos \beta & \cos \alpha \sin \beta \sin \theta - \sin \alpha \cos \theta & \cos \alpha \sin \beta \cos \theta + \sin \alpha \sin \theta \\ \sin \alpha \cos \beta & \sin \alpha \sin \beta \sin \theta + \cos \alpha \cos \theta & \sin \alpha \sin \beta \cos \theta - \cos \alpha \sin \theta \\ -\sin \beta & \cos \beta \sin \theta & \cos \beta \cos \theta \end{bmatrix}, \quad (4.4)$$

which is known as the Tait-Bryan $Z_1Y_2X_3$ matrix, written in α , β , θ angles for the rotations around Z , Y , and X axes, respectively.

Due to the geometric constraints of the mechanism, the revolute joint of limb A_1B_1 can only rotate around the y -axis. Similarly, the revolute joints of limbs A_2B_2 and A_3B_3 can only rotate around the axes $y = \sqrt{3}x$ and $y = -\sqrt{3}x$, respectively. These constraints can be expressed as:

$$B_{1y} = 0, \quad B_{2y} = \sqrt{3}B_{2x}, \quad B_{3y} = -\sqrt{3}B_{3x}. \quad (4.5)$$

By substituting these constraints and solving the equations, the dependent variables α , c_x , and c_y can be expressed in terms of the independent variables β , c_z , and θ , which correspond to roll, pitch, and heave inputs. The derived equations are as follows:

$$\alpha = \arctan \left(\frac{\sin \beta \sin \theta}{\cos \beta + \cos \theta} \right), \quad (4.6)$$

$$c_x = \frac{r \cos \alpha \cos \beta - r \cos \alpha \cos \theta - r \sin \alpha \sin \beta \sin \theta}{2}, \quad (4.7)$$

$$c_y = -r \cos \beta \sin \alpha. \quad (4.8)$$

4.1.2 Freeform Surface Modeling

Surface modeling is crucial for planning hexapod positions, especially with complex geometries. Initially, designs are made in CAD software like SOLIDWORKS, which uses NURBS for creating and visualizing complex shapes. The NURBS data is extracted by saving the design as an IGES (.igs) file and searching for NURBS entities (e.g., Type 128 for NURBS surfaces). This IGES file is imported into MATLAB using the IGES Toolbox. However, the imported data is often not straightforward, so a simple search algorithm in MATLAB locates the NURBS surface. The MATLAB NURBS Library then tiles the surface to identify the machining region and normal vectors of the tiles. Finding these normal vectors is necessary to maintain the beam incident angle (BIA) perpendicular, ensuring the laser beam is normal to the surface tangent.

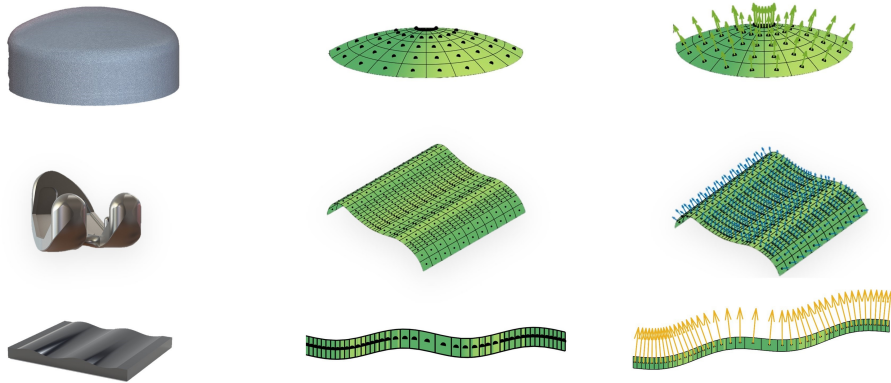


Figure 4.3: Sample tiled surfaces and the normal vectors.

This tiling method can also be applied for drilling, texturing, and surface finishing. Once the NURBS surface is tiled and normal vectors are determined, a

separate MATLAB code uses the kinematic equations to ensure a perpendicular BIA. Finally, tile angles and Cartesian positions are converted into PPMAC (Power Programmable Multi-Axis Controller) code and inputted to the hexapod. Figure 4.1 shows the tools and software used in these steps. To achieve a perpendicular BIA, the laser beam's position is treated as a unit vector pointing downwards, and the angle between this vector and each tile's normal vector is calculated. Figure 4.3 illustrates a tiled complex surface and its normal vectors. This angle is then used to update the rotation matrix, which recalculates the positions of the end-effector, points B1, B2, B3, and the surface normal vectors. If these positions are within the hexapod's workspace, they are processed by MATLAB and sent to the hexapod via PPMAC. The next section details the methodology for determining the workspace.

4.1.3 Workspace Analysis

Understanding the behavior and the physical limitation of a manipulator is essential especially when used for manufacturing purposes. For the correct positioning of the target point on a freeform surface by a parallel manipulator, the tangent vector at the target point must be perpendicular to the laser beam. To achieve this perpendicularity, the parallel manipulator must be capable of orienting the workpiece at the required angle. However, since it is known that the parallel manipulator cannot achieve every possible angle, it is necessary to determine its working envelope, or in other words, its workspace, to assess whether the freeform surface can be processed before starting the drilling operation. As mentioned earlier, the hexapod is composed of three parts: parallel (3-RPS) part, serial planar X-Y stage, and independent rotary motor around Z-axis. The parallel part is responsible for rotating the workpiece, with respect to the laser beam. Thus, the workspace analysis of the manipulator is done experimentally for the parallel (3-RPS) part of the hexapod. The experimental workspace is found by giving certain combinations of roll, pitch angles, and Z-axis positions (heave) that are incrementally increasing starting from zero to check if the hexapod can achieve the given inputs. Position data of the limbs when the combinations that are

successfully achieved by the hexapod are extracted from the built-in sensors. As the center of the platform (end effector) does not change its position by the rotation of the platform, the positions of the limbs were found. After recording the positions, expressing the envelope of the recorded points as a convex hull is a wise choice, both to represent the workspace as an envelope, and to determine whether a given point lies within the envelope. When the envelope is represented as a convex hull, checking whether a given point is inside the envelope becomes straightforward, either through a simple geometric search algorithm or even by plotting the point and the convex hull for visual inspection. Therefore, the next step is geometrically expressing the workspace as a convex hull.

Several different 3D convex hull algorithms proposed in the literature, even though they exhibit differences, most of them are based on checking which side of a plane a point is on. Thus, a brute force algorithm based on this fundamental operation and the well known gift wrapping algorithm are implemented in MATLAB and their performances compared based on how many point is given to the algorithms, final workspace is also represented as a convex hull for both of the algorithms. The main reason for using a brute force algorithm is to provide a more intuitive understanding of how the convex hull of a set of points can be computed algorithmically.

4.1.3.1 Brute Force Algorithm

Assuming that no four points are co-planar, one way of computing the convex hull of a given set of 3D points (which will be a polyhedron) is to check every possible triangular face (a,b,c) if it is a face on the convex hull by checking every other point in the given point set is at one side of the triangular face or not. If every other point is at one side, it means that triangular face is one of the faces that is at the outer of the given point set.

To compute which side of a plane a point is on, the normal vector of the plane should first calculated by the Equation 4.9.

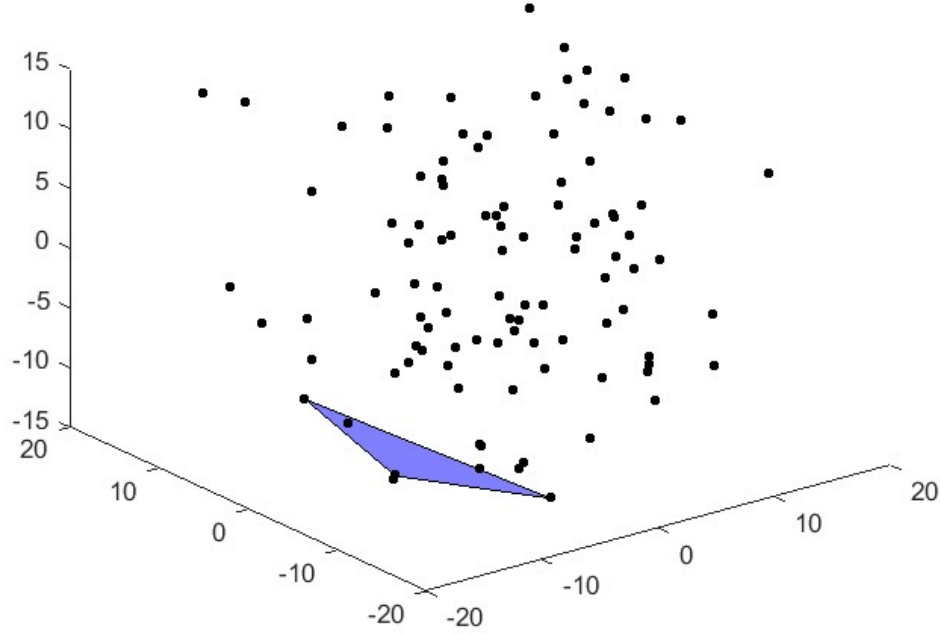


Figure 4.4: First triangle found to be used in gift wrapping algorithm.

$$q = (b - a) \times (c - a) \quad (4.9)$$

Equation 4.9 gives the normal vector (orthogonal to the plane composed by the points (a,b,c)).

$$(p - a) \cdot q \quad (4.10)$$

By checking the sign of the equation 2, we can understand if all the points are at one side or not. However, if any query point is co-planar to the triplet (a,b,c) , the equation will give 0. Sometimes, even if the result is not exactly zero, for the query points that are very close to be a co-planar point result can be very close to zero and this kind of case should be avoided. More comprehensive discussion is given in the further sections. A pseudo code for the brute force algorithm can

be as:

Algorithm 1 Brute Force Algorithm

```

1: procedure BRUTEFORCE(pointset)           ▷ The input is set of 3D points
2:   for  $i \leftarrow 1 : \text{length}(\text{pointset})$  do   ▷ Initial loop for finding the first point
3:      $a \leftarrow \min(\text{pointset}(i, :))$ 
4:     for  $j \leftarrow 1 : \text{length}(\text{pointset})$  do ▷ Second loop for finding the second
      point
5:        $b \leftarrow \text{pointset}(k, :)$ 
6:       for  $k \leftarrow 1 : \text{length}(\text{pointset})$  do ▷ Third loop for finding the third
      point
7:          $c \leftarrow \text{pointset}(k, :)$ 
8:         for  $l \leftarrow 1 : \text{length}(\text{pointset})$  do           ▷ Loop
      for constructing the face and checking the positions of each point according
      to the constructed face
9:            $\text{tri} \leftarrow [a, b, c]$            ▷ Constructing the face
10:           $p \leftarrow \text{pointset}(l, :)$            ▷ Taking the query point
11:           $q \leftarrow \text{cross}(a, b, c) / \text{norm}(\text{tri})$    ▷ Finding the normal vector
12:           $\text{sign} \leftarrow \text{sign}((p - a) * q)$        ▷ Checking the sign of the
      equation 2
13:          if allsignsareequal then
14:             $\text{onhull} \leftarrow [a, b, c]$  ▷ Assigning the face to the convex hull
15:            return onhull           ▷ Return convex hull
16:

```

The MATLAB implementation starts by taking a number which defines the number of points wanted to be inserted into the code, given as N and initiates a random point cloud and assigns it to *pointcloud*. Then, it finds the index of the bottom most point by using MATLAB's *min* and assigns it to *index*, then finds that index inside the *pointcloud*. Another array *remainingpoint* is created to assign the points left when the bottom most point is discarded from the point cloud. *onhull* array is also initiated for saving the faces found from the code. Then the given algorithm takes place.

In detail, array *b* is created to find the next point from the remaining points, *c* is for the other next point to form the triangular face, *q* is assigned for the value of the cross product and *test* is where we apply the equation 2, here we add 10^{-9} to the test which is for avoiding the points that are very close to be co-planar, in the existence of such points the algorithm doesn't work. *check*

is the value where we check whether there is any sign different than the other points. *condition1*, *condition2*, and *condition3* are all for being sure whether the face is checked in an earlier step or not. An if statement is put after to check these conditions and especially checking whether *check* = 1 or not. If the if these condition holds, we store the points to the *onhull* array which we initiated earlier.

4.1.3.2 Gift Wrapping Algorithm

Gift wrapping algorithm is one of the well-known algorithms for finding the 3D convex hull. The main idea is the same as in the Jarvis march algorithm which is applied for finding the convex hull of a 2D set of points [59]. Jarvis march algorithm starts by taking the bottom most point of a sorted list of point set which is guaranteed to be in the convex hull, and constructs an edge with the lowest polar angle from the point set, say the point "next", this edge will guaranteed to be on the convex hull. Then, it iterates through all points and constructs a line segment between the "next" point and all the other points, and takes the lowest polar angle with respect to the first edge constructed and repeats. In 3D, instead of checking the edges, the faces should be checked.

Therefore, instead of starting an edge which will guaranteed to be on the convex hull, in 3D it should start by finding a face that will guaranteed to be on the convex hull, such face can be seen in Figure 4.4. Just to find the first face, the first step of the brute force algorithm can be used which is explained in the previous subsection. After finding the first face we can iterate over every other point in the point set and take the one which forms the lowest polar angle with one of the boundary edges of the triangle. For the implementation, mainly the steps of reference [4] is used for gift wrapping. The results for a random set of points, as a benchmark test is given in Figure 4.5.

