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Experimental Study On Surface Roughness In Water Jet Cutting

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Disclaimer

I hereby declare that this Project is my own original work and has not been submitted before to any institution for assessment purposes. Further, I have acknowledged all sources used and have cited these in the reference section.

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Abstract

This thesis presents an experimental study focused on surface roughness in abrasive water jet (AWJ) cutting, with a particular emphasis on the intricate interplay of operational parameters. Commercial steel 2344, 12 mm in thickness, served as the material under investigation. The examination of pressure, traverse speed, and nozzle stand-off distance revealed that the traverse cutting speed played a pivotal role in influencing surface properties and near-edge microstructural features. Results discussion highlighted the nuanced effects of traverse cutting speed on surface characteristics, cut-edge roughness, and localized near-edge stresses. Future works were identified, suggesting avenues for optimization strategies, exploration of advanced materials, investigation into hybrid machining techniques, and consideration of environmental sustainability in AWJ processes. This thesis contributes valuable insights for refining AWJ machining strategies and sets the stage for further advancements in precision machining technologies.

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Chapter 1

Introduction

1.1 Introduction

Abrasive water jet machining is an exceptional process renowned for its ability to cost-effectively cut through nearly all materials, making it increasingly prevalent as a "standard tool" in machine shops worldwide. The fundamental technology behind it is both straightforward and highly intricate. The principle governing the utilization of the abrasive water jet for machining or finishing lies in the material's erosion upon contact with the jet.

The jet comprises two essential components: water and abrasive material, each serving distinct yet complementary purposes. The abrasive material's primary role within the jet stream is to generate erosive forces. Simultaneously, the jet's primary function is to transport the abrasive material to the workpiece for the purpose of erosion. The jet also propels the abrasive material at a velocity such that the impact and momentum alteration of the abrasive substance enable it to execute its function.

Furthermore, the water serves an additional purpose by carrying both the abrasive material and the eroded material away from the work area. This facilitates subsequent processing, as the removal of spent material is a crucial aspect of any machining process. Essentially, the water jet acts as a mechanism to efficiently clear the workspace, ensuring seamless operations.

1.2 Significance and Motivation

The significance of exploring abrasive water jet machining lies in its remarkable potential to cut diverse materials with cost-effectiveness, positioning itself as a burgeoning standard tool within global machine shops. This innovative technology holds both practical and strategic value for manufacturing processes, offering a versatile solution that addresses the machining needs of a wide array of materials.

The motivation to delve into this area stems from the unique attributes of abrasive water jet machining, where the interplay between water and abrasive material results in efficient material removal. As industries seek advanced methods to enhance precision and efficiency in cutting applications, the exploration of this machining technique becomes imperative. Furthermore, understanding its significance can pave the way for refining and optimizing the process, contributing to advancements in machining technology and the broader field of manufacturing.

1.3 Problems

While abrasive water jet machining presents itself as a promising and versatile technology, there are inherent challenges and issues that warrant careful examination. Identifying and addressing these problems are crucial for optimizing the efficiency and reliability of the machining process.

One notable issue is the potential for variations in surface roughness in the cut materials. The intricate interplay between the abrasive material, water, and the workpiece can result in irregularities that impact the final surface texture. Understanding and mitigating these variations are essential for ensuring consistent and high-quality outcomes in abrasive water jet cutting applications.

Another challenge pertains to the optimization of process parameters. The complex nature of the technology requires a comprehensive exploration of factors such as water pressure, abrasive flow rate, and standoff distance. Achieving an optimal balance among these variables is pivotal for maximizing cutting efficiency and minimizing potential drawbacks.

1.4 Aims and Objectives

1.4.1 Overall Aim

The overarching aim of this study is to conduct an experimental investigation into surface roughness in abrasive water jet cutting, with a focus on understanding the influencing factors and optimizing the process for enhanced machining outcomes.

1.4.2 Specific Objectives

Evaluate Surface Roughness Variations: Systematically examine and quantify the variations in surface roughness that occur during abrasive water jet cutting, considering different materials and operating conditions.

Identify Contributing Factors: Investigate the key parameters affecting surface roughness, including water pressure, abrasive flow rate, standoff distance, and material properties, to discern their individual and collective impacts.

Optimize Process Parameters: Determine the optimal combination of process parameters to achieve consistent and desired surface roughness outcomes, aiming for the highest precision and efficiency in abrasive water jet machining.

Develop Predictive Models: Establish empirical models or correlations that predict surface roughness based on the identified influencing factors, facilitating a deeper understanding of the machining process.

Provide Practical Recommendations: Offer practical recommendations and guidelines for industry practitioners and manufacturers to enhance the application of abrasive water jet cutting techniques in real-world scenarios.

By addressing these specific objectives, this research aims to contribute valuable insights to the field, advancing the knowledge base on abrasive water jet machining and fostering its continued evolution as a reliable and effective machining method.

1.5 Methodology

To achieve the outlined aims and objectives, a systematic and comprehensive methodology will be employed, integrating both experimental and analytical approaches. The methodology encompasses the following key components:

1.5.1 Experimental Setup

Establishing a controlled experimental environment is paramount. Utilizing a state-of-the-art abrasive water jet cutting system, experiments will be conducted across a range of materials commonly encountered in machining applications. The equipment will be calibrated for varying water pressures, abrasive flow rates, standoff distances, and material properties to capture a comprehensive dataset.

1.5.2 Surface Roughness Measurement

Precise measurement of surface roughness is critical for the evaluation process. Advanced metrology tools, such as profilometers and scanning electron microscopes, will be employed to assess the resulting surface characteristics. Multiple samples from each experimental condition will be analyzed to ensure statistical reliability.

1.5.3 Parametric Variation

The study will systematically vary key parameters, including water pressure, abrasive flow rate, standoff distance, and material types, to observe their impact on surface roughness. This iterative process will generate a rich dataset that forms the basis for analysis and optimization.

1.5.4 Data Analysis

Data collected from the experiments will undergo rigorous statistical analysis. Correlation studies and regression analyses will be employed to identify trends, dependencies, and interactions between the selected parameters and surface roughness outcomes. This analytical phase will contribute to the development of empirical models.

1.5.5 Model Development

Empirical models predicting surface roughness based on the identified influencing factors will be developed. These models will serve as valuable tools for understanding and predicting the behavior of abrasive water jet machining, aiding in the optimization of process parameters.

1.5.6 Validation and Optimization

The developed models will be validated through additional experiments, ensuring their reliability and applicability. The optimization phase will involve fine-tuning process parameters to achieve the desired surface roughness outcomes, further refining the understanding of the machining process.

1.5.7 Documentation and Reporting

A comprehensive documentation process will accompany each phase of the research. Results, analyses, and conclusions will be meticulously recorded. The findings will be presented in a structured and clear format, contributing to the academic knowledge base on abrasive water jet machining.

By adhering to this systematic methodology, the study endeavors to provide valuable insights into surface roughness in abrasive water jet cutting, offering practical implications for industry applications and future research endeavors.

Chapter 2

Literature Review

2.1 Introduction

Abrasive water jet machining has evolved as a cutting-edge technology, captivating the attention of researchers and industry professionals alike due to its unique capabilities in efficiently processing diverse materials. As a pivotal component of advanced manufacturing, this method harnesses the erosive power of a high-speed jet carrying abrasive particles, presenting a versatile solution for intricate cutting applications.

The literature review aims to provide a comprehensive understanding of the theoretical underpinnings that govern abrasive water jet machining. By delving into the existing body of knowledge, this chapter seeks to elucidate the key principles, mechanisms, and parameters influencing surface roughness in the context of this cutting technique. As we explore the theoretical background, attention will be devoted to identifying gaps in current understanding and areas where further research is warranted.

Furthermore, a critical examination of previous studies and works related to surface roughness in abrasive water jet cutting will be conducted. By synthesizing and analyzing the findings of these endeavors, we aim to discern patterns, trends, and varying approaches taken by researchers. This retrospective analysis will lay the foundation for the current study, establishing a contextual framework within which our experimental investigation can contribute novel insights and advancements.

In essence, this literature review serves as a gateway to the realm of abrasive water jet machining, setting the stage for a deeper exploration into the intricate interplay of factors affecting surface roughness. Through a meticulous examination of existing literature, this chapter seeks to build a solid foundation for our research, bridging the gap between past endeavors and the innovative strides we aim to make in understanding and optimizing abrasive water jet cutting processes.

2.2 The theoretical background

2.2.1 Principles of Abrasive Water Jet Machining

Abrasive water jet machining, as a cutting technique, operates on the fundamental principle of erosion induced by the impact of abrasive-laden high-speed water jets on a workpiece. The technology involves the convergence of two primary components: water and abrasive material. The water serves as a carrier medium for the abrasive particles, facilitating their acceleration to high velocities.

The erosive forces exerted by the abrasive particles on the workpiece result in material removal, making abrasive water jet machining a versatile tool for cutting a wide range of materials, including metals, ceramics, and composites. The effectiveness of this process lies in the kinetic energy transfer from the abrasive-laden water jet to the workpiece, leading to controlled erosion and precise cutting.

2.2.2 Parameters Influencing Surface Roughness

Achieving desired surface roughness in abrasive water jet machining involves a delicate balance of various parameters. Key factors include water pressure, abrasive flow rate, standoff distance, abrasive particle size, and traverse speed. Understanding the interplay among these parameters is crucial for optimizing the machining process and ensuring consistent surface finish.

Water Pressure: The pressure of the water jet directly influences the kinetic energy imparted to the abrasive particles, affecting their cutting efficiency and the resulting surface finish.

Abrasive Flow Rate: The quantity of abrasive material injected into the water stream impacts the abrasive concentration, influencing the erosive capabilities and, consequently, the surface roughness.

Standoff Distance: The distance between the nozzle and the workpiece, known as the standoff distance, plays a critical role in determining the jet's focus and, subsequently, the cutting precision and surface quality.

Abrasive Particle Size: The size of the abrasive particles affects the depth of cut and the overall material removal rate, thereby influencing the resultant surface roughness.

Traverse Speed: The speed at which the water jet traverses the workpiece surface determines the time the abrasive particles spend in contact with the material, influencing the machining outcome.

2.2.3 Challenges and Opportunities

While abrasive water jet machining offers versatility and efficiency, challenges such as surface irregularities and inconsistent roughness have been identified in the literature. Understanding the theoretical foundations of the process and the factors contributing to these challenges is essential for addressing them systematically. This theoretical background provides the groundwork for the subsequent exploration of previous studies and works, aiming to synthesize knowledge and identify avenues for further investigation.

2.3 The previous studies and works

2.3.1 Overview of Existing Research

A comprehensive review of previous studies and works related to surface roughness in abrasive water jet machining reveals a diverse landscape of research endeavors. Researchers and practitioners have explored this field with the aim of understanding the intricacies of the process and optimizing parameters for improved surface finish.

2.3.2 Surface Roughness Characterization

Numerous studies have focused on characterizing surface roughness in abrasive water jet-cut materials. Researchers have employed various metrology techniques, including profilometry and microscopy, to quantitatively and qualitatively assess the surface texture. These investigations have contributed valuable insights into the relationship between process parameters and the resulting surface finish.

2.3.3 Influence of Process Parameters

A significant body of literature delves into the influence of individual process parameters on surface roughness. Investigations into the effects of water pressure, abrasive flow rate, standoff distance, and traverse speed have been conducted to elucidate their impact on the quality of the machined surface. Understanding these relationships is crucial for optimizing the machining process.

2.3.4 Empirical Modeling

Several researchers have endeavored to develop empirical models correlating process parameters with surface roughness outcomes. These models serve as predictive tools, offering a quantitative understanding of the complex interactions governing abrasive water jet machining. The development and validation of such models contribute to the establishment of guidelines for practitioners seeking optimal machining conditions.

2.3.5 Challenges and Unexplored Areas

While existing studies have made significant contributions, certain challenges and unexplored aspects persist. Surface irregularities, variations in material properties, and the need for enhanced predictive models are areas that warrant further attention. This review highlights the gaps in current knowledge and sets the stage for the present study to address these challenges.

2.3.6 Emerging Trends and Innovations

Recent trends in abrasive water jet machining research include the integration of advanced technologies, such as artificial intelligence and machine learning, for process optimization. These innovations showcase the dynamic nature of the field and the ongoing efforts to push the boundaries of knowledge and application.

In synthesizing the wealth of knowledge encapsulated in previous studies, this literature review aims to distill key findings, identify gaps, and lay the groundwork for the experimental investigation into surface roughness in abrasive water jet cutting presented in this thesis. Building upon the insights garnered from existing works, the subsequent chapters will contribute to the evolving narrative of advancements in abrasive water jet machining.

Chapter 3

Material and Methods

3.1 How Does Abrasive Water Jets Work?

Abrasive water jet cutting involves the use of a high-velocity, cohesive stream comprising water and abrasive particles, capable of effectively cutting a wide range of materials. Operating at pressures between 40,000 to 55,000 psi, water is accelerated through a nozzle made of sapphire, ruby, or diamond. In the mixing region, induced vacuum forces draw in abrasive material, which becomes entrained and accelerated by the momentum of the water stream as it traverses the nozzle.

