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**THE DEVELOPMENT OF WATER JET GUIDED LASER
CUTTING TECHNOLOGY**

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IN
MECHANICAL ENGINEERING**

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THE DEVELOPMENT OF WATER JET GUIDED LASER CUTTING TECHNOLOGY

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**THE DEVELOPMENT OF WATER JET GUIDED LASER CUTTING
TECHNOLOGY**

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ABSTRACT

THE DEVELOPMENT OF WATER JET GUIDED LASER CUTTING TECHNOLOGY

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Ph.D. in Mechanical Engineering

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The goal of this research was to develop the waterjet guided laser technology. Design and manufacturing of the waterjet guided laser head and water jet guided laser cutting system, which makes this study distinctive, was carried out. With the developed waterjet guided laser head, the laser beam is transferred to the workpiece to be cut using water guidance, similar to a fiber optic cable, resulting in overcoming the focusing and cutting distance issues faced with conventional lasers. Thanks to the development of water jet guided laser technology, which is the main motivation of this study, experimental studies have been carried out to eliminate or minimize the surface roughness, burrs and thermal problems caused by high temperature that occur on the material surface as a result of conventional laser cutting. In order to demonstrate the differences and improvements in surface quality between conventional laser cutting and water-guided laser cutting methods, AISI 1020 steel sheets, which are commonly used in the industrial industry, were cut under the same conditions using these two technologies. Cutting factors such as material thickness, laser power and cutting speed, which all have an impact on laser cutting quality, were kept under control to get the optimal results. In order to determine the effect of factors on the surface roughness of traditional laser and waterjet guided laser cutting, the data obtained as a result of the experiments were statistically examined using ANOVA, an analysis of variance and a statistical model was created and evaluated. Microscopic examinations of conventional laser and waterjet guided laser cutting methods were performed to investigate surface morphology. The positive effect of waterjet guided laser cutting on the surface quality of materials has been demonstrated. It has been confirmed that this new technology is applicable in industrial areas and future recommendations are presented.

Key Words: Waterjet Guided Laser, Laser Cutting, Surface Roughness, Microscopic Examination, Surface Morphology

ÖZET

SU JETİ GÜDÜMLÜ LAZER KESME TEKNOLOJİSİNİN GELİŞTİRİLMESİ

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Bu çalışmada su jeti güdümlü lazer teknolojisinin geliştirilmesi hedeflenmiştir. Çalışmayı özgün kılan su jeti güdümlü lazer başlığının ve lazer kesim sisteminin tasarımı ve üretimi gerçekleştirilmiştir. Tasarlanan su jeti güdümlü lazer başlığı, lazer ışınının su güdümü ile bir fiber optik kablosu gibi kesim yapılacak iş parçalarına iletilmesi sağlayarak geleneksel lazerlerde karşılaşılan odak ve kesme mesafesi sorunlarının çözümüne katkı sağlanmıştır. Bu çalışmanın en temel motivasyonu olan su jeti güdümlü lazer teknolojisinin geliştirilmesiyle geleneksel lazer kesim sonucu malzeme yüzeyinde oluşan pürüzlülük, çapak ve yüksek ısıdan kaynaklı termal problemlerin yok edilmesi veya en aza indirilmesi için deneysel çalışmalar gerçekleştirilmiştir. Geleneksel lazer kesim ve su güdümlü lazer kesim işlemlerinin yüzey kalitelerindeki farklılıkları ve iyileştirmeleri ortaya koymak için imalat endüstrisinde yaygın olarak kullanılan AISI 1020 çelik levhalar bu iki yöntemle aynı şartlarda kesilmiştir. Optimum kesim sonuçlarının elde edilebilmesi için lazer kesim kalitesini etkileyen malzeme kalınlığı, lazer gücü ve kesme hızı gibi kesme parametreler kontrol altında tutularak kesimler yapılmıştır. Geleneksel lazer ve su jeti güdümlü lazer kesimlerin yüzey pürüzlülükleri üzerindeki faktörlerin etkisini belirlemek için deneyler sonucu elde edilen veriler bir varyans analizi olan ANOVA kullanılarak istatistiksel olarak incelenerek bir istatistiksel model oluşturularak değerlendirilmiştir. Geleneksel lazer ve su jeti güdümlü lazer kesim işlemlerinin mikroskopik analizi yapılarak yüzey morfolojisi incelenmiştir. Su jeti güdümlü lazer kesimin malzemelerin yüzey kalitesi üzerindeki olumlu etkisi ortaya koyulmuştur. Bu yeni teknolojinin endüstriyel alanlarda uygulanabilir olduğu doğrulanmış ve geleceğe yönelik öneriler sunulmuştur.

Anahtar Kelimeler: Su Jeti Güdümlü Lazer, Lazer Kesim, Yüzey Pürüzlülüğü, Mikroskopik Analiz, Yüzey Morfolojisi



“Dedicated to my love Esra”

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LIST OF ABBREVIATIONS

AWJ	Abrasive Waterjet Cutting
HAZ	Heat Affected Zone
CW	Continuous Wave
EDM	electrical discharge machining
LMJ	Laser Micro Jet
ANFIS	Adaptive Neuro Fuzzy Inference System
WJGL	Water Jet Guided Laser
DPSS	Pulsed Diode Pumped Solid State Lasers
ANOVA	Analysis of Variance
Nd:YAG	Neodymium-doped Yttrium Aluminum Garnet
CCD	Charged Coupling Devices
CNC	Computer Numerical Control
ANFIS	Adaptive Neuro-Fuzzy Inference System
WGL	Water Guided Laser

CHAPTER 1

INTRODUCTION

Technological advancements have led to the widespread use of modern production techniques in a variety of industrial and technology fields. Manufacturing processes need to be quick and excellent quality, and production expenditures need to be low in order to compete successfully on a global scale and reach big clients. Traditional production techniques cannot keep up with the demands of this cutting-edge, quick-paced competition [1]. Modern, automation-based production techniques have begun to play a key part in narrowing this gap, depending on scientific and technological advancements. Along with these innovative and modern production techniques, laser cutting fabrication technology has grown to be one of the most widely used in the business world, especially in high-profit and added-value sectors like semiconductor technology, healthcare, and aviation [2, 3].

Lasers have applications for precisely cutting a variety of metals, composite materials, and challenging-to-process ceramics [4]. Unlike other non-traditional processes, laser cutting eliminates mechanical stress, friction, and abrasion since there is no direct contact between the tool and the workpiece [5].

Laser characteristics, material thermophysical qualities, and cutting preferences all influence cutting quality in laser cutting technology. The laser's wavelength, continuous wave (CW) or pulsed mode of operation, and laser spot size at the processed material are its properties. Two process parameters are the assisted medium and the cutting speed. When cutting ferrous materials, the most popular assist medium is either a reactive gas, like O_2 , or an inert gas, such N_2 or Ar. The sheet thickness, thermal conductivity, density, specific heat, and melt viscosity all affect the cutting quality [6].

Its rapidity, superior surface treatment, and ease of extracting complicated designs also give it a significant market share. Notwithstanding these benefits, the extreme heat

energy that the laser emits causes wear and microstructural deterioration on the contact surfaces of the work piece. The primary flaws in laser cutting include a large heat affected zone (HAZ), taper cut, high dross adhesion, large kerf and poor cut surface [7].

Some laser micromachining technologies have been created to precisely remove the material by reducing the laser's high heat effect and to limit thermal damage that happens during laser processing procedures, ensuring damage-free machining. Heat-related issues have been attempted to be addressed with ultra-short-pulse lasers in order to cut without causing damage. This approach aims to stop heat buildup and conduction in the material by using a laser that generates beams with incredibly tiny pulse durations. Thermal stress or molten layers cannot be produced by ultrashort-pulse lasers, such as picosecond and femtosecond lasers, which can disintegrate material. The material layer is quickly destroyed before the atomic lattice cracks and heat transmission to the work material starts thanks to the unusually high photon energy of the lasers. Despite these advantages, the capacity of ultra-short duration lasers is insufficient for high material removal rates, and the high cost of photons makes it impossible to achieve the required efficiency [8].

Previous research may contain a variety of scientific articles on laser cutting operations for various materials using different types of lasers and their modes of operation to minimize these defects and surface quality. Thermal stress gradients develop as a result, and the material's surface softens. Unwanted microstructure issues could include heat cracking, hardness loss, local flow issues, and collapse [9, 10].

Another problem may arise from gases and liquids used in the laser processing. The workpiece can be directly affected from high energy absorption and it may be damaged because of sudden cooling-heating, melt formation and chemical reactions. As a result of these; various problems such as combustion, sintering, soldering, alloying may occur. Also, depending on the beam diameter of the laser used in micro machining processes, overheating can cause melting of the workpiece [11-13].

Another modern manufacturing method, abrasive waterjet cutting (AWJ), is one of the metal cutting processes that are used extensively in various fields and applications, along with today's developing technology. Except from extreme hard materials,

abrasive water jet cutting is the preferred method of cutting many materials at the desired thicknesses and shapes. The most remarkable feature of this cutting process is the "precision cold cutting" method, which does not leave a heat-affected cutting zone on the material. Despite these advantages, tapered surface formation and low transverse speeds especially cutting thick and hard materials is limiting this process [14–16].

Some studies were carried out with several factors under control. They used varying laser power, laser gas pressure, cutting rates, and notch thicknesses during the laser cutting process. Researchers conducted similar tests when cutting with a water jet, such as varying the water jet pressure, cutting speed, and cutting thickness. Another study compared laser and water jet cutting of stainless steel to determine which was best in terms of cutting quality. This study found that laser cutting is faster than waterjet cutting. The volume of material to be removed from the surface grows and both processes get slower as the thickness of the material being treated rises. When speed of the laser face is increased or decreased excessively, the surface quality deteriorates. In exceedingly slow cuts, the burning process accelerates and causes surface flaws. When a very fast cut is made, the laser beam does not fully penetrate the material and since the cutting angle and direction do not remain constant, curvatures occur on the cutting surfaces [17-20].

Slower rates in waterjet cutting often produce a higher surface quality. As a result, laser cutting has a narrower thickness range than waterjet cutting. Both cutting procedures produce a tiny quantity of slag and adhere to worn materials. The high-pressure gas used in laser cutting effectively breaks up molten droplets, resulting in clean cutting edges. Water jet cutting uses high-pressure water blasted with abrasives to remove cut materials and residues from the cutting areas, giving it a major advantage over laser [21, 22].

The width of the laser cutting edge is about 2-4 times less than that of waterjet cutting. This means that laser cutting can improve positioning precision while also reducing material waste. The cutting speed is one of the most critical criteria in determining the cutting gap width. A higher cutting speed results in a wider slot width. This explains why laser cuts are so thin. For waterjet cutting, the garnet strikes the cut surface at a fast speed, reducing the creation of streak patterns. It is believed that line patterns on

the laser cutting surface arise as a result of a cyclic burning action. On laser cut surfaces, the beam interacts with the material by burning it and when the beam is turned off and back on again, a new burning cycle begins, resulting in the production of various surface features. Another distinction between these two cutting technologies is that lasers can cut less reflective materials, such as mild and stainless steels, significantly faster. A water jet can cut through highly reflective and thicker materials at a relatively fast rate. Depending on the type of laser heat treatment, there is a thickness limit for the material being sliced. However, water jets can cut through very thick materials at modest rates. Furthermore, utilizing a fast-cutting speed and many passes might degrade thermal efficiency even more. [23-25].

The remarkable advantages of both the abrasive waterjet and laser technologies should be combined while their drawbacks are removed. Other approaches to water assisted laser cutting, including waterjet guided laser cutting, oxygen or gas assisted underwater cutting, and underwater laser cutting, have been tested by some researchers [26, 27].

Bernold Richerzhagen was the first to investigate waterjet guided laser technology. While a laser microjet was being created, the effects of waterjet pressure, laser cutting distance, and cooling effects were all investigated. A laser beam is directed within a stream of fine water to accomplish this [28].

Due to the different reflection coefficients of water and air, the laser beam is fully reflected at the water jet surface, just like it would be in an optical fiber. The fine water jet could be referred to as "liquid fiber with variable length". A combination laser and waterjet system were subsequently constructed, and research was done on the effect of laser heat and the elimination of cutting particles from the workpiece [29].

The focal distance of the water jet guided laser was found through additional research. Research on using a waterjet guided laser to cut thin sheet metal was done. This technique eliminated the need for focal adjustment by focusing a laser beam onto a stream of water, which then directed the beam onto the workpiece. Based on the laser characteristics, jet pressure, and diameter, it was established that a cutting distance of 50 mm is a reasonable upper limit for both flat and inclined surfaces. Challenges identified include the water jet's partial absorption of the laser beam and its

susceptibility to external disturbances, which can induce vibrations in the workpiece and disrupt the cutting process [30].

A waterjet guided laser was used to cut wafers. Wafers were sliced using both a traditional laser and a waterjet guided laser. The cutting quality of each method was compared. Waterjet guided laser cutting resulted in fewer structural modifications, no drawing, sharp cutting edges, a small beam diameter, and the least amount of mechanical strain during wafer cutting operations [31].

Research was done on the creation of an underwater laser cutting system with waterjet support. This cutting method created less turbulence and gas bubbles than the gas-assisted underwater laser cutting method. In order to develop waterjet guided laser cutting technology, this research aims to examine the characteristics of the laser beam in a variety of fluids. Consequently, water-assisted laser cutting results in a narrower kerf, lower cutting surface roughness, less dross, and a lower HAZ when compared to conventional (gas-assisted) dry cutting in laser operation [32].

Depending of the previous studies and critical points in the literature, this study will present an advancement and new modelling for cutting higher thicknesses on the waterjet guided laser system consisting of a novel waterjet nozzle integrated to laser head to eliminate the cutting and surface microstructure problems such as wide heat effected zone, micro cracks, roughness and melting encountered while cutting with laser.

1.1 Motivation of Study

In conventional laser cutting, it is necessary to precisely concentrate and manage the distance since the focused laser beam's working distance is restricted to a few millimeters or fractions of a millimeter due to beam divergence. This limits the kerf-to-depth ratio. Thus, cutting non-flat surfaces with changing depth of cut—also referred to as precision machining applications for delicate materials—is not possible to do well with traditional techniques since they need for focus and distance control. Additionally, lasers cause the material to become heat-affected, which can lead to damage such micro cracks, structural oxidation, or decreased fracture strength. The ablated material is redeposited on the workpiece surface, raising concerns about

contamination and deposition. These problems push this thesis to look for new uses for laser technology.

A novel cutting technology known as waterjet guided laser technology which is liquid streaming laser combines the benefits of water jet cutting (cold, long working distance) and conventional laser cutting (precise, rapid). This approach will successfully compete with disadvantages of well-known cutting methods, such as conventional laser, diamond saw, electrical discharge machining (EDM), water jet cutting and etching. This technology's advantages are especially noteworthy for its extremely narrow kerf cutting, delicate surface treatments, and high-precision processing of thin work pieces that are heat-and deformation-sensitive. This technology is even more appropriate in situations like the semiconductor industry where small, delicate parts of sensitive material require quick, accurate, and clean processing.

This thesis will develop a waterjet guided laser technology by using a laser beam that can be guided over a longer distance by being fully reflected at the air-water interface. The water jet removes ablated debris and prevents contamination, cooling the cut area and reducing heat effects. Essential cutting parameters like material thickness, laser power and cutting speed are carefully adjusted and investigated to determine their impact on cut surface quality. The experimental design includes a study of variations in laser cutting parameters. Additionally, the study pushes the boundaries of current technological capabilities in this field by examining the possibility of using fiber lasers as waterjet guided instruments.

1.2 Objectives of the Thesis

The primary goals of this thesis aim to enrich the scientific literature and benefit industrial applications through the achievement of the following advancements:

- The primary goal of the current study is to design a novel experimental setup of a waterjet guided laser machine. The laser's high cutting rate and cutting accuracy and cooling effect of the water jet will be combined. It will be focused on development of a novel designed waterjet nozzle and contribution will be made to the advancement of water jet guided laser technology.

- Another aim of this study is to eliminate the cutting and surface problems encountered while cutting with conventional lasers. Parameters such as material thickness, cutting distance, laser power, cutting speed and other laser characteristics which affect the cuts of materials will be controlled to obtain more precise and high-quality cutting surfaces. This research will bring together the advantages of laser and water jet cutting methods. This new approach will be an important stage for research and innovation of water jet integrated cutting technology.

1.3 Thesis Organization

Each chapter's content and arrangement have been carefully developed to provide a logical progression of ideas and to make it easier to communicate crucial results. The following paragraphs provide a concise summary of the content.

Chapter 1: Introduction

The first chapter of the thesis provides an overview of the topic, motivation, and study objectives. The chapter closes by outlining the following chapters.

Chapter 2: Literature Review

The literature review chapter investigates relevant literature and studies about the thesis issue. This examination covers all extant theories, concepts, and findings in the topic. The review focuses on significant research papers, theoretical frameworks and methodology used by earlier scholars. This chapter provides the theoretical framework and backdrop for the current study.

Chapter 3: Fundamentals of Conventional Laser Cutting and Waterjet Guided Laser Processes

This chapter discusses conventional laser cutting, waterjet guided laser technology, and their cutting concepts, parameters, and effects on materials' surfaces, and compares their effects on material surface structure.

Chapter 4: Materials and Method

This chapter describes the study's research methods in detail. It also explains the chosen approach by discussing its suitability for accomplishing the study objectives and ensuring the reliability and validity of the results.

Chapter 5: Design and Construction of Experimental Setup

This chapter focuses on the design, modeling, and construction of an experimental setup, including its components, assembly, method, and materials for laser cutting, which is the most important section of this thesis.

Chapter 6: Results and Discussion

The contributions of this study to the improvements in cutting quality have been highlighted. It was presented the findings of the study and interpreted the implications of the results.

Chapter 7: Conclusion

This chapter highlights the study's principal findings and the results. It summarizes the research aims and highlights the research's contributions. The chapter also examines the study's weaknesses and proposes options for future investigation. Finally, it provides a succinct review of the entire study and its significance.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature review in this thesis offers a thorough summary of current theories, research, and academic conversations pertaining to the subject. It critically analyses and integrates relevant literature, emphasizing principal discoveries, methodologies, and theoretical structures.

2.2 Waterjet Guided Laser Technology

One hybrid cutting technology is waterjet guided laser cutting, which uses a waterjet to guide a high power laser beam. When compared to conventional laser cutting or waterjet cutting alone, this combination improves cutting efficiency and flexibility, enabling higher cutting speeds and better quality.

2.2.1 Development of Waterjet Guided Laser Technology

Bernold Richerzhagen envisioned a material-cutting tool that combined laser and water jet features. After doing a lot of research, he created a hybrid machining technique. The 1994 patent for LMJ Microjet (LMJ) technology combines a low-pressure, hair-thin water jet with a laser to guide the laser beam through total internal reflection, much like a conventional optical fiber. The innovation of Richerzhagen differs greatly from both conventional laser machining and high-pressure water jet cutting. The laser's energy melts and vaporizes materials because the water pressure is too low to cut through them. Simultaneous cooling is ensured by guiding the laser within a water jet, essentially preventing heat damage to the material [33].

As shown in Figure 2.1, this creative arrangement entailed directing the laser beam into a nozzle inside a pressurized water chamber. The laser light was guided like an optical waveguide by coupling with the water jet. Stable and accurate water jet applied laser light to the workpiece, enabling controlled laser pulses to accomplish machining tasks. Crucially, the water jet prevented thermal damage to the workpiece by effectively removing molten material from the cut and by providing cooling [34].

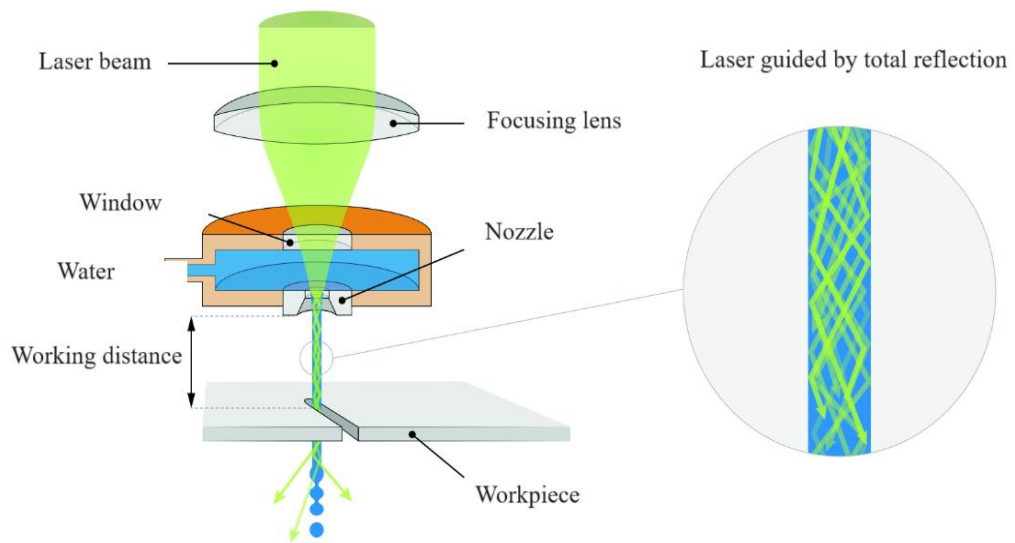


Figure 2.1 Schematic of waterjet guided laser experimental setup [35]

A decade later, Synova engineers summed up the technological developments behind this idea, which they called the Laser Microjet®. Important improvements over the years have been made to the coupling mechanism, the water jet's stability, and the efficiency of the used laser sources. The result of these advancements was the development of effective industrial machinery that could precisely cut through a variety of materials. Research on the cutting phenomenon is still ongoing, with the goal of further shrinking the water jet and extending the range of compatible laser sources [35].

According to published research, the cutting process can be improved by lessening the water jet's cooling effect. Another important factor is nozzle geometry, which influences cut quality by influencing water-jet pressure and velocity. This review

contrasts conventional laser methods with water-jet technology, without delving into the effects of water pressure on wave-guide phenomena and refractive index. A summary of current developments, technical difficulties, and upcoming trends in this developing field is provided at the end. Numerous investigations have been conducted across numerous domains in the advancement of this technology. Controlling the cutting conditions while cutting various materials has allowed for the execution of numerous experimental studies. The goal of these studies was to demonstrate the benefits of water jet guided laser cutting technology over conventional laser cutting [36].

2.3 Experimental Studies

A new simulation model was created by Wang et al. [37] especially for the purpose of cutting silicon wafers with this technology. Silicon wafer cutting is a crucial step in the manufacturing of wafers. It has historically been difficult to accomplish using traditional methods, but total reflection principles combined with water-jet guided laser processing have made it possible. The water jet's cooling effect, the uniform energy distribution of the waterjet guided laser, and the melting and removal of silicon were all taken into account in the model. The simulation's findings demonstrated how significantly the water jet's cooling effect affected the wafer's temperature field. The waterjet guided laser micromachining system's experimental trials verified that there was almost no energy loss over long distances and nearly uniform energy intensity throughout the waterjet cross-section. The performance of the silicon wafer cutting method was superior to that of the diamond saw and argon assisted laser cutting techniques due to the use of optimized machining parameters that produced clean cuts free of burrs, cracks, and heat affected zones.

Perrottet et al. [38] performed a study on cutting semiconductor wafer by using a waterjet guided laser. Semiconductor wafer cutting has been challenging with laser-based techniques due to the materials' brittleness and stringent cleanliness requirements. Conventional laser cutting creates a substantial heat-affected zone and produces numerous particles, leading to abrasive sawing becoming the industry standard for wafer dicing. However, abrasive sawing struggles to meet the demands of newer semiconductor devices, such as thin wafers and compound semiconductors.

New methods are being explored, including water jet guided laser technology, which offers a solution with significantly reduced heat-affected zones and cleaner wafer surfaces. This improvement is attributed to the water jet's cooling effect between laser pulses and its ability to remove molten material resulting from laser ablation. Recently, advancements have enhanced this technology by incorporating a device that applies a controlled thin water film across the entire wafer surface during cutting. This innovation helps suspend any generated particles, preventing them from depositing on the wafer surface.

Wang [39] concentrated on the material removal and energy density when machining aero engine components with a dual-laser waterjet guided laser system. The study looked into the variables affecting the LMJ system's energy density. It examines the impact of dominating parameters on the energy density. In order to clarify the connection between these crucial laser parameters and the material removal rate as well as the LMJ system's energy density, he created a mathematical model. The purpose of this model is to forecast and enhance laser machining procedures. The results imply that the use of waterjet guided laser technology holds promise for the synthesis of complex three-dimensional features in materials used in aerospace engines. It is appropriate for demanding applications because it minimizes damage and offers high quality, reproducibility, and high production rates.

The cutting properties of steel, titanium, and aluminum with a water jet guided laser system with a frequency doubled Nd:YAG laser were reported. The study looks at the effects of cutting depth on laser power, number of passes, and pulse repetition rate. More passes, lower pulse repetition rates, and stronger laser power can all lead to deeper cutting depths. It was found that the maximum cutting depths for aluminum were 8 mm, titanium was 4.7 mm, and steel was 1.5 mm. For instance, it was demonstrated that using a 40 W laser power in multiple passes, it was possible to achieve an effective cutting velocity of 0.1 mm/s in 8 mm aluminum. The kerf width is constant, spanning from 100 to 120 μm , irrespective of the cutting depth and process variables. As a result, the system achieves high aspect ratios, up to 12.5 in steel, 39.2 in titanium, and 66.7 in aluminum. This demonstrates the system's capacity for deep and high precision material cutting [40].

Perrottet et al. [41] were investigated on cutting GaAs-Wafer Dicing Using the Water jet Guided Laser. Semiconductor wafers, including GaAs, are becoming increasingly thinner, necessitating new dicing technologies for thicknesses below 150 μm . Existing methods like abrasive sawing are limited due to mechanical damage such as cracking and chipping, while conventional lasers pose risks of heat damage and safety concerns. The waterjet guided laser technology, combining laser and water jet, emerges as the most promising approach for thin GaAs wafer dicing. It offers superior speed and cleanliness compared to other methods, producing high-quality kerfs. The water jet, with a thin film on the wafer surface, effectively removes debris from laser ablation, and all toxic materials are carried away by water, preventing emission of toxic gases. It has demonstrated superior performance compared to other methods such as sawing, conventional dry laser cutting, and scribe and break techniques. The technology minimizes heat-affected zones by using a water-jet to cool the edges during laser ablation, efficiently removing molten material without adhesion. Cutting speeds are significantly higher than sawing methods, while maintaining excellent cut quality.

Li et al. [42] used water-jet guided laser technology to drill and cut magnesium alloy sheets in their experiments, and they compared the outcomes with traditional laser processing. The processing areas' morphology was analyzed, and the results showed clear variations. The processing areas of the water-jet guided laser processing were found to be clean, with very little residual molten material and very little heat damage. The walls of the holes and the sliced surfaces were smooth, had small slopes, and were covered in tiny, densely protruding particles. On the other hand, results from conventional laser processing indicated that there were visible secondary solidified layers and that processed areas were attached with a large amount of residues. When compared to traditional laser processing of magnesium-zinc alloys, waterjet guided laser drilling offered superior control over hole roundness and cleaner processing with macroscopic smoother surfaces.