Although the workspace can be determined using a brute force algorithm, it becomes slow when a large number of points are used, as the brute force algorithm has a time complexity of $O(N^4)$. In contrast, the gift wrapping algorithm has a time complexity of $O(N \cdot F)$, where N is the total number of points and F

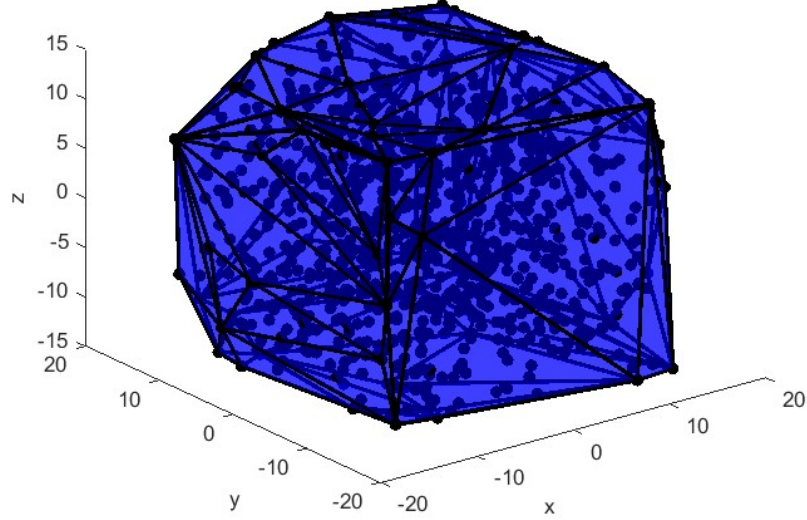


Figure 4.5: Convex Hull obtained from a random set of points using gift wrapping algorithm.

is the number of points on the convex hull. Since the total number of points is typically much larger than the number of points on the convex hull, the process can be approximated as $O(N)$. This makes finding the convex hull much faster and more efficient. Time complexity comparison of both algorithms are tested and the results are shown in Figure 4.6.

Finally, the result obtained from the Gift Wrapping algorithm of the experimental workspace is given in Figure 4.7. The result for each limb is given in Figure 4.8.

Looking at the workspace presented in Figure 4.7, three axes are shown: A1B1 Limb, A2B2 Limb, and Heave. A1B1 Limb and A2B2 Limb are the two legs of the parallel manipulator labeled in Figure 4.2b, which is provided to illustrate the reference frames. In Figure 4.7, these axes represent the maximum possible extensions of these limbs from their initial states. Given the positions of points B1 and B2 in Figure 4.2b, the position of B3 can also be determined because B1, B2, and B3 form an equilateral triangle. Therefore, knowing the extensions of the

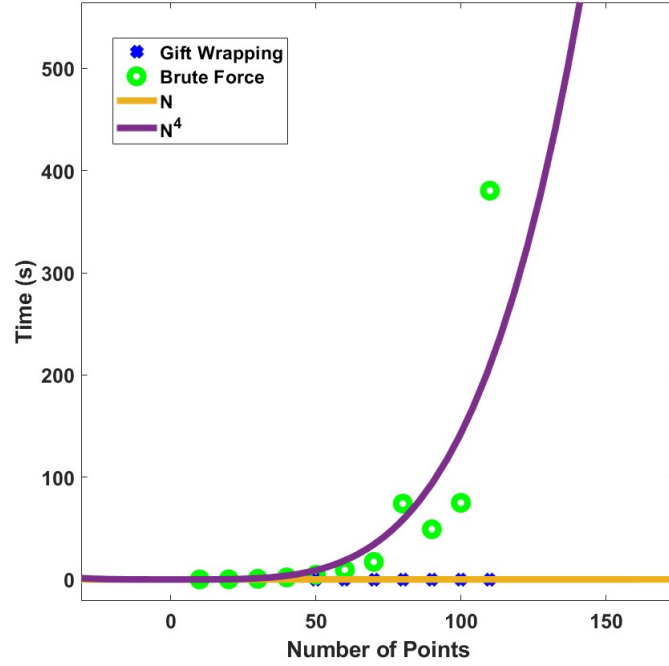


Figure 4.6: Time complexity comparison for both algorithms.

A1B1 and A2B2 limbs is sufficient to determine whether the position is reachable. On the other hand, In the setup provided here, since the laser is fixed in position, the focus point of the laser beam is also at a fixed point in space. As the surface of the workpiece must be at the focus point of the laser beam, the workpiece needs to be held at a certain height, considering its wall thickness. To achieve this height, the platform, or the end effector, must be raised upward along the z-axis. This height can be achieved by simultaneously extending all three limbs, named in Figure 4.2b, by the same amount. Furthermore, when an angle is to be applied to the platform, the limbs do not extend simultaneously. Instead, depending on whether the desired angle corresponds to pitch, yaw, or roll, some limbs extend while others naturally retract. Therefore, the z-axis position of the platform becomes the most critical constraint when determining whether an angle can be applied, as it directly affects the extension and retraction of the limbs. For this reason, the workspace must be calculated based on the two limbs and the height of the platform along the z-axis which is given as Heave in Figure 4.7. Therefore, Figure 4.8 indicates how much further the limbs can extend from a

Workspace of the Limbs A_1B_1 and A_2B_2 as a Function of Heave

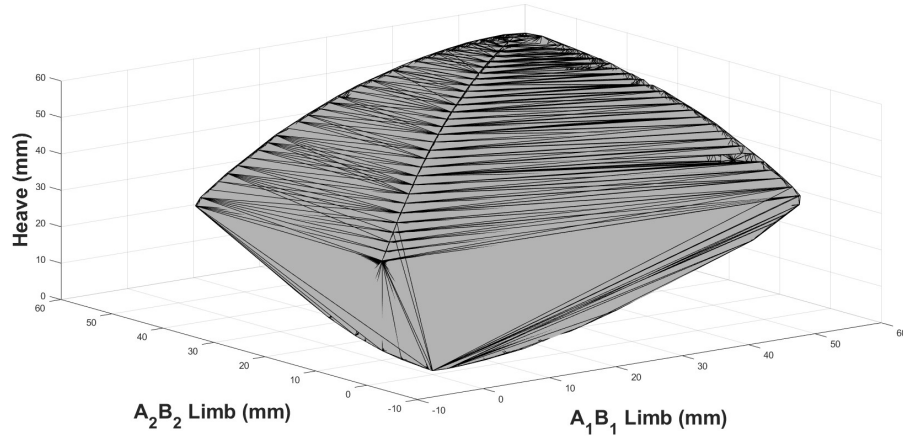


Figure 4.7: Workspace of the limbs as a convex hull.

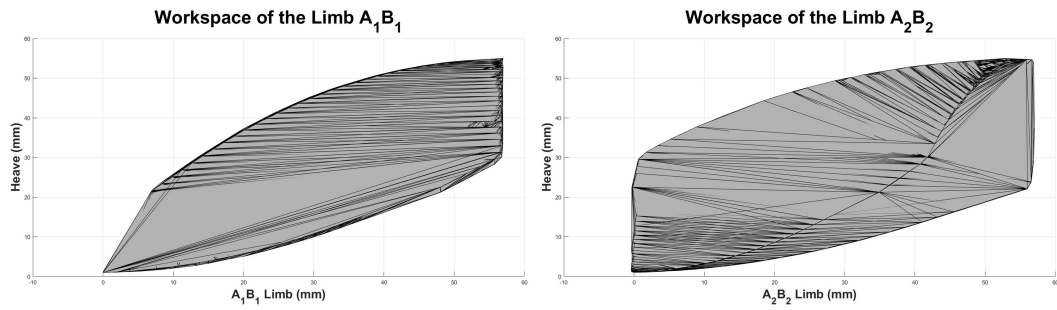


Figure 4.8: 2D Views of Workspace of the limbs as a convex hull.

specific z-axis position, i.e., when all limbs are extended in a coordinated manner to place the platform at a particular position along the z-axis. This information reveals the range of angles that can be applied based on the platform's position on the z-axis. Using this information, if the height required to bring any point of a workpiece to the laser beam's focal point is known, it can be determined whether the angle input needed to align the tangent vector of that point with the laser beam perpendicularly falls within or outside the workspace. If the point is within the workspace, it can be machined; if it is outside, it cannot be machined.

4.2 Laser Parameters

Laser trepan drilling is a highly nonlinear process, where the resulting hole can vary significantly based on numerous parameters. At this point, to determine how and to what extent specific parameters influence the hole outcomes, it is necessary to examine the correlations between input and output parameters by varying the input parameters for different outputs.

In this thesis, the hole output parameters were defined as machining time and total machined volume. Additionally, parameters such as hole depth and hole entrance diameter could have been selected as output parameters. However, since these parameters can be altered later through enlarging the trepan diameter or by applying the helical trepan drilling method with the help of the positioning system, which involves moving the workpiece upwards while trepanning. Here, the goal is to find the parameters that only affect the MRR which is Machined Volume / Machining Time.

On the other hand, the input parameters were selected as laser power, laser frequency, line distance, scan speed, and number of loops. The detailed definitions of these parameters are explained in the further subsections. In addition to these parameters, the pulse distance was kept constant at 0.05 mm for all experiments.

4.2.1 Laser Power and Frequency

In the literature, laser power and frequency are commonly selected as the most influential parameters related to the laser itself in determining hole outcomes. For this reason, power and frequency were also chosen as the laser-related input parameters in this thesis. To measure the effects of these parameters, other parameters were kept constant while only power and frequency values were incrementally varied.

As mentioned in Section 2 (Experimental Setup), the laser used in this study

has a peak power of 20 W, and the frequency can be tuned within the range of 25–60 kHz. Accordingly, in the first experimental set, three values were selected for power: 10 W, 15 W, and 20 W, and five values for frequency: 25 kHz, 35 kHz, 45 kHz, 55 kHz, and 60 kHz.

Line Distance (mm)	Scan Speed (mm/s)	Number of Loops	Hatch Distance (mm)
0.1	900	20	0.05

Table 4.1: Default values that are kept constant in the initial experimental set.

The values of the other parameters that are kept constant for the evaluation of power and frequency, along with the results obtained using these parameter values, are presented in Table 4.1 and Figure 4.9, respectively. A preliminary observation from the figure is that hole depths increase with increasing power and decreasing frequency.

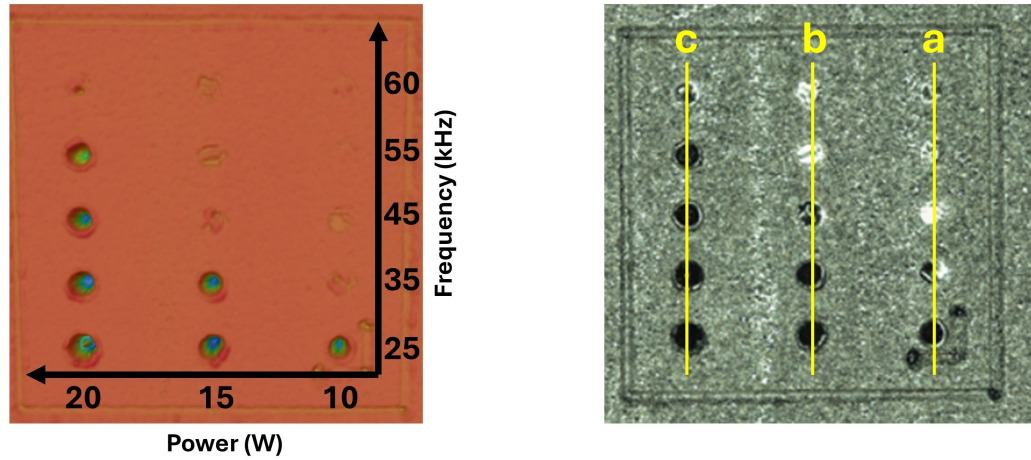


Figure 4.9: Overview of the holes machined with varying power and frequency parameters. Optical photo on the right, height map on the left.

When examining the height map provided in Figure 4.9, it can be observed that the pattern roughly resembles a lower triangular matrix. This indicates that with certain power-frequency combinations within the chosen parameter set, it is not possible to create a "hole" at all.

To analyze the results more thoroughly, section views were taken along the lines labeled a, b, and c in Figure 4.10 to investigate the geometry of the holes, and these views are presented in Figure 4.10. The measured hole diameters and depths from these section views are provided in Table 4.2.

Power (W)	Frequency (kHz)	Depth (μm)	Diameter (μm)	MRR ($\mu m^3/s$)
10	25	265.97	157.77	$1.73 \cdot 10^6$
15	25	294.62	178.22	$2.45 \cdot 10^6$
15	35	278.25	170.24	$2.11 \cdot 10^6$
20	25	274.16	203.85	$2.98 \cdot 10^6$
20	35	294.62	171.23	$2.26 \cdot 10^6$
20	45	282.34	173.95	$2.24 \cdot 10^6$
20	55	167.77	168.51	$1.25 \cdot 10^6$

Table 4.2: Resultant holes for different power and frequency combinations.

As previously mentioned, although the primary output parameters are not hole diameters and depths, these outcomes were examined to determine whether the selected parameters could successfully create a hole. The results provided in Table 4.2 represent the averages of five experiments conducted using only the parameter combinations where hole formation was successful. Based on the obtained results, it was observed that with laser powers of 20 W, 15 W, and 10 W, it was possible to create 4, 2, and 1 holes, respectively, using different frequencies. When the MRR values for these holes were calculated, it was found that as power increased and frequency decreased, the amount of removed material increased. However, since this did not affect machining time, the MRR value also increased. Therefore, disregarding other factors such as recast layer and taper angle, it becomes evident that the highest power (20 W) and the lowest frequency (25 kHz) should be selected as default settings for all experiments.