Upon exiting the nozzle, the stream manifests as a three-phase mixture of air, water, and abrasive particles, featuring a cutting diameter ranging from 0.020” to 0.060”. The actual cutting is executed by the high-velocity abrasive particles impacting the kerf face. Material removal from the kerf occurs in the form of microchips, leaving negligible effects on the overall material structure.

3.2 Methodology

Abrasive water jet machining proves to be a suitable and cost-effective method for a diverse range of procedures and materials, finding application across various sectors of modern industry. This versatile technique is prevalent in key industries such as automotive, aerospace, construction engineering, environmental technology, chemical process engineering, and industrial maintenance.

In the realm of manufacturing, the water jet technique serves multiple purposes, including material cutting, deburring through plain water jets, surface peening with plain water jets, conventional machining with water-jet assistance, cutting challenging materials using abrasive water jets, milling and 3-D shaping through abrasive water jets, turning with abrasive water jets, piercing and drilling via abrasive water jets, and polishing using abrasive water jets, among others.

Fundamentally, the process involves the flow of water from a pump through a plumbing system and out of a cutting head. The energy required for material cutting is derived by pressurizing water to high levels and then channeling this high-pressure water through a small orifice to create a high-intensity cutting stream. The inclusion of abrasive material enhances the cutting capabilities of the water jet, expanding its applicability to various machining tasks. water jet differs from the pure water jet in just a few ways. In pure water jet, the supersonic stream erodes the material. In the abrasive water jet, the water jet stream accelerates abrasive particles and those particles, not the water, erode the material. The abrasive water jet is hundreds, if not thousands of times more powerful than a pure water jet. Both the water jet and the abrasive water jet have their place. Where the pure water jet cuts soft materials, the abrasive water jet cuts hard materials, such as metals, stone, composites and ceramics. An abrasive water jet is a jet of water which contains abrasive material. Solid particles – the “abrasive” – join the water jet in mixing chamber (Fig. 1) and are focused by the abrasive nozzle. High pressure water enters the upper portion of the nozzle assembly and passes through a smalldiameter orifice to form a narrow jet. The water jet then passes through a small chamber where a Venturi effect creates a slight vacuum that pulls abrasive material and air into this area through a feed tube. The abrasive particles are accelerated by the moving stream of water, and together they pass into a long, hollow cylindrical nozzle. The nozzle acts like a rifle barrel to accelerate the abrasive particles. The abrasive and water mixture exits the nozzle as a coherent stream and cuts the material. It’s critical that the orifice and the nozzle be precisely aligned to ensure that the water jet passes directly down the center of the nozzle. Otherwise the quality of the abrasive water jet will be diffused, the quality of the cuts it produces will be poor, and the life of the nozzle will be short. In the past, most cutting head designs required the operator to adjust the alignment of the jewel and nozzle during operation. Modern cutting head designs rely on precisely machined components to align the orifice and nozzle during assembly, thereby eliminating the need for operator adjustments. Nozzles are approximately 70 mm long, with inside diameters that can vary from about 0.8 mm to 1.2 mm. The normal standoff distance between the nozzle and the work piece is usually between 0.25 mm and 2.5 mm.

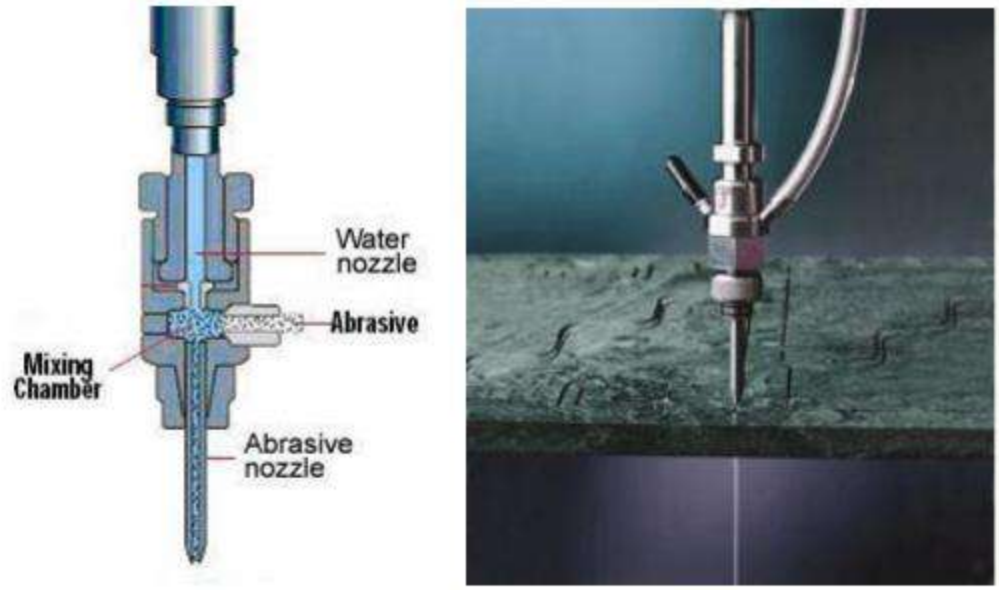


Figure 1. Abrasive water jet cutting head

3.2.1 INFLUENCING PARAMETERS OF ABRASIVE WATER JET CUTTING SPEED

The abrasive water jet cutting process relies on a myriad of process parameters, including water pressure, orifice diameter, standoff distance, abrasive rate, and cutting speed. Notably, the water nozzle diameter stands out as the key parameter governing cutting speed. Additionally, water pressure and abrasive rate exert significant influence on the cutting speed, with higher water pressure generally correlating to increased cutting speed.

A prevailing rule in abrasive water jet cutting is straightforward: higher pressure leads to elevated cutting speed and reduced costs. Consequently, operating the system with maximum pump power enhances cutting efficiency. Pump power, often measured in kilowatts (kW), is a pivotal factor, with 37 kW pumps being the most common, followed by 75 kW, 18 kW, and 112 kW pumps. The abrasive jet's power at the nozzle exit hinges on pressure, flow, and nozzle size, with changes in nozzle diameter having a more pronounced effect on power output than changes in pressure.

While there is a common belief that reducing abrasive rate saves costs, there exists an optimal performance point for abrasive water jets. As the abrasive rate increases, cut speed rises, and the cost per meter decreases, reaching an optimum balance. However, excessive abrasive usage may lead to clogging in the mixing chamber. The interplay between abrasive rate and water rate, as well as the influence of orifice/nozzle size combinations, affects cutting speed.

Orifice size plays a crucial role in determining the water output volume, with larger orifices typically resulting in faster cuts but requiring more pump power. Maintaining an optimal balance, a focusing tube approximately three times larger than the orifice is often recommended for efficient cutting. Common orifice/nozzle combinations, such as 6/21 (0.15/0.54 mm) and 13/43 (0.33/1.10 mm) for a water pressure of 400 MPa, are utilized.

The abrasive material employed in abrasive water jet cutting, commonly garnet, is rigorously screened and sized hard sand. Different mesh sizes, such as 120 mesh for a smooth surface, 80 mesh as a general-purpose option, and 50 mesh for slightly faster cuts with a slightly rougher surface, cater to diverse job requirements. The cutting speed is contingent on factors like material type, thickness, edge finish quality, and tolerance, varying in relation to the part's geometry.

3.2.2 Application and Material:

The applications and materials, which are generally machined using WJ and AWJ, are given below

Application

- Paint removal
- Cleaning
- Cutting soft materials
- Cutting frozen meat
- Textile, Leather industry
- Mass Immunization
- Surgery

- Peening
- Cutting
- Pocket Milling
- Drilling
- Turning
- Nuclear Plant Dismantling

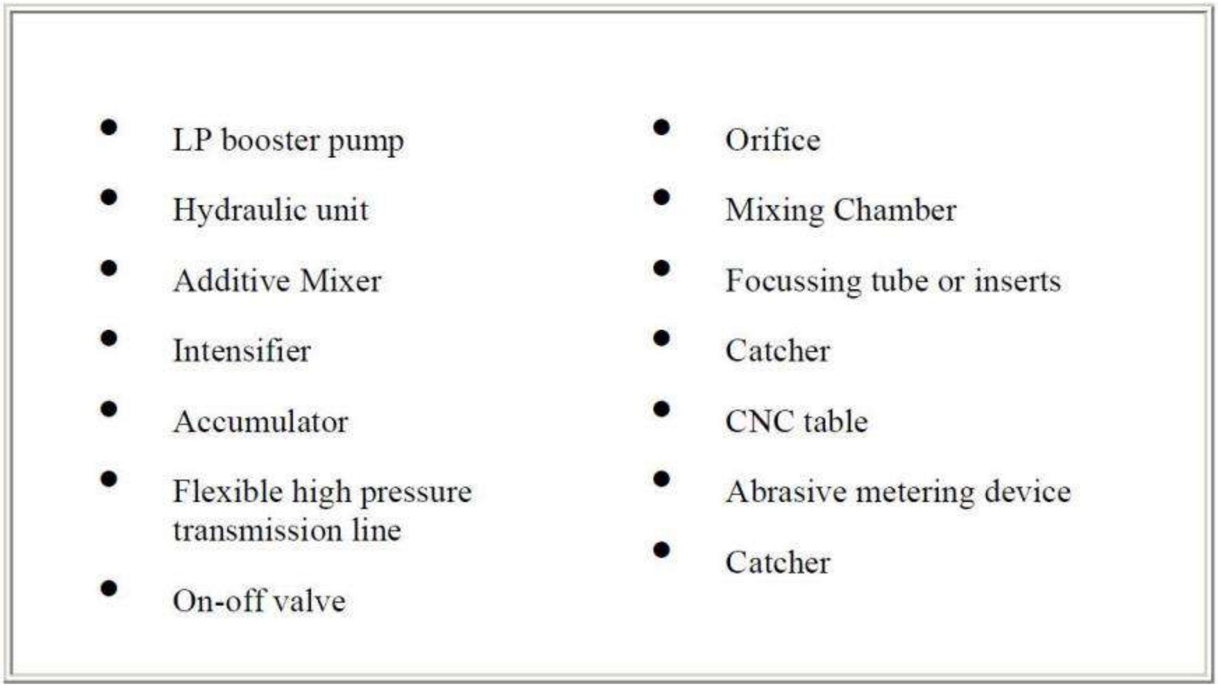
Materials:

- Steels
- Non-ferrous alloys
- Ti alloys, Ni- alloys
- Polymers
- Honeycombs
- Metal Matrix Composite
- Ceramic Matrix Composite
- Concrete
- Stone – Granite
- Wood
- Reinforced plastics
- Metal Polymer Laminates
- Glass Fibre Metal Laminates

The cutting ability of water jet machining can be improved drastically by adding hard and sharp abrasive particles into the water jet. Thus, WJM is typically used to cut so called “softer” and “easy-tomachine” materials like thin sheets and foils, non-ferrous metallic alloys, wood, textiles, honeycomb, polymers, frozen meat, leather etc, but the domain of “harder and “difficult-to-machine” materials like thick plates of steels, aluminium and other commercial materials, metal matrix and ceramic matrix composites, reinforced plastics, layered composites etc. are reserved for AWJM. Other than cutting (machining) high pressure water jet also finds application in paint removal, cleaning, surgery, peening to remove residual stress etc. AWJM can as well be used besides cutting for pocket milling, turning, drilling etc. One of the strategic areas where robotic AWJM is finding critical application is dismantling of nuclear plants.

3.2.3 Machine Description

Any standard abrasive water jet machining (AWJM) system using entrained AWJM methodology consists of following modules.



- LP booster pump
- Hydraulic unit
- Additive Mixer
- Intensifier
- Accumulator
- Flexible high pressure transmission line
- On-off valve
- Orifice
- Mixing Chamber
- Focussing tube or inserts
- Catcher
- CNC table
- Abrasive metering device
- Catcher

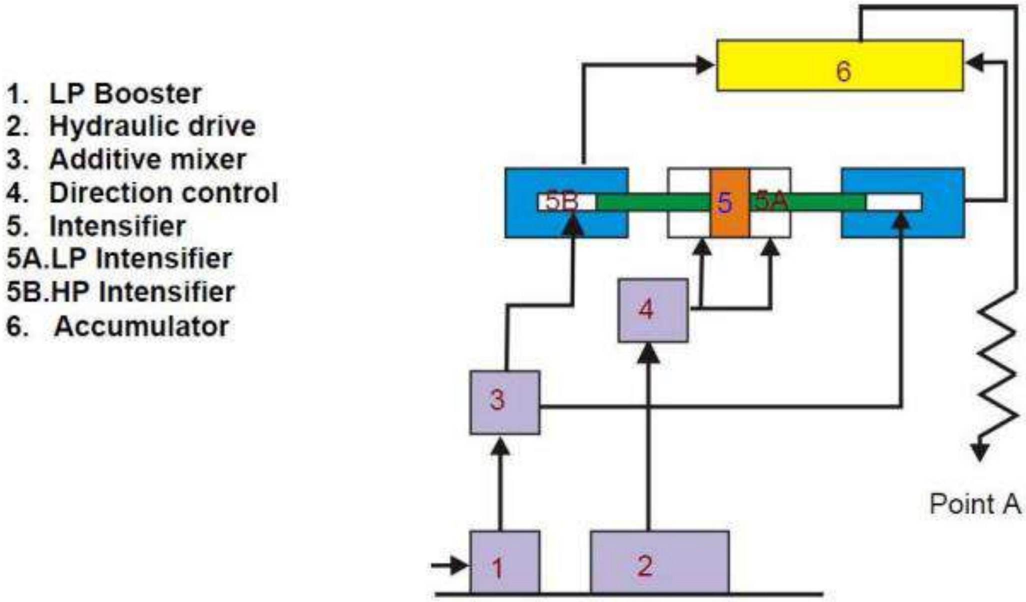


Fig. 2 Schematic set-up of AWJM

Intensifier, shown in Fig. 3 is driven by a hydraulic power pack. The heart of the hydraulic power pack is a positive displacement hydraulic pump. The power packs in modern commercial systems are often controlled by microcomputers to achieve programmed rise of pressure etc.