A study on low-pressure water jet assisted laser processing for drilling Al_2O_3 ceramics was conducted. This technique looks into how surface quality is affected by the laser processing parameters. The microstructural appearances of machining surfaces produced by the composite approach and traditional laser processing are compared. By measuring the 3D morphology of drilled holes, the study also looks at how laser

parameters and water jet velocity affect surface quality. The results show a considerable increase in surface quality when low-pressure water jet is incorporated into laser processing. This method improves processing quality stability and significantly lowers the amount of molten slag [43].

Ling et al. [44] were studied on the water-jet guided laser processing that represents an innovative compound micro-machining technique where the laser beam is fully reflected through a water-jet onto the workpiece. This study introduces a critical component, the coupling unit, designed to create a long, slim, high-pressure, and stable water-jet. The coupling unit ensures symmetry in the fluid field within the chamber, facilitating easy detection of the coupling quality between the laser beam and the water-jet using a CCD camera. The study found that a nozzle with a 0.18mm diameter hole achieved superior machining results compared to other nozzles, primarily due to its excellent surface quality. Experimental efforts focused on determining optimal machining parameters. The outcomes proved that there is a correlation between water-jet stability and laser energy attenuation. Even over long working distances, the laser energy did not significantly decrease, and the energy intensity was nearly uniform throughout the water-jet's cross-section. During cutting operations, the workpiece was efficiently cooled by high water-jet pressure, which avoided the development of burrs, cracks, and heat-affected zones.

In order to cut and scribe hard and brittle ceramic materials, Kalyanasundaram et al. [45] developed a novel waterjet cutting head that is integrated with a laser system. Thermal fracture of alumina samples was used to validate the efficacy of this LWJ cutting head. Air-assisted laser cutting's vaporization mode (focused beam) and thermal fracture mode (defocused beam) were compared. The findings demonstrated that, in comparison to the vaporization mode, the thermal fracture mode in both LWJ and air-assisted laser cutting required a significantly lower energy input for material separation (three to five times less). But when it came to cut surface characteristics like kerf width, recast zone, density of micro cracks, undercutting, and spatter, the LWJ cutting head performed better than the two air-assisted laser cutting modes combined. Through a number of methods, the cooperation of the laser and water jet during LWJ cutting enabled accurate material separation and excellent cut quality:

-Separating materials via the thermal shock-induced fracture mode, which is more efficient than melting and evaporating (with a laser alone) or eroding wear (with a water jet alone).

- A neatly cut surface as a result of the kinetic energy of the water jet aiding in the removal of fragments.

Mohseni and Zomorodi [46] carried out a waterjet guided laser cutting experiment. The investigation looked at a number of topics, such as the quality of the water jet, the decrease in the heat-affected zone, laser beam divergence, the total internal reflection of light in the water jet, and the limitations of utilizing the CO₂ laser for laser micro-jet cutting. The chamber was created using CATIA, ANSYS was used for analysis, and CNC machining was used to fabricate it using aluminum rod AA6061. A cutting distance limit of 50 mm was found to be dependable through testing. However, because water absorbs a lot of heat, the 500W CO₂ laser with a wavelength of 10.6 μm was found to be less suitable for coupling with a water jet. Successful experimental coupling of laser light and water jet was achieved, though challenges such as heat absorption by water, laser beam divergence, and other laser characteristics were recognized as primary limitations of this technique.

Subasi et al. [47] were researched on fabrication of nickel-based super alloys in aerospace. The high-temperature sections of a gas turbine endure extreme thermal and mechanical stress. Super alloys based on nickel are usually used to build these components in order for them to survive these severe environments. The application of water jet guided laser technology to micro drilling operations in aerospace jet engine components is a feasible solution. This method lessens the negative consequences of laser processing. This method offers several benefits over traditional laser machining, including constant focus, burr removal, minimum tapering, decreased heat affected zone, and no recast layers. Using waterjet guided laser technology, this study examines the impact of process duration and quality variations on various nickel-based super alloys used in aerospace [48-49].

The most important factors in laser cutting processes, including laser output power, repetition rate, cutting velocity, and number of passes, were studied by Qiao et al. [50], with special attention to how these factors interacted with mono-crystalline silicon

wafers. Critical factors influencing quality and productivity were found to be laser output power, cutting velocity, and repetition rate. The study also described the relationships between parameters of water jet guided laser micromachining and surface topography changes, highest aspect ratio evolution, and kerf edge variations. The results emphasized a number of the technology's benefits: absence of cracks and oxidation on the kerf edge and other surfaces, resulting in a very steep kerf profile as evidenced by a high kerf aspect ratio of up to 12.7.

2.3.1 Underwater Waterjet Guided Laser Cutting

Underwater waterjet laser cutting was studied. Due to significant convective losses in the waterjet from the hot molten layer and scattering losses from water vapor formed during laser, workpiece, and water interactions, underwater laser cutting assisted by waterjet had lower efficiency than gas-assisted laser cutting. As a function of laser power and waterjet velocity, this model predicted multiple critical output parameters, including maximum cutting speed, temperature at the cutting front, kerf width and the amount of laser power lost through various mechanisms. The model's accuracy in predicting cutting speed, kerf width, and cut front temperature was confirmed through experimental validation. According to the analysis, scattering in water vapor is the main loss mechanism that accounts for between 40 and 50 percent of laser power loss. Furthermore, it was found that these losses decrease at lower water-jet velocities and higher laser powers. Experimental approaches to address vapor-related problems were also investigated, such as examining the dynamics of vapor formation brought on by laser heating and the water jet's removal of it [51].

A study by Nikolic et al. [52] attempted to identify the key variables influencing the underwater laser process aided by water jets. Compared to other techniques, water-jet assisted underwater laser cutting is a gentler method because it has advantages like less turbulence, gas bubbles, and aerosols. However, a number of water losses reduce its effectiveness. Determining critical variables that are vital to the procedure is critical. The goal of this work is to forecast these parameters by utilizing the adaptive neuro fuzzy inference system, or ANFIS, which highlights important factors in data analysis. To ascertain their influence on predicting water-jet assisted underwater laser cutting parameters, three primary inputs were assessed: laser power, cutting speed, and

waterjet speed. The results of the analysis showed that the prediction of water-jet assisted underwater laser cutting parameters is highly influenced by the combination of laser power and cutting speed. Bottom kerf-width had the best prediction accuracy of all the parameters evaluated, demonstrating a strong correlation with the chosen inputs. On the other hand, the prediction accuracy of dross area per unit length was lower, indicating that it might be less influenced by the variables taken into account.

Another study on underwater laser cutting was conducted by Mullick et al. [53]. In conventional underwater laser cutting, molten material is expelled from the cutting zone by creating a dry atmosphere with a high-pressure gas jet next to the laser beam. Nevertheless, this process releases aerosols and waste gases, creates turbulence in water, and releases gas bubbles, all of which have the potential to contaminate the surrounding atmosphere, particularly when cutting radioactive materials. Using a high-power fiber laser, a waterjet assisted underwater laser cutting technique has been developed to address these problems. The study examined how different processing parameters affected cutting performance and found that faster cutting speeds resulted in increased energy efficiency. To further examine and improve the procedure, an energy balance model with several loss mechanisms was created. When compared to traditional gas jet-based techniques, the water-jet assisted underwater laser cutting technique shows promise for lowering environmental contamination and increasing energy efficiency.

Wagner et al. [54] tried to solve production problems of electronic packages. The abrasive sawing has been generally used to produce package singulation despite of difficulties such fast saw blunting caused by a variety of materials such as mold compound, copper and inside packages. In this study, the waterjet guided laser technology was used to produce burr-free cuts, which are crucial for the soldering operations that follow on electronic boards. By using customized cutting techniques, problems caused by the various thermal and optical characteristics of the materials utilized can be reduced. The water jet's cooling action makes it possible to achieve excellent cuts in a variety of materials, including copper and mold compound. This process guarantees wear-free singulation of copper-based electronic packages, in contrast to mechanical sawing.

2.3.2 An overview on critical issues of water-jet guided laser technology

Liu et al. [55] offered a thorough analysis of the important problems related to waterjet guided laser (WJGL) processing management. The laser-waterjet coupling is investigated, including the coupling unit, pertinent parameters, losses, modes of propagation, and problems such as speckle. They talked about numerical aperture, focal point, and laser wavelength as important variables influencing transmission efficiency. It draws attention to the hydrodynamic phenomena that are essential to WJGL, with a special emphasis on waterjet stability. The water jet's stabilization is greatly aided by the creation of a cavitation zone and the hydraulic flip that results from cavitation. The intricate process of liquid jet breakup is influenced by both extrinsic variables like ambient conditions and hydraulic parameters like pressure and flow rate as well as intrinsic factors like the hydrodynamic properties of water and nozzle geometry. It emphasizes how crucial water jet absorption of the laser is in determining the amount of laser power that reaches the workpiece. Together with laser wavelength, focal position, and numerical aperture, other factors that affect transmission efficiency include water's refractive index, which changes with temperature and wavelength.

In this chapter, a detailed literature research was conducted and the points focused on in past studies, the studies conducted and the application examples were examined. In this way, the experimental design, the road map of the thesis was drawn and the infrastructure was created.

CHAPTER 3

FUNDAMENTALS OF CONVENTIONAL LASER CUTTING AND WATERJET GUIDED LASER PROCESSES

3.1 Introduction

This chapter first explains the cutting concept of the conventional laser cutting method, as well as the cutting parameters and laser effects on the cut materials' cutting surfaces. Following that, the fundamentals of waterjet guided laser technology are described, together with its key characteristics and the surface characteristics of the materials that are cut on the cutting surface. A comparison of these two techniques on the material's surface structure is presented.

3.2 Conventional Laser Cutting

3.2.1 Definition and History of Laser Cutting

“Light Amplification by Stimulated Emission of Radiation” is known by acronym of LASER. Laser technology is widely employed in a variety of industries, including automotive, aerospace, electronics, and healthcare, since it can create elaborate and complicated patterns with great accuracy and low material waste.

Laser development has reached a number of significant milestones up to nowadays. Firstly, in reality, using the principles of quantum physics, renowned physicist Albert Einstein predicted in 1916 that stimulated photon emission might occur. At the Hughes Research Laboratories in Malibu, California, on May 16, 1960, American physicist T. Maiman constructed and operated the first laser. In 1967, P. Houldcroft made the first reported attempt to use a laser as a cutting tool, cutting a 1 mm thick steel sheet with a 300 W CO₂ laser assisted by oxygen. During 1970s, ultraviolet-wavelength lasers were produced, primarily for use in various microscale operations and medicinal applications. The first high power diode lasers were created in the late 1990s, and more

recently, disk and fiber lasers have been created. Many scientists believe that these lasers will take the position of Nd:YAG lasers [56].

3.2.2 Laser Beam Characteristics and Components of a Laser Beam Device

There are many other kinds of light sources such as fluorescent, filament bulbs, and electric arcs, a laser produces light with unique properties that make it useful for a variety of purposes. The light produced by the laser is monochromatic of a single wavelength, in contrast to other light sources like a regular bulb, a fluorescent lamp, or light from the sun as seen Figure 3.1 [57].

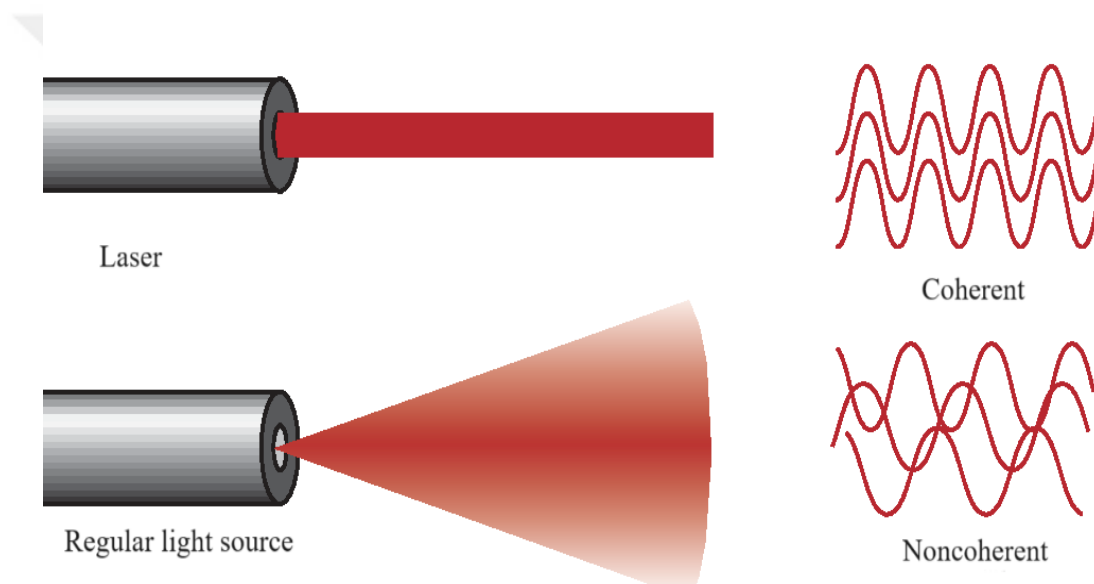


Figure 3.1 Light waves of laser and regular light source [57]

Devices specifically designed for the purpose can generate monochromatic laser beams with a single wavelength. The following are the parts of a laser device, as shown in Figure 3.2. A laser medium can be semiconductor crystals, molecules, atoms, or ions; the radiation beam can either pass through the laser medium once or bounce back and forth through it repeatedly with the help of a pumping process that raises the atoms' quantum mechanical energy levels.

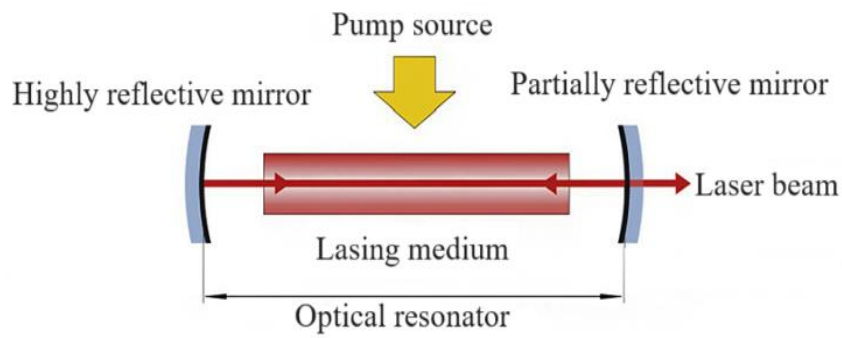


Figure 3.2 Main components of laser

3.2.3 Principles of Laser Cutting

Laser cutting is a non-contact, thermal method that can precisely and accurately cut complicated contours on a variety of materials.

The idea behind laser cutting is that photon energy from a focused laser beam is absorbed by a thin coating of metal on the surface. As shown in Figure 3.3, a coaxial jet of assist gas evacuates the evaporated molten material from the affected zone after a high power density beam concentrated in a spot melts and evaporates material in a fraction of a second.

Heat is produced from this absorbed energy, which brings the metal to its melting point and, in certain cases, the verge of vaporization. It can cut through practically any

material by heating, melting, and evaporating it in a narrow, precisely defined region [58].

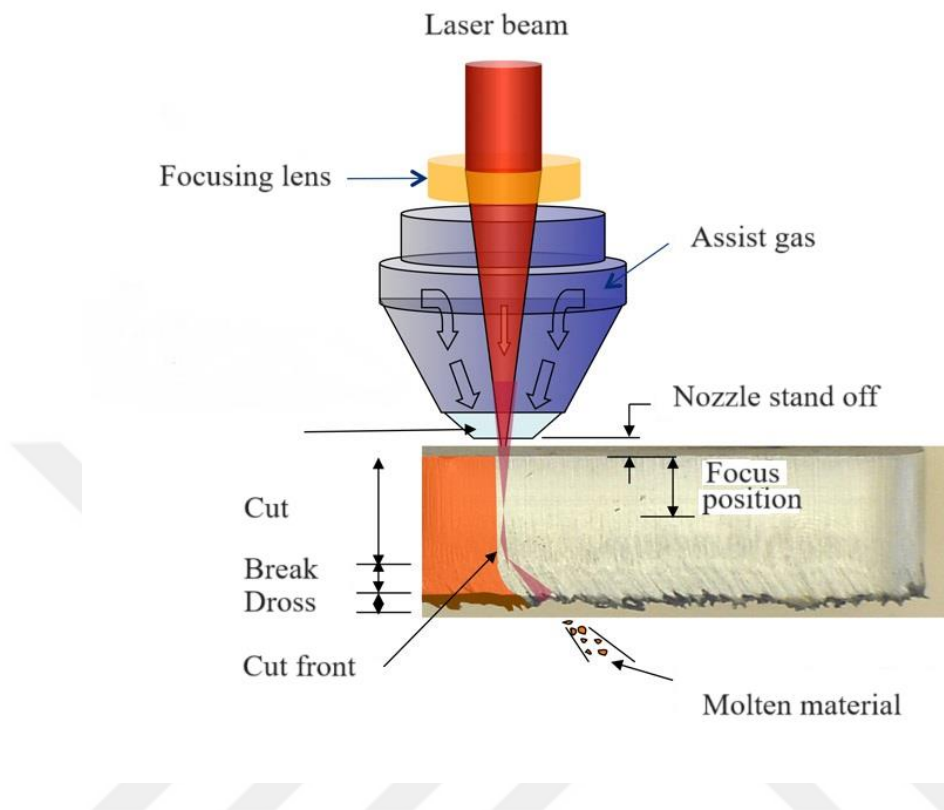


Figure 3.3 The schematic of laser cutting [58]

3.2.4 Types of Lasers

In laser cutting, there are five primary kinds of lasers that are utilized: CO₂ lasers, Nd: YAG lasers, fiber lasers, diode laser and disc laser.

3.2.4.1 CO₂ Lasers

Gas lasers based on an electrically stimulated carbon dioxide gas mixture are known as CO₂ lasers. Its wavelength is 10.6 μm . It is appropriate for use with a variety of plastics and non-metallic items because of its wavelength absorption properties. CO₂ lasers produce good-quality beams with a comparatively high efficiency. These lasers are highly effective and potent, finding extensive use in industrial settings for tasks including cutting, engraving, welding, and medical treatments. They can be used for a

variety of duties, from heavy-duty cutting to precise engraving, and their power ranges from a few watts to several kilowatts.

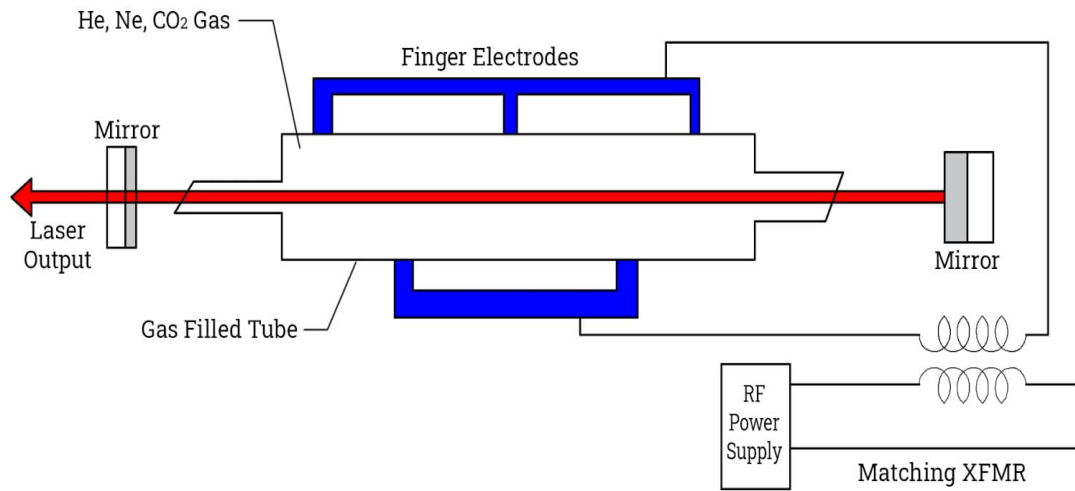


Figure 3.4 Schematics of CO₂ laser cutting system [59]

CO₂ lasers operate by employing electrical discharges or radio frequency stimulation to move CO₂ gas molecules to higher energy states as seen in Figure 3.4. The CO₂ molecules undergo important transitions between their vibrational and rotational energy states [59].

3.2.4.2 Nd:YAG Lasers

The most widely used high-power solid-state laser is the Nd:YAG laser. This is due to the energy level structure of Nd³⁺ for the four-level model and the better heat conductivity of YAG crystal over other laser materials. The Nd:YAG laser has pumping and oscillation wavelengths of 0.808 μm and 1.064 μm , respectively. Nd:YAG lasers are optically pumped by means of laser diodes or flashtubes.

Generally, pulsed Nd:YAG lasers are run in a mode known as Q-switching: A laser cavity is filled with an optical switch that is waiting to open until the neodymium ion population has reversed to its maximum. At maximal population inversion, the excited laser medium can be depopulated by the light wave passing through the cavity as seen in Figure 3.5 [60].

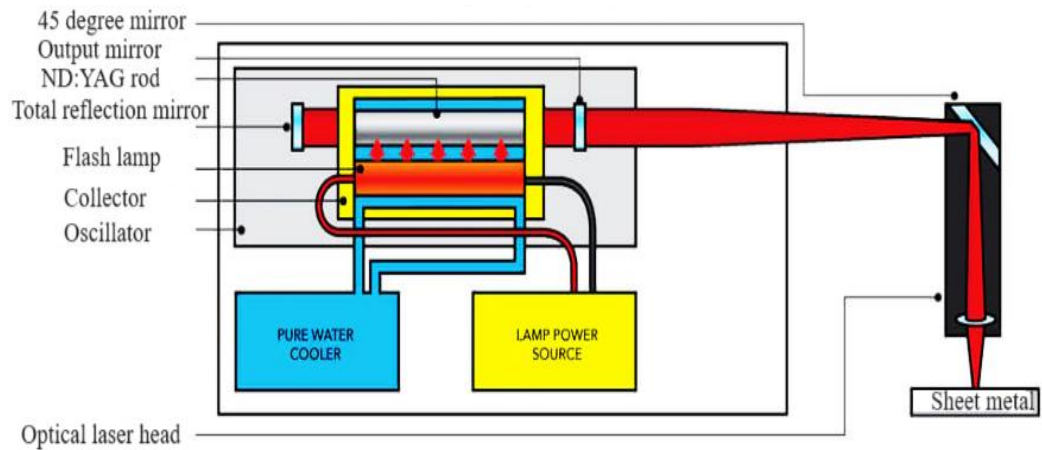


Figure 3.5 Schematics of Nd:YAG laser cutting system [60]

3.2.4.3 Fiber Lasers

A type of solid-state laser known as a fiber laser uses optical fibers as the active gain medium. As seen in Figure 3.6, these lasers function by absorbing raw light from the pump laser diodes and using a silicate or phosphate glass fiber to convert it into a laser beam with a specific wavelength of 1.064 μm .

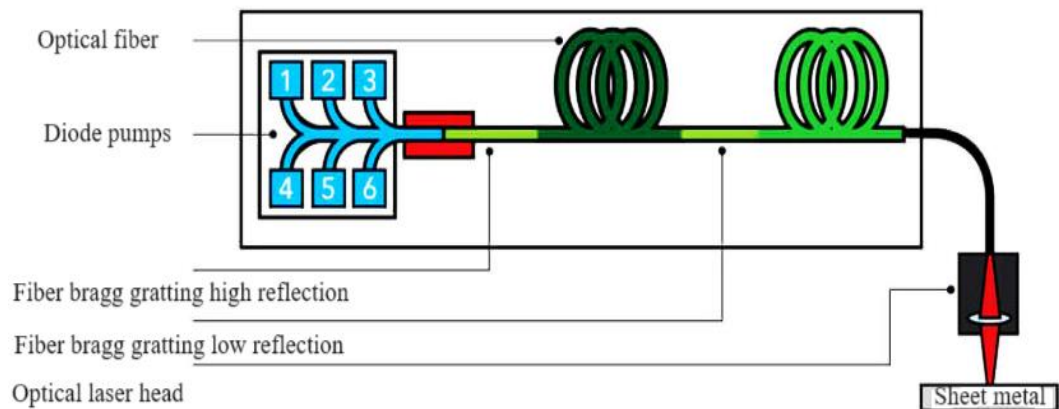


Figure 3.6 Schematics of fiber laser cutting system [61]

The fiber's core is doped with rare earth elements such as ytterbium (Yb), erbium (Er), neodymium (Nd), thulium (Tm), and holmium (Ho). The energy states required for lasing are supplied by these dopants. High-power diode lasers are used to optically pump the doped fiber. The dopant ions in the fiber core absorb the pump light, which

excite them to greater energy levels. Photons are released by these excited ions when they decay back to lower energy levels. The light inside the fiber is intensified by this stimulated emission mechanism.

Fiber lasers are better to other forms of lasers because they can produce and deliver laser light over an intrinsically flexible material, making delivery to the target and focusing point easier. This can be crucial for welding, folding, and laser cutting metals and polymers. High output power in comparison to other laser types is another benefit. Fiber lasers can produce extremely high optical gain since their active zones can span several kilometers [61].

3.2.4.4 Diode Laser

A laser diode is a type of semiconductor device that works similarly to a light-emitting diode. The diode's junction can produce lasing conditions when it is directly pumped with electrical current [61].

3.2.4.5 Disc Laser

A disk laser, also known as an active mirror, is a kind of solid-state diode-pumped laser that is distinguished by having its laser output and heat sink located on opposing sides of a thin sheet of active gain medium [61].

3.2.5 Laser Cutting Parameters

The following are the main variables that influence the laser cutting process [62]:

- Beam power
- Beam characteristics
- Traverse speed
- Assist gas
- Location of focal point relative to the workpiece surface.

3.2.5.1 Beam Power

The most important of the given parameters is the power. The maximal thickness that can be cut and/or the speed at which it can be cut both increase with power [62].

3.2.5.2 Beam Characteristics

In laser cutting operations, the most crucial beam parameters are:

Beam mode

The distribution of energy intensity across the beam cross section is shown by the beam mode. The mode is related to the beam's focussing capacity and can be likened to a cutting tool's sharpness. A beam dispersion as near to the fundamental as feasible is ideal for laser cutting. Larger focal spot sizes and a lower power density for the same output power are the results of higher order or multimode beams because they are more randomly distributed. This mode increases the thickness of the material that can be cut, speeds up cutting, and decreases the kerf width. This mode provides the highest density for a given power and can be focused to the laser's theoretically smallest focal size [62].

Stability

Stability of the beam is required to ensure that the beam power, mode, and direction (pointing stability) remain stable throughout time. The tolerances and surface finish that may be achieved with laser cutting are impacted by an unsteady beam. Thus, a stable beam improves quality and lessens variances in product output. One feature of the laser generator that is dependent on design is beam stability [62].