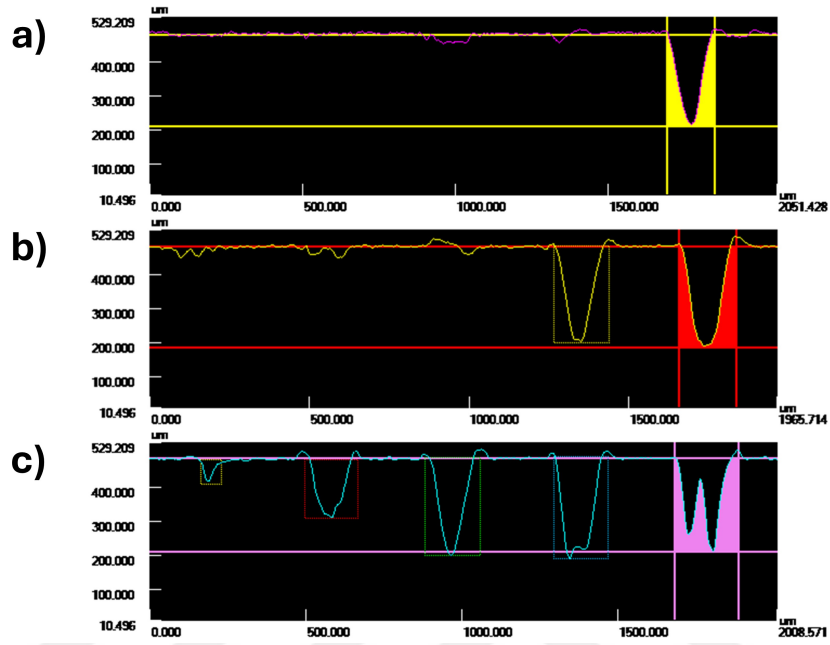


Figure 4.10: Section view taken from the lines labeled a, b, and c in Figure 1.

4.2.2 Line Distance, Scan Speed, and Number of Loops

As shown on the toolpath in the Figure 4.11, the line distance refers to the spacing between the concentric circles and the pulse distance is the distance between two pulses which is kept constant. Line distance affects the amount of energy delivered by the laser to a specific region, which in turn influences the total volume of material removed. On the other hand, scan speed directly impacts the time required to complete the given toolpath, thereby directly affecting the MRR. Finally, the number of loops represents how many times the given toolpath is repeated. As the number of loops increases, successive completion of the toolpath in the same region causes a continuous rise in the temperature of that region, which ultimately affects the total amount of material removed. Therefore, it is essential to determine the individual and relative effects of these parameters on MRR.

To examine the effects of these parameters, each parameter was tested within a specific range. In the first experimental set, Scan Speed was tested from 300 to 600 mm/s with increments of 100 mm/s, Number of Loops from 50 to 200

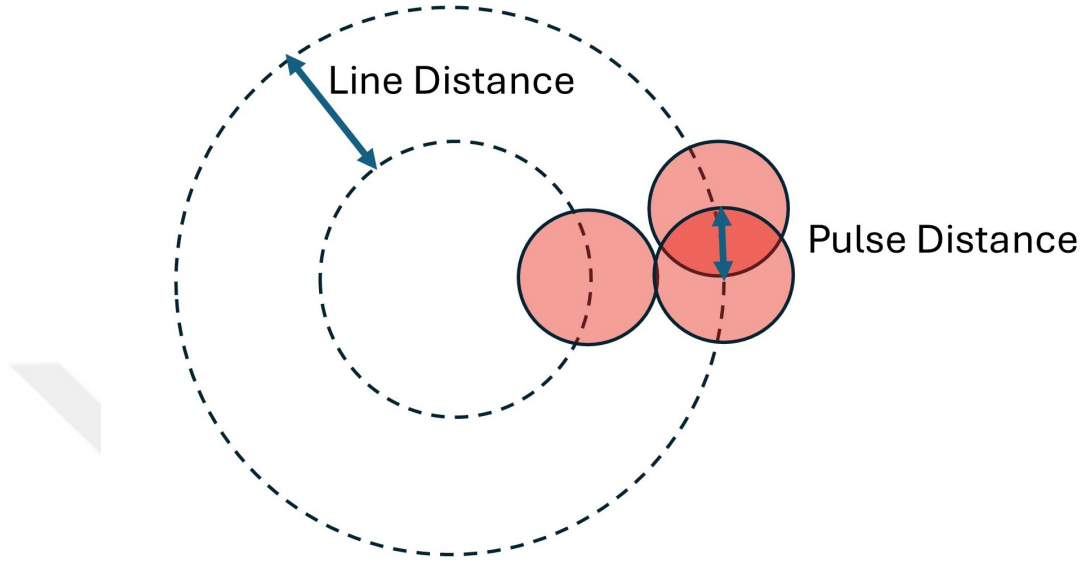


Figure 4.11: Line distance and pulse distance representation. Dashed lines indicate trepan trajectory.

with increments of 20 loops, and Line Distance from 0.00025 to 0.0025 mm. To analyze the individual effects of these parameters, the other parameters were kept constant. The default values used in this experimental set are provided in Table 4.1.

The individual effects of the three parameters on machined volume, machining time, and consequently MRR are shown in Figure 4.12. Figure 4.12 indicates that as Scan Speed increases from 300 mm/s to 500 mm/s, the total machined volume decreases, but an increase is observed when it further rises from 500 mm/s to 600 mm/s. Additionally, as expected, increasing scan speed reduces machining time. Based on these results, the effect of scan speed on MRR is provided in Figure 4.12.

In contrast to scan speed, increasing Number of Loops results in a proportional increase in machining time, as expected. A significant decrease in machined volume was observed between 50–100 loops, followed by an increase between 100–150 loops, and it remained constant between 150–200 loops. However, since machining time increases proportionally with the number of loops, it can be anticipated that MRR will decrease. Accordingly, the effect of the number of

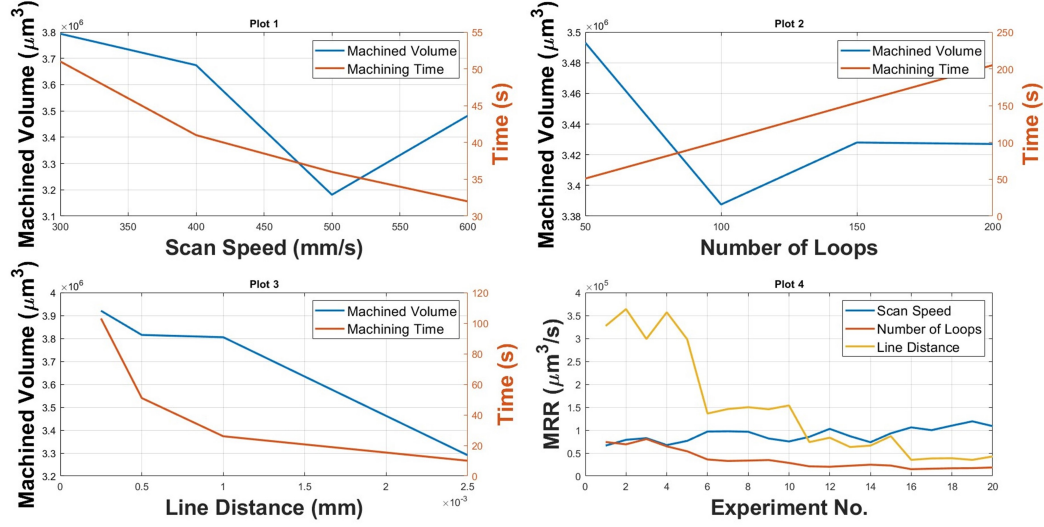


Figure 4.12: Effect of parameters on machined volume, time, and MRR. Experiment set 1.

loops on MRR is presented in Figure 4.12.

Increasing Line Distance, which means increasing the spacing between the concentric trepanning circles, reduces the total number of circles and consequently decreases machining time. However, a decrease in the total machined volume was also observed. Since this decrease occurs at different rates, the effect on MRR, as shown in Figure 4.12, reveals a drastic drop in MRR as line distance increases.

To understand the correlations between all parameters, a Pearson's correlation analysis was conducted, and the results are presented as a matrix in the Figure 4.13.

The Pearson correlation analysis was conducted to examine the correlations between the input parameters—scan speed, number of loops, and line distance (excluding laser power and frequency)—and the output parameters, machining time and machined volume (and indirectly, MRR). The correlation matrix values range from -1 to 1, where -1 indicates a completely negative correlation, 1 indicates a completely positive correlation, and 0 indicates no correlation.

In other words, if the correlation value is -1, it means that as the input value

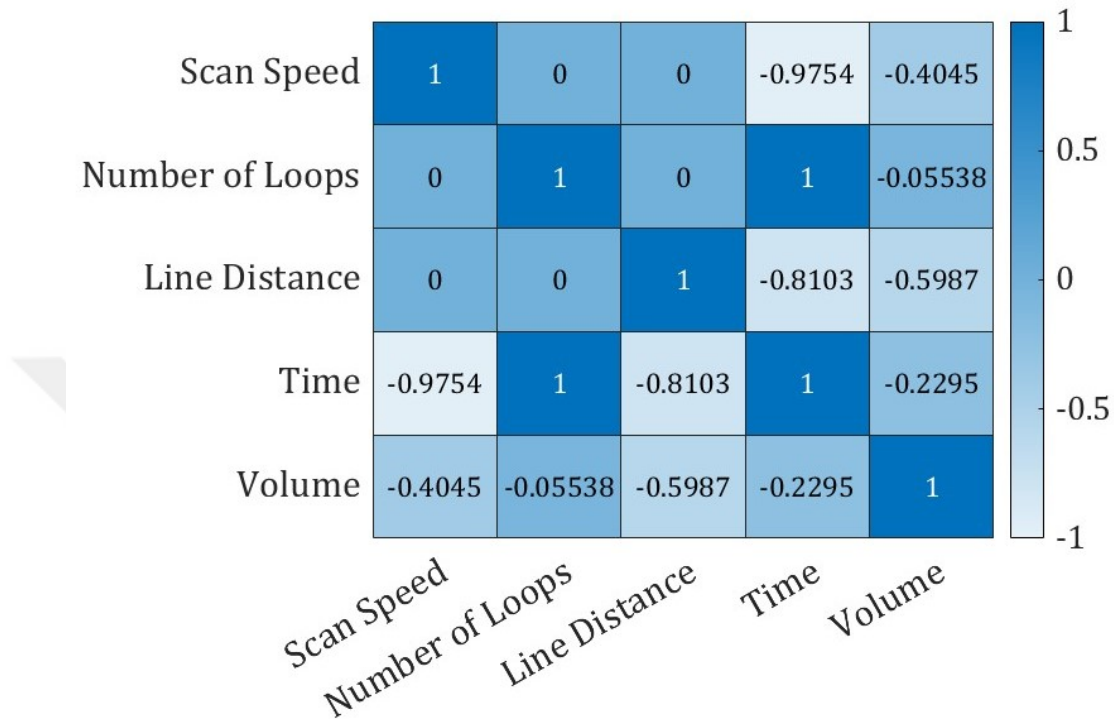


Figure 4.13: Correlation of parameters. 1 and -1 indicate perfectly positive and negative linear correlation. Experiment set 1.

increases, the corresponding output value decreases. Conversely, if the value is 1, it means that as the input value increases, the output value also increases. A value of 0 indicates no relationship between the two parameters, meaning that changes in one parameter do not affect the other.

When examining the matrix, the correlation of each parameter with itself naturally results in a value of 1, forming the diagonal of the matrix. Values of 0 generally appear between input parameters, which is attributed to the independence of these input parameters. For instance, the 0 correlation between scan speed and number of loops reflects that these two input parameters are independent of each other.

Upon examining the figure, a clear negative correlation between Scan Speed and Machining Time is evident, and it also appears to be negatively correlated with Machined Volume. Additionally, a direct proportionality between Number of

Loops and Time is clearly observed. However, no correlation was found between Number of Loops and Machined Volume within the range of 50–200 loops. This indicates that in this range, the number of loops does not have a significant effect on machined volume.

Another noteworthy finding is the counter-intuitive negative correlation between Machining Time and Machined Volume, which was contrary to expectations. This anomaly may be attributed to factors such as the number of loops consistently increasing machining time but having no effect on machined volume in this range.

Based on these findings, it is necessary to refine the parameter ranges for those parameters that directly affect machining time but do not influence machined volume proportionally, to ensure more accurate results.

Based on the observations from this experimental set, a second experimental set was prepared to determine the optimal parameters. The default values for this second experimental set are provided in Table 4.3.

Line Distance (<i>mm</i>)	Scan Speed (<i>mm/s</i>)	Number of Loops	Hatch Distance (<i>mm</i>)
0.1	900	20	0.05

Table 4.3: Default values that are kept constant in the initial experimental set.

When examining the default values provided, it was observed that the increase was not marginal but rather orders of magnitude. In this experimental set, to reach accurate results more efficiently, Scan Speed was investigated between 600 mm/s and 900 mm/s. Although a decrease in machined volume was observed between 600–700 mm/s, an increase was noted between 700–900 mm/s. Since machining time was already decreasing, the increasing machined volume significantly improved the MRR value.

For Number of Loops, tests were conducted between 10 and 40. While the

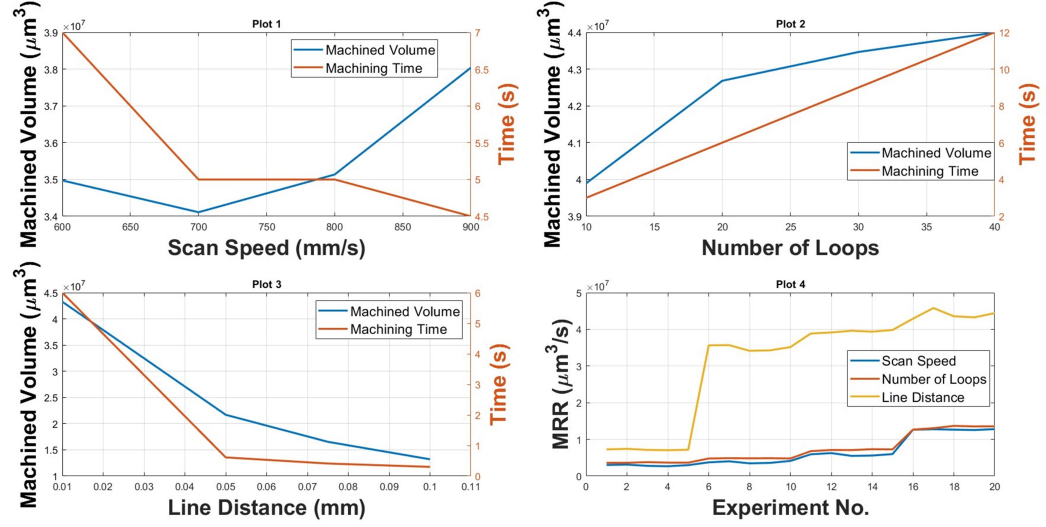


Figure 4.14: Effect of parameters on machined volume, time, and MRR. Experiment set 2.

relationship with machining time remained unchanged, machined volume consistently increased. However, as the number of loops approached 40, the rate of increase in machined volume slowed.