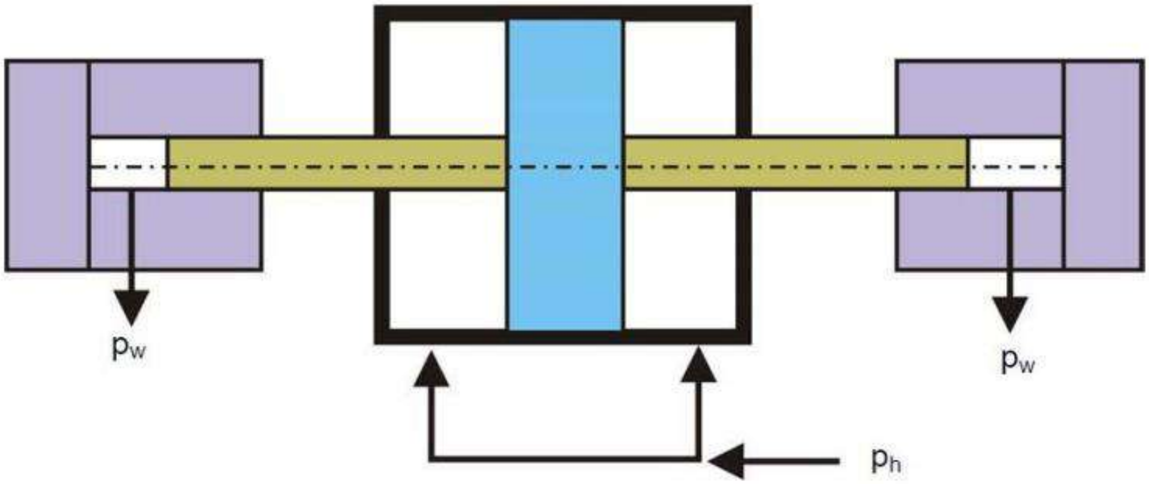


Fig. 3 Intensifier – Schematic

The hydraulic power pack delivers the hydraulic oil to the intensifier at a pressure of ph . The ratio of cross-section of the two cylinders in the intensifier is say A ratio (A = A large / A small). Thus, pressure amplification would take place at the small cylinder as follows.

$$p_h \times A_{l\,\mathrm{arge}} = p_w \times A_{small}$$

$$p_w = p_h \times \frac{A_{l\,\mathrm{arge}}}{A_{small}}$$

$$p_w = p_h \times A_{ratio}$$

Hence, if the hydraulic pressure is set at 100 bar and the area ratio is 40, the resulting pw (pressure on water) is calculated as 100 x 40, equaling 4000 bar. The intensifier is then activated by the hydraulic unit through a directional control valve. The water supply to the small cylinder of the intensifier can occur directly or be routed through a booster pump, elevating the water pressure to approximately 11 bar before entering the intensifier. In some cases, water treatment processes, such as softening, or the addition of long-chain polymers in an "additive unit," may be employed.

During the intensification process, high-pressure water is generated, as illustrated in Figure 4. However, when the larger piston changes direction within the intensifier, there can be a decline in the delivery pressure. To counteract such fluctuations, a substantial cylinder, known as an "accumulator," is incorporated into the delivery unit. Functioning akin to a flywheel in an engine, the accumulator mitigates water pressure variations. Subsequently, the high-pressure water is conveyed through flexible stainless steel pipes to reach the cutting head. It is noteworthy that these pipes are designed to carry water at 4000 bar (400 MPa) with flexibility and joints, ensuring a secure connection without any leakage. The cutting head comprises an orifice, mixing chamber, and a focusing tube or insert where the water jet is formed and blended with abrasive particles to create the abrasive water jet. Figure 4 provides a schematic and photographic representation of a cutting head or jet former. The typical diameter of the flexible stainless steel pipes is 6 mm, facilitating the transportation of water to the jet former or cutting head.

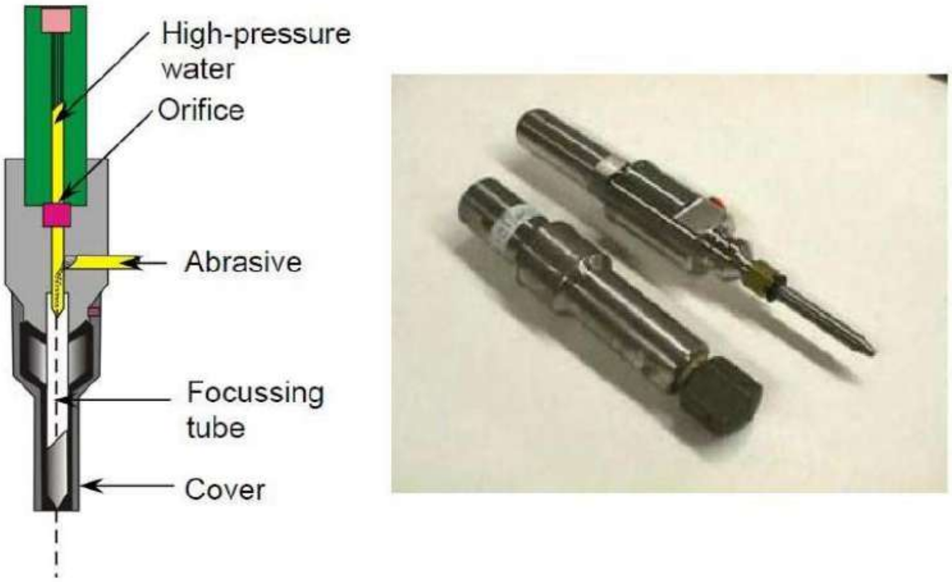


Fig. 4 Schematic and photographic view of the cutting head (Photograph Courtesy – Omax Corporation, USA).

The potential or pressure head of water undergoes a transformation into velocity head by allowing high-pressure water to pass through a small-diameter orifice, typically ranging from 0.2 to 0.4 mm. The resulting velocity of the water jet can be approximated, assuming no losses, using Bernoulli's equation: $v_{wj} = \sqrt{\frac{2p_w}{\rho_w}}$, where p_w represents water pressure, and ρ_w is the density of water. Notably, the orifices are commonly crafted from sapphire, with a typical lifespan of approximately 100 to 150 hours in commercial machines.

In water jet machining (WJM), this high-velocity water jet is directly applied for the intended purpose, while in abrasive water jet machining (AWJM), it is directed into the mixing chamber. The mixing chamber typically possesses an inner diameter of 6 mm and a length of 10 mm. As the high-velocity water exits the orifice into the mixing chamber, it creates low pressure (vacuum) within the chamber. Metered abrasive particles are then introduced into the mixing chamber through a designated port.

3.2.4 Mixing

Fig. 5 schematically shows the mixing process. Mixing means gradual entrainment of abrasive particles within the water jet and finally the abrasive water jet comes out of the focussing tube or the nozzle.

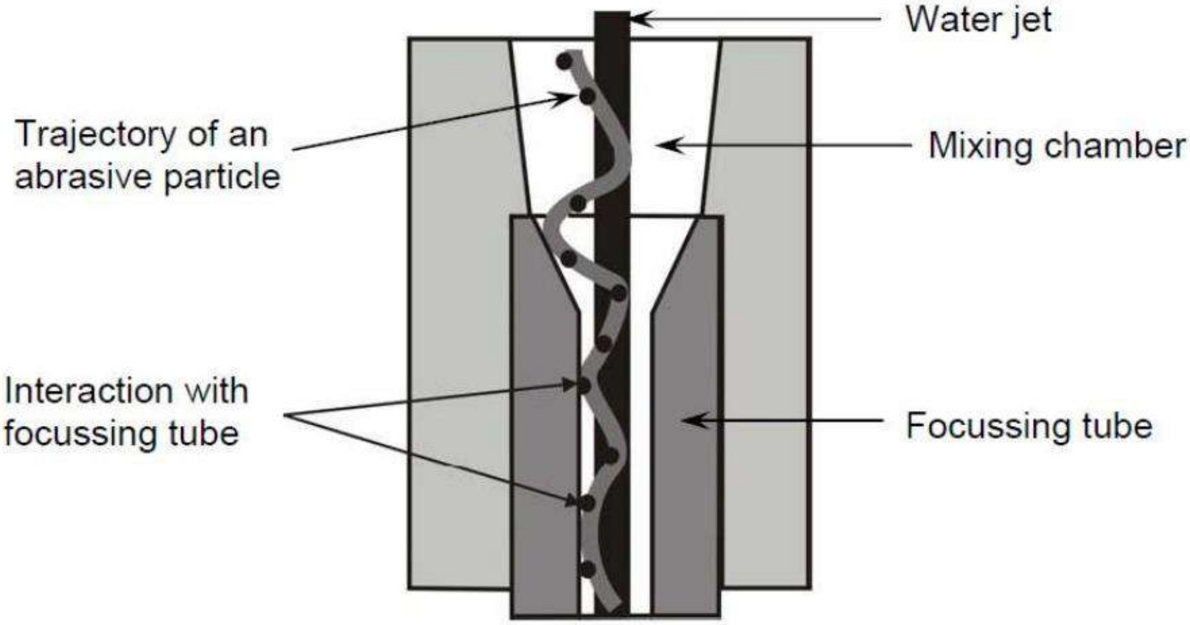


Fig. 5 Schematic view of mixing process

Throughout the mixing process, the acceleration of abrasive particles occurs gradually as momentum is transferred from the water phase to the abrasive phase. When the jet ultimately exits the focusing tube, both the water and abrasive phases are assumed to be at the same velocity.

The mixing chamber, depicted in Figures 5 and 6, is immediately succeeded by the focusing tube or inserts. Typically crafted from tungsten carbide (a powder metallurgy product), the focusing tube boasts an inner diameter ranging from 0.8 to 1.6 mm and a length of 50 to 80 mm. Tungsten carbide is chosen for its resistance to abrasion. Despite attempts by abrasive particles to enter the jet during mixing, the interplay of buoyancy and drag forces deflects them away. These particles continue interacting with the jet and the inner walls of the mixing tube until they are accelerated through the momentum of the water jet.

3.2.5 suspension jet

In entrained AWJM, the abrasive water jet, which finally comes from the focussing tube or nozzle, can be used to machine different materials. In suspension AWJM the abrasive water jet is formed quite differently. There are three different types of suspension AWJ formed by direct, indirect and Bypass pumping Fig. 6 shows the working principle of indirect and Bypass pumping system of suspension AWJM system.

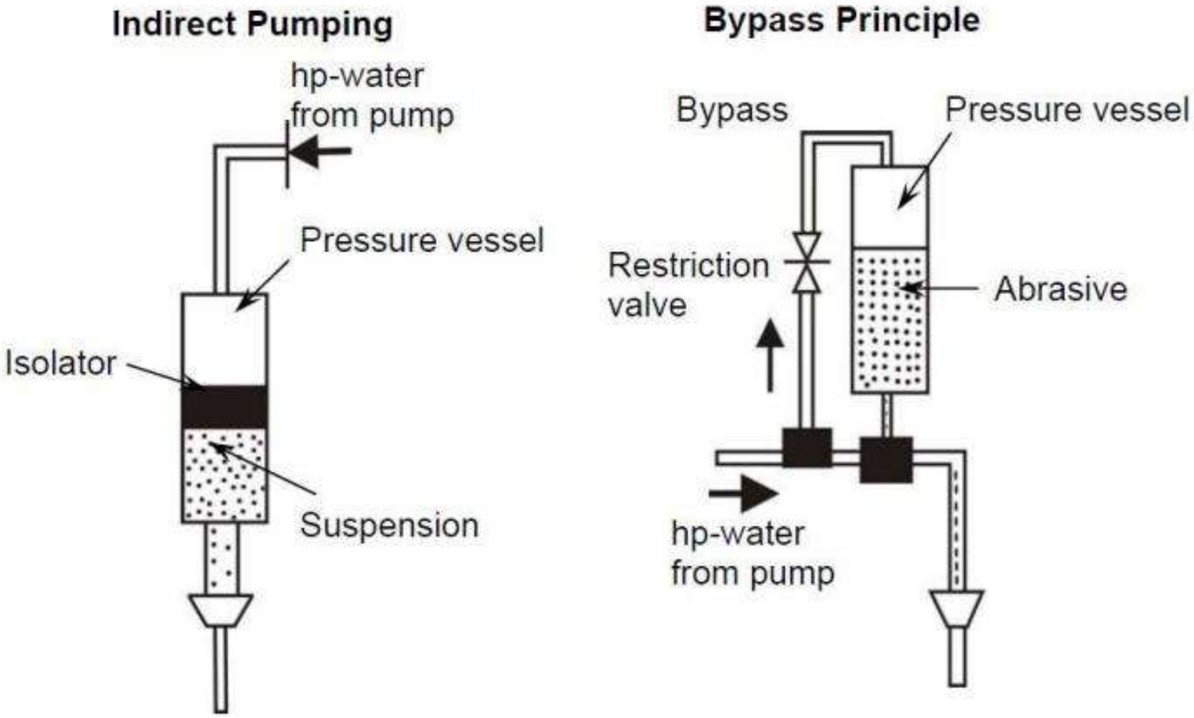


Fig. 6 Schematic of AWJM (Suspension type).