Polarization

The cut quality is dependent on the plane of polarization orientation; a circularly polarized beam usually yields a better cut when the cutting direction is changed. Variations in the kerf, edge smoothness, and perpendicularity of the cut work piece are indicative of random polarization of a laser beam. This is primarily due to the way that polarization modifies the material's absorption capacity. However, as the plane of polarization is oriented in the opposite direction to the cutting direction, as shown in

Figure 3.7, energy absorption decreases. This causes the cutting speed to decrease, the kerf to widen, and the edges to become less square and more uneven in relation to the material's surface [62].

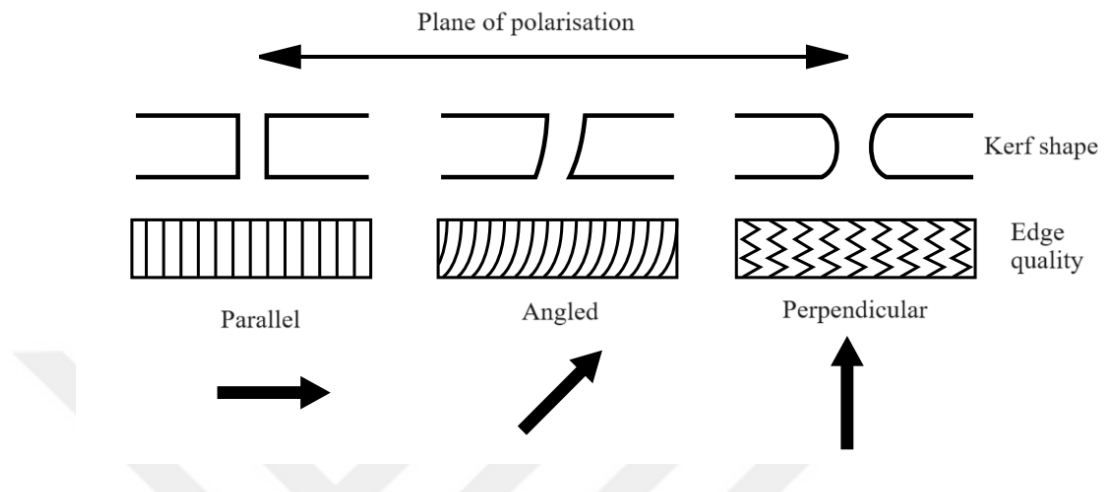


Figure 3.7 Impact of plane-polarized laser alignment on the quality of the cut [62]

Beam form (Pulsed or Continuous Wave)

For laser cutting, pulsed and continuous wave (CW) beams can be utilized. Surface roughness for pulsed beams decreases as pulse duty increases, indicating that pulse duty has an impact on cut quality. The ratio of the entire cycle time to the amount of time the laser beam is on during a single cycle is called the pulse duty. In addition, at low pulse rates (number of pulses per second), the maximum cutting speeds that can be attained are greatly lowered. This is because the material has enough time to cool down significantly in between pulses when the pulse rate is low. This contributes to the exothermic oxidation reaction's suppression, which lowers the process's overall efficiency. Moreover, there is a higher chance of dross formation at low pulse frequencies since the material cools down in between pulses [62].

3.2.5.3 Traverse Speed

When the workpiece is thicker, the greatest speed that may be attained for a given laser power drops. A plot of the cutting speed variation with thickness for a given power

will typically show two limiting curves as seen in Figure 3.8. The top curve shows the fastest possible speed for a specific thickness. There is unfinished cutting above this curve. Self-burning takes place below the lower curve. Put otherwise, the substance keeps burning even in the absence of the laser. This frequently results in a rough surface and a wider kerf [63].

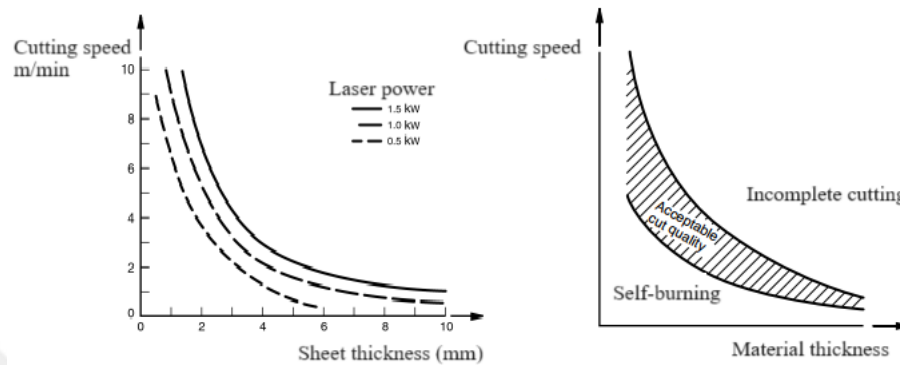


Figure 3.8 Variation of cutting speed and limiting curves for cutting speed with workpiece thickness [63]

3.2.5.4 Assist Gas

Commonly used gases include air, nitrogen, oxygen, and inert gases. During cutting, exothermic reactions require oxygen or air, which increases cutting efficiency. Alternatively, to aid in the removal of the molten metal without oxidation, an inert gas, typically argon, is utilized. The decision between oxygen and air is essentially economic when an exothermic reaction is desired. Although air is less expensive, it needs higher flow rates to generate the same amount of thermal energy. Moreover, air may introduce other gases, like nitrogen, into the sliced surface, strengthening it [63].

The following are some of the purposes of the assist gas used in laser cutting:

- Aids in the molten metal's ejection through the work piece's back.
- Prevents splatter on the lens.
- Provides a heat source, causing an exothermic reaction that aids in cutting, similar to oxygen-assisted steel cutting.

3.2.5.5 Location of Focal Point Relative to The Workpiece Surface

Consistently locating the focal point in relation to the workpiece surface is crucial due to beam divergence.

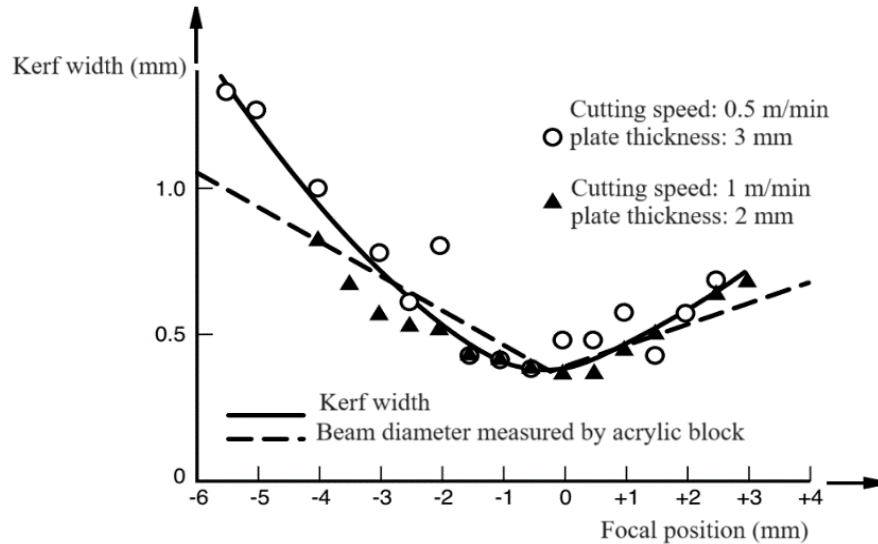


Figure 3.9 Focus position's impact on kerf width [63]

The optimal outcome (lowest kerf width) is achieved when the focal point is situated either directly above or slightly below the workpiece surface in Figure 3.9. It may be better to place the focus one-third of the thickness of the plate below the surface for thick plates [63].

3.2.6 Advantages of Laser Cutting

One of the most popular advanced technologies in metal fabrication is laser cutting. Manufacturers can cut metal using a variety of processes, but one of the most sophisticated is laser cutting. Because laser cutters can cut precisely and faster than other technologies for cutting flat sheets, fabricators frequently select them for their cutting needs. Discover the advantages of utilizing laser cutters for metal in the sections that follow [63].

- **Precision and Accuracy:** High-quality cuts with minimal tolerance.
- **Versatility:** Capable of cutting a wide range of materials.

- **Speed:** Faster than traditional cutting methods.
- **Non-contact Process:** Reduces material contamination and wear.

3.2.7 Limitations of Laser Cutting

Laser cutting has certain disadvantages despite all of its benefits. Among them are [63]:

- **Material Thickness:** Limited to materials of certain thicknesses.
- **Initial Cost:** High upfront cost for equipment.
- **Reflective Materials:** Difficulty cutting highly reflective materials like copper and aluminum.

3.2.8 Surface Quality of Laser Cutting

Surface striations, dross formation and cracking are the main factors that affect the quality of the cut workpiece.

Surface striations

Striation is the recurring emergence of lines on the laser-cut surface that alters the surface's appearance and geometric accuracy. The cut edge of a laser cut has recurring striations. Surface striations can result in stress and unanticipated geometric changes, necessitating further finishing steps to achieve a smooth finish. Stitches are usually distinct and symmetrical from the top to the bottom of the cut edge in thin sections. On the other hand, as Figure 3.10 illustrates, in thick sections, these striations typically exhibit a well-defined top cut edge but become more erratic towards the bottom [64].

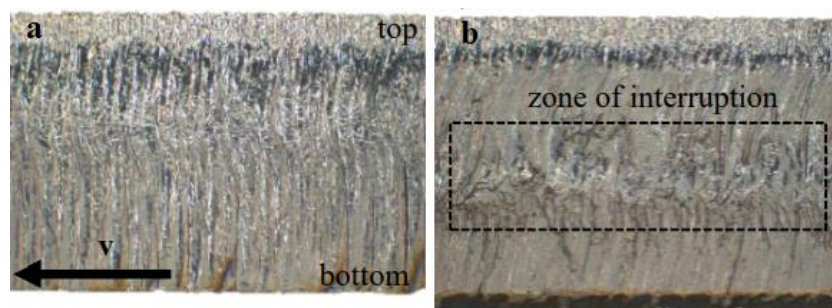


Figure 3.10 Striation in the cut surface; a) regular form b) interrupted form [64]

The main reasons of these striations are as follows:

- Vibrations from the motion unit.
- Laser power fluctuations.
- Gas flow fluctuates.
- Hydrodynamics of molten metal flow.

Dross formation

Roughness, dross adhesion, and heat-affected zone are commonly used to evaluate the quality of a laser cut edge. Dross is a solidified drop of material that adheres to the lower edge of a workpiece during laser cutting as seen in Figure 3.11. Dross formation is determined by the molten material's surface tension and viscosity. The higher surface tension or viscosity, the greater the potential to create dross, which inhibits the molten material from flowing smoothly out of the reaction zone [65].

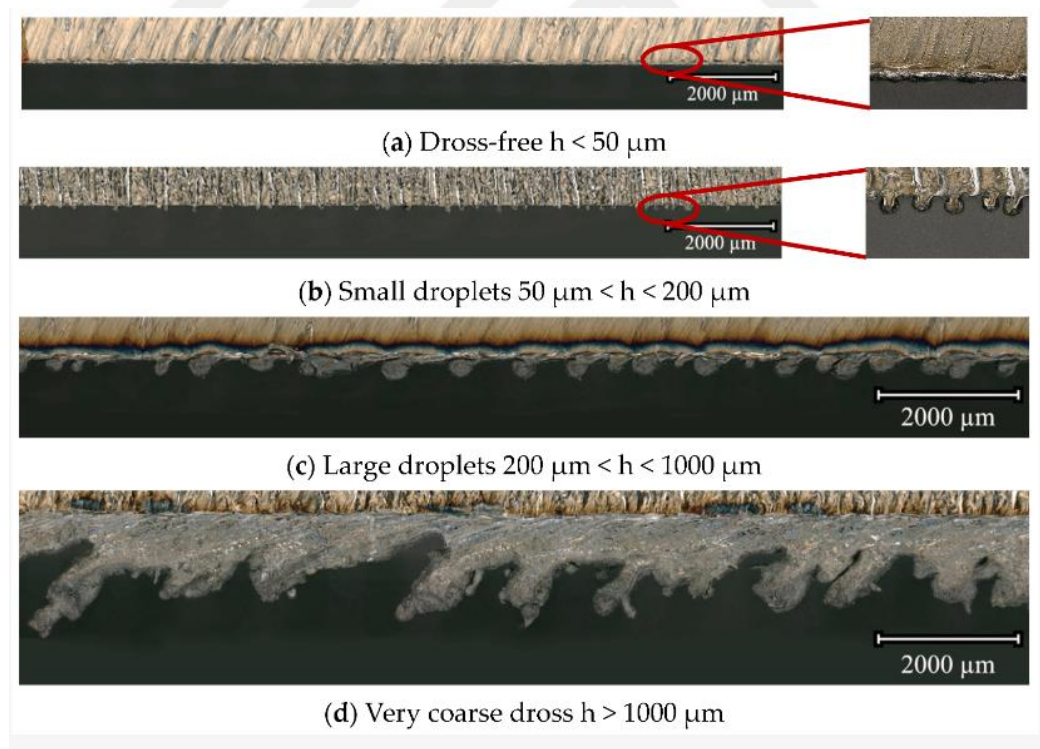


Figure 3.11 Dross according to their size; a) dross-free, b) small, c) large, d) very coarse [65]

Cracking

Laser cutting can result in a recast layer on the surface. Because lasers melt and burn some metal, remelted materials are deposited around the cut edges and at the bottom of the cut. This layer of deposited materials is extremely strained and may break, particularly if it is an oxide. Although these fractures are tiny, they can spread throughout the material, resulting in bigger cracks. This is particularly true for inner corners with short radii, where stresses are larger [66].

3.3 Waterjet Guided Laser Technology

3.3.1 Definition and History of Laser Waterjet Guided Laser Technology

Waterjet guided laser (WGL) technology is a sophisticated cutting process that combines laser cutting precision with the benefits of waterjet technology. This technology employs a laser beam directed by a thin, high-pressure waterjet, which serves as a flexible optical fiber, directing laser energy precisely onto the material to be sliced. The waterjet cools the material while cutting, decreases thermal distortion, and helps to remove debris from the cutting zone.

An experiment, conducted in October 1841, provided the first demonstration of "fusion" between light and water. Professor Daniel Colladon of Geneva University delighted lecture audiences using an optical phenomenon called 'light guiding', which is based on complete internal reflection.

An electric arc lamp was the light source in Colladon's model. Through the water tank and along a jet shooting out of a hole on the opposite side, light was concentrated via a lens. Complete internal reflection held the light rays in the liquid when they briefly touched the jet's edge at a certain angle. The beams of light rolled along the water jet's arcing path until they splattered into a collection pan. As it were, the light trailed the water's curvature [67].

There were attempts to integrate the two technologies, laser and water jet, into a single hybrid process in the 1980s. As of right now, Aesculap, Germany, has the only known patent application (DE 3643284 December 1986). It explained how to connect a laser

beam to a water jet for medical purposes by encircling the laser fiber tip with a water jet [68].

A modified version of an optical transmission system was visualized by Richerzhagen. Mixed outcomes were obtained with Richerzhagen's coupling unit. The nozzles failed rapidly even though his models and calculations indicated that all light should travel through the nozzle. In essence, just like with the ETA setup, this setup was leading to nozzle damage. A patent application (FR 2 676 913, May 1991) in the name of LASAG (a division of the Swatch group that had co-financed the EPFL lab) was prepared by Richerzhagen when he was working on his PhD dissertation. Bernold Richerzhagen developed a hybrid machining technique.

The Microjet (LMJ) technology, patented in 1994, combines a laser with a low-pressure hair-thin water jet that directs the laser beam via total internal reflection, similar to a standard optical fiber. Richerzhagen's technique varies significantly from high-pressure water jet cutting and conventional laser machining.

The modest water pressure is insufficient for cutting through the material. Instead, the laser energy melts and vaporizes it. The water jet guided system described in this application is based on the previously mentioned idea of having a huge chamber for a water flow that is almost stationary [69].

3.3.2 Waterjet Guided Laser Components and Characteristics

The major subsystems of a waterjet guided laser apparatus are shown in detail in Figure 3.12. In contrast to traditional laser cutting systems, this system includes a specifically designed nozzle that guides the laser with water, a water pump to supply water to the system with a purification system.

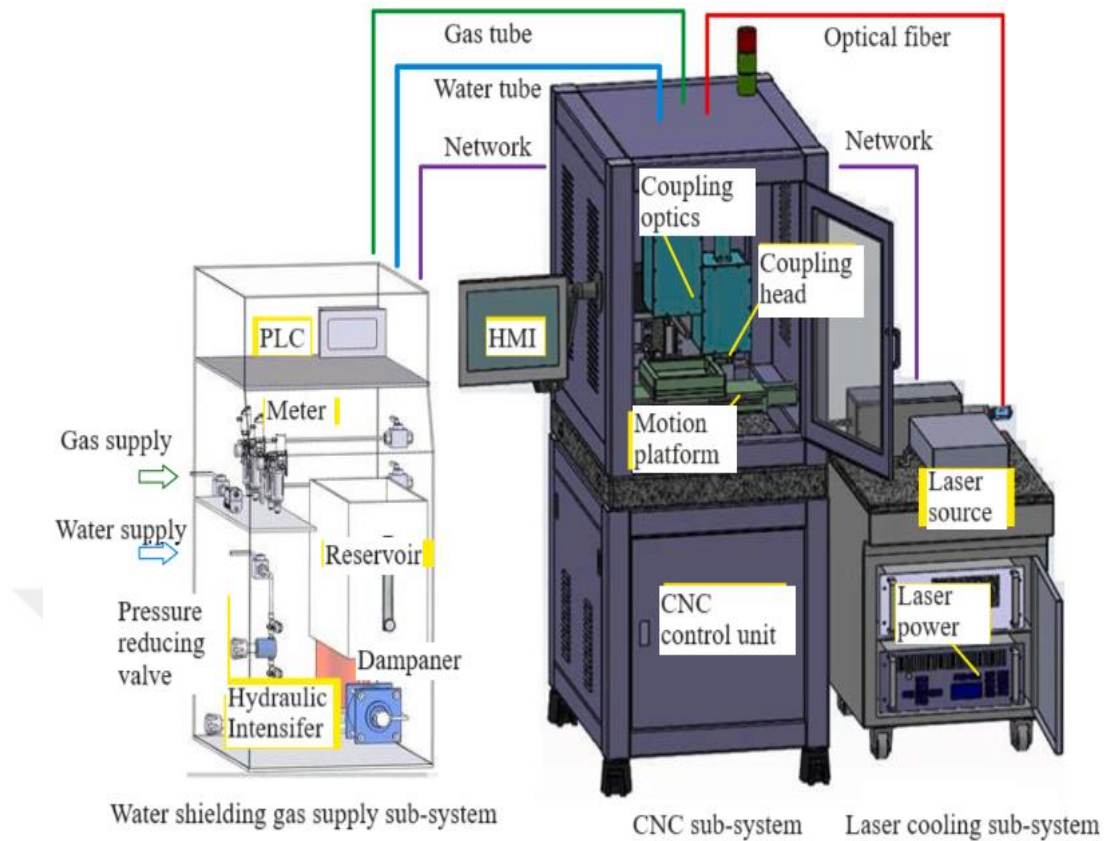


Figure 3.12 The major subsystems of a waterjet guided laser apparatus [70]

The basic parts and their main properties to create the system are described below [71]:

Laser Source: The main component that produces the laser beam. Common laser sources include CO₂, fiber and Nd:YAG lasers.

Waterjet Nozzle: This component produces a high-pressure spray of water that guides the laser beam to the cutting surface. The waterjet serves to cool the material and prevent heat from spreading.

High-Pressure Pump: Produces the required pressure for the waterjet, which normally ranges between 5 MPa and 300MPa.

The beam delivery system: It consists of mirrors, lenses, and fibers that route the laser beam from the source to the waterjet nozzle.

Cutting Head: The unit that combines the laser beam and the waterjet stream to accurately target the material.

Control System: Computer Numerical Control (CNC) systems that manage the cutting action and operation.

Filtration and Recirculation System: Filters and recirculates the water used in the process to reduce waste and environmental effect.

Safety Enclosures: Enclosures and systems designed to protect operators from laser beams and high-pressure water streams.

3.3.3 Principles of Waterjet Guided Laser Technology

The cutting principles of a waterjet guided laser (WJGL) system entail the cooperative application of a high-pressure waterjet stream and a laser beam to accomplish precision material cutting.

3.3.3.1 Operating principles

The laser beam is guided toward the middle of the waterjet stream as shown in Figure 3.13. A capillary laminar water jet, which functions as a hair-thin optical fiber with variable length, is created by forcing medium pressure water with a pressure range of 5 to 300 MPa through an aperture in a chamber filled with compressed water.

Because of this alignment, the waterjet can efficiently serve as a waveguide for the laser beam, transferring its energy to the cutting point. The orifice diameters vary from 50 to 1000 μm . In order to withstand wear, the nozzles placed near the water chamber's exit are made of sapphire, ruby or diamond. The amount of water used is around 1 liter per hour at 30 MPa. Because water quality standards are so stringent, degassed ultra-pure water is supplied.

The waterjet cools the region being cut by the laser as it passes through the material. This cooling lessens the extent of the heat-affected zone (HAZ) and minimizes thermal damage [72].

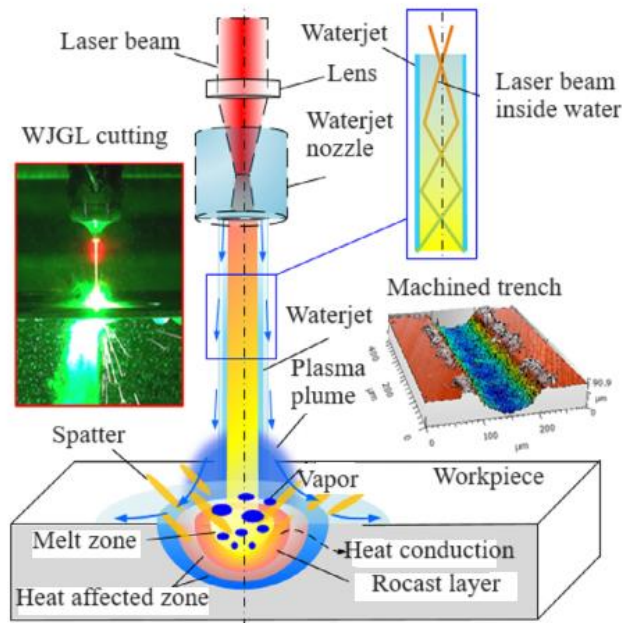


Figure 3.14 Material removal process [74]

Laser power is activated, guiding a laser pulse to the work piece's surface, transferring energy to the material being processed, absorbing it and heating the target area. Heat builds in processing regions, causing material to melt and evaporate. Low laser flux causes material to evaporate or sublime, but high flux transforms it to plasma, separating the water jet from the workpiece.

Laser pulses collapse vapor flume, plasma disappears, water jet cools ablation zone, reduces heat accumulation, flushes debris, prevents burr formation, and completes laser ablation round.

The ablation process consists of continuous heating and cooling, with the duration and interval time of laser pulses being regulated to improve machining speed and material cooling effects. While laser ablation dominates material removal by forming the melt pool, vapor and plasma plume, the waterjet, with its high heat capacity, can significantly influence the thermodynamics and kinetics of the ablated matter, providing good heat management as well as debris cleaning from the work zone [75].

3.3.4 Advantages of Waterjet Guided Laser Technology

Waterjet guided laser technology has the advantages of high surface quality and many other compared to conventional laser cutting [76].

- **High accuracy:** The combination of laser accuracy and waterjet guiding enables extremely exact cutting.
- **Minimal Thermal Damage:** Waterjet cooling minimizes the heat-affected zone, protecting the integrity of heat-sensitive materials.
- **Smooth Edges:** The elimination of dirt and cooling action provide smoother edges, which reduces the need for post-processing.
- **Versatility:** Capable of cut a variety of materials, including metals, ceramics, composites, and nonmetals.
- **Efficiency:** Faster cutting speeds and higher material removal rates than typical laser cutting.

3.3.5 Limitations of Waterjet Guided Laser Technology

While waterjet guided laser technology offers various advantages, there are certain restrictions that must be considered [77]:

- **Initial Cost:** The initial cost of establishing a WGL system is substantial owing to the complex technology and equipment required.
- **Operating Costs:** Maintenance and operation can be costly, including consumables like water and abrasives, as well as the electricity required to run both the laser and waterjet components.
- **Technical Expertise:** Technical expertise is required to operate a WGL system, which adds to labor costs and operational complexity
- **Maintenance:** Because the system integrates two sophisticated technologies, there are more components that might wear out or fail, necessitating frequent maintenance and potentially causing additional downtime.
- **Beam Delivery:** The process of directing a laser beam through a waterjet introduces new factors that can impact beam quality and accuracy. It might be more difficult to ensure steady beam delivery and focus than direct laser cutting.

- **Cooling Effect on Energy Loss:** It causes the laser heat power to decrease and causes cutting energy losses.

3.3.6 Surface Quality of Waterjet Guided Laser Technology

One of the primary benefits of waterjet-guided laser technology is the high surface quality it achieves, especially in precision machining and microfabrication.

In comparison to standard laser cutting, this method generates smoother surfaces with reduced roughness values. The presence of the waterjet aids in the effective evacuation of molten material, decreasing heat affected zone (HAZ), surface striations, burr development and resulting in cleaner cuts as seen in Figure 3.15 and Figure 3.16.

The waterjet also helps to maintain a steady cutting process, resulting in a constant and high-quality surface finish. The waterjet stabilizes the laser beam, minimizing divergence and increasing cut precision. This accuracy is critical for applications that need tight tolerances and intricate geometries [78-80].