Finally, for Line Distance, the trend of decreasing machined volume and machining time with increasing line distance continued. However, since the rates of decrease for these two outputs differed, an increase in MRR was observed.

The correlation analysis conducted here provides much more intuitive and clear results compared to the previous experiment set. For instance, it shows an almost perfect positive correlation between Machining Time and Machined Volume, which is a highly intuitive outcome.

Similarly, in this set, the correlation between Scan Speed and Machining Time is perfectly negative, aligning with expectations, as logically, if trepanning speed increases, the time spent on machining should decrease. In the previous correlation analysis, this relationship was not perfectly negative.

Regarding Number of Loops, while the range in the previous set (50–200 loops) showed no effect on machined volume, in this set's range (10–40 loops), a positive

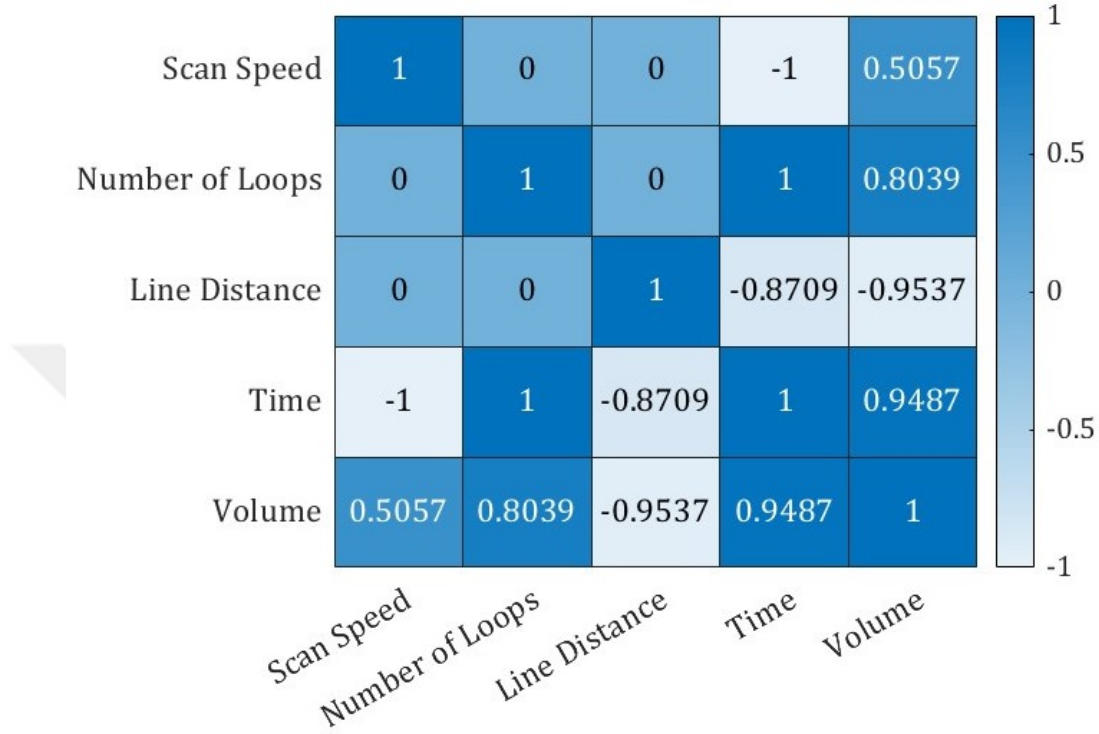


Figure 4.15: Correlation of parameters. 1 and -1 indicate perfectly positive and negative linear correlation. Experiment set 2.

correlation between machined volume and number of loops was observed. When considering the results of both correlation analyses for number of loops, the conclusion can be drawn that between 10–50 loops, the number of loops directly increases machined volume, but beyond 50 loops, further increases do not affect machined volume while significantly increasing machining time.

For Line Distance, the correlation’s sign remained unchanged but approached perfect negativity in this set. This result is also within logical expectations, as decreasing line distance increases the total energy delivered to the machined area, while the corresponding increase in the number of concentric circles directly increases machining time, thereby creating an inverse relationship between the two.

Considering all these results, the optimally selected parameters for the experimentally examined factors affecting only MRR are chosen as 900 mm/s for scan

speed, 40 for number of loops, 0.01mm for line distance.

4.3 Trepan Drilling on Freeform Surfaces

Through following the steps mentioned in the previous sections and based on the correct parameters found in the previous subsection, the results obtained for drilling holes on the normal vectors of a complex surface and angular holes on a flat surface are given in Figure 4.16 and Figure 4.17 respectively. A total of 10 holes were drilled on the complex surface and 11 holes were drilled on flat surface to verify the effectiveness of the proposed methodology. The overall results in Figure 4.16 represent that the holes are successfully drilled in the normal directions of the sinusoidal surface. The parts A and B on Figure 4.16 zoom in to the regions where the highest angle input is needed for hexapod to rotate. Measurement taken from both parts points out that the holes are very close to be perpendicular to the surface tangents which is another way to verify that the laser beam is in perpendicular incidence with the surface normal.

On the other hand, overall results in Figure 4.17 depict that the holes were drilled with desired angles on the flat surface. Holes number 1 to 5 desired to be drilled with a 15, 12, 9, 6, and 3 degrees to the surface with clockwise rotation respectively, hole number 6 is desired to be perpendicular to the surface, and holes number 7 to 11 desired to be drilled with a 3, 6, 9, 12, 15 degrees to the surface with counterclockwise rotation respectively. The resulting width, height, and angle between the hole and surface normal measurements for the holes in Figure 4.16 and angle between the hole and surface normal measurements for the holes in Figure 4.17 are given in Table 4.4 and Table 4.5 respectively. The results indicate that that the proposed methodology is effective in accurately drilling holes using nanosecond pulsed laser on the normal vectors of a complex surface. These findings suggest that the approach proposed in the study can be reliably used in practical applications where precise drilling on complex surfaces or angular drilling on flat surfaces is required

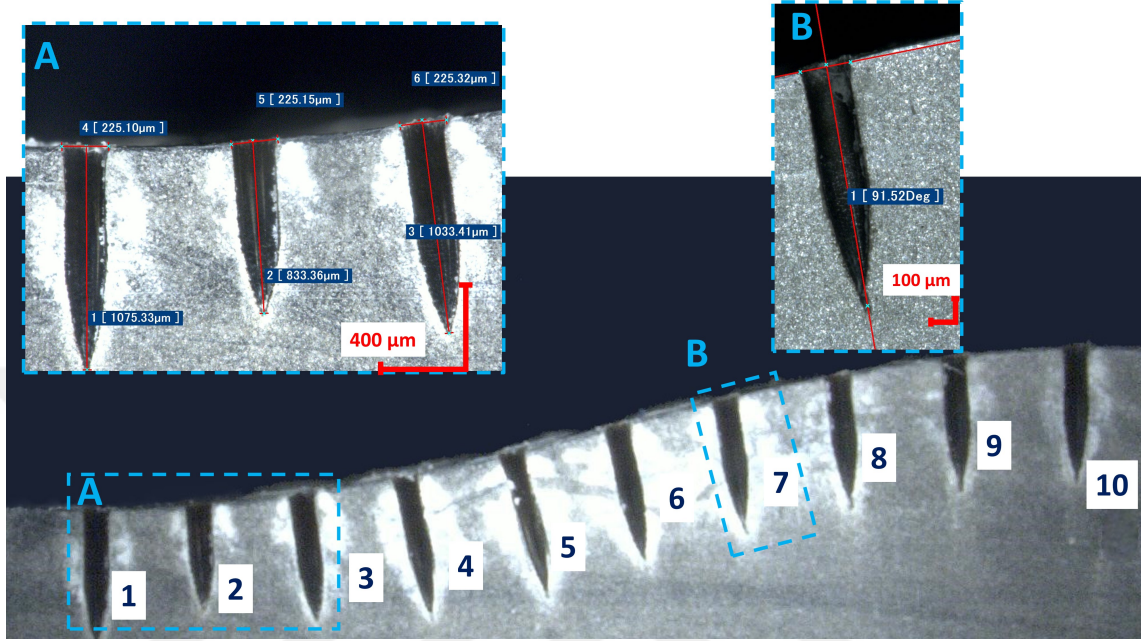


Figure 4.16: Complex surface hole drilling results. Box A: Typical width and depth measurement. Box B: Highlighting the outlier hole and its angle measurement.

From Table 4.4 it's observable that the widths of the holes are generally consistent, mostly around $225 \mu\text{m}$. The standard deviation for the widths of the holes is $7.21 \mu\text{m}$, this indicates that most of the hole widths are close to each other. However, hole number 10 is a notable outlier with $201.1 \mu\text{m}$ when the standard deviation is considered. Moreover, the average height of the holes and standard deviation of the holes are approximately $1058.6 \mu\text{m}$ and $86.9 \mu\text{m}$ respectively, which points out that the standard deviation for the height of the holes is bigger than the width of the holes. On the other hand, hole number 2 is significantly lower than the average height with $833.4 \mu\text{m}$ meaning that hole number 2 deviates more than 2.6 standard deviations. The most important result for the experiment for drilling holes on a complex surface is the angle between the hole and the normal vector. The results for angles in Table 4.4 are obtained by measuring the angle between the tangent of the hole entrance and the hole. Thus, when 90° is the perfect result and thereby the results are promising, ranging from 89.6° to 91.5° . The biggest outlier is hole number 7, highlighted in box B in Figure 4.16, which makes 91.5° with the tangent line. Figure 4.17 and Table 4.5

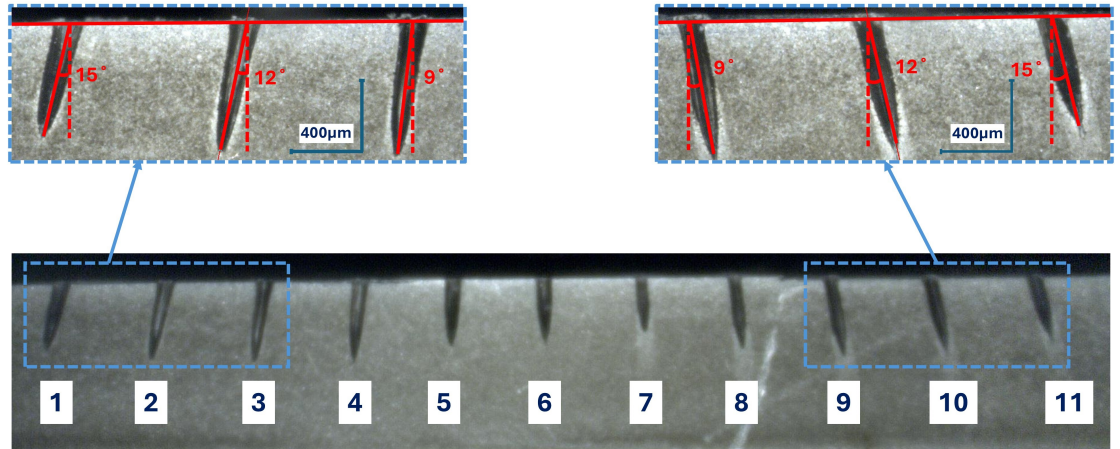


Figure 4.17: Flat surface angular hole drilling results. The scale is in micrometers.

shows the results for the holes drilled with an angle on a flat surface. Boxes with dashed outlines in Figure 4.17 are for showing how the angular measurements were made. Overall, the actual measured angles of the holes are very close to the desired angles, which reflects that the level of precision is high. Although the difference between the desired holes and the actual holes are very small, it tends to increase as the desired angle approaches 0° . This suggests that achieving a hole with 90° might be more challenging with the proposed setup and may need special attention.

Hole Number	Width (μm)	Height (μm)	Angle ($^{\circ}$)
1	225.1	1075.3	89.9
2	225.2	833.4	90.4
3	225.3	1033.4	90.3
4	225.6	1106.2	90.8
5	225.7	1192.1	89.6
6	225.4	1093.0	90.5
7	224.1	1103.4	91.5
8	225.1	1035.5	90.3
9	221.1	1058.2	90.6
10	201.1	1055.3	90.4

Table 4.4: Width, Height, and Angle measurements of the holes drilled on a complex surface.

Hole Number	Desired Angle ($^{\circ}$)	Actual Angle ($^{\circ}$)	Difference ($^{\circ}$)
1	15.00	15.04	0.04
2	12.00	12.01	0.01
3	9.00	8.98	0.02
4	6.00	5.89	0.11
5	3.00	2.78	0.22
6	0.00	0.81	0.19
7	3.00	3.20	0.20
8	6.00	6.22	0.22
9	9.00	9.06	0.06
10	12.00	12.05	0.05
11	15.00	15.05	0.05

Table 4.5: Desired Angle and Actual Angle of the holes drilled on a flat surface.

Chapter 5

Micro De Laval Nozzle Drilling

In this section, a strategy aimed at potentially addressing the issues of methods previously presented for micro nozzle fabrication in the Literature Review chapter by utilizing the experimental setup given will be discussed. The results regarding the effects of the input parameters used in this strategy on the geometric and morphological characteristics of the fabricated micro nozzles will be shared and analyzed. A figure illustrating the typical parts and dimensions of a micro-de Laval nozzle is provided in Figure 2.5.