In suspension AWJM, preformed mixture of water and abrasive particles is pumped to a sufficiently high pressure and store in pressure vessel. Then the premixed high-pressure water and abrasive is allowed to discharge from a nozzle to form abrasive water jet.

3.2.6 Catcher

After the abrasive jet has been employed in machining, it may possess a considerable level of energy, varying according to the specific application. To prevent potential damage to any part of the machine or harm to operators, it is imperative to contain this high-energy abrasive water jet. A device known as a "catcher" is utilized to absorb and dissipate the residual energy of the abrasive water jet. Figure A7 illustrates three distinct types of catchers: the water basin type, submerged steel balls, and the TiB2 plate type.

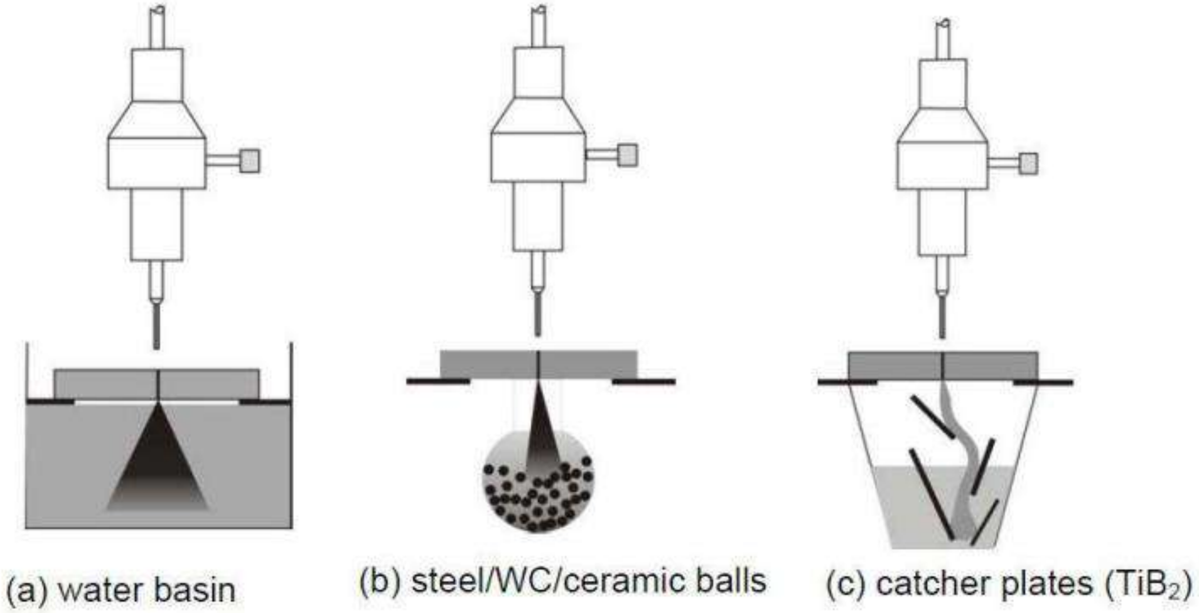


Fig. (A7) Some typical catchers

Additionally, the catcher can be classified as either pocket type or line type. In the pocket type, the catcher basin moves alongside the jet, while in the line type, the catcher basin traverses only along one axis of the CNC table, covering the width of the other axis.

Several noteworthy papers have concentrated on elucidating key process mechanisms for machining both ductile and brittle materials. Others have delved into the development of systematic experimental statistical approaches and artificial neural networks, aiming to predict the correlation between operational variable settings and machining rate, as well as accuracy in surface finishing. Abrasive jet machining (AJM) is recognized as an appealing and efficient method for working on hard and brittle materials [12]. The mechanisms and characteristics of abrasive jet machining have been prominent themes in recent research. AJM has gained increasing acceptance for deburring applications, offering an advantage over manual deburring methods by automatically generating edge radii, thereby enhancing the quality of deburred components.

In the removal of burrs and the generation of a convex edge, the process was found to vary based on parameters such as jet height and impingement angle, with a fixed standoff distance (SOD). Notably, the influence of other parameters, including nozzle pressure, mixing ratio, and abrasive size, was deemed insignificant. The SOD emerged as the most influential factor affecting the size of the radius generated at the edges. An increase in the nozzle-to-target distance (NTD) was found to correspond to an increase in hole diameter, as depicted in Figure B7.

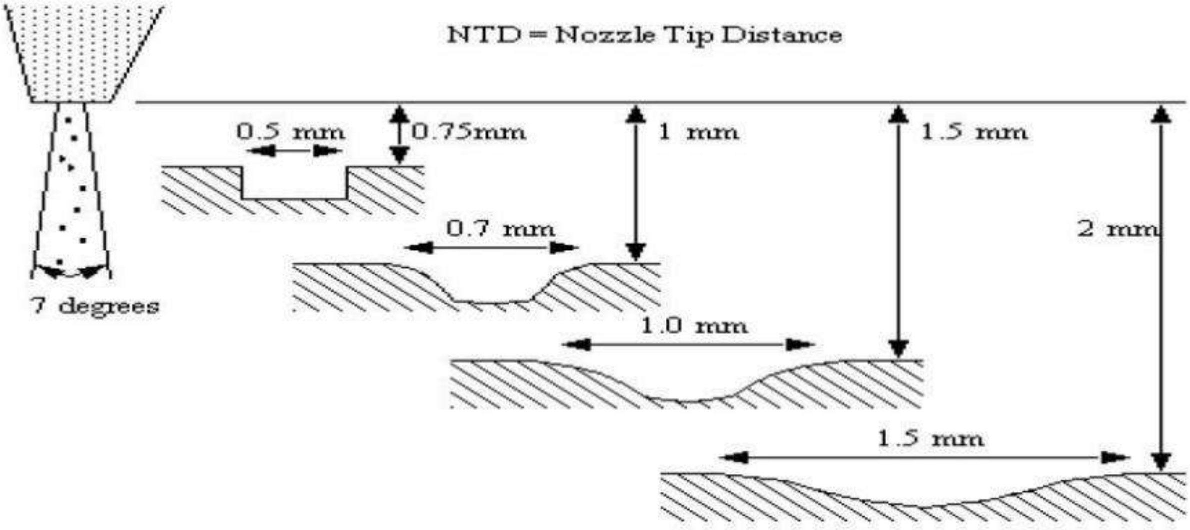


Fig. B7 Effect of nozzle tip distance (NTD) on diameter of hole

Chapter 4

Implementation

4.1 Introduction

The general domain of parameters in entrained type AWJ machining system is given below:

- Orifice – Sapphires – 0.1 to 0.3 mm
- Focussing Tube – WC – 0.8 to 2.4 mm
- Pressure – 2500 to 4000 bar
- Abrasive – garnet and olivine - #125 to #60
- Abrasive flow - 0.1 to 1.0 Kg/min
- Stand off distance – 1 to 2 mm
- Machine Impact Angle – 60o to 900
- Traverse Speed – 100 mm/min to 5 m/min
- Depth of Cut – 1 mm to 250 mm

The mechanism underlying material removal in water jet machining and abrasive water jet machining is notably intricate. In abrasive water jet machining (AWJM) of ductile materials, the primary mode of material removal involves low-angle impacts by abrasive particles, leading to ploughing and micro-cutting. This process was thoroughly investigated initially by Finnie [1], as documented in the edited volume by Engels [1]. Additionally, at higher angles of impact, material removal entails plastic failure of the material at the point of impact, a phenomenon initially explored by Bitter [2,3]. Hashish [4] later unified these models, applying them to AWJM. In the case of AWJM of brittle materials, material removal, apart from the aforementioned models, occurs due to crack initiation and propagation resulting from the brittle failure of the material. Kim et al. [5] extensively delved into this aspect within the context of AWJM.

In water jet machining, the material removal rate may be assumed to be proportional to the power of the water jet.

$$MRR \propto P_{wj} \propto c_d \times \frac{\Pi}{4} d_o^{\ 2} \times \sqrt{\frac{2 p_w^{\ 3}}{\rho_w}}$$

$$MRR = u \times c_d \times \frac{\Pi}{4} d_o^{\ 2} \times \sqrt{\frac{2 p_w^{\ 3}}{\rho_w}}$$

The proportionality constant u is the specific energy requirement and would be a property of the work material.

Fig. 8, Fig. 9, Fig. 10 and Fig. 11 show the cut generated by an AWJM in different sections. It is called a kerf.

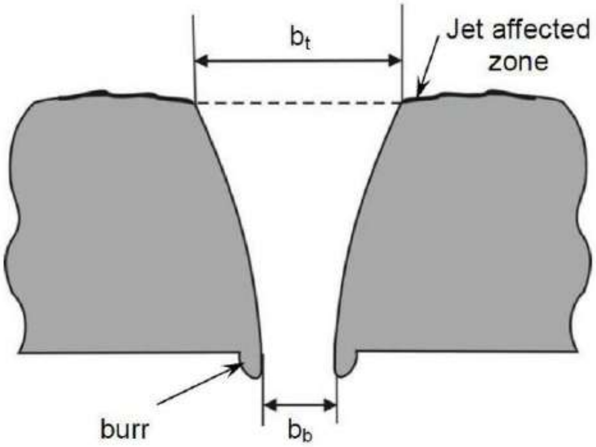


Fig. 8 Schematic of AWJM kerf

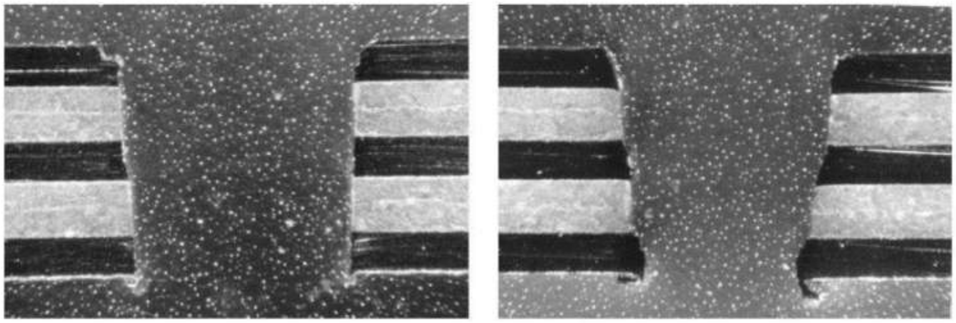


Fig. 9 Photographic view of kerf (cross section)

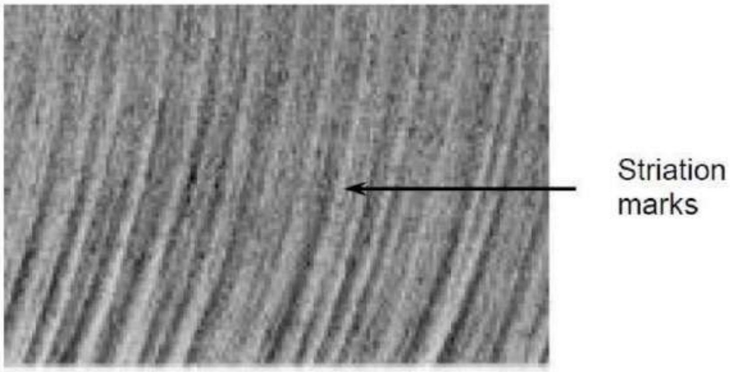


Fig. 10 Photographic view of kerf (longitudinal section)

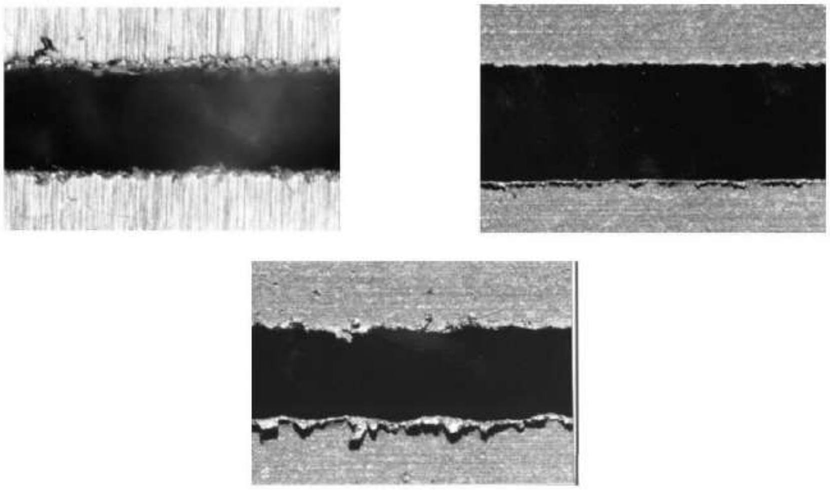


Fig. 11 Photographic view of the kerf (back side)

The upper portion of the kerf exhibits a greater width than the lower section. Typically, the top width of the kerf aligns with the diameter of the abrasive water jet (AWJ). To reiterate, the diameter of the AWJ corresponds to the diameter of the focusing tube or insert when the stand-off distance is approximately 1 to 5mm. Increasing the cutting ability of the AWJ serves to reduce the taper angle of the kerf. In Figure 12, a longitudinal section of the kerf is depicted, showcasing that the surface quality at the top of the kerf is relatively superior compared to the lower part. The bottom section displays repeated curved line formations. Material removal at the top of the kerf is attributed to the low-angle impact of the abrasive particle, while at the bottom, it is primarily through plastic failure. The formation of striations is a consequence of repeated instances of plastic failure.