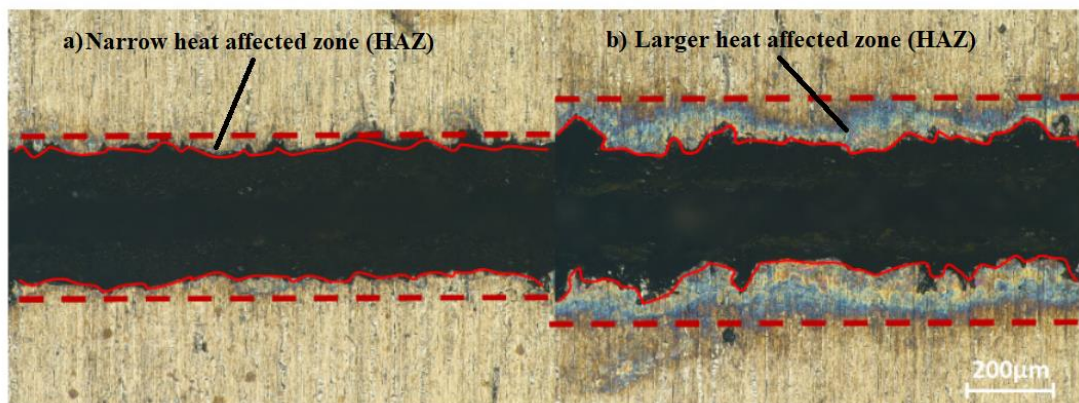


Figure 3.15 Heat affected zones (HAZ) a) waterjet guided cutting,
b) conventional laser cutting [81]

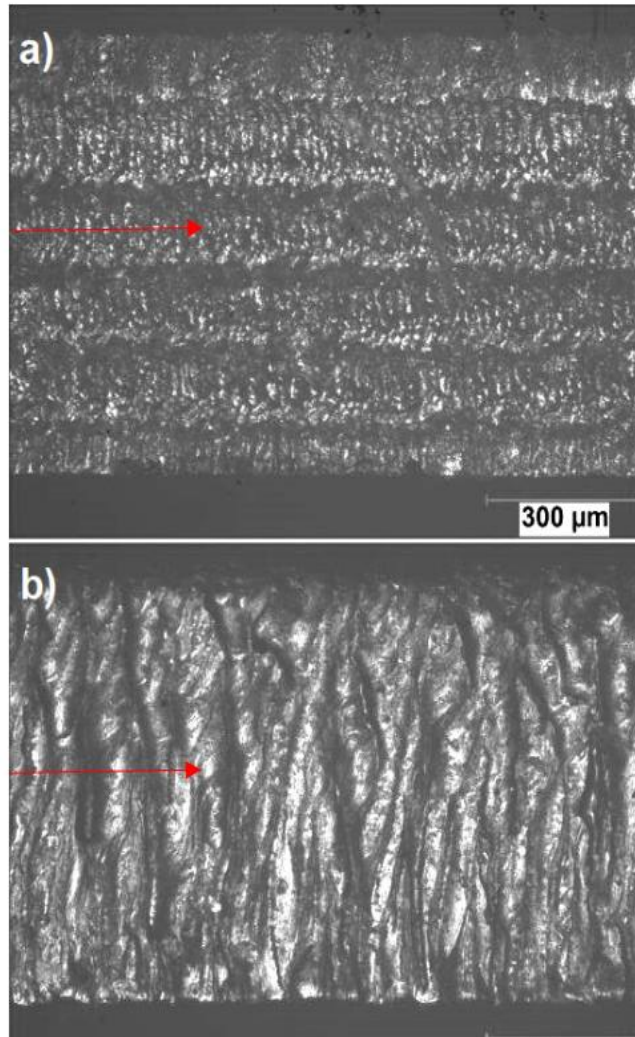


Figure 3.16 Surface striations of Inconel 625 samples cut with: a) waterjet guided cutting, b) conventional laser cutting [82]

3.4 Comparison of Conventional Laser Cutting and Waterjet Guided Laser Technology on Cutting Surface Quality

The surface quality of materials produced with cutting processes is crucial for many industrial applications. Conventional laser cutting and waterjet guided laser cutting are the two most common procedures, each with its own set of properties that influence cut surface quality. This section compares two methods according to surface roughness, heat effects, edge accuracy and material integrity [83].

Conventional Laser Cutting:

Surface Roughness: Higher surface roughness owing to heat effects and material re-solidification at cut edges. This can produce rough and uneven surfaces that require post-processing.

Heat-Affected Zone (HAZ): A larger heat affected zone can result in thermal distortion, material deformation, and mechanical characteristics changes.

Thermal Damage: Micro cracks and thermal strains are more likely to occur, compromising the integrity of heat-sensitive materials.

Edge Quality: Burrs, dross, and unevenness on edges can be caused by molten material adhering to the cut edge. Thicker materials and faster cutting rates can reduce precision.

Post-Processing: Often, further procedures such as grinding or polishing are required to attain the appropriate surface quality.

Waterjet Guided Laser Cutting:

Surface Roughness: Lower Ra values result from the waterjet's cooling and cleaning effect. The water helps to remove molten material, resulting in smoother surfaces. In general, the cuts are more consistent and cleaner, requiring fewer further finishing operations.

Heat-Affected Zone (HAZ): Significantly decreased HAZ. The waterjet continually cools the material, eliminating excessive heat buildup and reducing thermal distortion.

Thermal Damage: Minimal heat impact preserves the material's mechanical qualities and reduces the possibility of micro cracking.

Edge Quality: The edges are sharper and cleaner, with less burrs and dross. The waterjet helps to stabilize the laser beam, which improves cut precision. Excellent precision, particularly for complicated and high-tolerance cuts. The combination of laser accuracy and waterjet cooling produces extremely accurate edges.

Post-Processing: Due to the exceptional quality of the cut surface, less post-processing is necessary.

In general, waterjet guided laser cutting produces a higher-quality surface than conventional laser cutting. The cooling action of the waterjet reduces heat damage and surface roughness while also improving edge sharpness and material integrity. This makes waterjet guided laser technology especially useful for applications needing great precision while minimizing heat effect [84].

In this chapter, it was discussed how the typical laser cutting process works, as well as the cutting parameters and laser effects on the cutting surfaces of the cut materials. Following that, the principles of waterjet guided laser technology were discussed, along with its main characteristics and the surface properties of the materials cut on the cutting surface. Detailed information was obtained to create the experimental setup of the thesis study and it provided guidance for the modeling and method of the experimental setup design.

CHAPTER 4

MATERIALS AND METHOD

4.1 Introduction

This chapter includes a full explanation of the materials, machines, and procedures used to produce the study results. This chapter begins with the description of the materials, cutting operations, roughness analysis and microstructural analysis of cutting surfaces. This chapter attempts to make it easier to replicate and evaluate the study's findings by outlining the research process and offering a transparent explanation of the materials and procedures employed.

4.2 Materials

In this study, cutting of different materials was tried for trial purposes. Finally, AISI 1020 steel sheets were chosen, because of its widespread use in industry. The chemical compound and properties of AISI 1020 steel are shown in Table 4.1 and 4.2. AISI 1020 steel with thicknesses of 1.5 mm, 2 mm, 2.5 mm, and 3 mm as shown in Figure 4.1, respectively were cut by conventional laser and waterjet guided laser in the experiments.

Table 4.1 Properties of AISI 1020 steel

Young's modulus (GPa)	186
Density (kg/m ³)	7.87
Modulus of rigidity (Gpa)	72
Yield strength (N/mm ²)	384
Poisson's ratio	0.29
Thermal conductivity (W/km)	51.9
Specific heat capacity (J/g-°C)	0.486

Table 4.2 Chemical composition wt. % of AISI 1020 steel

C	Si	Mn	S	P	Mo
0.17	0.12	0.48	0.031	0.014	0.018

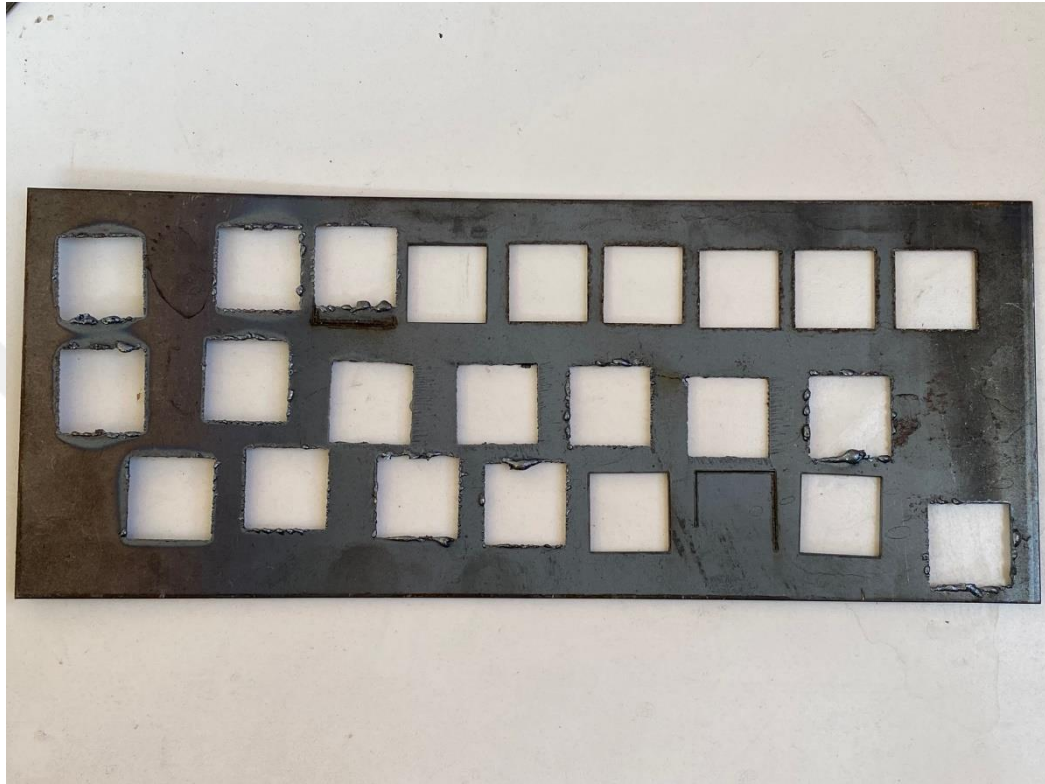


Figure 4.1 AISI 1020 steel sheet

4.3 Methods

A waterjet guided laser was manufactured to perform cutting experiments. The technical drawings and three-dimensional design of this system were designed with the Solidworks program. After three-dimensional design and modeling were completed, the prototype phase started and assembly was made. This system consists of main cutting head. It consists of a laser unit that will perform the cutting process and a water jet unit connected to this laser unit as seen in Figure 4.2.

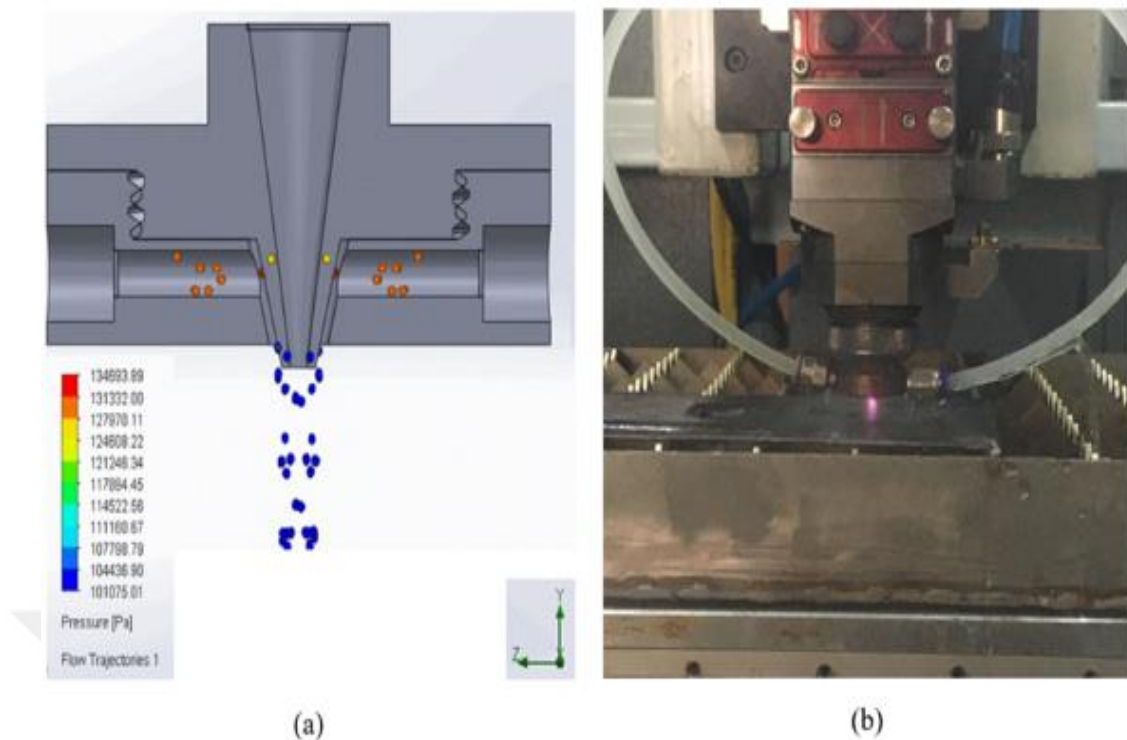


Figure 4.2 General view of waterjet guided laser system

Research has been conducted on various cutting parameters by applying laser cutting experiments to steel sheets with various thicknesses. Smoother machining surfaces have been tried to be obtained by changing parameters such as cutting speed and laser power. It has been demonstrated in past studies that the distance of the laser to the workpiece, material structure and gas pressure have a significant effect on the cutting thickness size and surface precision [85].

4.4 Roughness Testing

The cut samples were analyzed using optical Polytec TMS100 3D profilometer shown in Figure 4.3, in accordance with ISO 4287-4288 standards [86].

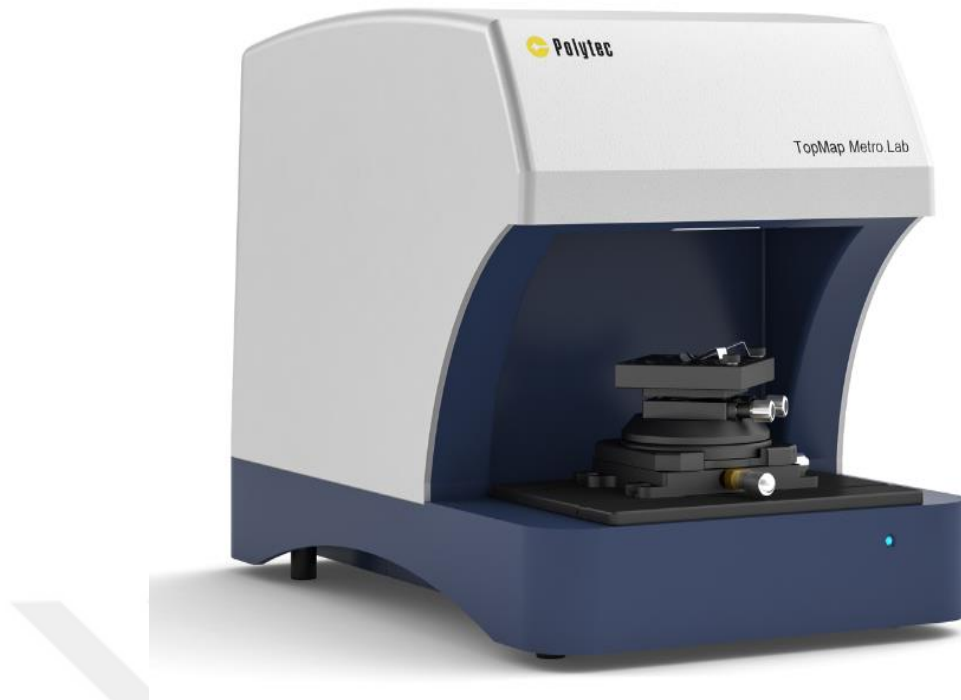


Figure 4.3 Polytec TMS100 3D profilometer

Average roughness (R_a) values were measured along three independent lines on the surface and the average was calculated. The lines were drawn 0.25 mm below the top and 0.25 mm above the bottom boundaries of the specimens, as seen in Figure 4.4.



Figure 4.4 Roughness measurement method

4.5 SEM Analysis

Images captured by scanning electron microscopy (SEM) (Gemini 300, Zeiss, Oberkochen, Germany) as shown in Figure 4.5 are also taken in order to compare the burr generation of the waterjet guided laser cut surface with the conventional laser cut surface.



Figure 4.5 General view of Gemini 300 scanning electron microscope

4.6 Anova Analysis

The impacts of the factors on surface roughness for waterjet-guided laser cutting are also statistically defined using analysis of variance (ANOVA). This method helps in understanding the role of laser cutting parameters and their interactions in determining the surface roughness of cut materials.

CHAPTER 5

DESIGN AND CONSTRUCTION OF EXPERIMENTAL SETUP

5.1 Introduction

In this chapter, design, modeling and construction of the experimental setup is explained. This section will provide detailed information about the design and manufacturing of the experimental setup. The components that make up the experimental setup and their assembly into a single experimental setup will be explained. Additionally, the method of experiments and the materials used in laser cutting will be introduced.

In this study, a novel waterjet guided laser cutting system was manufactured. An inventive waterjet nozzle was designed in order to guide the laser beam on the workpiece.

5.2 Configuration and Principles of Experimental Setup

A waterjet guided laser cutting machine which consists of a fiber laser head, a laser resonator with a cooling unite, an assisted gas system, 3 axis CNC controller system, computer control system, a water pump with filtration system and a novel designed waterjet nozzle was manufactured. Cutting processes are performed on the laser cutting unit shown in Figure 5.1.



Figure 5.1 Experimental cutting design of waterjet guided laser cutting system

5.2.1 Laser Source Resonator

In order to guide the laser light through water, high wavelength of a laser was preferred. Continuous wave (CW) JPT-1000C resonator was used as a laser source as seen in Figure 5.2. The resonator has a wavelength of 1080 nm and maximum pulse repetition frequency of 20,000 Hz.

The resonator also has cooling system which is flow rate of 12 L/min and pressure of 7 Bar. It can be connected a computer and laser cutting settings and options such as output mode selection, status monitoring and alarm and warning operations were controlled by a computer.



Figure 5.2 Laser source resonator

5.2.2 Laser Cutting Head

A OSPRI-LC209 fiber laser head shown in Figure 5.3 which has maximum rated power of up to 2 kW, focusing length of 125 mm and collimation length of 100 mm, was used in the design.



Figure 5.3 Laser cutting head

5.2.3 CNC Control and Three Axis Movement Unit

The unit provides CNC control to the waterjet guided laser system shown in Figure 5.4. Cutting parameters are chosen and followed by computer screen. Three axis movement is managed by motion platform. This unit also can be manually controlled in order to create an angled cut.



Figure 5.4 CNC control and three axis motion unit

5.2.4 Water Pump System

A water pump unit is designed and added to the system as seen in Figure 5.5. Water flow was provided within the planned water jet guided laser cutting nozzle by a water pump equipped with a filtering system. The cutting head receives filtered water from the water provider that is needed for the procedure. Even though the pump's water flow rate can be changed, a steady $2.25 \text{ m}^3/\text{s}$ flow rate was employed.



Figure 5.5 Water pump unit with filtration

5.2.5 Waterjet Nozzle Design

The most critical point of this study is to transfer and guide the laser beam to the workpiece in pressurized water with the least laser power loss. The three main goals that should be taken into account when designing a nozzle are that the water wall should function as a full mirror, preventing any potential turbulence flow and allowing the laser beam to be transported continuously without losing focus. For this reason, the correct design of the waterjet nozzle is of great importance.

Different type of designs and flow analyses for these designs were created in the SOLIDWORKS software in order for guiding the laser on the cutting head. The goal of the models was to ensure that water moves vertically in the direction of the workpiece.

5.2.5.1 One Side Inlet Waterjet Nozzle Models

Figure 5.6 displays the flow analysis for the first design. It was determined by means of analyses that the water did not flow vertically. As seen in Figure 5.7, the water flow in the first tip sample composed of copper material used to confirm the analysis was turbulent rather than flowing at a straight angle as predicted by the study.

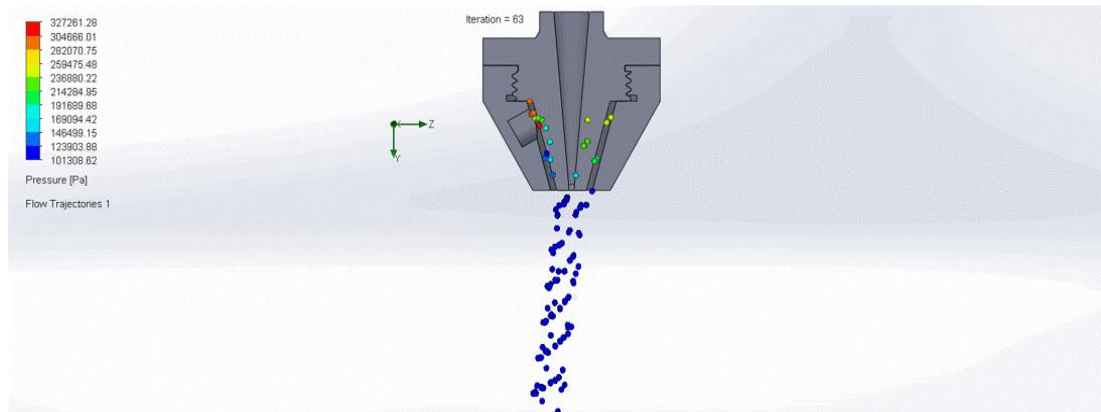


Figure 5.6 One side inlet nozzle 3D flow model

As a result of the examinations made on the first laser cutting head, a turbulent flow was obtained. In addition, the focal point of the laser was outside the optimum distance, which reduced the effect of the laser.



Figure 5.7 Water flow in one side inlet design

Furthermore, in conventional laser cutting with this nozzle, it has been discovered that having the laser's focal point outside of the optimum distance reduces the cutting effect.

5.2.5.2 Double Sided Inlet Waterjet Nozzle Models

In light of these concerns, double sides inlet sample was created and modelled in Figure 5.8 and water flow analyses were performed in a range of tip geometries. In order to ensure that the water flows at a steeper angle and to reduce the turbulence effect, water is considered to enter the nozzle from two different ends in the designs.

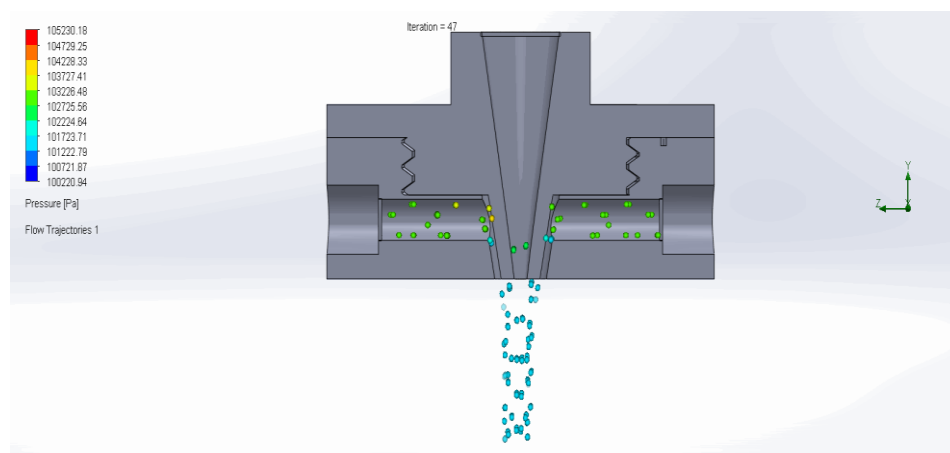


Figure 5.8 Double sided inlet nozzle 3D flow model



Figure 5.9 Water flow in double sided design

Figure 5.9 depicts the water flow through the laser head during the cutting process as well as the flow analysis of the tip geometry that offers the optimal flow and is employed in cutting procedures. Additionally, its length was taken to be equal to the laser's own tip length so that the laser focus does not change.

The 3D models showed that the water flow in the double inlet model had a more laminar flow and the water bundles moved together up to a certain distance without dispersion when the single and double water inlet models were compared. Design development continued on models with double water inlets.

5.2.5.3 Nozzle Design Critical Points

In order ensure laminar flow, prevent dissemination over a certain distance and preserve pressure loss, nozzle model needs to be specifically designed. The three criteria that are displayed in Figure 5.10 are crucial for this point. Designs were created based on reference values throughout the 3D modeling process by taking certain dimensions below into consideration. The following is an overview of these:

- Water inlet diameter (A): 1.5 mm, 2 mm and 2.5 mm.
- Nozzle diameter (B): 1 mm, 1.5 mm and 2 mm.
- Water inlet angle (C): 22°, 33° and 44°.

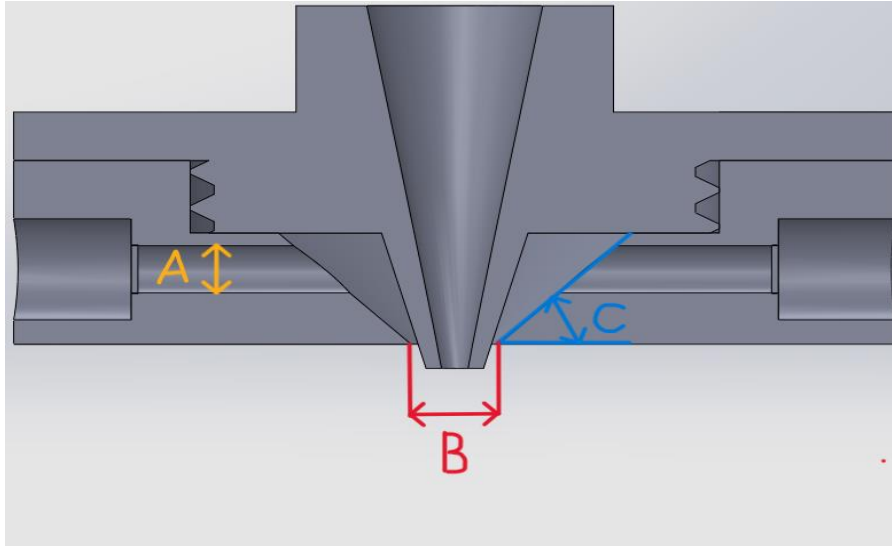


Figure 5.10 Critical dimensions in waterjet nozzle design

When the inlet diameter is set at 1.5 mm, nozzle diameter of 1 mm and low inlet angle of 22° , the water flows fast but intermittently. Furthermore, the flow axis is shifted as seen in Figure 5.11. This shift makes it impossible to guide the laser. Both focus shift and laser power will result in a decrease in cutting quality.

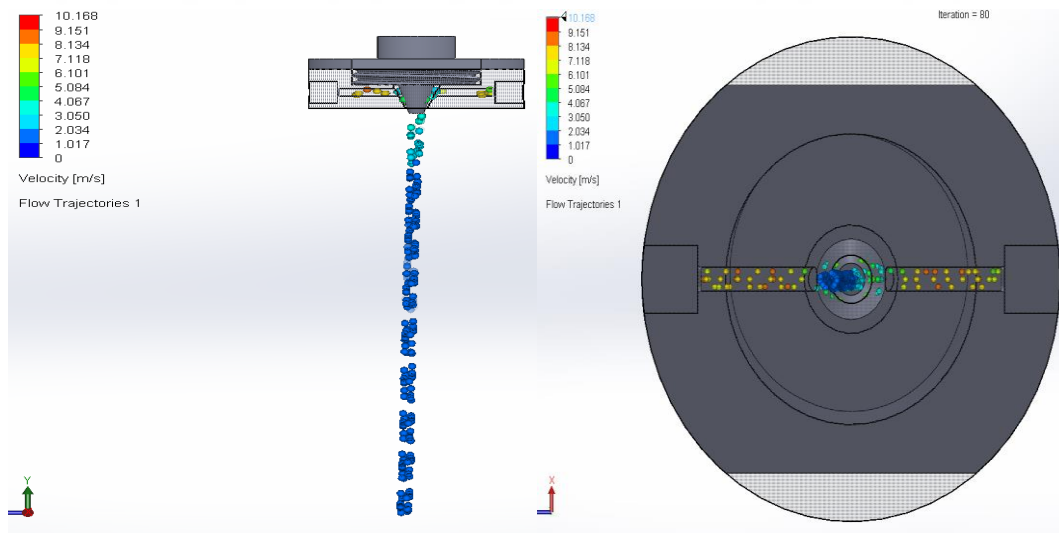


Figure 5.11 Nozzle dimensions of A(1.5mm), B(1 mm), C(22°)

When the inlet diameter is set at 2 mm, nozzle diameter of 1 mm and inlet angle of 44° as shown in Figure 5.12, the water flows in very laminar lines. Water flows at a constant speed and in a single stream with a certain distance.