For a theoretical de Laval nozzle, one of the most important parameter out of the ones that are given in the Figure 2.5 is the throat diameter. It can be defined as the smallest diameter measurable along the nozzle. Literature suggests that the throat diameter determines the mass flow through the nozzle and the ratio between the throat and exit area determines the outlet velocity and outlet pressure of the exhaust flow. On the other hand, it is suggested that inlet diameter and half angle have little or no impact to the overall flow compared to the outlet diameter and half angle. Also, these parameters should be in a certain range in order to work as a microthruster. Thus, these three parameters are taken as the limiting factors of the overall geometry. However, in practice, it is noted in the literature that sidewall roughness is the most effective parameter for the performance of a de Laval nozzle. Therefore, for an ideal de Laval nozzle, sidewall

roughness must be minimized while keeping other geometrical parameters in a certain range. Thus, the sidewall roughness of the fabricated nozzles has also been shared.

5.1 Developed Method

In laser trepanning, when drilling a hole perpendicular to a flat workpiece surface, the resulting hole is theoretically expected to have a conical shape due to the shape of the laser beam. If a 90-degree angle and laser parameters are maintained constant throughout the drilling process, the resulting conical hole is expected to have a consistent taper angle. However, literature has shown that this taper angle can be controlled by adjusting the angle between the laser and workpiece to something other than 90 degrees. [60].

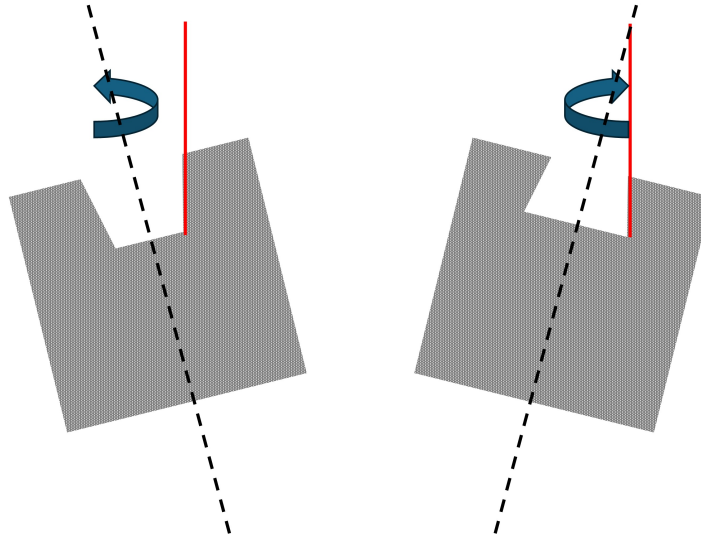


Figure 5.1: Representation of ablation areas for different central axis - laser beam alignments. Red and dashed lines used to indicate laser beam and central axis respectively.

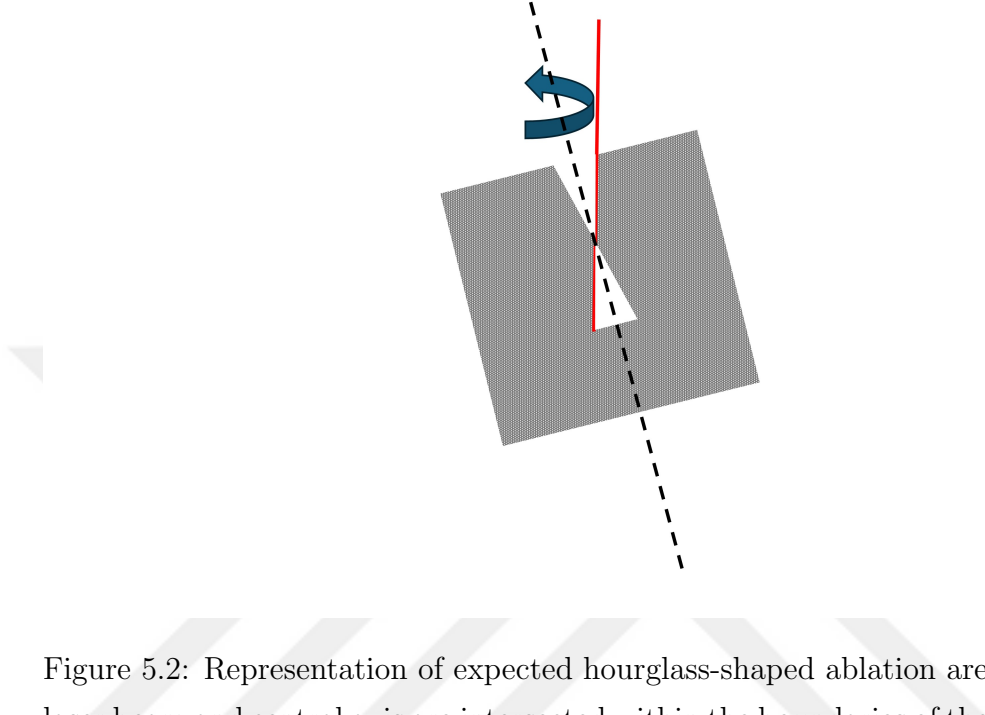


Figure 5.2: Representation of expected hourglass-shaped ablation area when the laser beam and central axis are intersected within the boundaries of the workpiece. If a workpiece with a thickness equal to the depth of the drilled hole is used, or if the workpiece is cut from the point where the hole ends, it becomes possible to obtain a de Laval nozzle with this alignment.

The two configurations shown in Figure 5.1 illustrate two different taper angle formations that can be achieved when the workpiece is rotated in different directions: one exhibits a converging taper, while the other exhibits a diverging taper. The reason that taper control is possible when the angle between the laser and workpiece deviates from 90 degrees is that the laser ablates different areas in different angles. Based on this information, if a configuration is created where the laser beam and the central axis of the platform intersects somewhere within the boundaries of the workpiece, the resulting ablation area would theoretically resemble an hourglass shape (Figure 5.2, that can be used as a micro De Laval nozzle.

Using the given experimental setup, this effect can be achieved by first tilting the hexapod's platform to align the central axis and the laser beam so that

they intersect within the boundaries of the workpiece. Afterwards, when the platform, and thus the workpiece, is rotated around this central axis, a hole with a theoretically converging-diverging shape should be obtained.

In Figure 5.3, the alignment between the laser beam and the central axis after tilting the platform of the hybrid hexapod is shown, with a zoomed-in view provided on the right. The theoretical ablation area, after the workpiece is rotated around this central axis, is represented in blue and labeled as the "hole". The experiments were conducted based on this developed method.

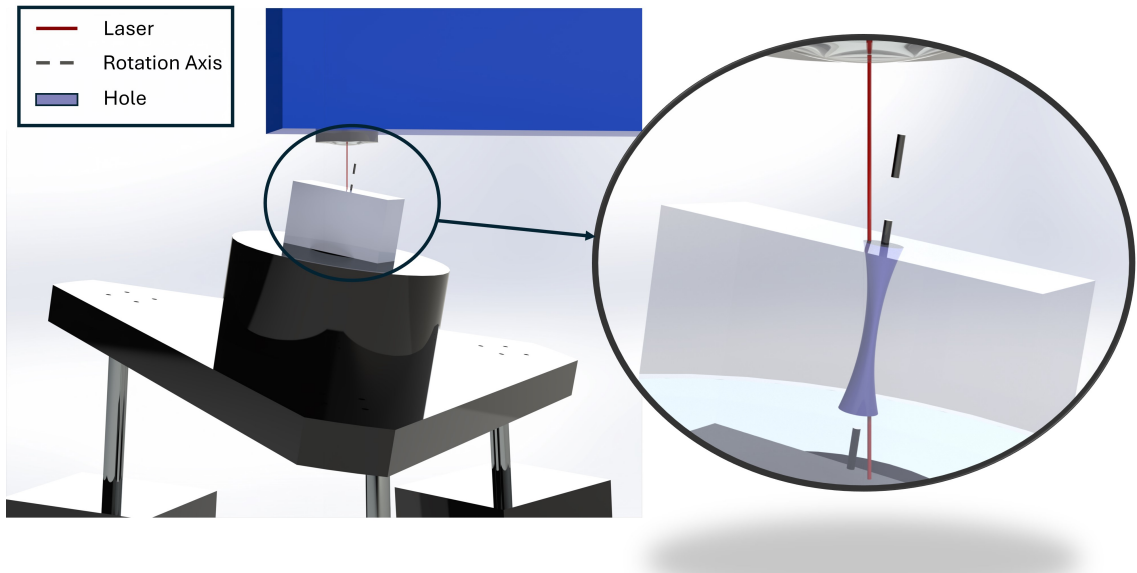


Figure 5.3: Representation of de Laval nozzle drilling strategy on the experimental setup.

With this alignment, various input parameters influence the geometric and morphological characteristics of the micro nozzles with a converging-diverging profile. For instance, these parameters include the distance between the central axis and the laser beam, the tilt angle of the platform, the rotation speed, the scan speed of the galvo scanner, laser power, and laser frequency. In the previous chapter, laser-related parameters were analyzed in terms of their effects on MRR, and optimal parameters were determined. Among these optimal parameters, the

values for line distance and the scan speed of the galvo scanner found in the previous chapter were used. However, since laser power and laser frequency might have a significant impact on the sidewall roughness of the obtained holes, these parameters were reevaluated in this chapter. On the other hand, experimental results showed that the platform's tilt angle only affects the inlet or outlet half-angles of the nozzle, and its effect was not further analyzed.

The issue with the developed method is that it can only be achieved with the configuration shown in Figure 5.3, as the laser is fixed. This limitation prevents drilling at points other than the designated spot on the workpiece. In other words, when the central axis and laser beam are positioned exactly as in Figure 5.3, moving the end-effector changes the intersection point, making it impossible to drill the desired hole.

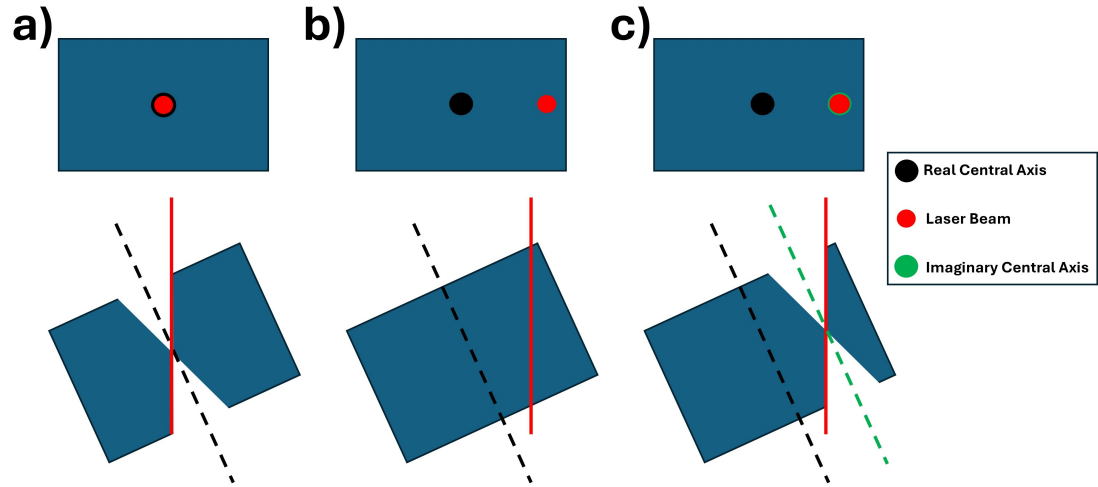


Figure 5.4: The positions where micro nozzles are to be fabricated are shown, with the top views displayed above and the front views below: a) The converging-diverging profile that can be drilled when the laser is manually aligned with the correct point on the actual central axis, b) When the laser is moved to a different point away from the actual central axis, c) The converging-diverging profile that can be drilled at the different point in (b) using the imaginary central axis created there.

When the initial alignment in the Figure 5.4 is examined, it can be observed

that when the workpiece is positioned on the platform exactly at the point where the micro nozzle is to be fabricated using the developed method, the ablation area theoretically forms a converging-diverging shape. However, if another micro nozzle is to be created at a different location on the same workpiece by translating the platform, the central axis naturally translates along with the platform as it given in (b) in Figure 5.4. As a result, the intersection of the central axis and the laser beam within the boundaries of the workpiece, which is essential for achieving the converging-diverging profile, is lost.

The idea used to eliminate this problem is that if the platform can be rotated around an imaginary central axis parallel to the actual central axis at the location where the hole is to be created, differing from the initial alignment, the problem can be resolved which is schematically shown in Figure 5.4 (c). A translation matrix is needed that could create imaginary central axes. In other words, a translation matrix should be developed to compensate for the positional error caused by rotation around the actual central axis, allowing to treat the desired drilling point as if it were the central axis. For this, the workpiece is modeled in a Cartesian coordinate system as a three-dimensional geometry. The vertices and faces of the prism are defined mathematically, allowing for precise manipulation in subsequent steps. The initial center of the workpiece is calculated using the mean position of all vertices. Later, a target point for drilling is selected within the workspace volume. This point represents the desired position of the hole's central axis. Concurrently, a surface normal vector is defined at this point, representing the initial position and orientation of the hole relative to the laser beam. This 3D vector is then used as the rotation axis of the end effector.