In Figure 11, the exit side of the kerf is depicted. Despite having been machined with the same diameter of the abrasive water jet (AWJ), variations in width are evident owing to the tapering of the kerf. Additionally, noticeable burr formation is observed at the exit side of the kerf in all three instances.

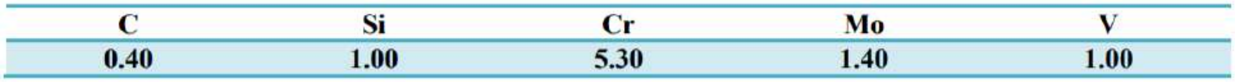
Thus, in WJM and AWJM the following are the important product quality parameters.

- striation formation
- surface finish of the kerf
- tapering of the kerf
- burr formation on the exit side of the kerf

While the models presented by Finnie, Bitter, Hashish, and Kim offer comprehensive insights into the material removal mechanism, their applicability demands extensive information on various aspects and parameters, which may not be readily accessible.

4.2 Experimental Procedure

Specimen detail:



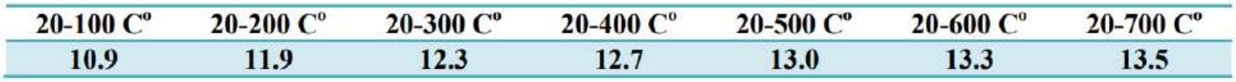
C	Si	Cr	Mo	V
0.40	1.00	5.30	1.40	1.00

Steel properties

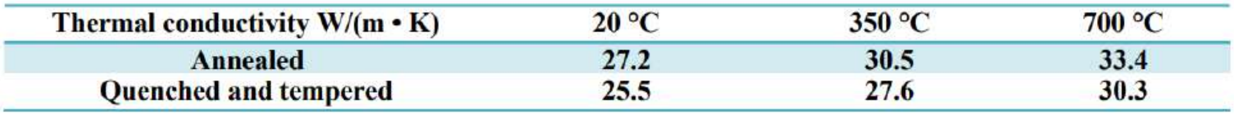
High hot-wear resistance, high hot tensile strength and toughness. Good thermal conductivity and insusceptibility to hot cracking.Can be water-cooled to a limited extent.

Physical properties

Coefficient of thermal expantion 10-6m/(mo .K)



20-100 C°	20-200 C°	20-300 C°	20-400 C°	20-500 C°	20-600 C°	20-700 C°
10.9	11.9	12.3	12.7	13.0	13.3	13.5



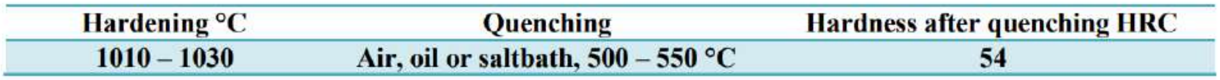
Thermal conductivity W/(m • K)	20 °C	350 °C	700 °C
Annealed	27.2	30.5	33.4
Quenched and tempered	25.5	27.6	30.3

Applications

Hot-work steel for universal use. Pressure casting dies and metal extrusion tools for processing light metals, forging dies, mandrels. Moulds, screws and barrels for plastic processing, nitride ejectors, hot-shear blades.

Heat treatment

Soft annealing °C	Cooling	Hardness HB
750 – 800	Furnace	max. 230



Hardening °C	Quenching	Hardness after quenching HRC
1010 – 1030	Air, oil or saltbath, 500 – 550 °C	54

Tempering °C	100	200	300	400	500	550	600	650	700
HRC	53	52	52	54	56	54	50	42	32

Fig. 12 specimen for the testing parameters.

Pressure = 2500 bar. Stand-off distance = 3 mm.

V = 30 mm/min. V = 60 mm/min. V = 90 mm/min.

Pressure = 2500 bar. Stand-off distance = 5 mm.

V = 30 mm/min. V = 60 mm/min. V = 90 mm/min.

Pressure = 2500 bar. Stand-off distance = 7 mm.

V = 30 mm/min. V = 60 mm/min. V = 90 mm/min.

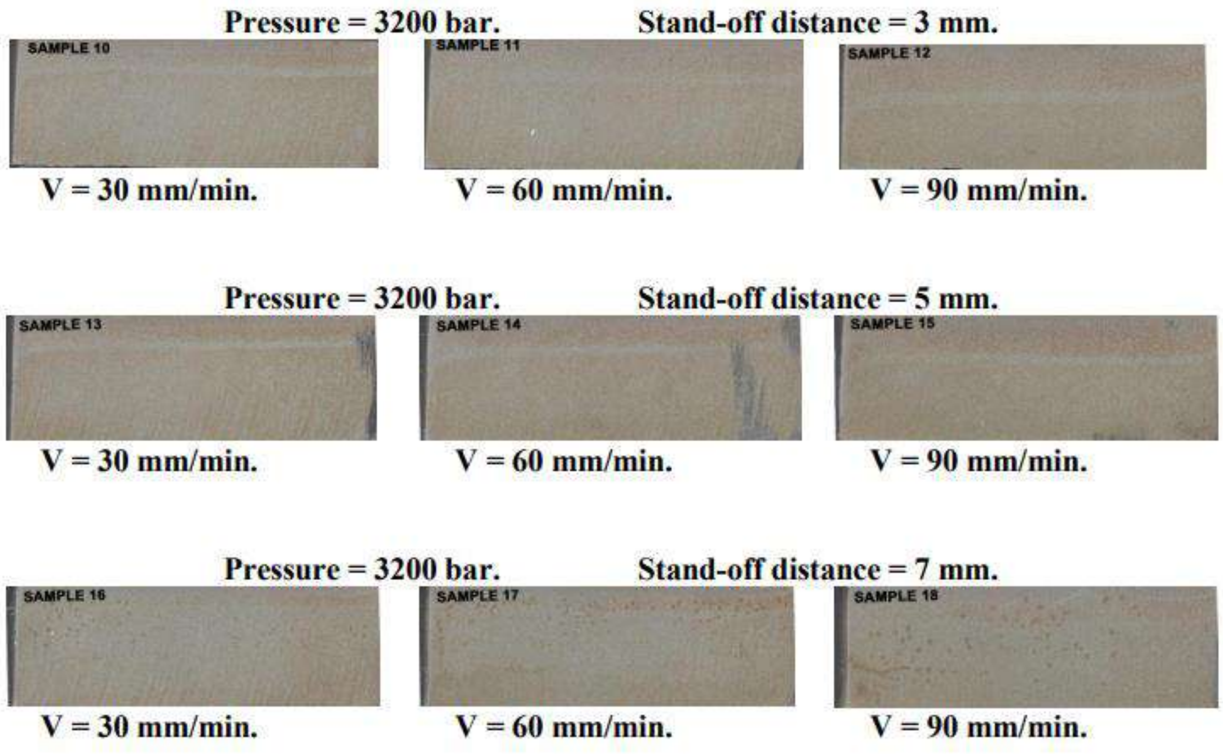


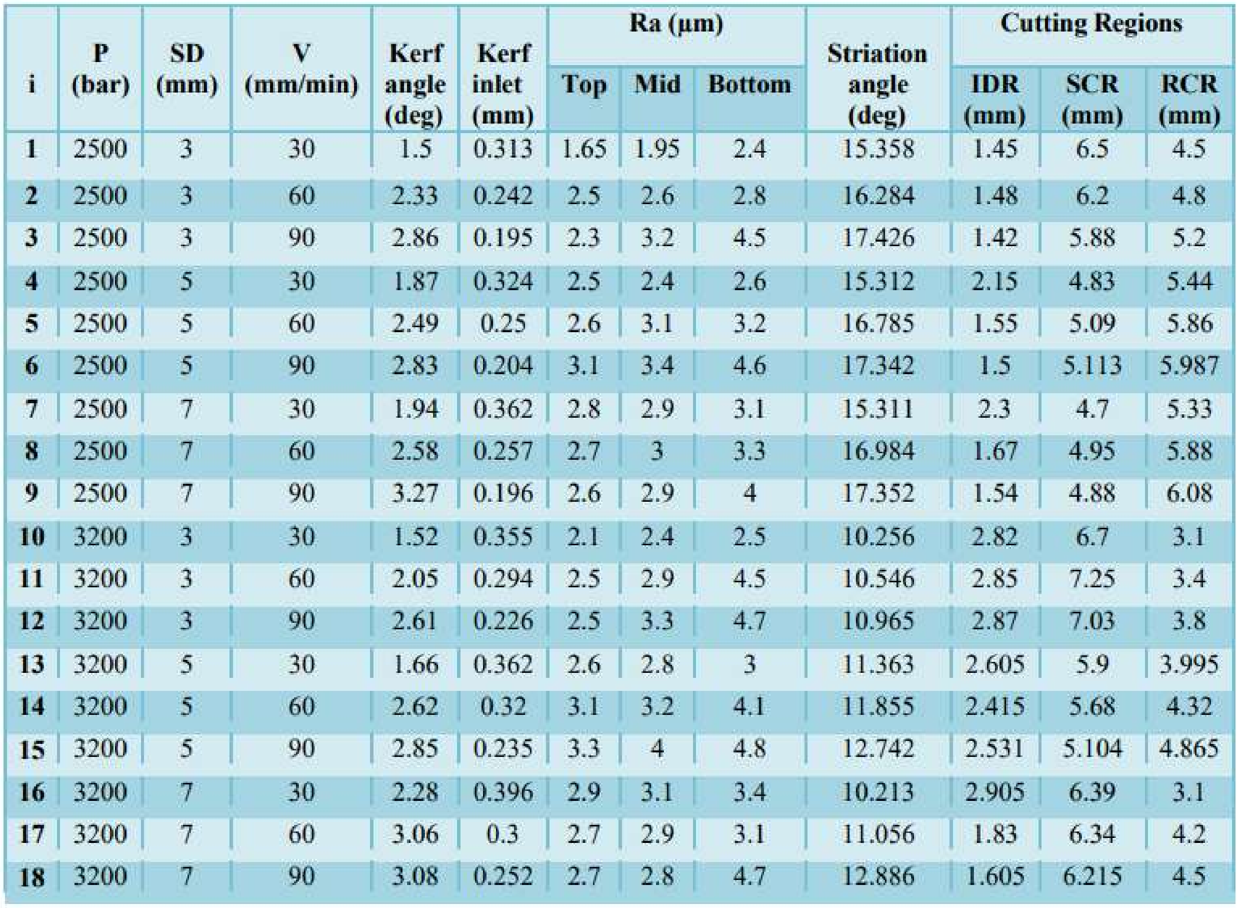
Fig. 13 specimen detail After Cutting process.

The material selected for this study was commercial steel 2344, possessing a thickness of 12 mm. The nominal chemical and physical composition of the steel is detailed in the table provided above. The experiments were conducted using an Abrasive Water Jet (AWJ). Various traverse speeds of 30, 60, and 90 mm/min were employed at two different pressures: 2500 and 3200 bar, as depicted in Figure 13. The experiments included different stand-off distances, ranging from 3, 5, and 7 mm, while the angle remained constant with the abrasive flow rate. Post-machining, the microstructures of the cutting surfaces were examined using a scanner.

The average surface roughness for the machined surface was measured in three distinct regions on each surface: IDR (Initial Damage Region), SCR (Smooth Cutting Region), and RCR (Rough Cutting Region), as illustrated in Figure 14.