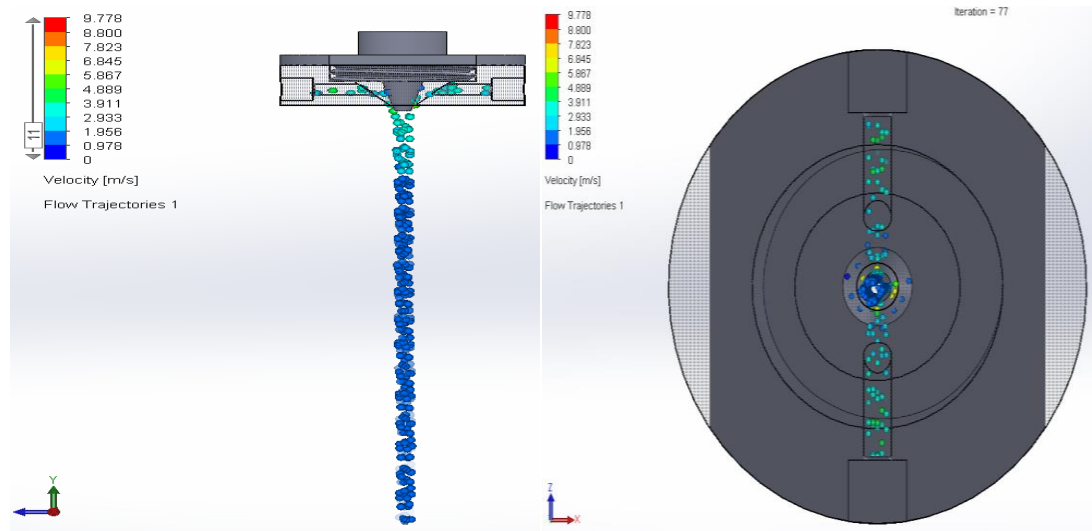


Figure 5.12 Nozzle dimensions of A(2 mm), B(1 mm), C(44°)

When the inlet diameter is set at 2.5 mm, nozzle diameter of 1 mm and inlet angle of 33°, the water flows laminar without dispersion but slowly shown in Figure 5.13. Increasing inlet diameter of 2.5 mm causes a turbulent flow.

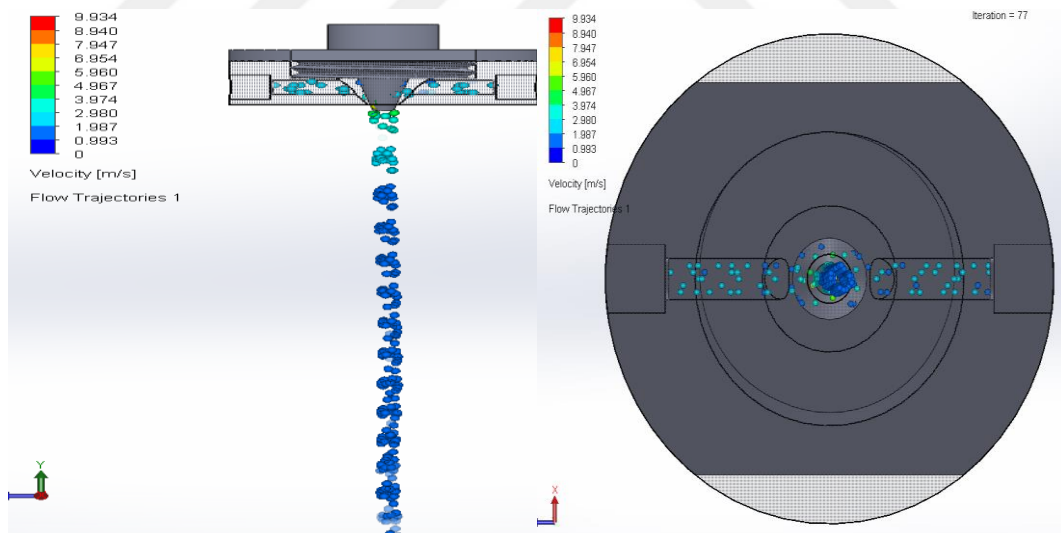


Figure 5.13 Nozzle dimensions of A(2.5 mm), B(1 mm), C(33°)

When the inlet diameter is set at 1.5 mm, nozzle diameter of 1.5 mm and inlet angle of 33°, the water flows laminar but slowly as seen in Figure 5.14.

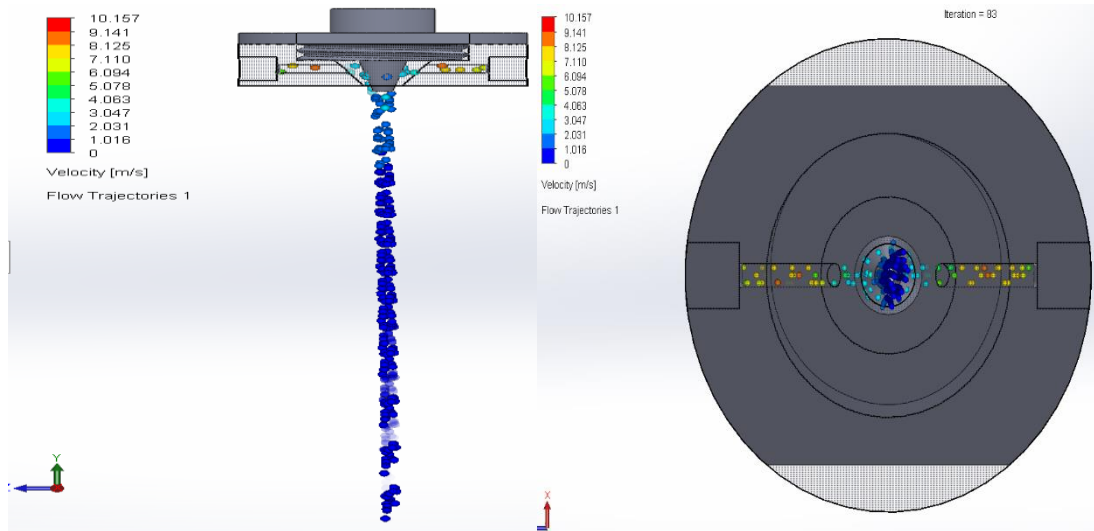


Figure 5.14 Nozzle dimensions of A(1.5 mm), B(1.5 mm), C(33°)

When the inlet diameter is set at 2 mm, nozzle diameter of 1.5 mm and inlet angle of 22°, the water flows laminar but the water flows intermittently shown in Figure 5.15.

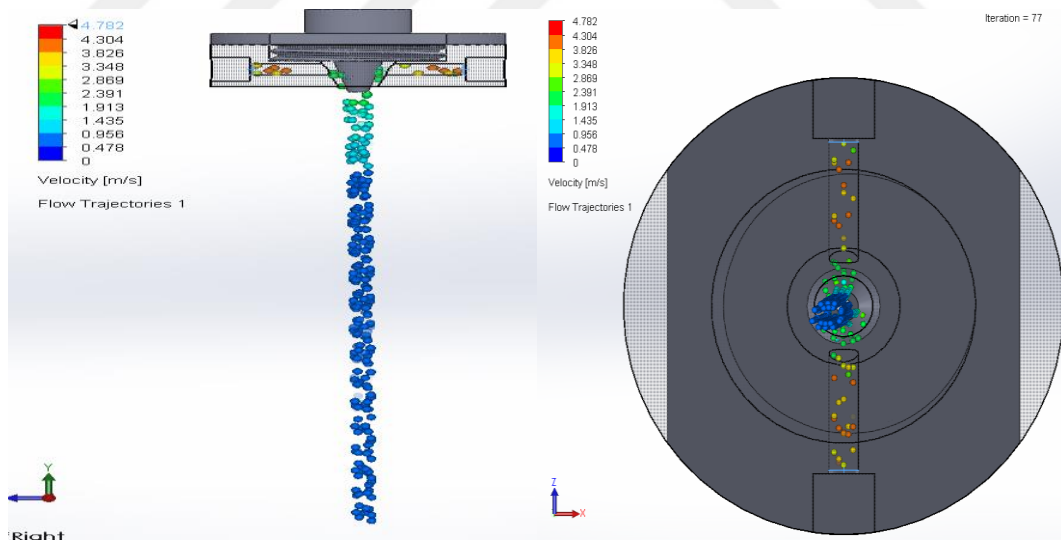


Figure 5.15 Nozzle dimensions of A(2 mm), B(1.5 mm), C(22°)

When the inlet diameter is set at 2.5 mm, nozzle diameter of 1.5 mm and inlet angle of 44°, the water flows laminar but shift shown in Figure 5.16.

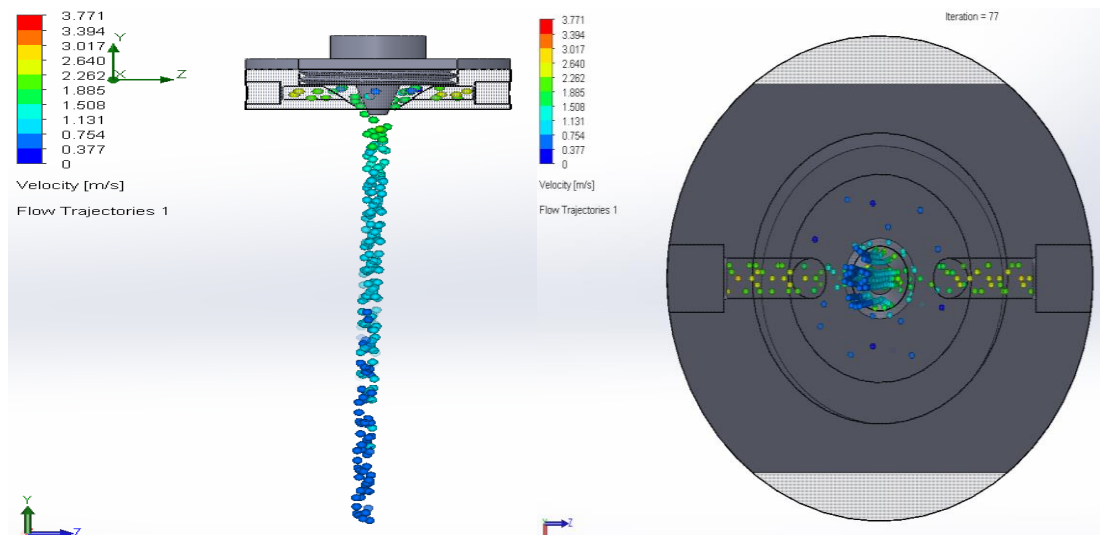


Figure 5.16 Nozzle dimensions of A(2.5 mm), B(1.5 mm), C(44°)

When the inlet diameter is set at 1.5 mm, nozzle diameter of 2 mm and inlet angle of 44°, the water flows turbulent also it is shifted shown in Figure 5.17.

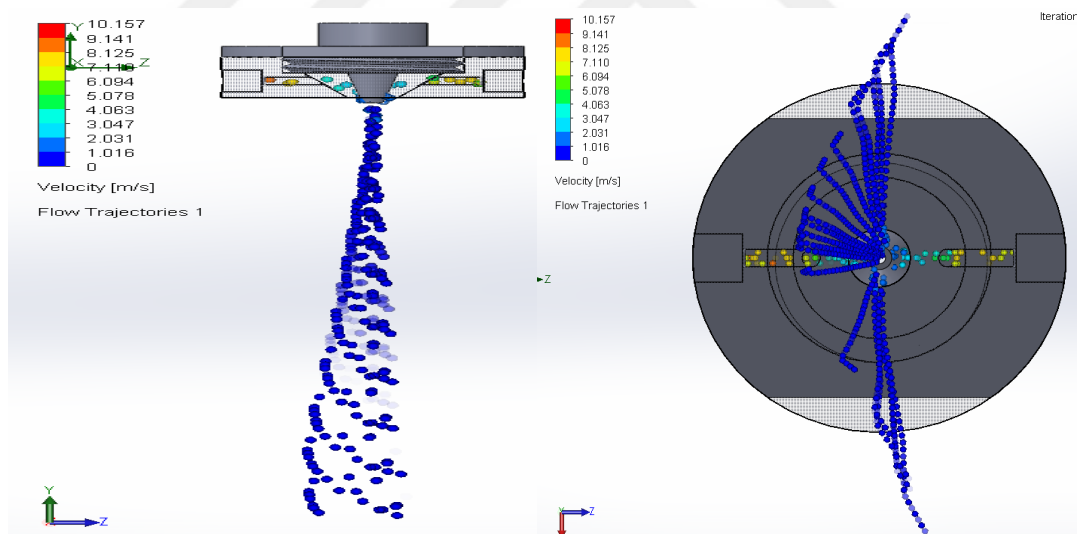


Figure 5.17 Nozzle dimensions of A(1.5 mm), B(2 mm), C(44°)

When the inlet diameter is set at 2 mm, nozzle diameter of 2 mm and inlet angle of 33°, the water flows turbulent also it is shifted shown in Figure 5.18. When inlet diameter and nozzle diameter are increased, the flow is turbulent.

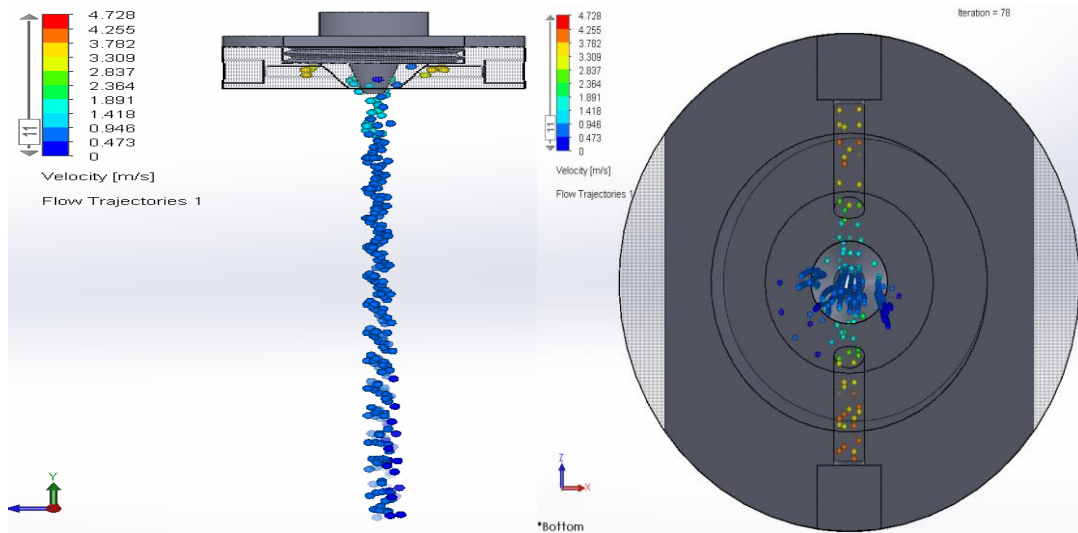


Figure 5.18 Nozzle dimensions of A(2 mm), B(2 mm), C(33°)

When the inlet diameter is set at 2.5 mm, nozzle diameter of 2 mm and inlet angle of 22°, the water flows turbulent also it is flowing intermittently shown in Figure 5.19. Also, the velocity is low.

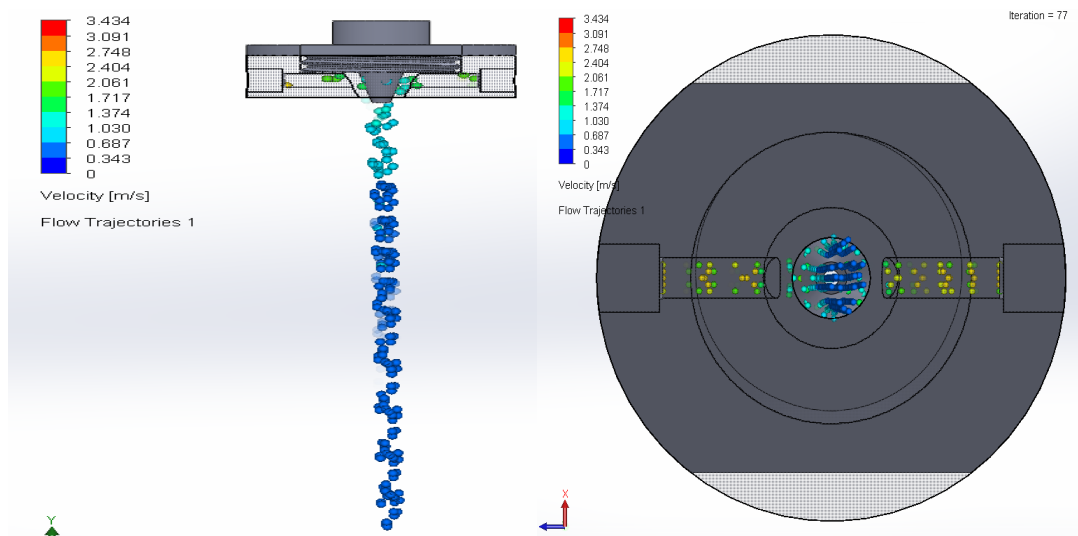


Figure 5.19 Nozzle dimensions of A(2.5 mm), B(2 mm), C(22°)

In the designs, it was also considered to create holes around the exit of the laser for the exit of water. For example, the model shown in Figure 5.20 has 8x1.2 mm holes. The

design was produced using a 3D printer and water flow was tested. As seen in the figure, it was observed that the water was distributed at the hole exit.

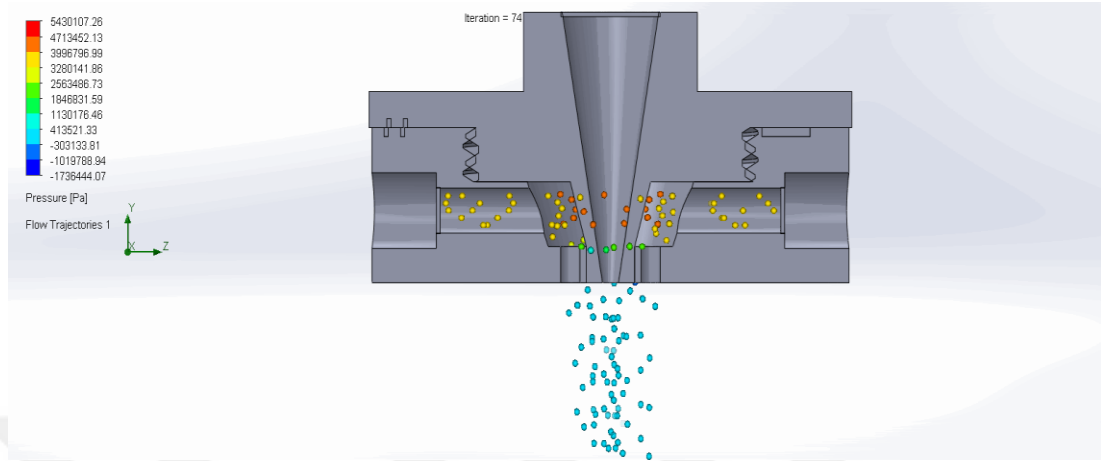


Figure 5.20 Nozzle with 8x1.2 mm holes

Finally, Figure 5.21 illustrates the desired water flow as a result of 3D models, with the inlet diameter set at 2 mm, the nozzle diameter at 1 mm, and the inlet angle at 44° . Water moves in highly laminar lines in a single stream that flows a specific distance and at a constant speed of 4 m/s. This model was manufactured and experiments were carried out.

The most important and novel part of the experimental design is the waterjet nozzle which is guide laser beams to workpiece. This uniquely designed nozzle transmits the laser beams onto the material to be cut without scattering. While modeling this nozzle, holes were designed for water and auxiliary gas inlets. The exit hole is designed to coincide with the focal point of the laser. The intersection of the nozzle exit hole with the focal point of the laser is very important for cutting and transmitting laser beams without loss. Nozzles with exit holes of different diameters are designed and tried. Finally, the nozzle with the inlet diameter set at 2 mm, the nozzle diameter at 1 mm and the inlet angle at 44° was designed to enable both conventional and waterjet guided cutting processes, with a stand-off distance of 2 mm during conventional laser and with a stand-off distance of 20 mm during waterjet guided cutting operations [87].

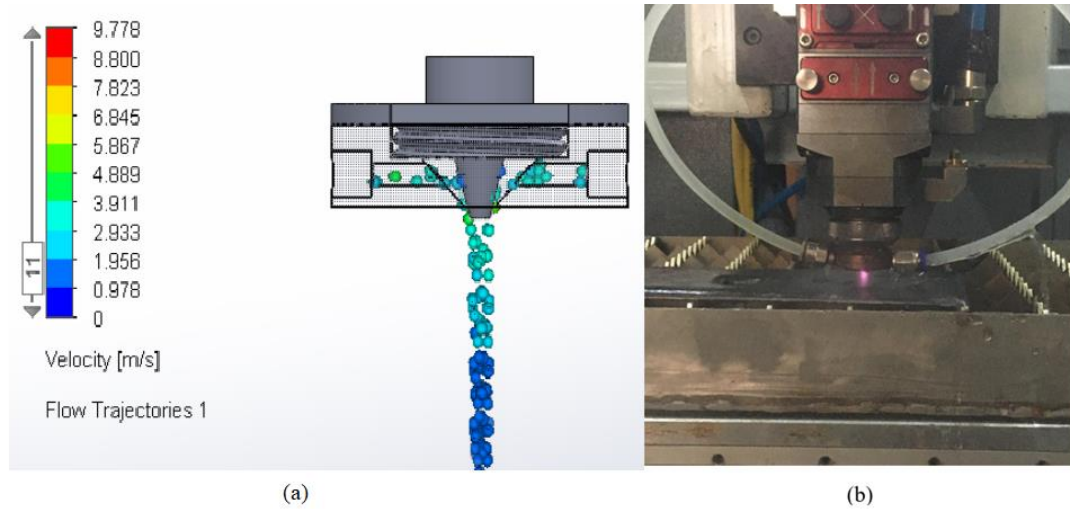


Figure 5.21 View of waterjet nozzle a) 3D model design; b) manufactured nozzle

5.3 Assembly of Experimental Setup

Combining the above-mentioned parts into a single body machine shown in Figure 5.22 and working together in harmony is one of the most critical points of this work. Primarily, various designs were made with 3D design programs. All the parts that will make up the waterjet guided laser system have been carefully assembled and made operational.

As the first step, the conventional laser cutting section was created. The cutting performance of the laser system and the precision of the cuts were examined. Correct operation of the movement unit was ensured during design and assembly. Additionally, the harmonious operation of the parts after assembly is a very important factor. The vibration of the cutting head and the precise and sensitive orientation of the movement system during laser cutting have been carefully studied to avoid problems that would reduce the cutting quality.



Figure 5.22 Assembly of waterjet guided laser system

CHAPTER 6

RESULT AND DISCUSSION

6.1 Introduction

The main goal of this study was to enhance the cut surface quality and surface roughness of materials with a conventional fiber laser and a proposed waterjet guided laser cut system. It is achieved that to eliminate and minimize the heat effect zones, microstructure deteriorations and chemical deteriorations that occur in laser cutting by using this new waterjet guided laser cutting system.

In this study, a waterjet guided laser cutting system was developed and assembled. Conventional lasers provide various advantages in manufacturing technology. Despite these advantages, the intense heat and energy released by lasers cause wear, chemical changes and damage in the microstructures of the cutting surfaces where the laser interacts with the workpiece.

Numerous tests were carried out on AISI 1020 steel sheets of varied thicknesses of 1.5 mm, 2 mm, 2.5 mm and 3 mm by controlling laser cutting parameters such as cutting speed and laser power. Surface roughness caused by various cutting parameters was used to compare the cutting surfaces produced by conventional laser and waterjet-guided laser procedures.

The effects of different parameters such as cutting speed, laser power, water pressure on the surface and processing quality were revealed with microscope images. The contributions of this study to the improvements in cutting quality have been highlighted.

6.2 Experimental Results

6.2.1 Comparison of Conventional Laser and Waterjet Guided Laser Cutting Parameters

Surface roughness values from waterjet guided laser cutting and conventional laser cutting are shown in Table 6.1. The numerals, "WGL" for waterjet guided laser cutting and "L" for conventional laser cutting, indicate how the cutting method affects surface quality.

A conventional laser was used to cut all samples under the same conditions that might have been safely sliced using the waterjet guided laser cutting approach. The samples for which the waterjet guided laser was unable to cut have their surface roughness eliminated from the table.

Table 6.1 The average surface roughness (Ra) results vary depending on the thickness of the sheet

Exp. No	Cutting Speed [mm/min]	Laser Power [W]	1.5 mm		2 mm		2.5 mm		3 mm	
			Ra (μm)		Ra (μm)		Ra (μm)		Ra (μm)	
			L	WGL	L	WGL	L	WGL	L	WGL
1	15	400	3.365	1.045	3.525	2.047				
2	15	500	4.292	1.342	3.905	2.645				
3	15	600	5.532	1.707	5.245	2.665	3.685	1.752		
4	15	700	2.951	1.773	5.575	2.962	3.791	1.965	4.161	2.160
5	15	800	3.552	1.342	3.855	2.284	3.767	2.172	4.082	2.157
6	15	900	3.927	1.912	4.337	3.694	5.421	2.152	4.651	2.705
7	15	1000	3.432	2.035	3.482	2.205	3.855	2.835	4.480	3.467
8	20	400	3.573	1.007	4.365	1.392				
9	20	500	3.542	1.252	4.907	2.062				
10	20	600	5.025	1.647	4.502	2.105	3.867	1.210		
11	20	700	5.195	1.165	4.165	2.414	4.205	1.930	6.107	2.082

12	20	800	5.337	2.054	6.035	3.212	4.857	2.137	5.362	2.187
13	20	900	3.545	1.685	4.957	3.572	4.347	2.981	4.627	2.685
14	20	1000	4.213	1.992	4.777	2.614	4.912	2.281	4.085	3.391
15	25	400	3.932	0.937						
16	25	500	2.785	1.225	4.965	1.192				
17	25	600	2.702	1.265	5.197	0.965	3.732	1.377		
18	25	700	3.312	1.517	4.832	0.911	3.705	2.202		
19	25	800	2.922	1.802	4.325	0.665	3.844	2.802	3.130	2.072
20	25	900	4.558	1.525	3.654	0.835	2.917	1.875	3.072	2.692
21	25	1000	5.515	1.972	5.757	1.647	3.052	2.945	3.591	3.297
22	30	400								
23	30	500	3.187	1.017						
24	30	600	3.335	1.095	1.735	0.630	3.935	2.472		
25	30	700	3.054	2.002	1.965	1.227	3.645	2.150		
26	30	800	3.457	2.057	2.872	0.965	3.515	3.112	4.122	1.990
27	30	900	3.612	2.092	2.332	1.037	4.297	2.610	4.502	2.602
28	30	1000	3.182	1.817	3.127	0.812	3.642	2.422	3.460	3.242

In the experimental design, 28 cutting experiments with conventional laser and waterjet guided laser were carried out to make these comparisons. Cutting speeds of 15 mm/min, 20 mm/min, 25 mm/min and 30 mm/min, respectively were used to cut 1.5 mm, 2 mm, 2.5 mm and 3 mm thicknesses of AISI 1020 steel sheets in the experiments.