The first step is to rotate the workpiece around the defined axis. The normalized normal vector at that position can be written as:

$$\|\vec{u}\| = \sqrt{u_x^2 + u_y^2 + u_z^2} = 1, \quad (5.1)$$

Then, to create the rotation matrix around the vector u , Rodrigues' Rotation Formula can be used:

$$R = \cos(\theta)I + (1 - \cos(\theta))\vec{u}\vec{u}^T + \sin(\theta)[\vec{u}]_x, \quad (5.2)$$

where I is the 3x3 identity matrix, $\vec{u}\vec{u}^T$ is the outer product of $\vec{u}$ with itself, $[\vec{u}]_x$ is the skew-symmetric matrix derived from u for the cross product.

$$[\vec{u}]_x = \begin{bmatrix} 0 & -u_z & u_y \\ u_z & 0 & -u_x \\ -u_y & u_x & 0 \end{bmatrix} \quad (5.3)$$

So, the rotation matrix can be written as:

$$R = \begin{bmatrix} \cos(\theta) + u_x^2(1 - \cos(\theta)) & u_x u_y(1 - \cos(\theta)) - u_z \sin(\theta) & u_x u_z(1 - \cos(\theta)) + u_y \sin(\theta) \\ u_y u_x(1 - \cos(\theta)) + u_z \sin(\theta) & \cos(\theta) + u_y^2(1 - \cos(\theta)) & u_y u_z(1 - \cos(\theta)) - u_x \sin(\theta) \\ u_z u_x(1 - \cos(\theta)) - u_y \sin(\theta) & u_z u_y(1 - \cos(\theta)) + u_x \sin(\theta) & \cos(\theta) + u_z^2(1 - \cos(\theta)) \end{bmatrix} \quad (5.4)$$

After, the position of the hole can be calculated after the rotation as:

$$\vec{p}_r = R \cdot \vec{p}_i, \quad (5.5)$$

Where $\vec{p}_i$ is the initial position of the hole and $\vec{p}_r$ is the position of the hole after rotation. To ensure that the hole remains fixed during the rotation, the translation vector that compensates for the rotation can be calculated as:

$$\vec{t} = \vec{p}_d - \vec{p}_r, \quad (5.6)$$

where $\vec{p}_d$ is the desired hole position, and $\vec{p}_r$ is the hole position after rotation. Using the translation vector, the desired position of each vertex can be found by simply adding the translation vector to the position of the vertex after rotation, which gives the desired position of the hole.

Since the hexapod have control over each six axes simultaneously, when the translation vector is calculated in each step, the position of the hexapod can be adjusted accordingly using the translation vector in each row of the G-Code. Therefore, with this method, De Laval-type micro nozzles can be automatically fabricated at any desired location on a flat-surfaced workpiece by generating G-code and using a system capable of simultaneous positioning.

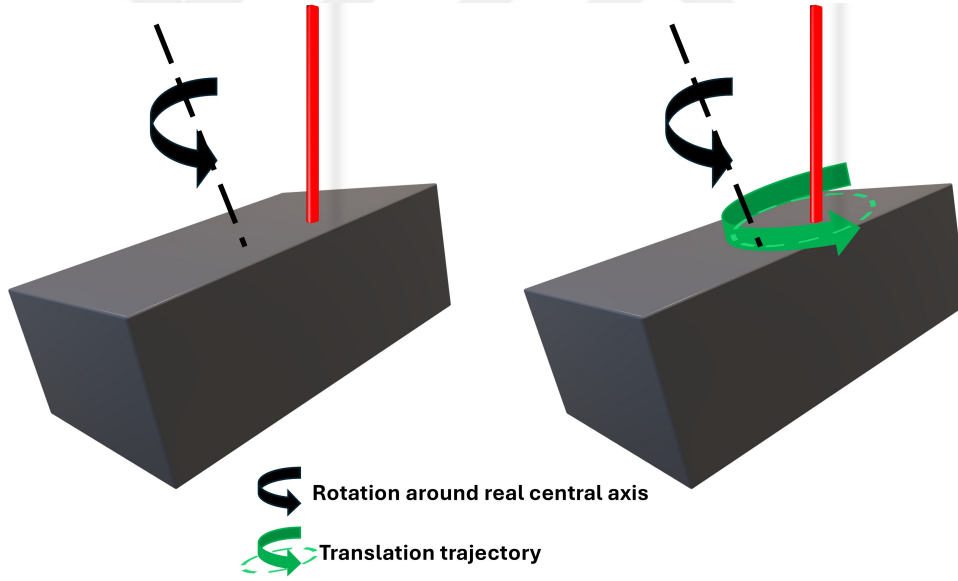


Figure 5.5: Laser beam and real central axis alignment when micro nozzle is wanted to be machined another point (left), The translation trajectory required for the laser beam to rotate around the imaginary central axis (right).

In Figure 5.5, the left representation shows the position of the laser beam and the actual central axis for fabricating a micro nozzle at an arbitrary point on the workpiece. On the right, the translation trajectory required to compensate for the positional difference caused by the rotation around the central axis is

provided. When the rotation around the central axis and the given translation trajectory are executed simultaneously, it becomes possible to fabricate a micro nozzle at any desired point.

5.2 Process Parameters

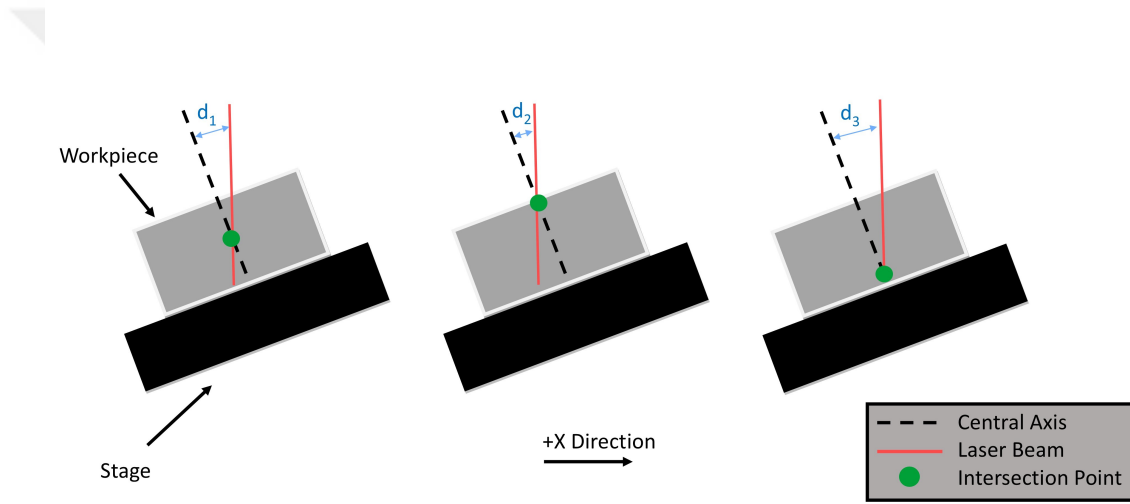


Figure 5.6: The effect of Central Axis - Laser Beam distance. d_2 is the smallest distance and the intersection is at the top of the workpiece, d_3 is the biggest distance and the intersection is at the bottom, d_1 is in between them and the intersection is in the middle.

The process related input parameters are chosen as central axis - laser beam distance, rotation speed, and number of loops. An explanatory figure for the effect of the distance between the central axis of the platform and the distance is given in figure for three different alignments, central axis and laser beam intersecting in the middle, on the top and on the bottom while the only thing that is changing is the distance between them which are given as d_1 , d_2 , and d_3 . This distance directly effects the throat position, as the intersection point defines its position, and the inlet diameter. The rotation speed defines how much the workpiece will rotate around its central axis and number of loops defines how many times it will rotate around the central axis. On the other hand, the laser equipment

related parameters are selected as laser power, laser frequency, and the trepan diameter. The laser power and frequency were explained in detail in the previous section. The parameter trepan diameter refers to the internal rotation of the laser performed within the laser galvo scanner itself. It should be emphasized that in the method we developed, in addition to the rotational motor attached to the hexapod, the laser galvo scanner also rotates the laser beam internally.

5.3 Measurements

As important as fabricating a De Laval-type nozzle is the accurate measurement of the fabricated nozzle. To achieve the most precise measurements, a rectangular piece of aluminum 2024 alloy was prepared, and a rectangular section was cut using EDM (Electrical Discharge Machining) based on a zero-tolerance principle. The holes were drilled along this cut line. This allowed the hole to be observed in section view after the EDM-cut part was removed. Subsequently, the nozzle parameters (outlet diameter, throat diameter, sidewall roughness, and outlet half-angle) could be measured from the section view using a microscope.

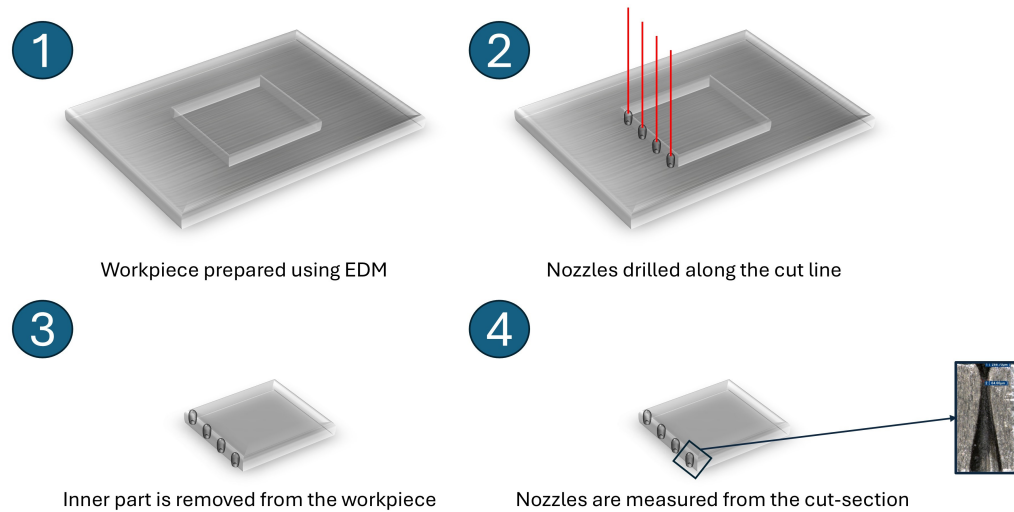


Figure 5.7: Measurement steps of fabricated de Laval nozzles.

Since this measurement method required a new EDM cut for each experimental set, an alternative, simpler method was developed, where the holes were drilled on the edge of the piece instead. As no significant difference was observed between the holes created by the two methods, the measurements presented in this thesis were taken from holes drilled at the edge of the piece. When using this method, it is crucial to ensure that the hole is precisely centered along the edge of the part for accurate assessment. To address this, as shown in the Figure 5.8, only the alignments where the hole was closest to being perfectly centered were accepted. Holes that were offset inside or outside the edge were excluded from measurements and were not included in the results.

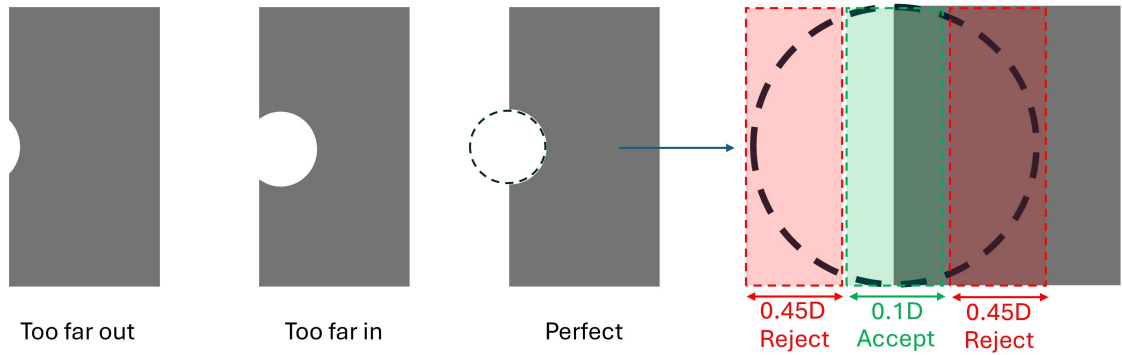


Figure 5.8: Accept and reject ranges for a fabricated de Laval nozzle.

Once the correct holes were selected, geometric measurements could be directly performed using the microscopes provided in the experimental setup. However, the primary issue with the measurements is that the nozzle geometry is curved rather than planar. While roughness measurements can be conducted on planar geometries in specific ways, these methods are not applicable to curved geometries. To address this, a section curve was first fitted to the curved geometry using VK Analysis software, effectively flattening the curved geometry into a planar form. This process can be seen in the Figure 5.9.

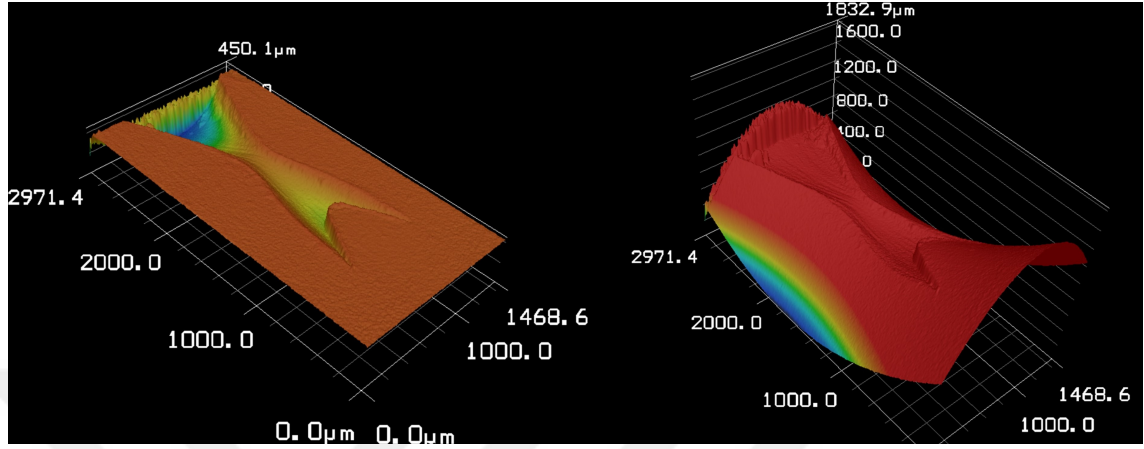


Figure 5.9: Flattening (right) the curved geometry of the nozzle (left) for roughness measurements in VK Analysis Software.