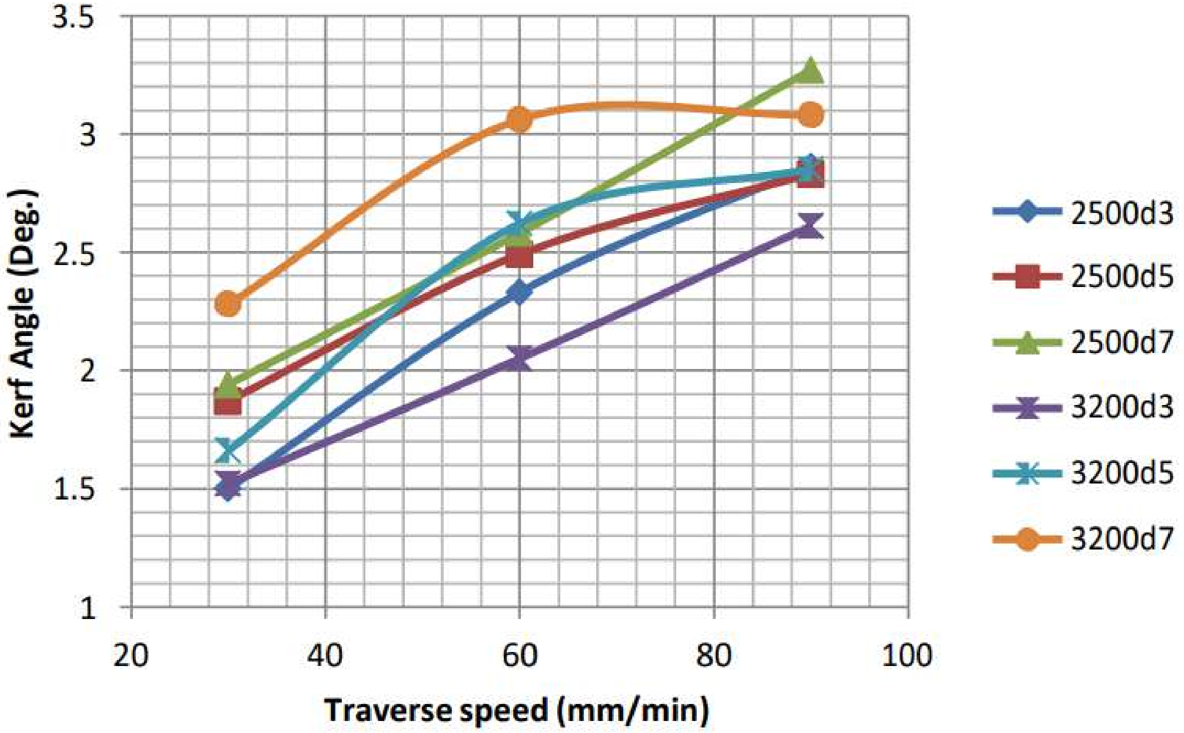
Fig. 14 Cutting zone (Damage regions) for the specimen.

Parameter:



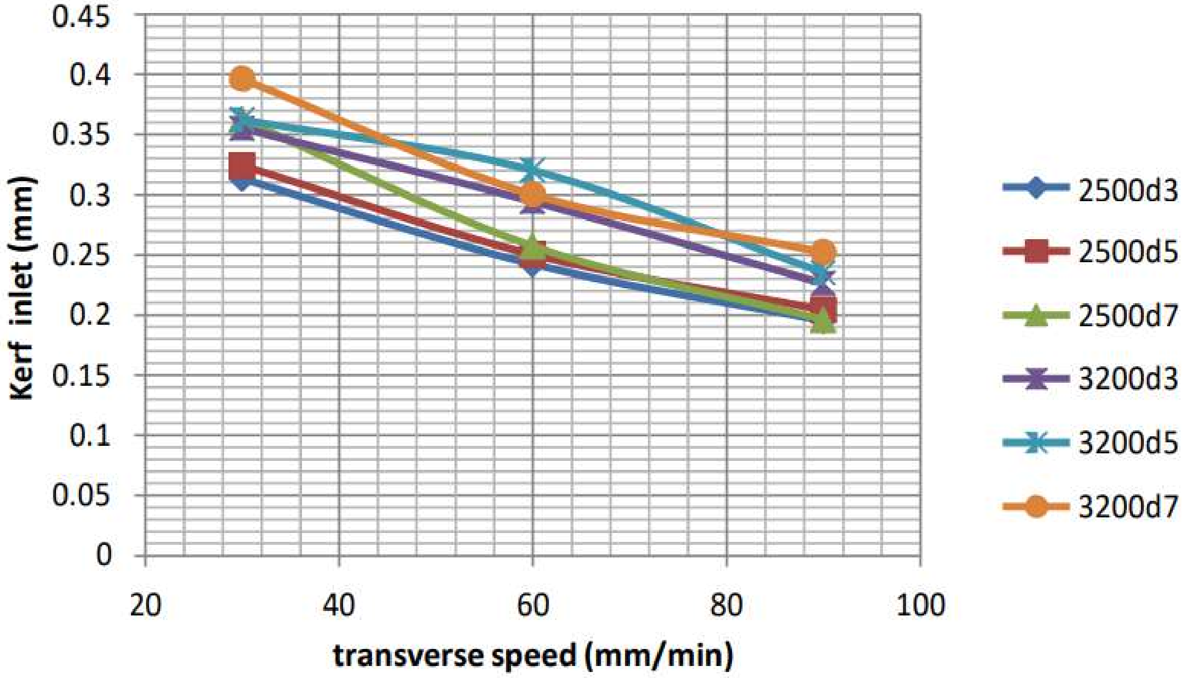
i	P (bar)	SD (mm)	V (mm/min)	Kerf angle (deg)	Kerf inlet (mm)	Ra (µm)			Striation angle (deg)	Cutting Regions		
						Top	Mid	Bottom		IDR (mm)	SCR (mm)	RCR (mm)
1	2500	3	30	1.5	0.313	1.65	1.95	2.4	15.358	1.45	6.5	4.5
2	2500	3	60	2.33	0.242	2.5	2.6	2.8	16.284	1.48	6.2	4.8
3	2500	3	90	2.86	0.195	2.3	3.2	4.5	17.426	1.42	5.88	5.2
4	2500	5	30	1.87	0.324	2.5	2.4	2.6	15.312	2.15	4.83	5.44
5	2500	5	60	2.49	0.25	2.6	3.1	3.2	16.785	1.55	5.09	5.86
6	2500	5	90	2.83	0.204	3.1	3.4	4.6	17.342	1.5	5.113	5.987
7	2500	7	30	1.94	0.362	2.8	2.9	3.1	15.311	2.3	4.7	5.33
8	2500	7	60	2.58	0.257	2.7	3	3.3	16.984	1.67	4.95	5.88
9	2500	7	90	3.27	0.196	2.6	2.9	4	17.352	1.54	4.88	6.08
10	3200	3	30	1.52	0.355	2.1	2.4	2.5	10.256	2.82	6.7	3.1
11	3200	3	60	2.05	0.294	2.5	2.9	4.5	10.546	2.85	7.25	3.4
12	3200	3	90	2.61	0.226	2.5	3.3	4.7	10.965	2.87	7.03	3.8
13	3200	5	30	1.66	0.362	2.6	2.8	3	11.363	2.605	5.9	3.995
14	3200	5	60	2.62	0.32	3.1	3.2	4.1	11.855	2.415	5.68	4.32
15	3200	5	90	2.85	0.235	3.3	4	4.8	12.742	2.531	5.104	4.865
16	3200	7	30	2.28	0.396	2.9	3.1	3.4	10.213	2.905	6.39	3.1
17	3200	7	60	3.06	0.3	2.7	2.9	3.1	11.056	1.83	6.34	4.2
18	3200	7	90	3.08	0.252	2.7	2.8	4.7	12.886	1.605	6.215	4.5

4.3 Results



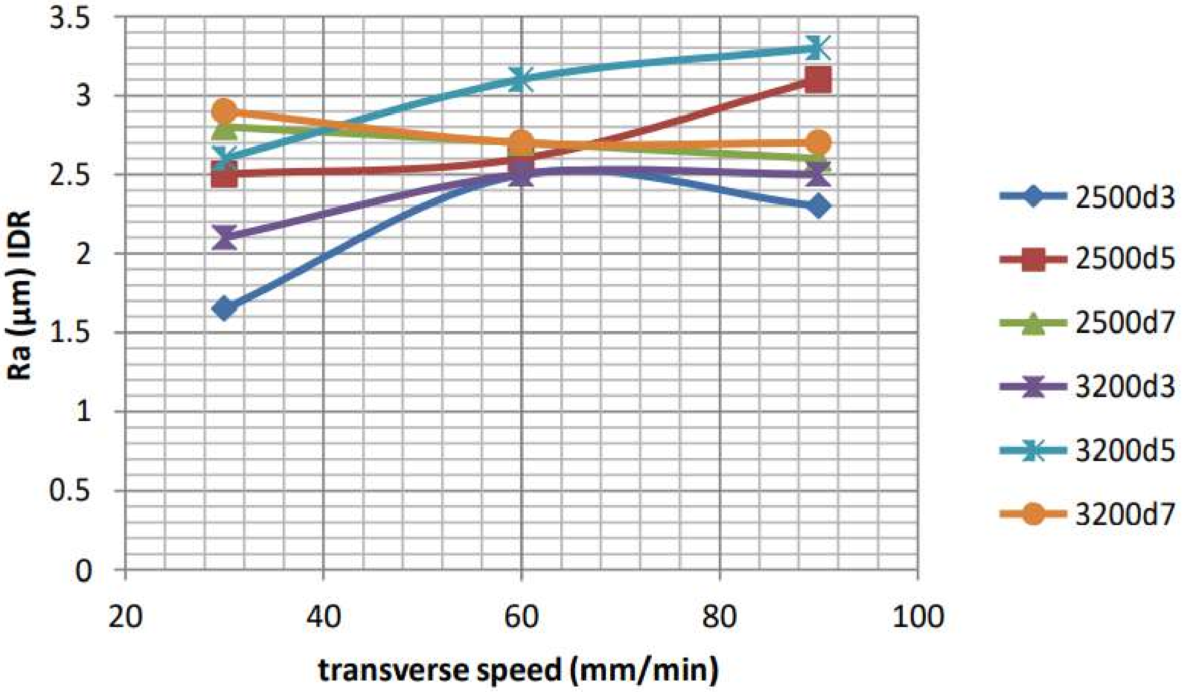
Graph 1 Shows the Relation between Kerf angle & Transverse speed.

Graph 1 indicates that the kerf angle degree increases with the traverse speed. However, this variation is more pronounced at 2500 bar compared to 3200 bar, showcasing a more substantial change at the lower pressure. In this context, the pressure level significantly influences the observed effect.



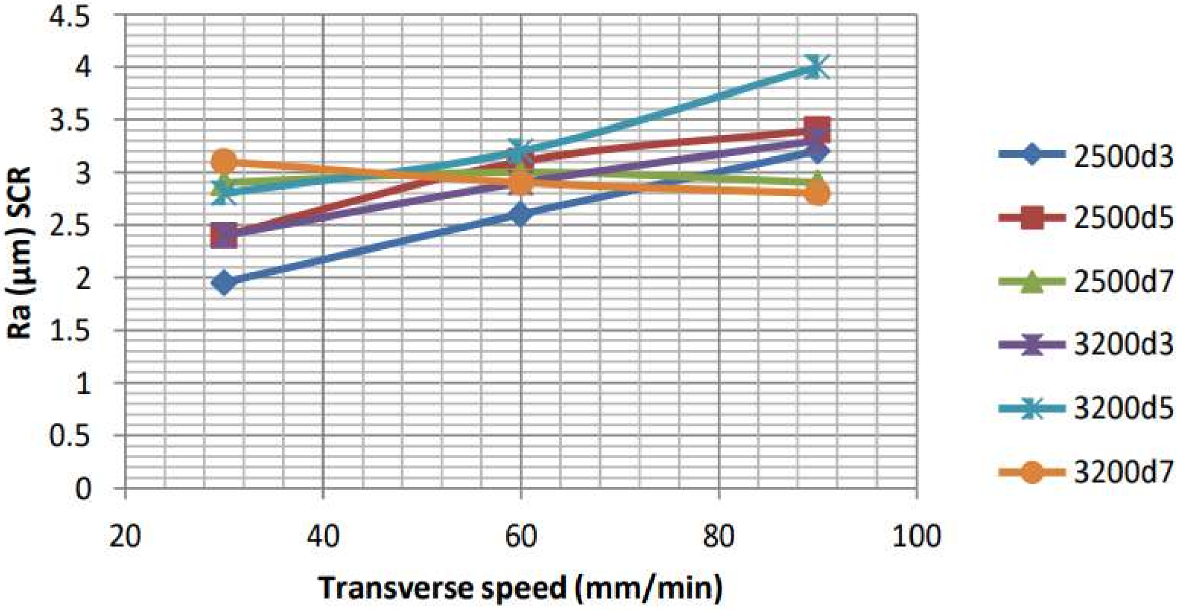
Graph 2 Shows the Relation between Kerf inlet & Transverse speed.

In Graph 2, the kerf inlet decreases as the traverse speed increases, indicating an inverse relationship between them. Notably, at 2500 bar, the kerf inlet is less compared to the value observed at 3200 bar.