The other controlled cutting factor was laser power. Cutting operations were carried out by two methods, respectively, by setting the laser power as 400 W, 500W, 600W, 700W, 800W, 900W and finally 1000 W.

6.2.1.1 Effect of Cutting Speed on Cutting and Surface Roughness

In order to compare effect of cutting speed on cutting and surface roughness for different thicknesses, laser power was kept constant during performing cutting operations. Thus, the effect of changing laser cutting speeds on cutting and surface roughness was examined.

Table 6.2 Effect of cutting speed on surface roughness at 400 W laser power

			1.5 mm		2 mm		2.5 mm		3 mm	
			Ra (μm)		Ra (μm)		Ra (μm)		Ra (μm)	
Exp. No	Cutting Speed	Laser Power	L	WGL	L	WGL	L	WGL	L	WGL
	[mm/min]	[W]								
1	15	400	3.365	1.045	3.525	2.047				
8	20	400	3.573	1.007	4.365	1.392				
15	25	400	3.932	0.937						
22	30	400								

During cutting operations at 400 W constant laser power as seen in Table 6.2, when the cutting speed increases from 15 mm/min to 30 mm/min, there is an increase in surface roughness of steel sheets thicknesses of 1.5 mm and 2 mm for conventional laser. However, when checking at waterjet guided laser cutting under the same conditions, the surface roughness is generally smaller than that made with conventional laser.

It can be commented that the surface roughness increases when the material thickness increases. Additionally, it can be seen in the table that the surface roughness increases when the material thickness increases. The increase in material thickness has become a limiting factor for cutting operations at 400 W in both cutting methods as seen in Figure 6.1.

When the surface roughness of the cuts was assessed, it was seen that water jet guided laser performed better than normal laser cutting. At 25 mm/min, the waterjet guided laser offers substantial improvement, particularly for 1.5 mm thickness, where

roughness decreases from 3.932 μm to 0.937 μm . the max surface improvement is seen at this condition.

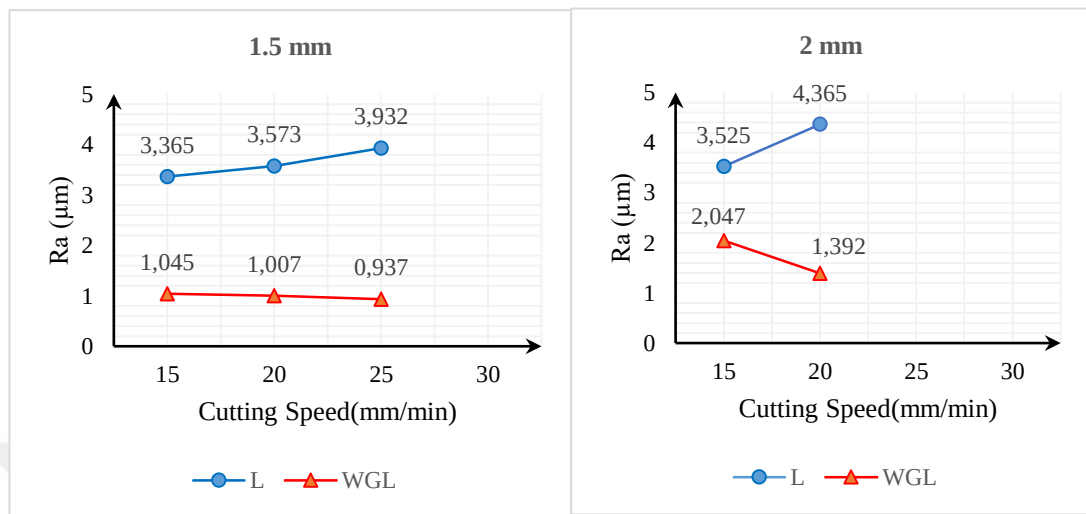


Figure 6.1 Change of surface roughness at 400 W laser power

The smallest surface roughness value of 0.937 μm was obtained in waterjet guided laser cutting at a speed of 25 mm/min on a 1.5 mm thick steel sheet. The highest surface roughness, with a value of 4.365 μm , was observed in 2 mm thick steel sheet in traditional laser cutting. The cutting operations were failed at thickness of 2.5 mm and 3mm.

Table 6.3 Effect of cutting speed on surface roughness at 500 W laser power

			1.5 mm		2 mm		2.5 mm		3 mm	
			Ra (μm)		Ra (μm)		Ra (μm)		Ra (μm)	
Exp. No	Cutting Speed	Laser Power	L	WGL	L	WGL	L	WGL	L	WGL
	[mm/min]	[W]								
2	15	500	4.292	1.342	3.905	2.645				
9	20	500	3.542	1.252	4.907	2.062				
16	25	500	2.785	1.225	4.965	1.192				
23	30	500	3.187	1.017						

The surface roughness of steel sheets obtained from the experiments in which the laser power was kept constant at 500 W and the cutting speed was changed are presented in Table 6.3.

The surface roughness of 1.5 mm and 2 mm thick steel sheets was examined when the cutting speed was increased. It is seen that the surface roughness generally decreases in waterjet guided laser cutting methods as shown in Figure 6.2. However, conventional laser cutting roughness's are different and there is no linear change for surface roughness.

Increased material thickness and cutting speed have been limiting factors for both cutting processes. In experiments where the cutting speed was 30 mm/min and the plate thickness was greater than 2 mm, cutting could not be done and no data could be obtained.

As in the previous 400 W experiments, it was observed that the surface roughness increased when the sheet thickness increased. In both cutting methods, it was observed that increasing the material thickness had a negative effect on the surface roughness.

Besides, when the cutting results at 400 W and 500 W are compared, it is thought that increasing laser power causes an increase in surface roughness in laser and waterjet guided laser cutting.

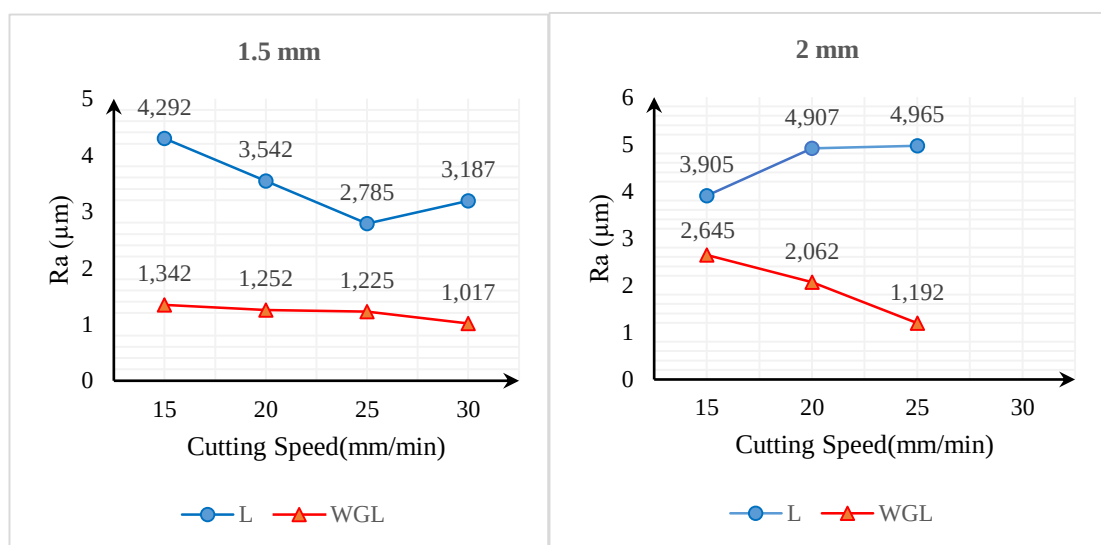


Figure 6.2 Change of surface roughness at 500 W laser power

In experiments with 1.5 mm thickness, when the cutting speed increased, the surface roughness generally decreased in both cutting methods. The smallest roughness value 1.017 μm was obtained from waterjet guided laser cutting for 1.5 mm thick steel sheets. In experiments with 2 mm thickness, the roughness in waterjet guided laser cutting decreased with increasing speed. However, it has been observed that surface roughness increases in conventional laser cutting. The highest surface roughness of 4.965 μm value was acquired from 2 mm thick steel sheets.

At 25 mm/min, the waterjet guided laser offers substantial improvement, particularly for 2 mm thickness, where roughness decreases from 4.965 μm to 1.192 μm . The cutting operations were failed at thickness of 2.5 mm and 3mm.

Table 6.4 Effect of cutting speed on surface roughness at 600 W laser power

			1.5 mm		2 mm		2.5 mm		3 mm	
			Ra (μm)		Ra (μm)		Ra (μm)		Ra (μm)	
Exp. No	Cutting Speed [mm/min]	Laser Power [W]								
			L	WGL	L	WGL	L	WGL	L	WGL
3	15	600	5.532	1.707	5.245	2.665	3.685	1.752		
10	20	600	5.025	1.647	4.502	2.105	3.867	1.210		
17	25	600	2.702	1.265	5.197	0.965	3.732	1.377		
24	30	600	3.335	1.095	1.735	0.630	3.935	2.472		

Table 6.4 shows the surface roughness of steel sheets derived from studies in which the laser power was held constant at 600 W while the cutting speed was adjusted.

In experiments where 1.5 mm thick steel sheets were cut by both methods, surface roughness generally decreased when the cutting speed was increased.

In experiments where 2 mm thick steel sheets were cut by both methods, surface roughness generally decreased when the cutting speed was increased. However, the data in conventional laser cutting appear an increment deviation to 5.197 μm at speed of 25 mm/min as seen in Figure 6.3.

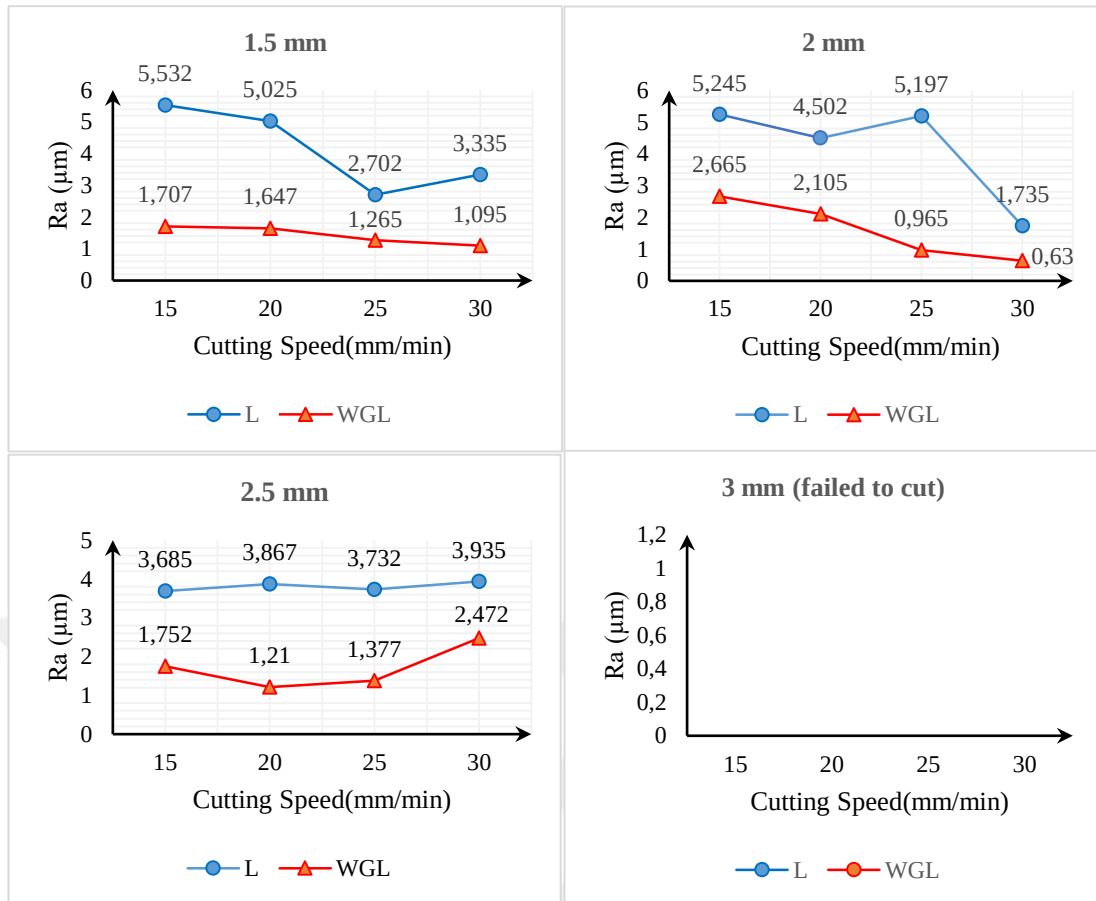


Figure 6.3 Change of surface roughness at 600 W laser power

In cutting operations on 2.5 mm thick steel sheets, there is no linear increase or decrease in surface roughness in the cuts made with both of two methods. However, waterjet guided laser cutting has better surface roughness than conventional laser cutting.

Cutting of 3 mm thick steel sheets could not be done using two methods. Thickness still remains the limiting factor.

When the surface roughness of the cuts made at 500 W and 600 W power is compared, the surface roughness of the cuts at 1.5 mm and 2 mm made at 600 W is generally higher than cuts at 500 W.

In the experiments, the lowest surface roughness was measured as 0.630 μm when cutting with a waterjet guided laser at a speed of 30 mm/min. The highest surface

roughness was measured as 5.532 μm when cutting with conventional laser at a speed of 15 mm/min.

The data shows that waterjet guided laser cutting dramatically improves surface roughness compared to conventional fiber laser cutting, especially for thinner materials and at higher cutting speeds.

At 25 mm/min, the waterjet guided laser offers substantial improvement, particularly for 2 mm thickness, where roughness decreases from 5.197 μm to 0.965 μm .

Table 6.5 Effect of cutting speed on surface roughness at 700 W laser power

Exp. No	Cutting Speed [mm/min]	Laser Power [W]	1.5 mm		2 mm		2.5 mm		3 mm	
			Ra (μm)		Ra (μm)		Ra (μm)		Ra (μm)	
			L	WGL	L	WGL	L	WGL	L	WGL
4	15	700	2.951	1.773	5.575	2.962	3.791	1.965	4.161	2.160
11	20	700	5.195	1.165	4.165	2.414	4.205	1.930	6.107	2.082
18	25	700	3.312	1.517	4.832	0.911	3.705	2.202		
25	30	700	3.054	2.002	1.965	1.227	3.645	2.150		

Table 6.5 shows experimental data comparing surface roughness for sheet thicknesses of 1.5 mm, 2 mm, 2.5 mm, and 3 mm when cut with the conventional laser and the waterjet guided laser at 700 W power.

Conventional laser and waterjet guided laser surface roughness was examined when the cutting speed increased while cutting 1.5 mm and 3 mm thick steel sheets. While the speed increases in both cutting methods, there is no linear decrease. However, surface roughness resulting from waterjet guided laser cutting gives better results than conventional laser.

When the surface roughness of 2 mm thick steel sheets is examined, an improvement in surface quality generally occurs when the cutting speed increases up to 25 mm/min at waterjet guided laser.

Additionally, the waterjet guided laser processing from velocity of 15mm/min to 30 mm/min significantly reduces surface roughness for all thicknesses compared to the conventional laser during experiments 4, 11, 18 and 25.

Thicker materials, such as 3 mm, also cut from both methods, although the data is limited for the highest speed settings.

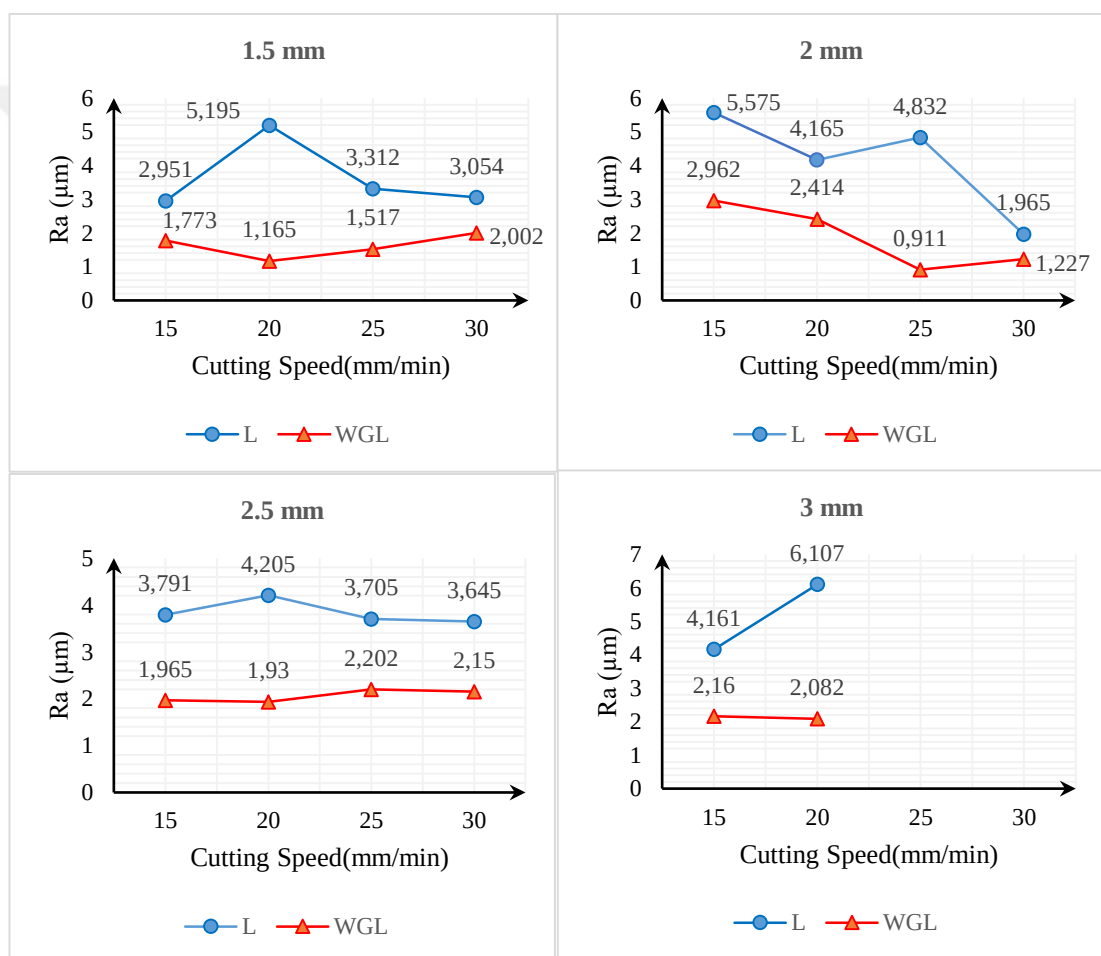


Figure 6.4 Change of surface roughness at 700 W laser power

The lowest surface roughness value of 0.911 μm was obtained from waterjet guided laser cutting of 2 mm thick steel sheet, while the highest value of 6.107 μm was

obtained from conventional laser cutting of 3 mm thick steel sheet. High thickness such as 3mm is very limited for cutting and surface roughness.

Table 6.6 Effect of cutting speed on surface roughness at 800 W laser power

Exp. No	Cutting Speed [mm/min]	Laser Power [W]	1.5 mm		2 mm		2.5 mm		3 mm	
			Ra (μm)		Ra (μm)		Ra (μm)		Ra (μm)	
			L	WGL	L	WGL	L	WGL	L	WGL
5	15	800	3.552	1.342	3.855	2.284	3.767	2.172	4.082	2.157
12	20	800	5.337	2.054	6.035	3.212	4.857	2.137	5.362	2.187
19	25	800	2.922	1.802	4.325	0.665	3.844	2.802	3.130	2.072
26	30	800	3.457	2.057	2.872	0.965	3.515	3.112	4.122	1.990

Effect of cutting speed from 15 mm/min to 30 mm/min on surface roughness at 800 W laser power was shown in Table 6.6.

At 15 mm/min, the waterjet guided laser technique dramatically improves surface roughness across all thicknesses compared to conventional laser. Roughness is decreased by 1.5 mm to 1.342 μm, 2 mm to 2.284 μm, 2.5 mm to 2.172 μm, and 3 mm to 2.157 μm as shown in Figure 6.5.

At 20 mm/min, the waterjet guided laser cutting significantly reduces roughness for 1.5 mm (5.337 μm to 2.054 μm), 2 mm (6.035 μm to 3.212 μm), 2.5 mm (4.857 μm to 2.137 μm), and 3 mm (5.362 μm to 2.187 μm).

At 30 mm/min, the waterjet guided laser cutting improves performance by lowering roughness from 1.5 mm to 2.057 μm, 2 mm to 0.965 μm, 2.5 mm to 3.112 μm, and 3 mm to 1.990 μm.

At 25 mm/min, the waterjet guided laser offers substantial improvement, particularly for 2 mm thickness, where roughness decreases from 4.325 μm to 0.665 μm. The best surface improvement was observed at this condition.

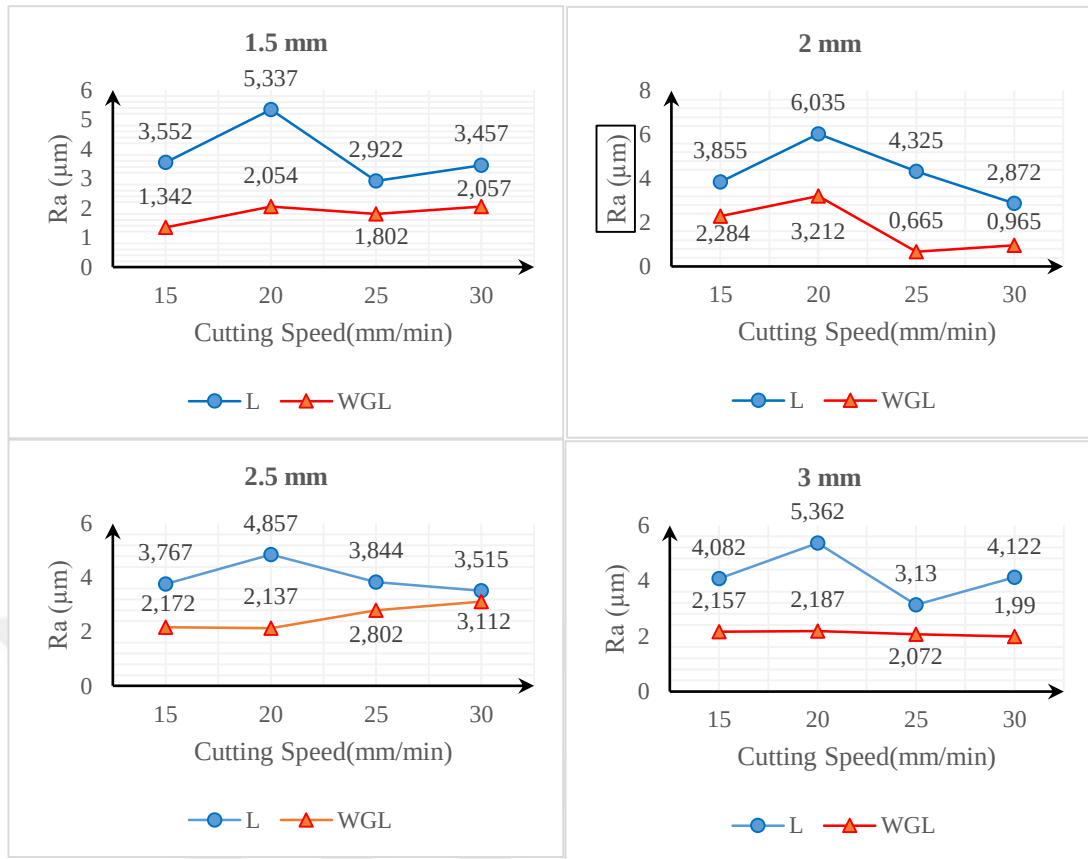


Figure 6.5 Change of surface roughness at 800 W laser power

With the power reaching to 800 W, 3 mm thick pieces were cut in both cutting methods. This shows that increasing laser power enables the cutting of thick metal sheets.

Table 6.7 Effect of cutting speed on surface roughness at 900 W laser power

Exp. No	Cutting Speed [mm/min]	Laser Power [W]	1.5 mm		2 mm		2.5 mm		3 mm	
			Ra (μm)		Ra (μm)		Ra (μm)		Ra (μm)	
			L	WGL	L	WGL	L	WGL	L	WGL
6	15	900	3.927	1.912	4.337	3.694	5.421	2.152	4.651	2.705
13	20	900	3.545	1.685	4.957	3.572	4.347	2.981	4.627	2.685
20	25	900	4.558	1.525	3.654	0.835	2.917	1.875	3.072	2.692
27	30	900	3.612	2.092	2.332	1.037	4.297	2.610	4.502	2.602

Table 6.7 displays experimental data comparing the surface roughness across sheet thicknesses of 1.5 mm, 2 mm, 2.5 mm, and 3 mm for cuts made using a conventional laser and a waterjet guided laser at a power level of 900 W.