Once a certain degree of planarity was achieved, the results were filtered in accordance with ISO 4287:1997 standards. The roughness values obtained through this filtering process are presented in detail in the Results and Discussion section for different parameters.

5.4 Results and Discussions

Up to this section, a laser micromachining experimental setup was presented, which involves a hybrid hexapod and a nanosecond fiber laser. Next, the maximum reachable envelope, or workspace, of the hybrid hexapod was determined. Then, the process parameters required for nanosecond laser drilling were selected based on experimental data to maximize material removal in the shortest possible time. In this part, a method developed for fabricating De Laval nozzles is demonstrated. This section will present the results of the De Laval nozzles produced by combining these findings and discuss these results in detail.

5.4.1 Overall Geometry and Trepan Diameter

In this subsection, before conducting more detailed measurements, only the geometric accuracy of the fabricated De Laval nozzles will be presented and discussed. First, multiple fabricated De Laval nozzle geometries will be shown, followed by the nozzles that were produced according to the values provided in [10], and these will be further discussed.

According to Louwerse et al., the throat diameter of a micro De Laval nozzle must be between 50 and 300 micrometers to achieve the required thrust. After numerous trials, focus was placed on De Laval nozzles with a throat diameter smaller than 300 micrometers while maintaining a 1:3 ratio between the throat and outlet diameters. The resulting main nozzle and its measurements are presented in the Figure 5.10.

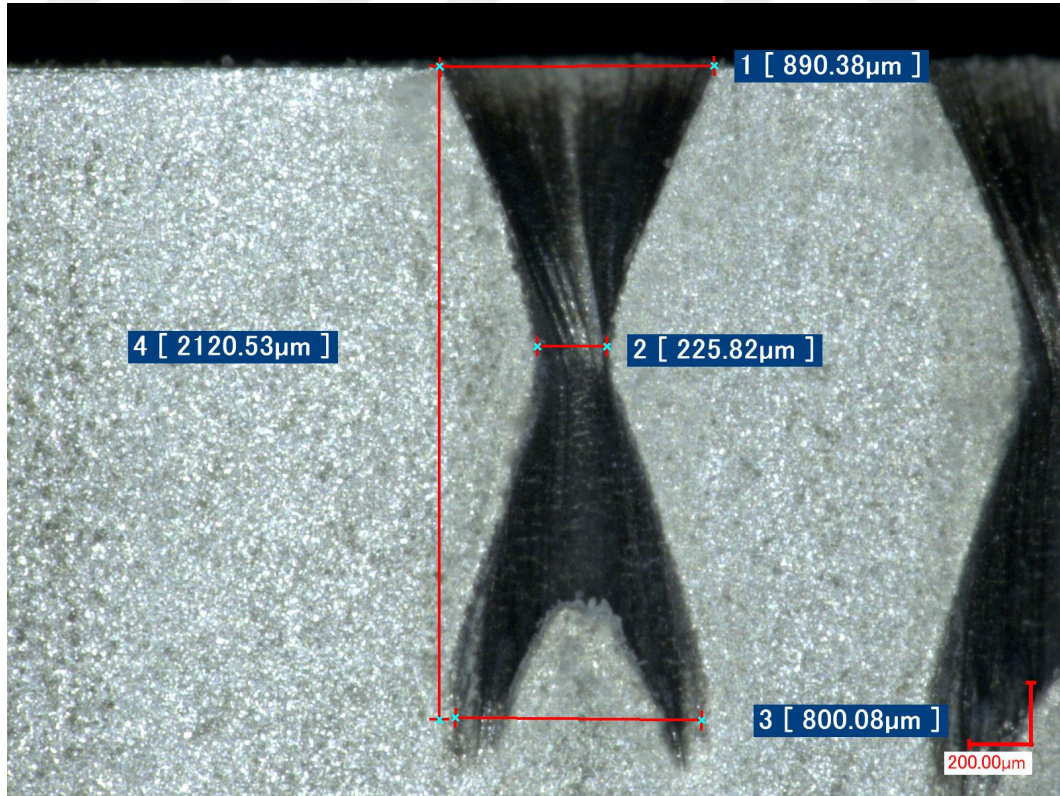


Figure 5.10: Main de Laval nozzle fabricated with the given parameters in the literature.

The input and output parameters used to fabricate this nozzle are provided in the Table 5.1. As previously mentioned, when the parameters were analyzed based on their effect on MRR in the earlier section, the most suitable parameters for laser power and frequency were determined to be 20 W and 25 kHz, respectively. These parameters were directly applied to produce the De Laval nozzle shown in the Figure 5.10.

Input Parameters		Output Parameters	
Power	20W	Throat Diameter	225.82 μm
Trepan Diameter	0.3 mm	Outlet Diameter	890.38 μm
Frequency	25 kHz	Outlet Angle	25.43°
Rotation Speed	768 $\mu\text{m}/\text{ms}$	Roughness (Average)	3.44 μm
Number of Loops	24		

Table 5.1: Input and Output Parameters of main De Laval nozzle fabricated.

Additionally, the trepan diameter (internal rotation of the laser) was set to 0.3 mm. It should be noted that, based on experimental results, De Laval nozzles could not be fabricated with trepan diameters smaller than 0.3 mm for this setup. The number of loops was chosen as 24.

Although the output parameters given in the literature [10], which include the geometrical measurements of the De Laval nozzle, align well with the values reported, further experiments were conducted to reduce the throat diameter and improve the 1:3 ratio between the throat and outlet diameters. The experiments conducted for each parameter and their results are provided in the subsequent subsections.

As previously mentioned, De Laval nozzles could not be fabricated with trepan diameters smaller than 0.3 mm in this setup. Therefore, holes were separately drilled with trepan diameters of 0.4 mm, 0.5 mm, and 0.6 mm, and the results of these holes are presented in the Figure 5.11.

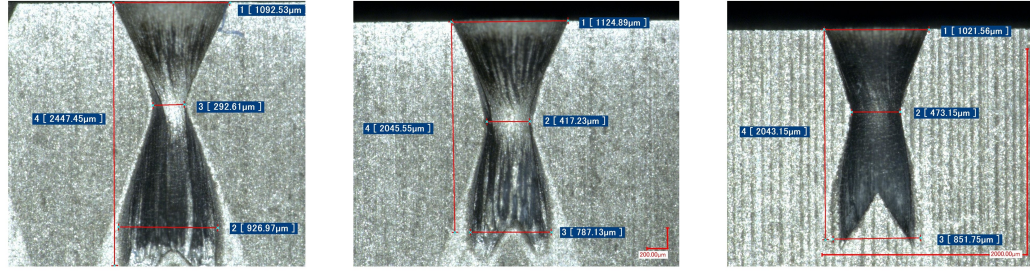


Figure 5.11: De Laval nozzles fabricated with 0.4mm, 0.5mm, 0.6mm trepan diameters from left to right respectively.

As seen in the Figure 5.11, the throat diameter increases with trepan diameters of 0.4 mm, 0.5 mm, and 0.6 mm, indicating that as the trepan diameter increases, the throat diameter also increases. In fact, for trepan diameters of 0.5 mm and 0.6 mm, the throat diameter exceeds the maximum allowable value of 300 micrometers, as mentioned by Louwerse et al. [10], reaching 417.23 μm and 473.15 μm , respectively. Therefore, it can be concluded that the desired nozzle geometry could not be achieved with trepan diameters of 0.5 mm and 0.6 mm.

On the other hand, although the De Laval nozzle produced with a 0.4 mm trepan diameter is geometrically acceptable, the nozzle produced with a 0.3 mm trepan diameter is a safer choice due to the throat-outlet diameter ratio and because the throat diameter remains well below 300 μm .

Thus, the 0.3 mm trepan diameter will be used as the baseline in subsequent experiments. After setting this trepan diameter, the roughness values will also be analyzed alongside geometric consistency for the remaining input parameters, and the suitability analysis will be conducted accordingly.

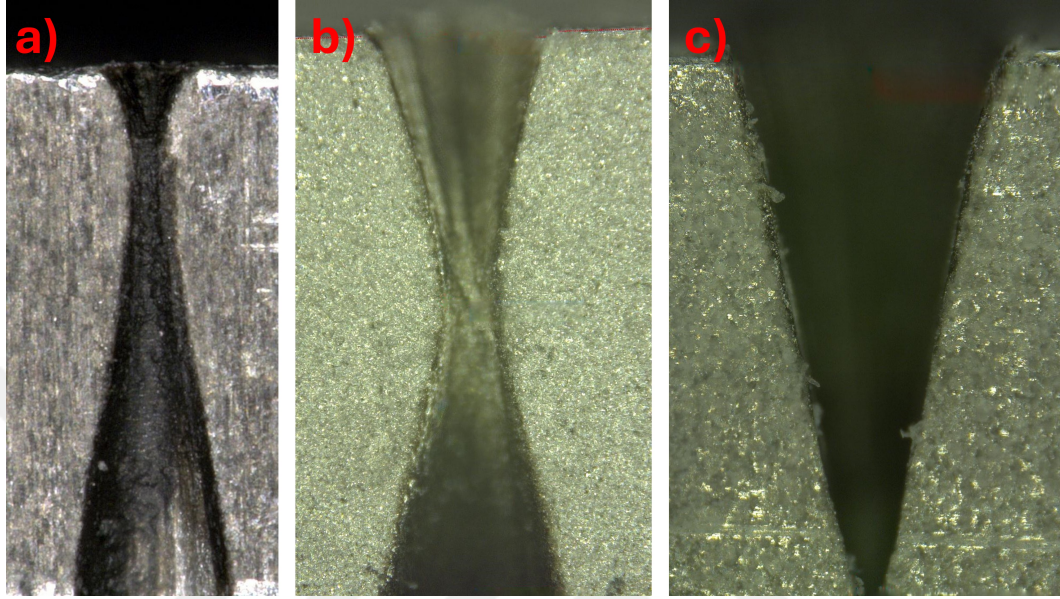


Figure 5.12: Representation of shifting in throat position that is achievable by arranging central axis - laser beam distance.

As explained in Figure 5.6, the developed method also allows the throat position to be adjusted for different nozzle designs. The three holes shown in Figure 5.12 correspond to the throat position being near the inlet (left), at the center (middle), and at the bottom (right), respectively which are achieved only by arranging central axis and laser beam distance.

5.4.2 Effect of Laser Frequency

Although 25 kHz was previously observed as the most suitable frequency value for various applications, a separate frequency comparison is necessary for the fabrication of De Laval nozzles. Accordingly, similar to the trepan diameter comparison, three different frequency values were selected: 30 kHz, 35 kHz, and 40 kHz. Apart from these frequency values, the parameters provided in Table 5.1 were kept constant. The results corresponding to the varying frequency values are presented in Table 5.2 and the images of the nozzles are given in Figure 5.13.

Frequency	Throat (μm)	Outlet (μm)	Ratio
30 kHz	309.18 (+84)	934.31 (+44)	3.02 (-0.92)
35 kHz	287.07 (+61)	820.96 (-70)	2.86 (-1.08)
40 kHz	338.98 (+113)	841.09 (-50)	2.48 (-1.46)

Table 5.2: Effect of laser frequency on the results compared to the main nozzle.

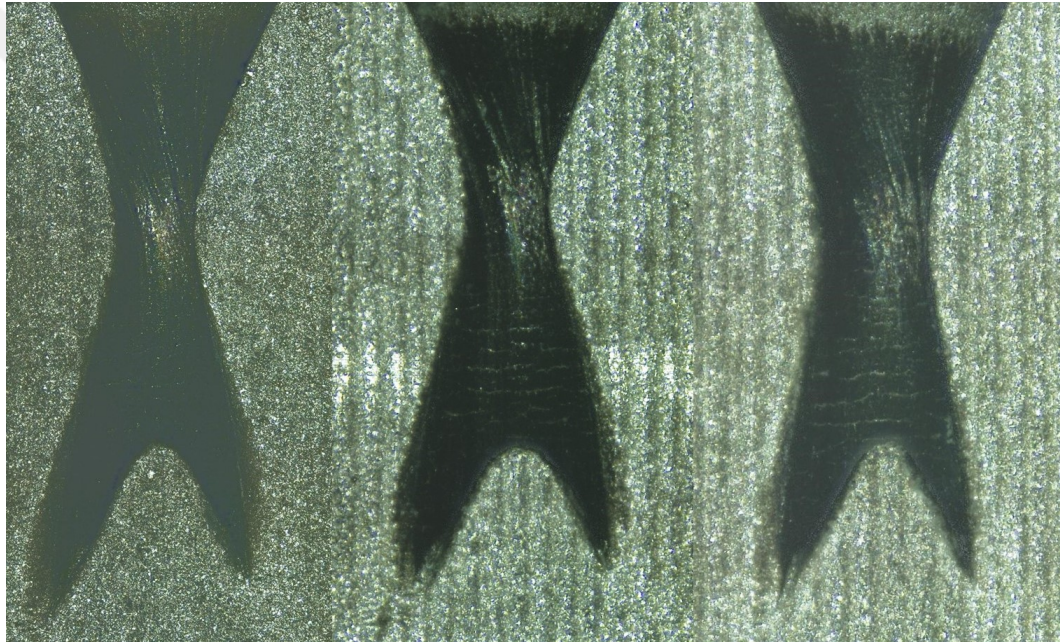


Figure 5.13: Resulting nozzles for different laser frequencies 30kHz, 35kHz, 40kHz from left to right respectively.

The values in parentheses next to the results in Table 5.2 indicate how much the diameters deviate from the main nozzle given in Figure 5.10. As seen in Table 5.2, the throat-to-outlet diameter ratio increases as the frequency increases, which is undesirable. On the other hand, in the experiments conducted at these frequency values, the desired throat diameter (less than 300 μm) was achieved only at 35 kHz.