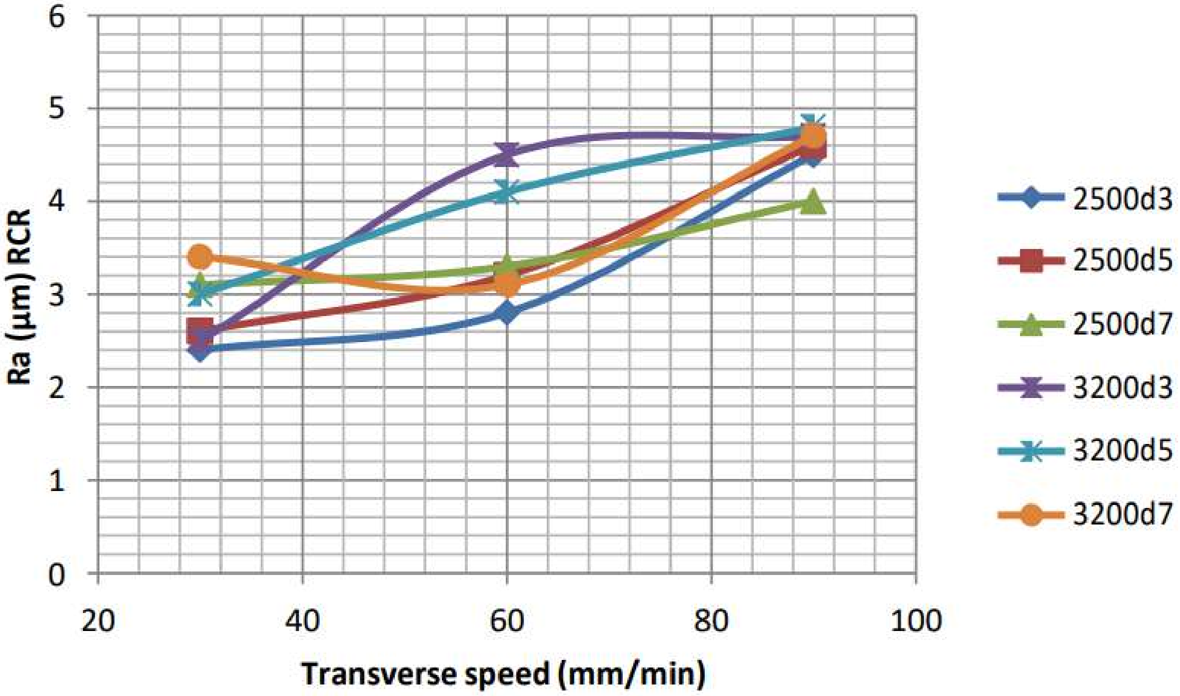
Graph 3 Shows the Relation between Ra-IDR & Transverse speed.

In graph 3 shown with increasing the traverse speed cause to increase in surface roughness at IDR (Initial Damage Region) thus; at a pressure 2500 bar surface roughness become less than the 3200 bar according to the curves.



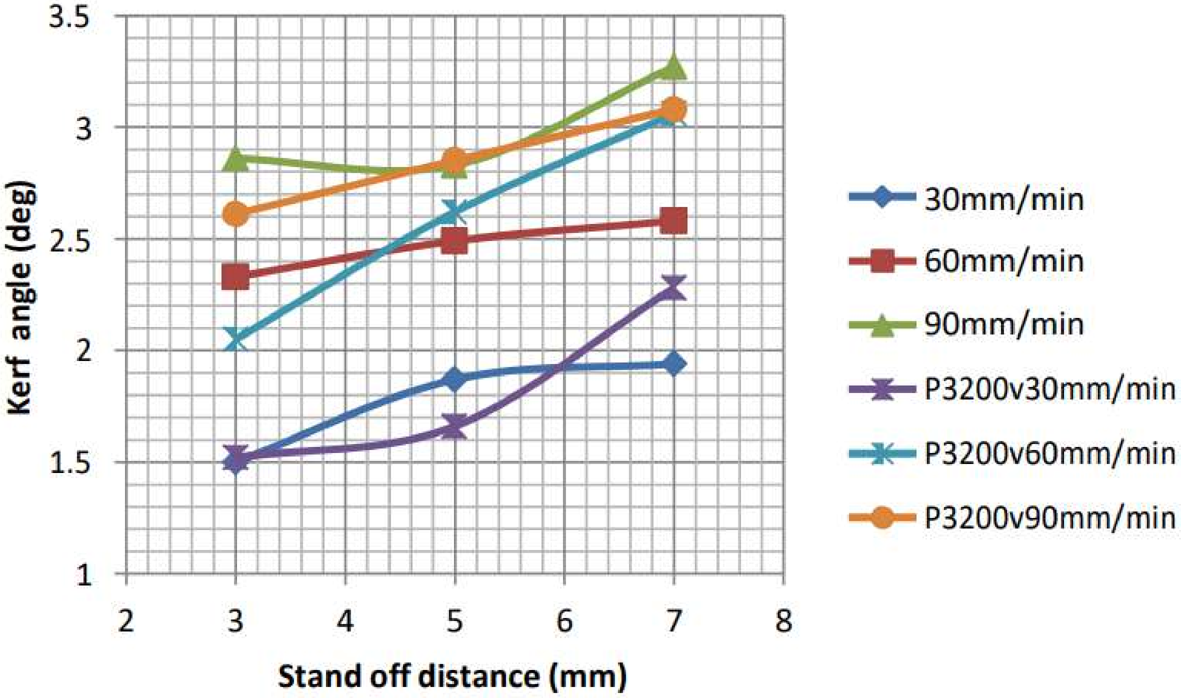
Graph 4 Shows the Relation between Ra-SCR & Transverse speed.

In graph 4 shown with increasing the traverse speed cause to increase in surface roughness at SCR (Smooth Cutting Region) thus; at a pressure 2500 bar surface roughness become less than the 3200 bar according to the curves. The same situation at IDR.



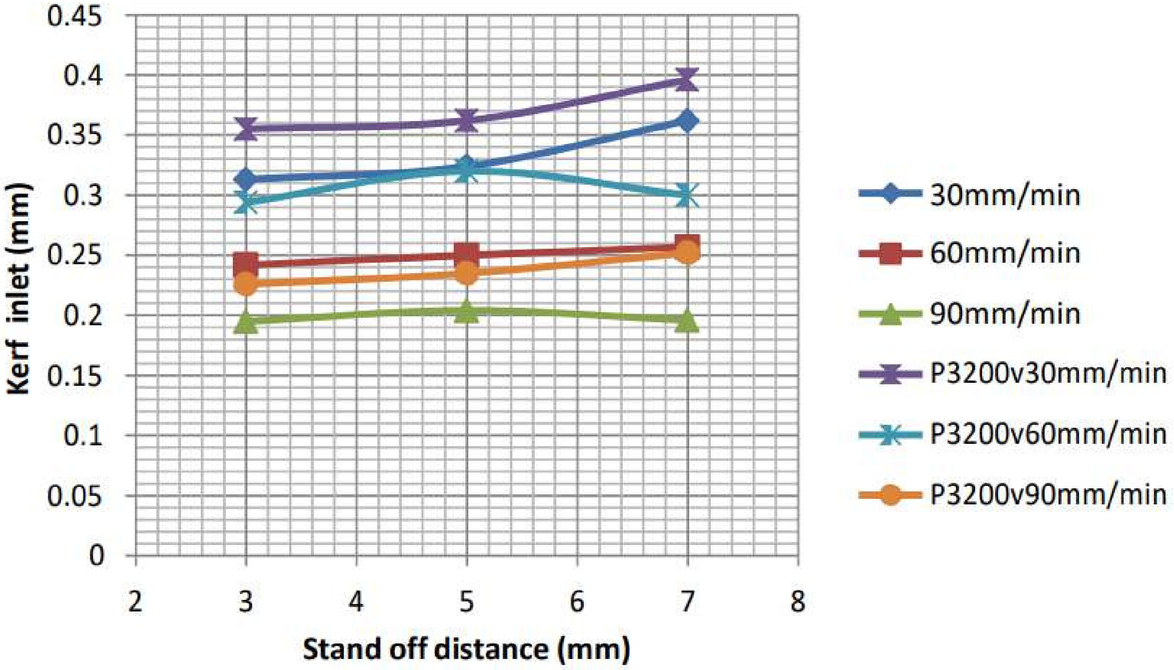
Graph 5 Shows the Relation between Ra-RCR & Transverse speed.

In graph 5 shown with increasing the traverse speed cause to increase surface roughness at RCR (Rough Cutting Region) thus; at a pressure 2500 bar surface roughness become less than the 3200 bar according to the curves.



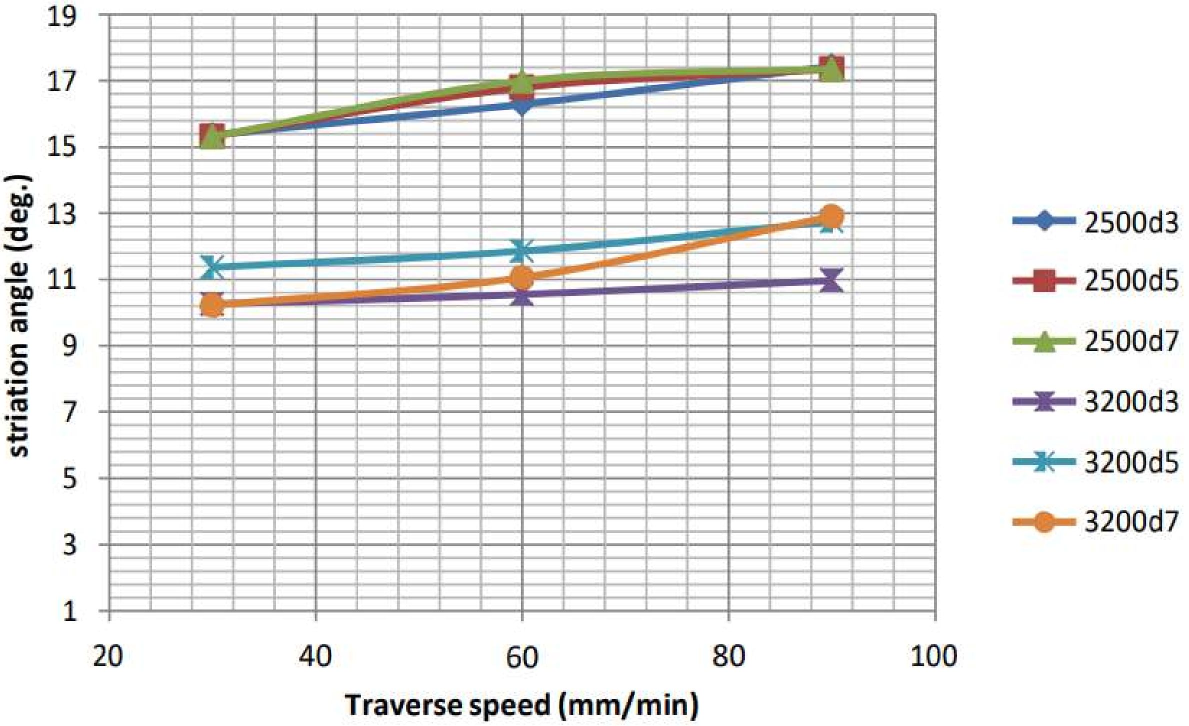
Graph 6 Shows the Relation between Kerf angle & Standoff distance.

According to the graph 6. Due to the increment in kerf angle by the stand-off distance, since it increased with increasing the traverse speed.



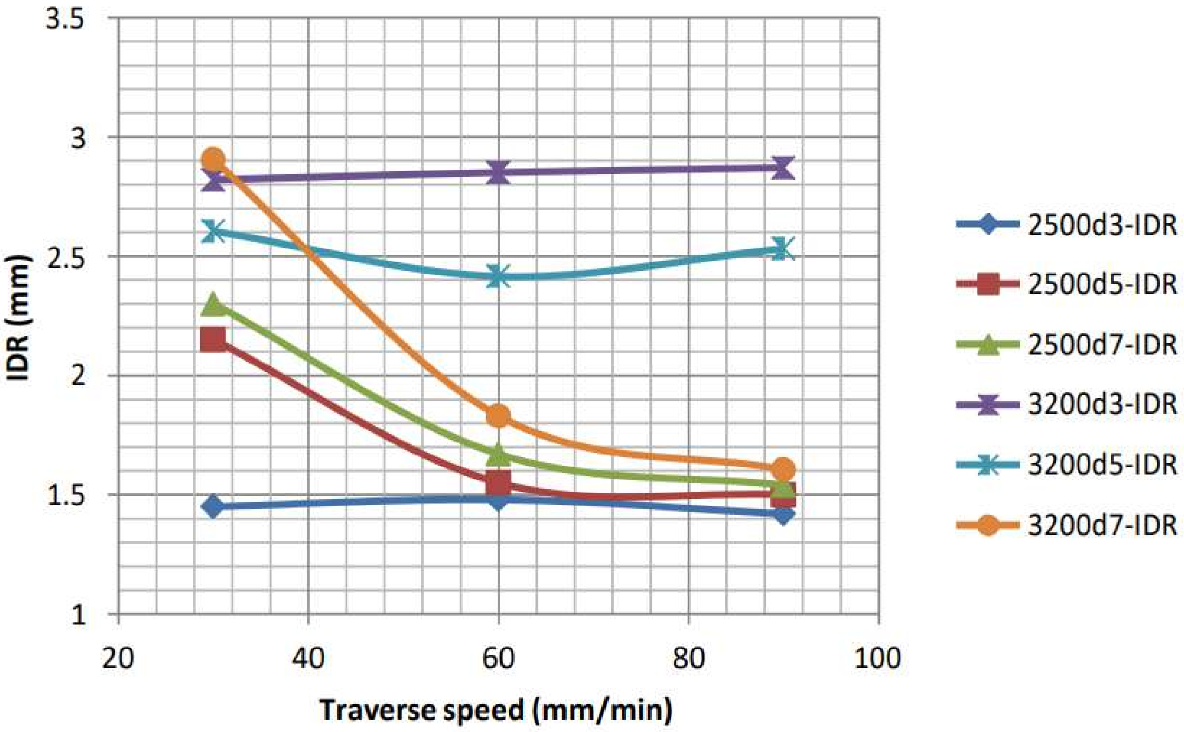
Graph 7 Shows the Relation between Kerf inlet & Standoff distance.