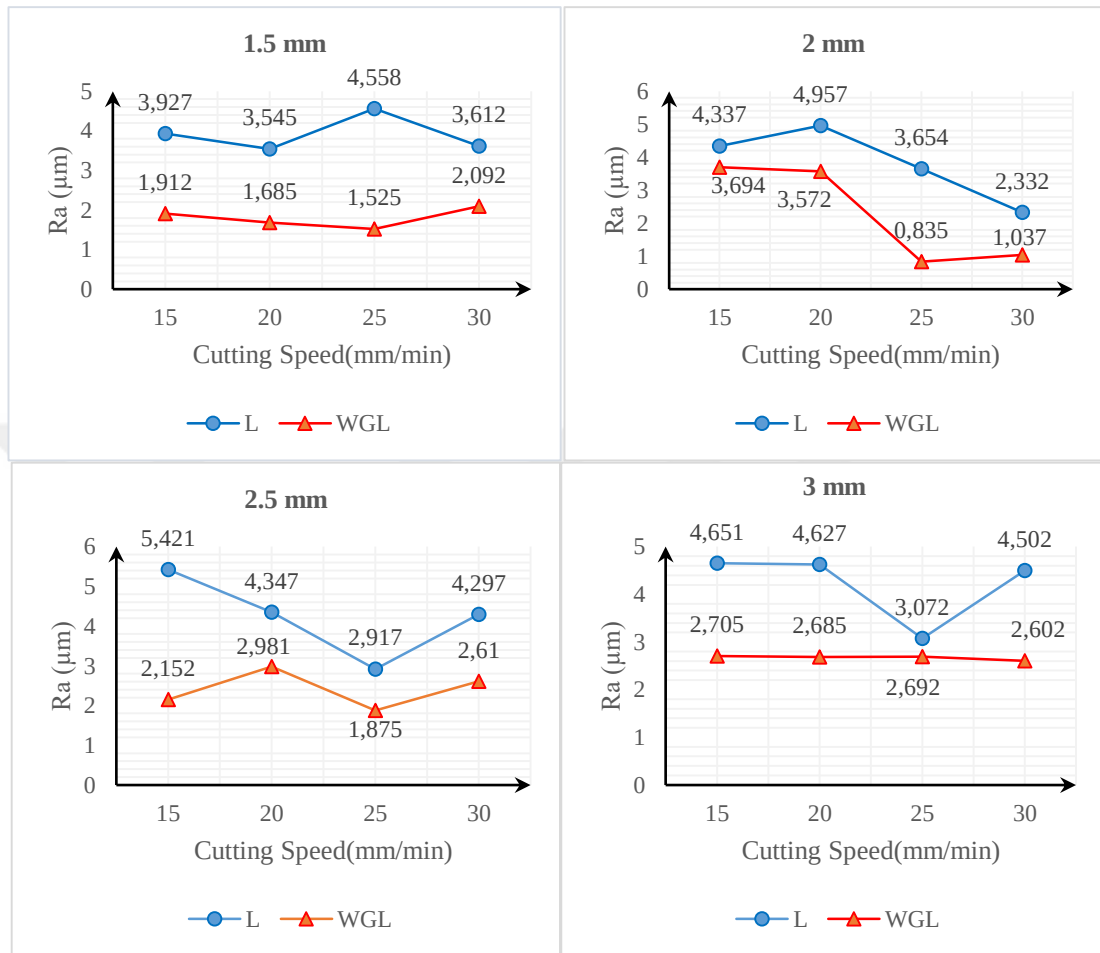


Figure 6.6 Change of surface roughness at 900 W laser power

In 1.5 mm thick cuts, surface roughness decreases in the two cutting methods when the speed is 15 mm/min and 20 mm/min.

The waterjet guided laser method at 15 mm/min, significantly improves surface roughness for all thicknesses compared to conventional laser.

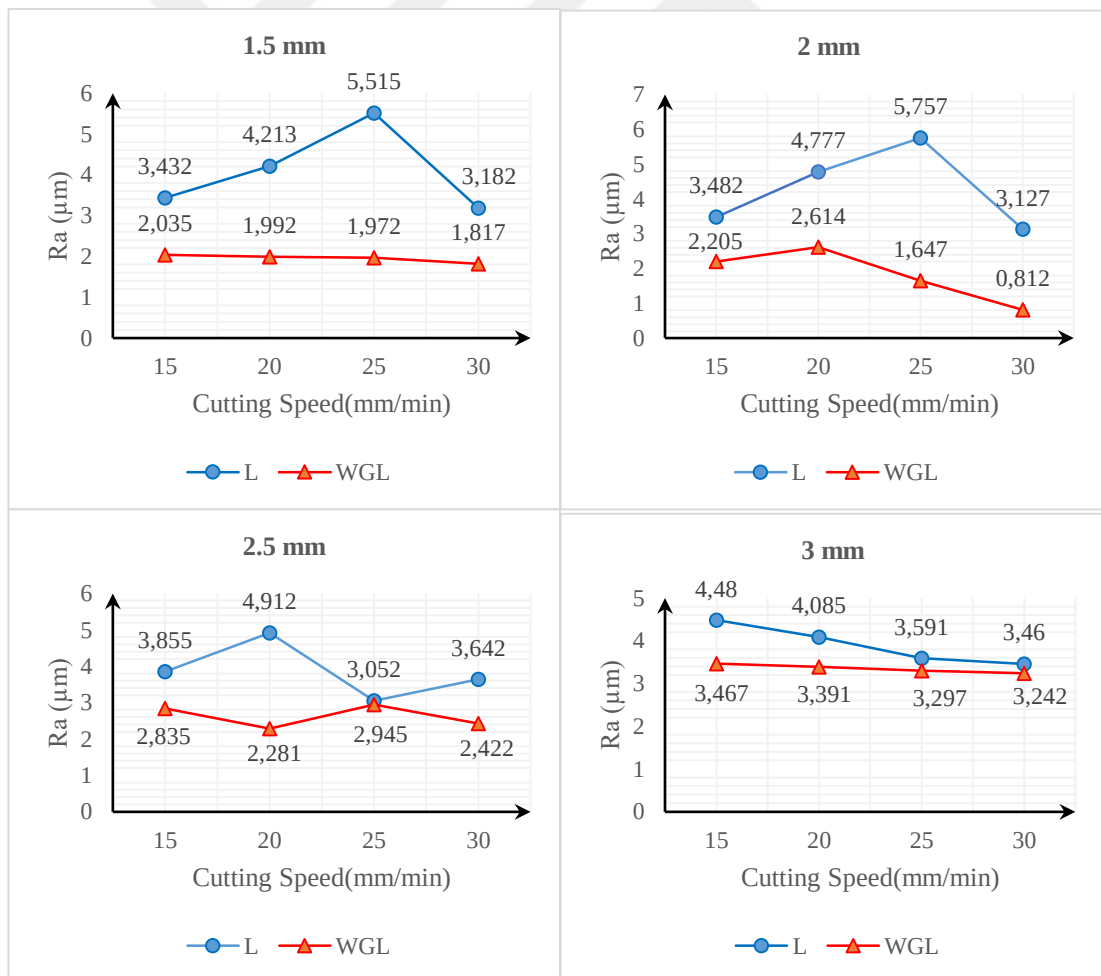
The 1.5 mm, 2 mm and 2.5 mm thicknesses show the most significant improvement with the waterjet guided laser method across different cutting speeds, particularly at 25 mm/min as seen in Figure 6.6.

The waterjet guided laser provides significant improvement at 25 mm/min, the best for 2 mm thickness where roughness drops from 3.654 μm to 0.835 μm .

Table 6.8 Effect of cutting speed on surface roughness at 1000 W laser power

Exp. No	Cutting Speed [mm/min]	Laser Power [W]	1.5 mm		2 mm		2.5 mm		3 mm	
			Ra (μm)		Ra (μm)		Ra (μm)		Ra (μm)	
			L	WGL	L	WGL	L	WGL	L	WGL
7	15	1000	3.432	2.035	3.482	2.205	3.855	2.835	4.480	3.467
14	20	1000	4.213	1.992	4.777	2.614	4.912	2.281	4.085	3.391
21	25	1000	5.515	1.972	5.757	1.647	3.052	2.945	3.591	3.297
28	30	1000	3.182	1.817	3.127	0.812	3.642	2.422	3.460	3.242

Table 6.8 displays the surface roughness of steel sheets obtained from experiments in which the laser power was kept constant at 1000 W while the cutting speed was varied.

**Figure 6.7** Change of surface roughness at 1000 W laser power

The waterjet guided laser significantly at 25 mm/min reduces roughness from 5.757 μm to 1.647 μm for 2 mm thickness. It was seen that cutting 2 mm thick sheet at a speed of 25 mm/min provided the best proportional improvement compared to conventional laser cutting on the cutting surface roughness.

Besides, the waterjet guided laser cut at 30 mm/min and 1000 W continues to perform better surface quality, reducing roughness for 1.5 mm from 3.182 μm to 1.817 μm , for 2 mm from 3.127 μm to 0.812 μm .

At thickness of 1.5 mm, 2.5 mm and 3 mm as seen in Figure 6.7, when cutting speeds are increased to 25 mm/min and 30 mm/min, it is observed an enhancement on surface roughness's for both methods.

It has been observed in both methods that the thickness of the steel sheets and the laser power are important factors on the cutting and surface quality of the parts. After a critical value of higher laser power and speed are generally provided better surface quality at the waterjet guided laser cuttings.

Ultimately, the waterjet guided laser approach surpasses the conventional fiber laser in terms of surface smoothness across all thicknesses and cutting speeds evaluated, demonstrating its ability to produce smoother cuts.

6.2.1.2 Effect of Laser Power on Cutting and Surface Roughness

The cutting speed was kept constant throughout the cutting operations in order to compare the impact of laser power on surface roughness and cutting for varying thicknesses. As a result, the impact of varying laser power on surface roughness and cutting processes was investigated.

The surface roughness results of the experiments carried out at varying laser powers at a constant speed of 15 mm/min are shown in Table 6.9.

Table 6.9 Effect of laser power on the surface roughness at speed of 15 mm/min

			1.5 mm		2 mm		2.5 mm		3 mm	
			Ra (μm)		Ra (μm)		Ra (μm)		Ra (μm)	
Exp. No	Cutting Speed	Laser Power								
	[mm/min]	[W]	L	WGL	L	WGL	L	WGL	L	WGL
1	15	400	3.365	1.045	3.525	2.047				
2	15	500	4.292	1.342	3.905	2.645				
3	15	600	5.532	1.707	5.245	2.665	3.685	1.752		
4	15	700	2.951	1.773	5.575	2.962	3.791	1.965		
5	15	800	3.552	1.342	3.855	2.284	3.767	2.172	4.082	2.157
6	15	900	3.927	1.912	4.337	3.694	5.421	2.152	4.651	2.705
7	15	1000	3.432	2.035	3.482	2.205	3.855	2.835	4.480	3.467

The surface roughness improvement values of cuts made on 1.5 mm thick steel sheets generally decrease as the power is increased.

The significant improvements are shown using the waterjet guided laser method performed at 600 W for 1.5 mm, going from 5.532 μm to 1.707 μm , 2 mm, going from 5.245 μm to 2.665 μm , and 2.5 mm, going from 3.685 μm to 1.752 μm as shown in Figure 6.8.

The best surface roughness for 1.5 mm is reduced from 5.532 μm to 1.707 μm using the waterjet guided laser at 600 W.

When laser power is increased from 500 W to 900 W, the improvement of surface roughness of cuts performed on steel sheets with a thickness of 2 mm typically decline.

The waterjet guided laser process significantly improves the 1.5 mm and 2 mm thicknesses at various laser power settings.

When the cutting power is increased, the surface roughness of cuts performed on steel sheets that are 3 mm and 3.5 mm thick get closer to each other compared conventional laser and waterjet guided laser.

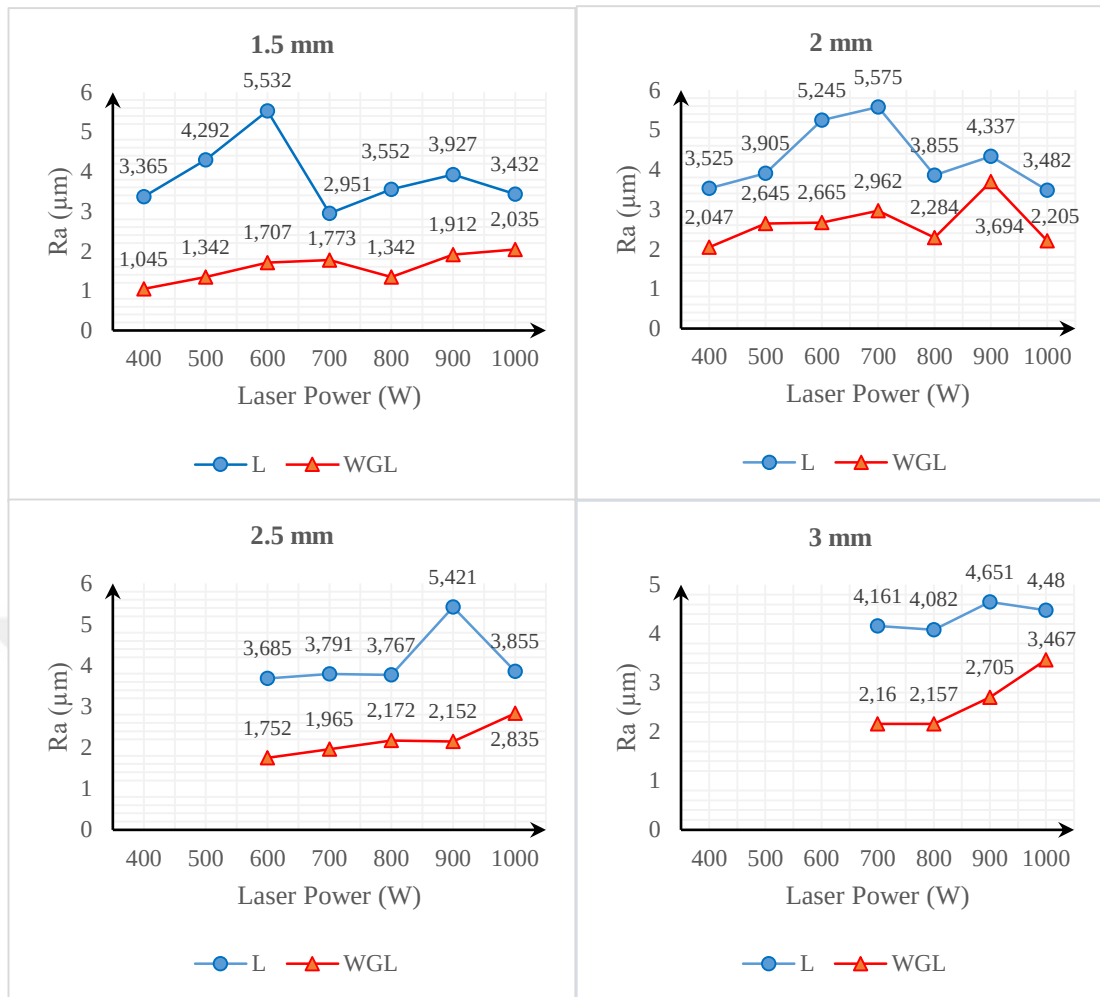


Figure 6.8 Change of surface roughness at speed of 15 mm/min

Besides, the waterjet guided laser improves surface roughness of thicker materials of 2.5 mm and 3 mm, with demonstrable improvements found at all tested power levels.

Table 6.10 Effect of laser power on the surface roughness at speed of 20 mm/min

Exp. No	Cutting Speed [mm/min]	Laser Power [W]	1.5 mm		2 mm		2.5 mm		3 mm	
			Ra (μm)		Ra (μm)		Ra (μm)		Ra (μm)	
			L	WGL	L	WGL	L	WGL	L	WGL
8	20	400	3.573	1.007	4.365	1.392				
9	20	500	3.542	1.252	4.907	2.062				

10	20	600	5.025	1.647	4.502	2.105	3.867	1.210	
11	20	700	5.195	1.165	4.165	2.414	4.205	1.930	6.107 2.082
12	20	800	5.337	2.054	6.035	3.212	4.857	2.137	5.362 2.187
13	20	900	3.545	1.685	4.957	3.572	4.347	2.981	4.627 2.685
14	20	1000	4.213	1.992	4.777	2.614	4.912	2.281	4.085 3.391

Table 6.10 demonstrates effect of laser power at constant 20 mm/min velocity on surface roughness of two methods.

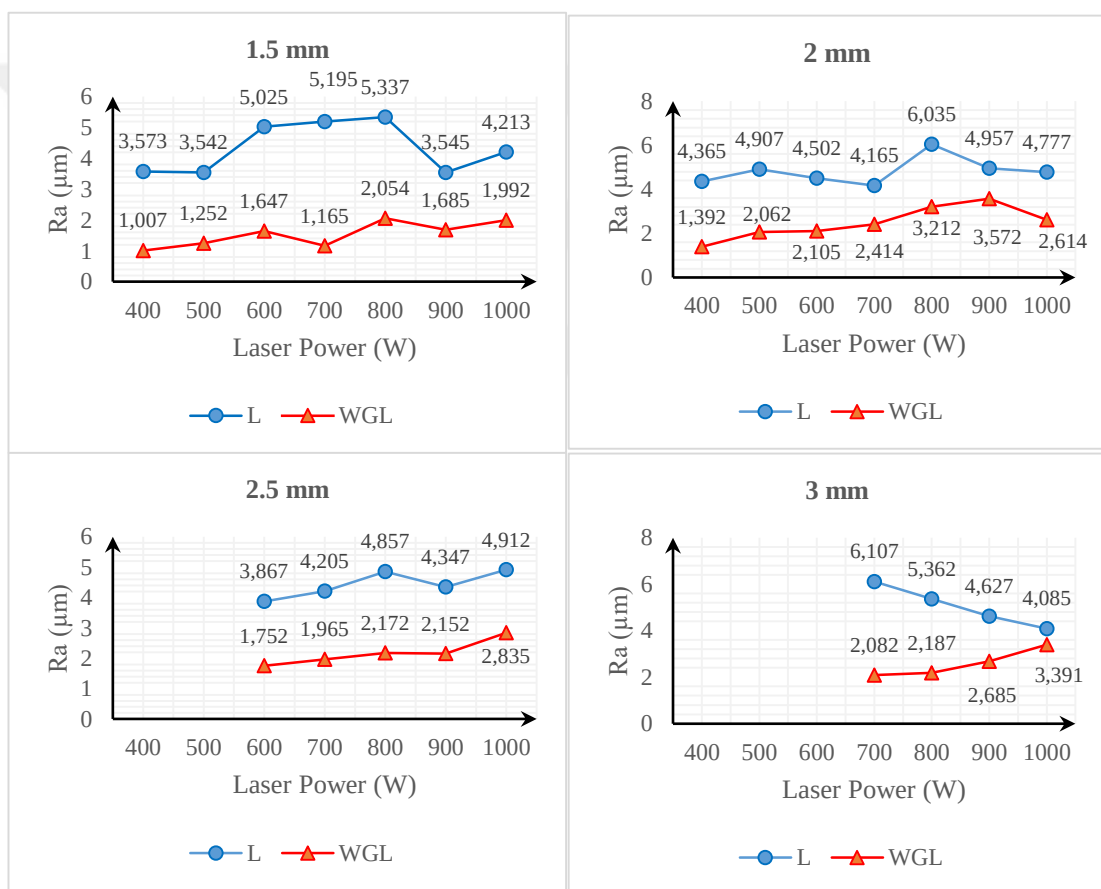


Figure 6.9 Change of surface roughness at speed of 20 mm/min

When power is increased, the surface roughness of waterjet guided laser shows an initial increase as well but remains relatively always lower than conventional laser. The waterjet guided laser process at 700 W significantly reduces surface roughness for 1.5 mm from 5.195 μm to 1.165 μm as seen in Figure 6.9.

The surface roughness of conventional laser shows an increment significantly for lower thicknesses of 1.5 mm and 2 mm up to 800 W. The effect of laser power on surface roughness is significant, with a general trend of increasing roughness with higher power levels, peaking at around 800 W to 900 W for most thicknesses. The surface roughness of waterjet guided laser is generally lower than that measured conventional laser roughness, indicating the dependency on the measurements.

The data obtained from the experiments clearly demonstrates that waterjet guided laser cutting significantly improves surface roughness compared to conventional laser cutting across various laser power levels and material thicknesses.

Variations in roughness values suggest that there is an optimal laser power range for achieving desired surface finishes, which is critical for different material thicknesses. These observations can help in optimizing laser cutting processes to achieve the best possible surface quality by selecting appropriate laser power settings for different material thicknesses.

Table 6.11 Effect of laser power on the surface roughness at speed of 25 mm/min

			1.5 mm		2 mm		2.5 mm		3 mm	
			Ra (μm)		Ra (μm)		Ra (μm)		Ra (μm)	
Exp. No	Cutting Speed [mm/min]	Laser Power [W]	L	WGL	L	WGL	L	WGL	L	WGL
15	25	400	3.932	0.937						
16	25	500	2.785	1.225						
17	25	600	2.702	1.265						
18	25	700	3.312	1.517						
19	25	800	2.922	1.802	4.325	0.665	3.844	2.802	3.130	2.072
20	25	900	4.558	1.525	3.654	0.835	2.917	1.875	3.072	2.692
21	25	1000	5.515	1.972	5.757	1.647	3.052	2.945	3.591	3.297

The experimental results in the Table 6.11 indicate that increasing the laser power generally reduces the surface roughness in waterjet guided laser method with some exceptions at conventional cutting speeds and depths:

At the cutting speed of 25 mm/min, increasing laser power from 400 W to 1000 W results in lower surface roughness across various thicknesses from 1.5 mm to 3 mm than conventional laser.

However, at the highest laser power of 1000 W, the surface roughness increased again, especially for the 1.5 mm and 2.5 mm thicknesses.

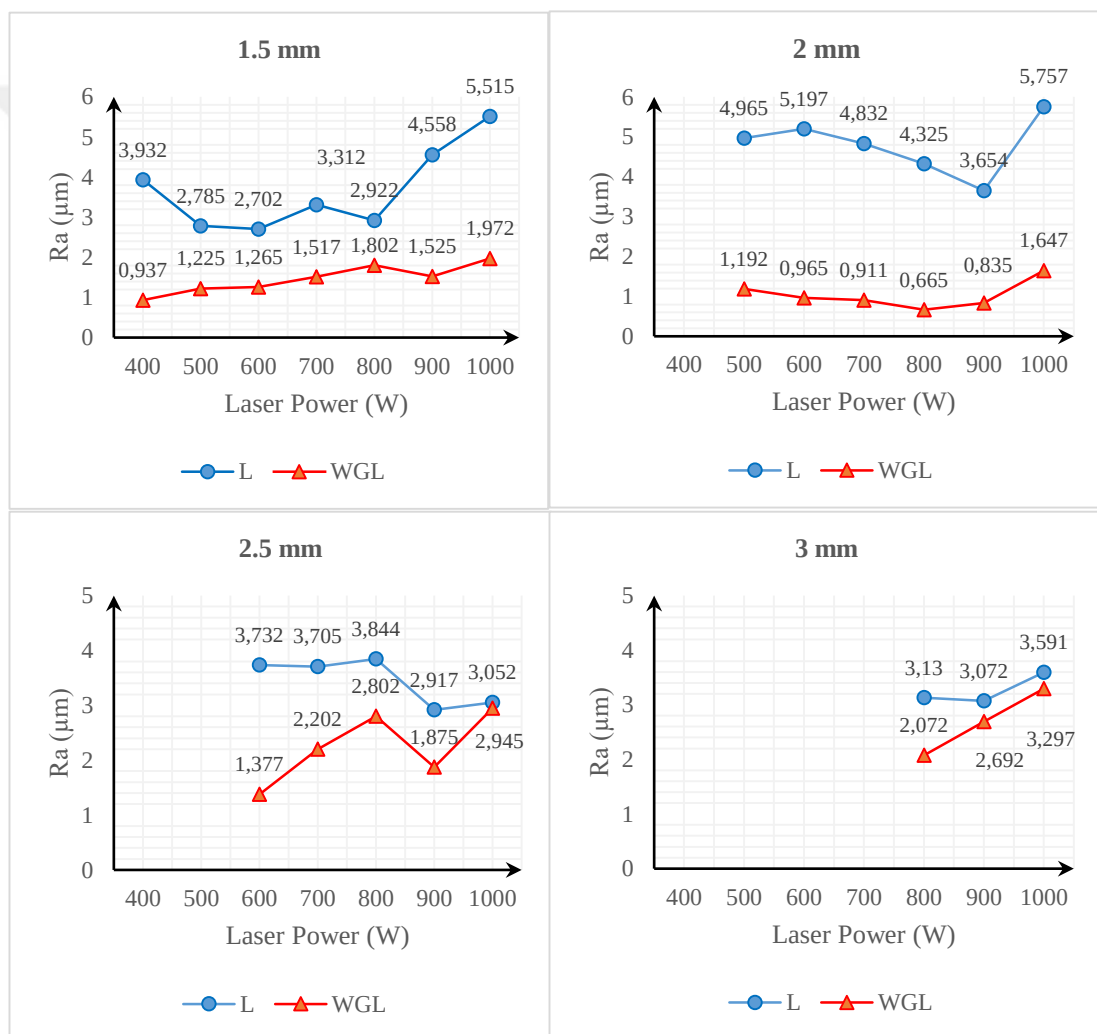


Figure 6.10 Change of surface roughness at speed of 25 mm/min

The effect of laser power on surface roughness is more complex. At lower laser powers of 400 and 500 W, it is thought that increasing the cutting speed can increase the

surface roughness due to increased tool vibration. But at higher laser powers of 500 W and above, it is thought that increasing the cutting speed can improve the surface quality by softening the machining area and reducing cutting forces.

The lowest surface roughness values were achieved at the higher laser powers of 700-900 W, with Ra values around 0.6-1.6 μm as seen in Figure 6.10. When conventional laser and waterjet guided laser cutting surface roughness's were compared, the best surface roughness improvement was observed in 2 mm thick samples at 800 W laser power.

The interaction between laser power and depth of cut is also important. Increasing the depth of cut tends to increase the surface roughness, but this effect can be mitigated by using an optimal laser power.

Table 6.12 Effect of laser power on the surface roughness at speed of 30 mm/min

Exp. No	Cutting Speed [mm/min]	Laser Power [W]	1.5 mm		2 mm		2.5 mm		3 mm	
			Ra (μm)		Ra (μm)		Ra (μm)		Ra (μm)	
			L	WGL	L	WGL	L	WGL	L	WGL
22	30	400								
23	30	500	3.187	1.017						
24	30	600	3.335	1.095	1.735	0.630	3.935	2.472		
25	30	700	3.054	2.002	1.965	1.227	3.645	2.150		
26	30	800	3.457	2.057	2.872	0.965	3.515	3.112	4.122	1.990
27	30	900	3.612	2.092	2.332	1.037	4.297	2.610	4.502	2.602
28	30	1000	3.182	1.817	3.127	0.812	3.642	2.422	3.460	3.242

Table 6.12 shows surface roughness values of the conventional and waterjet guided laser at constant 30 mm/min and increasing laser powers.

The roughness values at higher laser powers 900 W and 1000 W tend to be higher compared to lower laser powers 500 W and 600 W.