Although not observed at 40 kHz, improvements in average roughness values were noted at 30 kHz and 35 kHz, with reductions of 0.77 μm and 0.58 μm ,

respectively. While these frequency values were not selected as optimal for this study due to failing to meet the geometric expectations (1:3 ratio and throat diameter $< 300 \mu\text{m}$), they may be applicable for other purposes.

5.4.3 Effect of Laser Power

Although the optimal power parameter for MRR was previously determined to be 20 W in earlier sections, other parameters such as arithmetic mean roughness and throat diameter have gained importance in this context, necessitating a re-evaluation of the optimal laser power. The main nozzle drilled with the maximum laser power of 20 W is shown in Figure 5.10.

In the experiments conducted, it was observed that De Laval nozzles could not be fabricated with laser powers below 10 W using this setup. Based on this, the experimental parameters were set as 10 W, 12.5 W, and 15 W. The nozzle parameters obtained from these experiments are provided in Table 5.3 and the resultant holes are given in Figure 5.14.

Power	Throat (μm)	Outlet (μm)	Ratio
10 W	192.61 (-33)	811.70 (-79)	4.21 (+0.26)
12.5 W	292.62 (+67)	992.53 (+102)	3.39 (-0.05)
15 W	310.38 (+85)	866.51 (-24)	2.79 (-1.16)

Table 5.3: Effect of laser power on the results compared to the main nozzle.

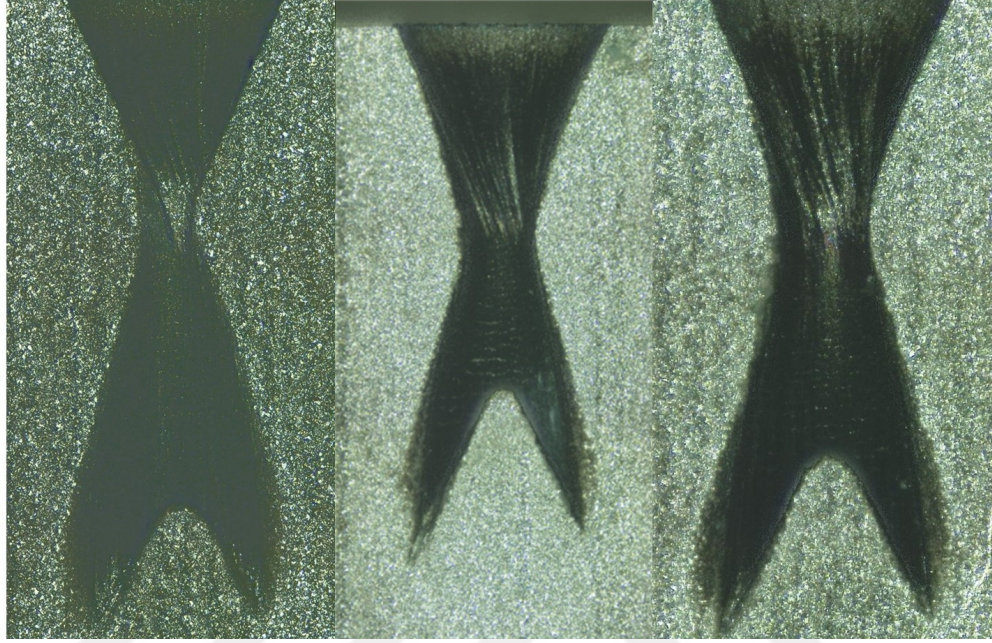


Figure 5.14: Resulting nozzles for different laser powers 10W, 12.5W, 15W from left to right respectively.

As seen in Table 5.3, at a laser power of 15 W, a decrease in the throat-to-outlet diameter ratio and an increase in the arithmetic mean roughness value were observed. These results indicate that 15 W cannot be selected as the optimal parameter. Furthermore, although a nozzle was successfully fabricated at 12.5 W laser power with a 1:3 throat-to-outlet ratio and a throat diameter smaller than 300 μm , no improvement was observed in either the ratio or the arithmetic mean roughness value compared to the main nozzle.

However, at 10 W laser power, an improvement in the throat-to-outlet ratio, achieving a ratio of 1:4.21, and a reduction in the arithmetic mean roughness value by 0.16 were observed.

5.4.4 Effect of Number of Loops

The number of loops parameter used here is not the same as the one in the previous sections. In the earlier sections, the number of loops referred to the number of times the laser galvo scanner would complete a given toolpath. However, in De Laval nozzle fabrication, no specific toolpath was defined for the galvo scanner; it was simply rotated around a ring.

Here, the number of loops represents the parameter that determines how many times the hexapod rotates around its central axis in total. While the main De Laval nozzle was fabricated using 24 rotations, results were obtained here using 12, 16, and 20 rotations. The results are provided in Table 5.4 and the images of the results are given in Figure 5.15.

No. Of Loops	Throat (μm)	Outlet (μm)	Ratio
12	342.16	1003.16	2.93 (-0.99)
16	307.2	988.34	3.22 (-0.73)
20	290.25	987.28	3.40 (-0.55)

Table 5.4: Effect of number of loops on the results compared to the main nozzle.

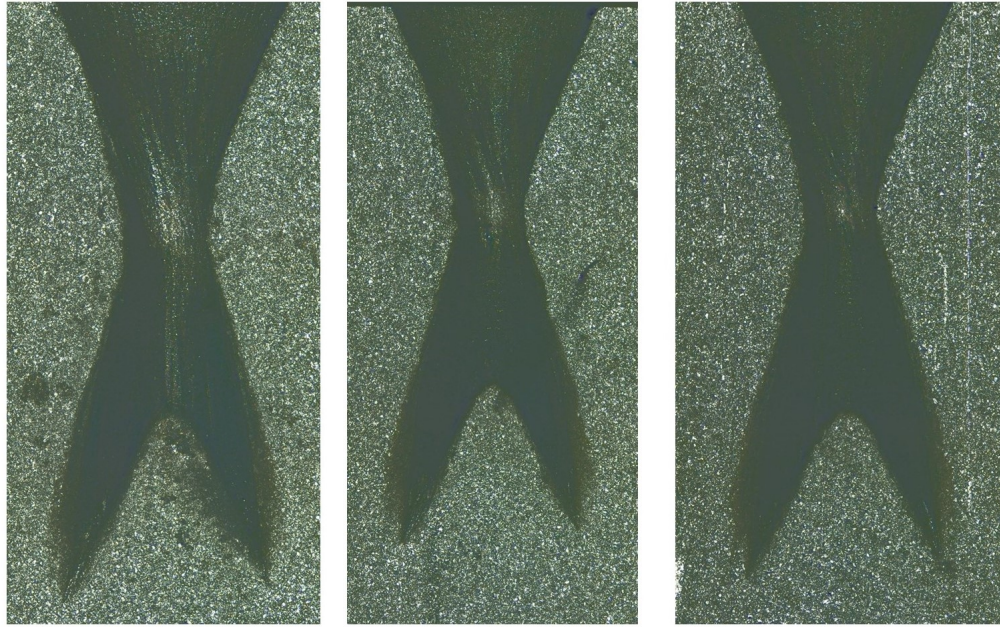


Figure 5.15: Resulting nozzles for different number of loops 12, 16, 20 from left to right respectively.

When the values provided in Table 5.4 are examined, the most significant finding regarding the effect of the number of loops is the nearly linear increase in the throat-to-outlet ratio as the number of loops increases. When analyzed alongside the main De Laval nozzle, it is observed that for every 4 loops, the throat-to-outlet diameter ratio increases by an average of 0.18–0.38.

However, the same effect is not observed for the arithmetic mean roughness. Except for the 0.49 μm improvement in roughness observed at 16 loops, similar roughness values were obtained across the other settings.

The conclusion that can be drawn from this is to increase the number of loops rather than reducing it. Therefore, to determine the optimal parameter, the number of loops should be set above 24.

5.4.5 Effect of Rotation Speed

The scan speed parameter described in the previous sections referred to the speed at which the laser galvo scanner performed the trepanning operation. In contrast, the rotation speed parameter used here indicates the rotational speed of the hexapod platform around its central axis.

Therefore, the scan speed parameter determined based on MRR in the previous sections was used as is. The experimental results are tabulated in Table 5.5, and the corresponding images are presented in Figure 5.16.

Rot. Speed	Throat (μm)	Outlet (μm)	Ratio
360	317.79	1011.64	3.18 (-0.77)
512	225.63	985.16	4.31 (+0.36)
640	286.01	993.63	3.47 (-0.48)

Table 5.5: Effect of rotation speed on the results compared to the main nozzle.

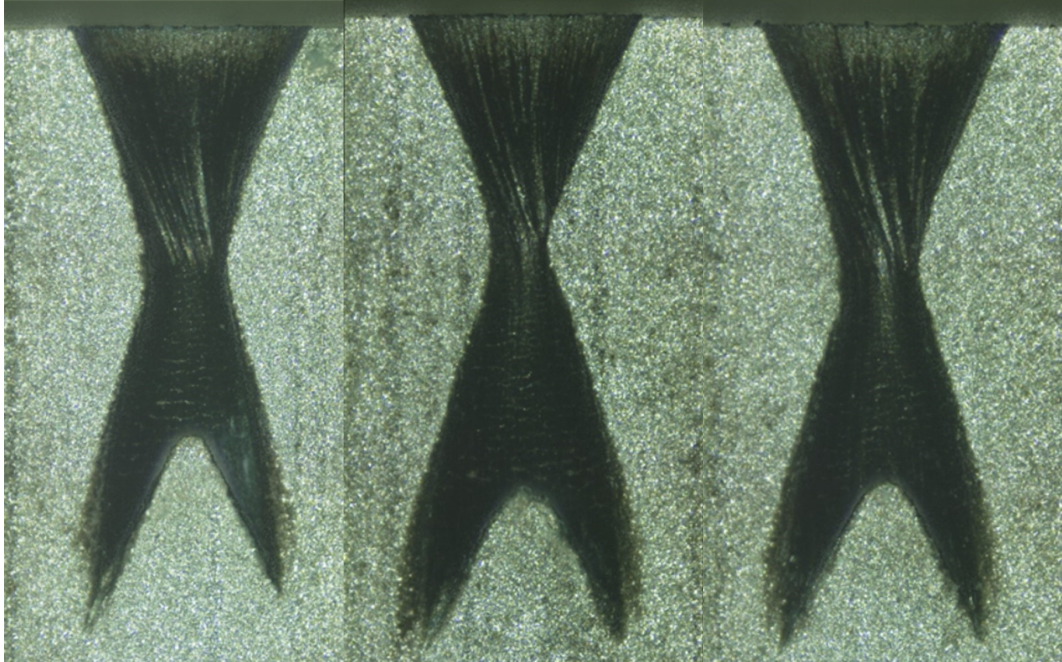


Figure 5.16: Resulting nozzles for different number of loops 12, 16, 20 from left to right respectively.

The most significant improvement compared to the main nozzle was observed with changes in rotation speed. The arithmetic mean roughness value improved at all rotation speeds below 768 $\mu\text{m}/\text{ms}$. Although a decline in the throat-to-outlet ratio was observed at 360 $\mu\text{m}/\text{ms}$ and 640 $\mu\text{m}/\text{ms}$, a 0.36 improvement in the ratio and a 0.93 μm reduction in the arithmetic mean roughness value were achieved at 512 $\mu\text{m}/\text{ms}$. Accordingly, selecting a rotation speed of 512 $\mu\text{m}/\text{ms}$ should yield the most favorable results.

5.4.6 Comments on the Results

The experimental results demonstrate that, most importantly, De Laval-type nozzles can be fabricated using the provided setup and the proposed method. It should additionally be noted here that all fabricated nozzles are in the form of a blind hole—meaning they have an entry point but no exit. The reasoning behind this is that the nozzle’s length and the maximum diameter it could reach at the bottom were initially unknown; these dimensions could only be determined by fabricating the nozzle in a blind manner. Later, when adapting the process to real-world applications, a nozzle with both an entry and an exit can be produced and utilized by drilling into a workpiece with a thickness exactly matching the determined nozzle length. The first fabricated De Laval nozzle has been validated through the literature as conforming to the geometry of De Laval nozzles commonly used in various fields. Using parameters previously determined as optimal in earlier applications, this nozzle was fabricated, and the effects of trepan diameter, laser power, laser frequency, number of loops, and rotation speed on improving both roughness and overall geometric features were re-examined. Ultimately, the parameter set yielding the best results from the tested parameters was selected.

However, as mentioned in the literature review section, De Laval nozzles have numerous applications, making it nearly impossible to determine a universally optimal nozzle parameter set for all applications. The fabrication method for De Laval nozzles described in this section demonstrates that such nozzles can be

produced in a single step using a commercially available nanosecond laser without requiring an additional positioning step.

Therefore, while the resulting nozzles may require post-processing or additional modifications for specific applications, this method provides a foundation for versatile nozzle production. For instance, studies by Cai et. al. [2] have shown that for micro-sized De Laval nozzles, Rz values exceeding $4.87\text{ }\mu\text{m}$ significantly reduce nozzle efficiency. As a next step, the fabricated nozzles should undergo testing and efficiency analysis to validate their performance.

Chapter 6

Conclusion and Future Work

In this study, using a micro-machining setup enabled by the integration of a 6-axis hybrid hexapod and a nanosecond laser, micro-scale holes were drilled on freeform surfaces and on flat surfaces with angle. In addition, a novel method is developed for the fabrication of micro de Laval nozzles is presented and it was observed after the experimental investigation that the key parameters of the nozzle geometry align with those reported in the literature. Furthermore, the effects of the process parameters on the geometric and morphological characteristics of the fabricated nozzles were analyzed. The results indicate that the developed method could be a potential alternative for a cost-effective and single-step micro De Laval nozzle fabrication.

Future work will focus on reducing the roughness of nozzles produced using this method, fabricating different types of nozzles, automating the process to make it more commercially viable, and testing the real-world applicability of the fabricated nozzles through experimental or analytical methods.

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