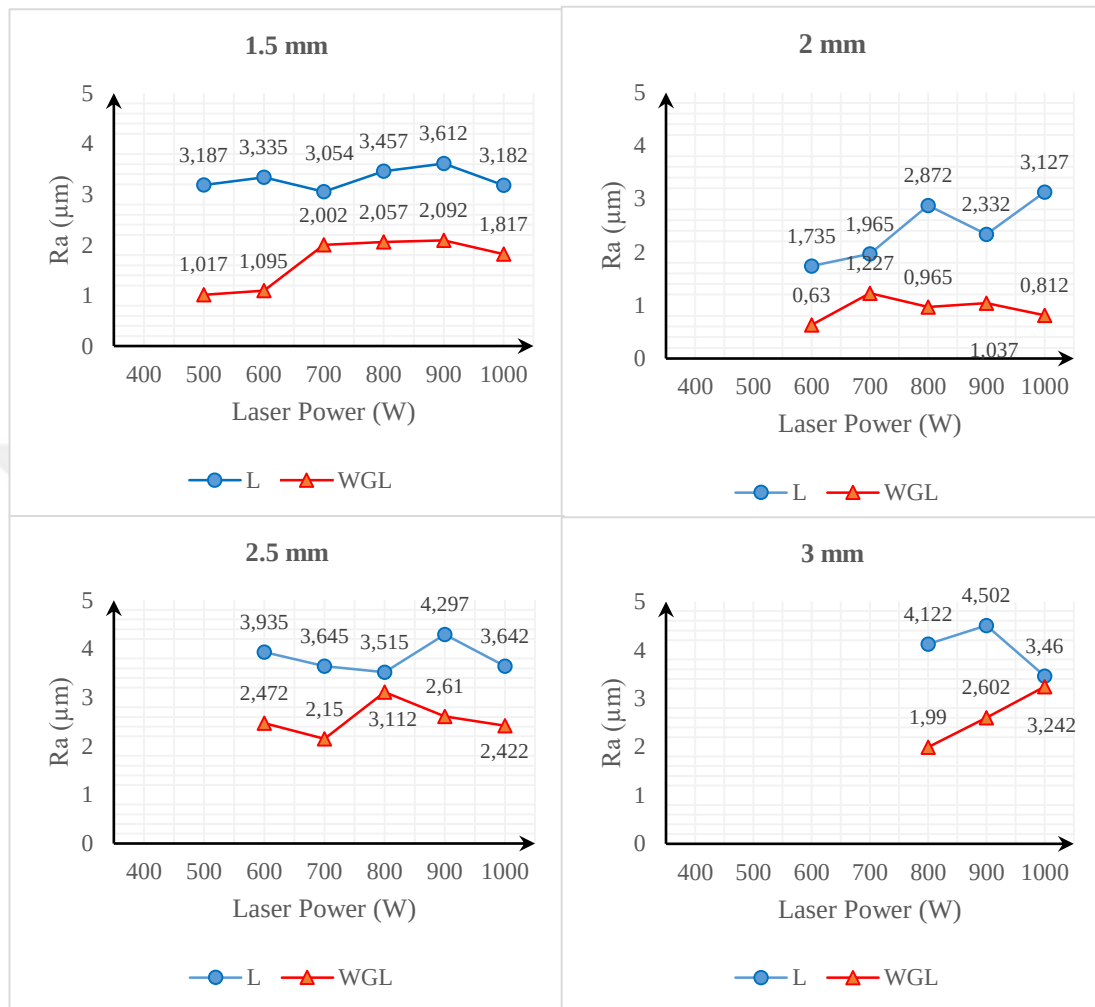


Figure 6.11 Change of surface roughness at speed of 30 mm/min

Intermediate laser powers 700 W and 800 W show more balanced roughness values across different depths.

Generally, deeper cuts at 2.5 mm and 3 mm exhibit higher roughness compared to shallower cuts at 1.5 mm and 2 mm as seen in Figure 6.11.

The roughness values at 2 mm depth show significant variation, indicating sensitivity to laser power adjustments. Waterjet guided laser roughness value of 0.630, showing low roughness, which is favorable.

In summary, increasing the laser power generally reduces surface roughness in waterjet guided laser operations, but the optimal laser power depends on the specific cutting speed and depth of cut. There are complex interactions between these parameters such as thickness and laser power that affect the final surface quality.

6.3 Analysis of Variance (ANOVA) Experimental Results

The experimental results are statistically examined using an analysis of variance (ANOVA) to define effect of factors on surface roughness in waterjet guided laser and conventional laser cutting as shown in Table 6.13. This analysis helps to determine the effect of cutting speed, laser power, and material thickness on surface roughness, as well as any correlations between these variables.

The surface roughness model was used to examine the cubic effects of sheet metal thickness (A), cutting speed (B), and laser power (C). The ANOVA results showed that the independent factors had a significant impact on the answers, and the results showed that the proposed model fits the experimental data accurately.

There is a strong statistical correlation between the words (B) and (A^2B), with p-values less than 0.05. Cutting speed (B) and the squared (second-order) term (A^2B) were shown to be significant variables in the association between surface roughness and independent parameters. The results of the ANOVA did not show any statistical significance for other terms.

$$\begin{aligned} \text{Surface Roughness } (\mu\text{m}) = & 1.88 + 0.3539A - 0.9926B + 0.5695C + 0.2876AB + \\ & 0.3277AC - 0.1837BC - 0.2140A^2 + 0.1803B^2 + 0.0266C^2 - 0.2167ABC + 0.6074A^2 \\ & B + 0.4684A^2 C + 0.0853AB^2 + 0.2227AC^2 - 0.2859B^2 C + 0.0580BC^2 - 0.2741A^3 + \\ & 0.5434B^3 - 0.1202C^3 \end{aligned} \quad (1.1)$$

Equation (1.1) describes a surface roughness prediction model for waterjet guided laser cutting with coded variables. Furthermore, cutting speed was shown to be the most relevant individual factor, followed by laser power and sheet thickness.

Table 6.13 Model summary and ANOVA with surface roughness response for the waterjet guided laser

Source	Sum of Squares	df	Mean Square	F-Value	p-Value	
Model	28.06	19	1.48	5.38	<0.0001	significant
A-Material Thickness	0.3770	1	0.3770	1.37	0.2455	
B-Cutting Speed	3.10	1	3.10	11.28	0.0013	
C-Laser Power	1.03	1	1.03	3.76	0.0569	
AB	0.7397	1	0.7397	2.69	0.1055	
AC	0.1458	1	0.1458	0.5309	0.4688	
BC	0.1477	1	0.1477	0.5378	0.4659	
A²	0.2210	1	0.2210	0.8048	0.3729	
B²	0.3876	1	0.3876	1.41	0.2390	
C²	0.0015	1	0.0015	0.0053	0.9420	
ABC	0.1778	1	0.1778	0.6476	0.4239	
A²B	2.67	1	2.67	9.72	0.0027	
A²C	0.4428	1	0.4428	1.61	0.2086	
AB²	0.0557	1	0.0557	0.2030	0.6538	
AC²	0.0703	1	0.0703	0.2560	0.6146	
B²C	0.3790	1	0.3790	1.38	0.2442	
BC²	0.0103	1	0.0103	0.0376	0.8469	
A³	0.2278	1	0.2278	0.8296	0.3657	
B³	1.00	1	1.00	3.65	0.0604	
C³	0.0323	1	0.0323	0.1178	0.7326	
Residual	18.12	66	0.2745			
Cor Total	46.18	85				

6.4 Response Surface Analysis of Process Parameters

6.4.1 Response Surface Analysis of Laser Power and Cutting Speed

In Figure 6.12, the 3D plots display the response surfaces for roughness variations across different thicknesses, showing how they vary with laser power and cutting speed.

The three-dimensional surface plot of a 1.5 mm-thick AISI 1020 sheet plate is shown in Figure 6.12a. It was observed that as the laser power was decreased, the roughness values showed a relative decrease. Simultaneously, an improvement in roughness was observed at notably lower values as the cutting speed increased.

Cutting speed was discovered to have a higher impact than laser power. Figure 6.12b shows that comparable results were obtained using a sheet that was 2 mm thick.

However, as Figures 6.12b and 6.12c demonstrate, the trends in cutting speed and laser power were discovered to be comparable in the 2 mm and 2.5 mm specimens.

Comparing samples with a thickness of 3 mm to the other three 3D plots, a clear pattern was observed, as shown in Figure 6.12d.

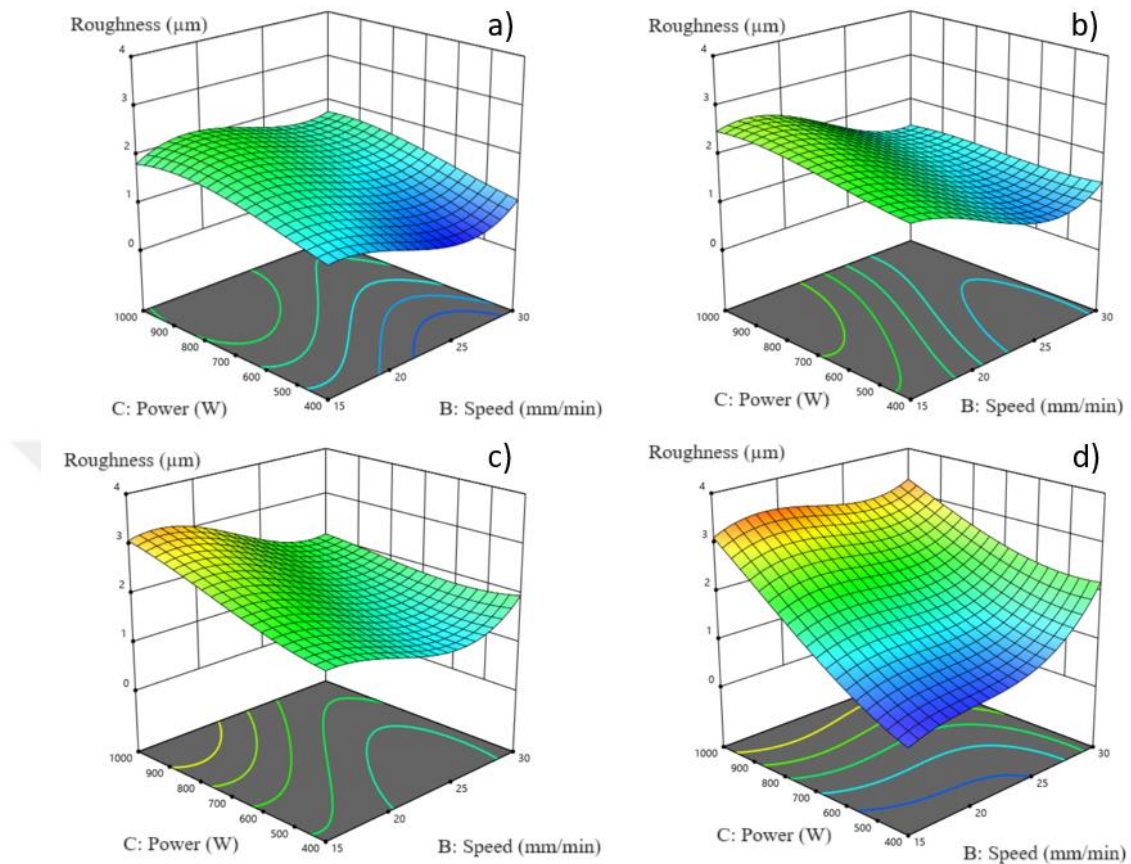


Figure 6.12 Response surface 3D graphs showing how waterjet guided laser cutting's independent variables of cutting power (C) and speed (B) affect surface roughness. AISI 1020 steel sheets come in the following thicknesses: a) 1.5 mm, b) 2 mm, c) 2.5 mm, and d) 3 mm.

The results demonstrated that the effects of cutting speed and laser power on surface roughness were more pronounced for samples with a thickness of 3 mm. Samples that were 3 mm thick showed a distinct pattern in comparison to the other three 3D plots. It was discovered that the effects of cutting speed and laser power on surface roughness were significantly stronger in samples with a thickness of 3 mm.

Another noteworthy finding is that cutting speed was more effective here than it was in other sample groups, although the trend's direction had also shifted. In general, when

speed increased surface roughness reduced for thicknesses of 1.5 mm, 2 mm, and 2.5 mm.

On the other hand, the lowest surface roughness was found for samples with a thickness of 3 mm at the slowest speed tested at 15 mm/min. It was originally believed that the newly created nozzle design made cutting at high speeds more difficult when sheet steel thickness was raised, which is why the trend in surface roughness results in 3 mm thick cuts changed.

The literature has shown that, in this particular scenario, moderate speeds can be preferred over high rates after a certain thickness [88], provided that the laser capacity remains constant. The experiment's findings show that cutting quality was significantly impacted by laser power.

This suggests that surface roughness was influenced by the cutting speed as well. A faster cutting speed resulted in a shorter waterjet cooling effect on the material, which severely abraded the surface.

Conversely, a slower cutting speed made it possible for the waterjet to engage with the material surface for a greater amount of time. As a result, during the laser pulse, more heat may be released, which would reduce heat transfer and accumulation inside the material [75, 89, 90].

6.4.2 3D Surface Topography Analysis Conventional Laser and Waterjet Guided Laser Cutting Processes

The example of a macro and three-dimensional surface topography picture at 2 mm thickness, 600 W and 30 mm/min for the conventional and waterjet guided laser cut sample is presented in Figure 6.13. Surface quality can be compared between different surfaces using 3D surface topography pictures, where the local color difference between peaks and valleys indicates surface quality. It is evident that the various cutting techniques used resulted in notable differences in surface textures. It is anticipated that the damaged surface will be the consequence of the conventional laser method's high laser power release.

Waterjet guided laser cutting clearly removes the deformed and uneven surfaces found in conventional cutting processes under the same conditions, taken from 3D surface topography images as well as macro photographs.

Moreover, a significant distinction in burr formation was noted between the samples that were laser-cut conventionally and those that were guided by a waterjet. As anticipated, the waterjet guided laser cutting procedure produced very little burr formation.

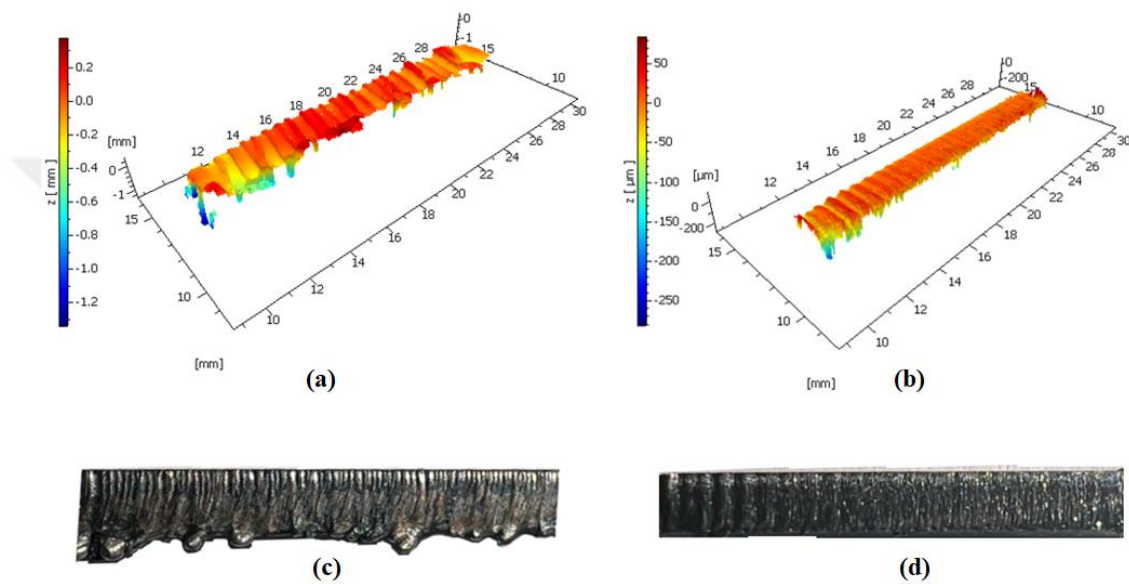


Figure 6.13 3D topography and macro view of the surface cut by (a, c) conventional laser and (b, d) waterjet guided laser, respectively

The conventional laser cutting method exhibited rough burr growth on its surface due to high heat energy exposure during high laser powers, in contrast to the waterjet guided laser cutting process operating under identical conditions.

Evidence that the waterjet guided nozzle did not significantly aid burr development, even if it could cut high-laser powers, was perceived from this.

This was interpreted as indicating that, despite the ability of water jet guided nozzle to reduce surface roughness, burr development was not considerably promoted by it while cutting at high laser powers. This burr formation-related condition was also noted in previous waterjet guided laser studies [81,89,90].

6.4.3 SEM Analysis of Conventional Laser and Waterjet Guided Laser Cutting Processes

SEM pictures of two samples with a thickness of 2 mm are shown in Figure 6.14. The samples were cut at a speed of 30 mm/min and a laser power of 600 W using both conventional laser cutting and waterjet guided methods.

Figures 6.14a, c and e show the SEM images of samples cut using a waterjet guided laser; Figures 6.14b, d and f show the SEM images of materials cut with a conventional laser cutting system.

SEM images of surface morphology were obtained from three different perspectives within the images: the cut surface, the top surface (to assess the quality of the upper edge of the cut more thoroughly), and the bottom surface (to assess the quality of the lower edge of the cut entirely). This allowed for a clear and comprehensive examination and understanding of the processing traits of two laser processing techniques. In waterjet guided laser cutting, Figures 6.14a, b demonstrate a decrease in white layer formation. This is because water simultaneously cools the cutting surface during cutting.

The waterjet guided laser was found to greatly reduce the waveform on the cut surfaces, as seen in Figures 6.14c, d. This can be explained by a more uniform laser power distribution across the part surface.

Finally, it was shown in Figures 6.14e, f that the microstructure of waterjet guided laser cutting is thinner and more regular than that of conventional laser cutting.

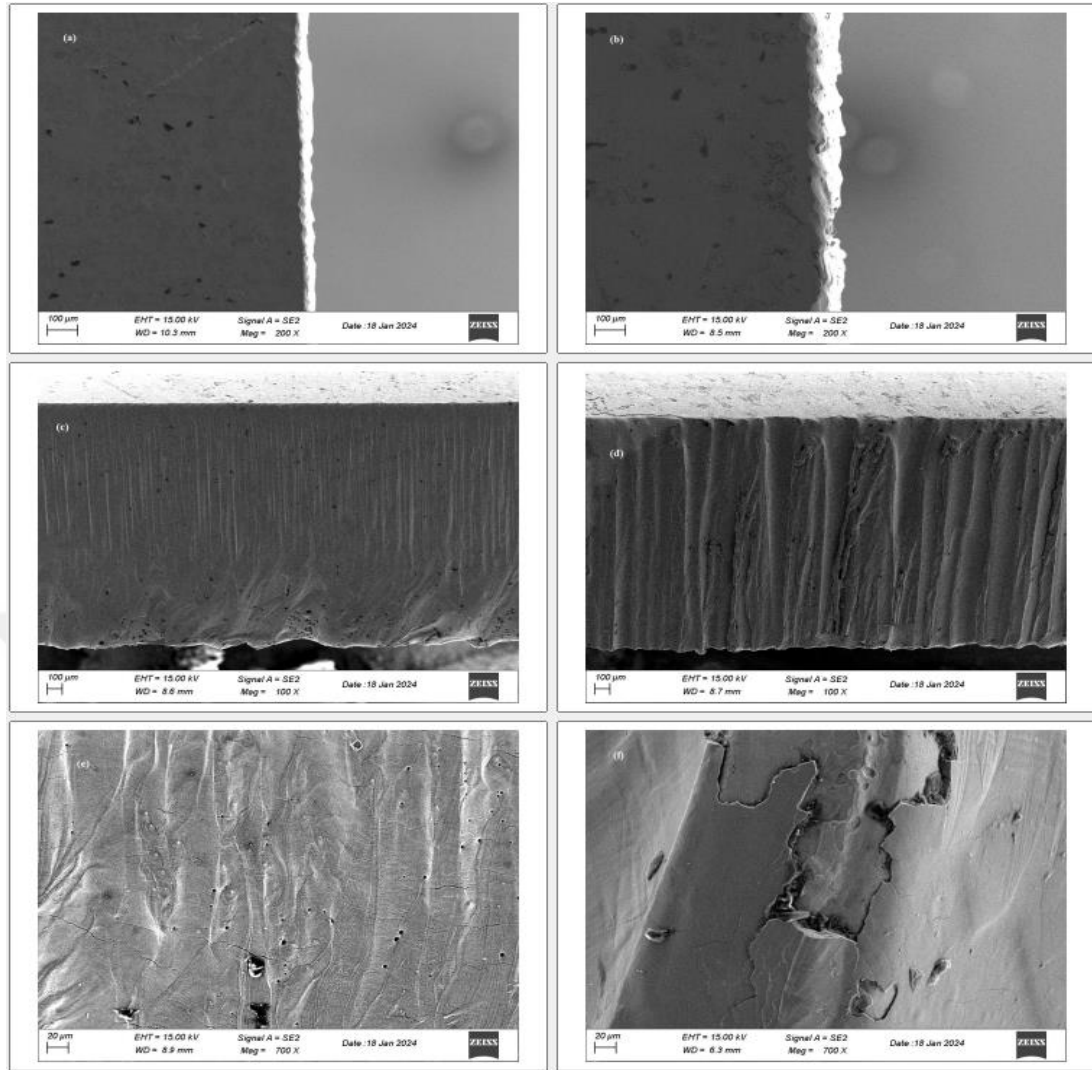


Figure 6.14 Top cutting surface SEM morphologies by (a) waterjet guided laser and (b) conventional laser; cutting surface SEM morphologies by (c) waterjet guided laser and (d) conventional laser; magnified cutting surface SEM morphologies by (e) waterjet guided laser and (f) conventional laser.

It is apparent that surface quality is significantly improved by waterjet guided laser technology. The water's pressure affect prevents slag from building up and adhering to the surface. Smoother surfaces are achieved and the heat-affected zones are narrower.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Introduction

The development of a novel material processing technique which is waterjet guided laser technology has been promoted by performing this study. Alternative nozzle designs have been modelled to guide the laser beams with the least amount of loss. The most efficient nozzle has been identified and comparison cuttings using conventional laser and waterjet guided laser have been made.

The created water jet guided laser head helped to solve the focus and cutting distance problems experienced in conventional lasers by transferring the laser beam to the workpiece to be cut via water guiding, similar to a fiber optic cable. In contrast to conventional lasers, which can only cut objects up to 1-2 mm away, this innovative design allows for cuts up to 20 mm away.

The main motivation behind this work is the literature's investigation into the use of low-power lasers for cutting thin metal sheets and composite materials. A 1 kW waterjet guided laser is being designed and achieved to cut steel sheets in the 1.5 mm to 3 mm thickness range that will show promise for widespread industrial applications.

For both cutting procedures, the primary cutting parameters of laser power and cutting speed were experimentally evaluated over a range of values to determine their impact on surface quality. Additionally, the effect of material thickness on the results was looked into.

The top and lower limit of cutting parameters for both cutting speed and laser power were determined for AISI 1020 material in comparison with material thickness. Accordingly, specific type of experimental design was not used in this investigation.

The following is a summary of the research's findings:

- Surface roughness was significantly reduced by waterjet guided laser cutting in comparison to conventional laser cutting.
- An ANOVA analysis was conducted using the surface roughness measurements obtained from the waterjet guided laser cutting method investigation. The statistical study shed light on how material thickness and cutting factors affect surface roughness.
- The waterjet guided laser cutting process was found to depend critically on laser power, with AISI 1020 steel sheets not being cut at powers lower than 400 W. Additionally, it was shown that laser power had a negative overall influence on cutting quality and a considerable impact on surface quality in both cutting processes.
- It is presumed that the cooling action of water inhibits cutting at low laser powers and that the threshold power value needs to be exceeded in order to cut with a waterjet guided laser.
- Another important factor that varied depending on the thickness of the material was found to be the cutting speed. When the cutting speed was increased for material thicknesses ranging from 1.5 mm to 2.5 mm, the surface roughness decreased; But when the material thickness went to 3 mm, the surface roughness rose.
- Cutting speed was discovered to be the most significant specific factor, followed by laser power and sheet thickness.
- Analyses of surface topography and macrostructure showed that, in comparison with conventional laser cutting, waterjet guided laser cutting significantly decreased burr development.
- SEM images demonstrated that waterjet guided laser cutting significantly improved surface waviness and produced fewer white layers than conventional laser cutting. Moreover, the microstructure of the cutting surface was more uniform and finer.
- The investigation also came to the conclusion that fiber lasers may be used successfully for waterjet guided laser cutting procedures because of their high wavelength.

Depending on ANOVA results as a model suggestion, the findings indicate that for improved surface roughness control in waterjet-guided laser operations, one should concentrate on maximizing the cutting speed and taking into account the relationship between material thickness and cutting speed.

7.2 Recommendations for Future Work

The investigation's findings open up a lot of possibilities for additional study and advancement in the field of waterjet guided laser technology.

Studies on design issues including the rigidity of the laser head and water jet head as well as vibrations and hydrodynamic problems occurring during cutting can be conducted considering waterjet guided laser technology has a more complicated design than conventional laser technology.

As stated in one of the study's findings, this study can serve as motivation for future research focused at minimizing laser power loss in waterjet guided laser cutting due to the cooling effect of water during ablation.

Comparative investigations on the evaluation of physical, chemical, and mechanical properties can be carried out by obtaining specific shape test samples with waterjet guided laser technology and conventional laser using the same cutting parameters.

Although waterjet guided laser technology is costlier than conventional lasers, primarily due to its higher water consumption, it can serve as an inspiration for studies on sustainability-related topics.

It is possible to provide innovative studies to reduce the turbulence effect of water and prevent laser beam dispersion by carrying out novel and inventive investigations on nozzle designs.

It will be feasible to contribute to the development of this technology and its use in new different areas by carrying out innovative research on the enhancement of artificial intelligence- and machine learning-supported models on waterjet guided laser technology.

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PUBLICATIONS

The publications included in this thesis has been presented at conferences or published in other journals. This is an index that is available:

Articles

- [1].M. Paksoy, H. Çandar, and N. F. Yılmaz, The Advancement of Waterjet-Guided Laser Cutting System for Enhanced Surface Quality in AISI 1020 Steel Sheets, *Materials*, vol. 17, no. 14, 2024, doi: 10.3390/ma17143458.

Conference Papers

- [1].M. Paksoy, H. Çandar, N. F. Yılmaz and M. F. Kalkan, Sulu Kesim ile Lazer Kesimin Yüzey Kalitesi Üzerindeki Etkisi: Su Güdümlü Lazer Başlığı Tasarımı ve Uygulaması, *The International Conference of Materials and Engineering Technology (TICMET'23)*, 13-16 November, 2023, Trabzon/Turkey.
- [2].M. Paksoy, M. F. Kalkan, H. Çandar, and N. F. Yılmaz, Investigation of Material Surface Quality in Dry and Water-Assisted Cutting with Fiber Laser, *The International Conference of Materials and Engineering Technology (TICMET'20)*, 05-07 November, 2020, Gaziantep/Turkey.
- [3].M. Paksoy, H. Çandar, and N. F. Yılmaz, Behaviour of Laser Beam Characteristics in Different Fluids, *The International Conference of Materials and Engineering Technology (TICMET'19)*, 10-12 October, 2019, Gaziantep/Turkey