At graph 7 shown. Due to the increment in the kerf inlet by stand-off distance, but it's very small.



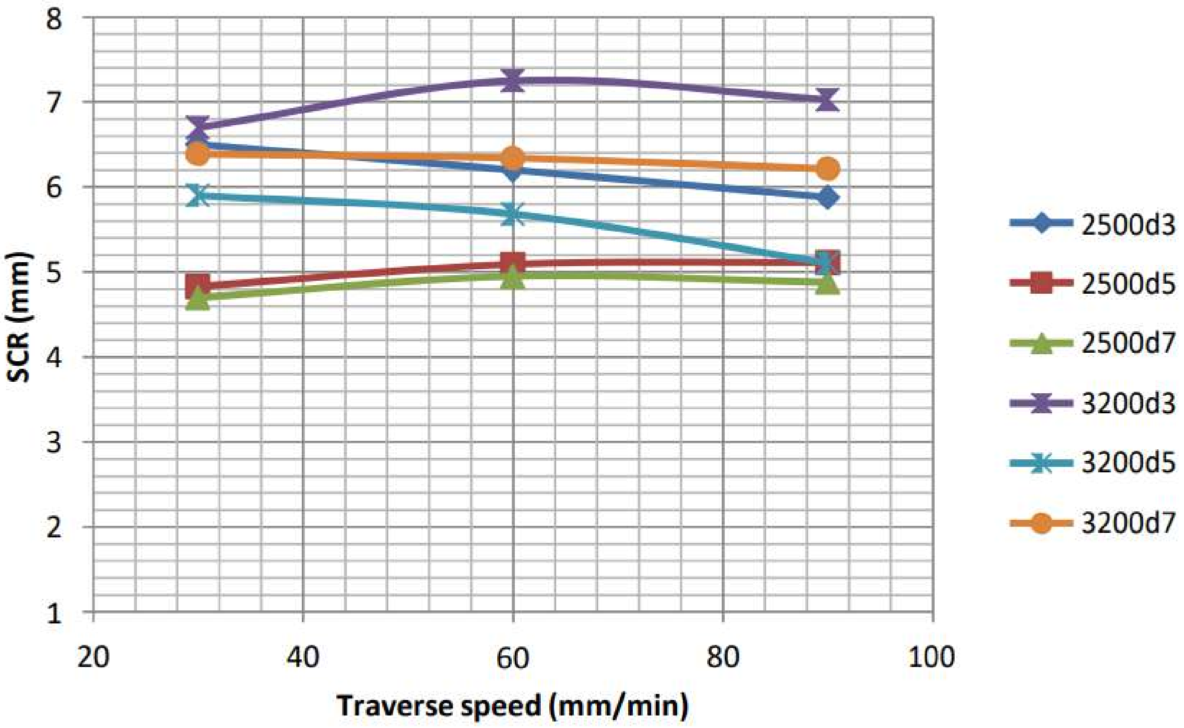
Graph 8 Shows the Relation between striation angle & Traverse speed.

At graph 8 shown above. Due to the increase in the striation angle by traverse speed. In the different manner of the pressure we note that the same increment, but striation angle decreased with pressure rise.



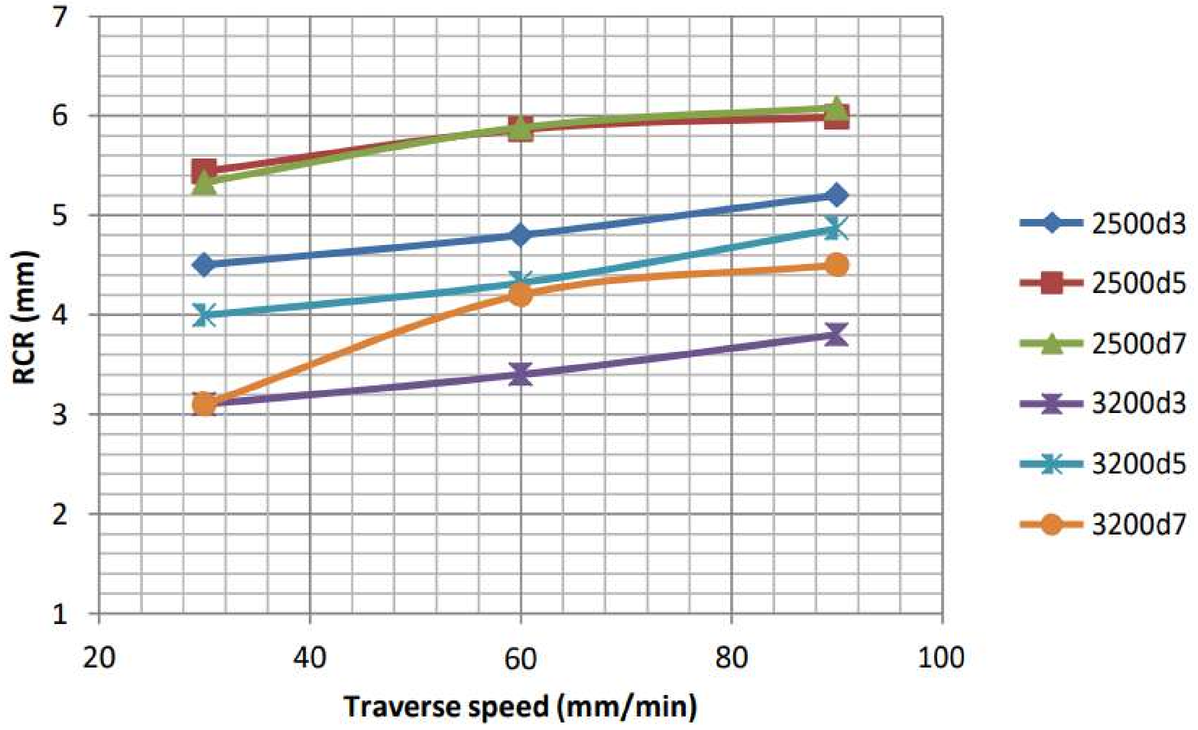
Graph 9 Shows the Relation between IDR & Traverse speed.

At graph 9 shown. The increment in the initial damage region by increasing the pressure and decreased by increasing the traverse speed, but it differ in the other manner as shown clearly on the graph.



Graph 10 Shows the Relation between SCR & Traverse speed.

At graph 10. Again due to the increment of the Smooth Cutting Region by the pressure increment although; by increasing the traverse speed it drops down and this is differ from manner to other as shown clearly at the graph.



Graph 11 Shows the Relation between RCR & Traverse speed.

At graph 11. Due to the increment in the Rough Cutting Region by the increasing traverse speed and the RCR decreased by increasing the pressure.

4.3.1 Advantages AWJM

- Cut virtually any material
- Fast setup and programming
- Little fixturing for most parts
- Almost no heat generated on your part
- No mechanical stresses
- Machine thick material
- very safe
- Environmentally friendly
- No start hole required
- Narrow kerf removes only a small amount of material
- No deflection of the rest of the workpiece takes place,thus the process is suitable for flexible materials
- Burr production is minimal.

4.4 conclusion

The study delved into the impact of various operational parameters, including pressure, traverse speed, and nozzle stand-off distance.

It was observed that manipulating the traverse cutting speed effectively governed the surface properties resulting from the Abrasive Water Jet (AWJ) cutting process. This, in turn, influenced both the surface and microstructural properties near the edge.

Moreover, the control of traverse cutting speed was identified as a determining factor in the cut-edge roughness characteristics of AWJ surfaces. Adjusting the traverse cutting speeds had additional effects on the localized near-edge stresses, allowing for a balance between work hardening levels and the formation of the surface roughness profile during the AWJ cutting process.

The unique capability of AWJ to cut with high accuracy without employing heat is leveraged in effective applications. Such applications are justified based on the attainment of high part quality and the elimination of secondary operations. When considering all associated costs, abrasive waterjet cutting emerges as the most cost-effective solution for numerous applications.

Chapter 5

Discussion, conclusion and future works

5.1 Introduction

The preceding chapters have provided a comprehensive exploration of the experimental study on surface roughness in water jet cutting, specifically focusing on the abrasive water jet (AWJ) process. Various operational parameters, including pressure, traverse speed, and nozzle stand-off distance, were systematically investigated to discern their effects on the cutting outcomes. This section delves into the discussion and interpretation of the obtained results, shedding light on the intricate interplay of these parameters and their implications for surface roughness in AWJ machining.

The examination of the traverse cutting speed emerges as a central theme in this study, as it was identified as a pivotal factor in influencing both surface properties and near-edge microstructural features. The intricacies of how altering traverse cutting speeds impacts cut-edge roughness properties and localized near-edge stresses will be explored in detail. Furthermore, the unique capabilities of AWJ, particularly its accuracy in cutting without generating heat, will be considered in the context of applications that prioritize high part quality and the reduction of secondary operations.

This chapter not only reflects on the outcomes of the experimental study but also lays the groundwork for drawing meaningful conclusions and outlining potential avenues for future research in the realm of water jet cutting. The subsequent sections delve into a detailed discussion of the obtained results, followed by concluding remarks and a glimpse into the potential directions for future investigations.

5.2 Results Discussion

The investigation into the effects of operational parameters on surface roughness in abrasive water jet (AWJ) cutting has yielded valuable insights. The traverse cutting speed, in particular, emerged as a key determinant in shaping the surface properties and near-edge microstructural characteristics.

5.2.1 Traverse Cutting Speed

Manipulating the traverse cutting speed proved to be a potent tool for controlling the surface properties induced by the AWJ cutting process. The observed variations in surface and near-edge microstructural properties highlight the sensitivity of the cutting outcomes to this parameter. Higher traverse cutting speeds were associated with distinct changes in the surface features, emphasizing the dynamic relationship between cutting speed and surface quality. This nuanced understanding is crucial for tailoring AWJ cutting processes to specific requirements, where achieving optimal surface properties is paramount.

5.2.2 Cut-Edge Roughness

The influence of traverse cutting speed on cut-edge roughness properties was notable. As cutting speeds were adjusted, discernible changes in cut-edge roughness characteristics were observed. The intricacies of this relationship can be instrumental in achieving desired surface finishes for diverse applications. The ability to modulate cut-edge roughness through control of traverse cutting speed offers a practical avenue for optimizing the machining process based on specific requirements.

5.2.3 Localized Near-Edge Stresses

Beyond surface properties, the study revealed that altering traverse cutting speeds influences localized near-edge stresses. Striking a balance between work hardening and the formation of the surface roughness profile is crucial for achieving desired outcomes. This nuanced understanding of the interplay between cutting speed and localized near-edge stresses contributes to the refinement of AWJ machining strategies.

In summary, the results discussion emphasizes the intricate relationships uncovered during the experimental study. The impact of traverse cutting speed on surface properties, cut-edge roughness, and localized near-edge stresses underscores the need for a nuanced approach to AWJ machining. The insights gained pave the way for more informed decision-making in practical applications and lay the foundation for the conclusive remarks to follow in the subsequent section.

5.3 Conclusion

The study delved into the impact of various operational parameters, including pressure, traverse speed, and nozzle stand-off distance.

It was observed that manipulating the traverse cutting speed effectively governed the surface properties resulting from the Abrasive Water Jet (AWJ) cutting process. This, in turn, influenced both the surface and microstructural properties near the edge.

Moreover, the control of traverse cutting speed was identified as a determining factor in the cut-edge roughness characteristics of AWJ surfaces. Adjusting the traverse cutting speeds had additional effects on the localized near-edge stresses, allowing for a balance between work hardening levels and the formation of the surface roughness profile during the AWJ cutting process.

The unique capability of AWJ to cut with high accuracy without employing heat is leveraged in effective applications. Such applications are justified based on the attainment of high part quality and the elimination of secondary operations. When considering all associated costs, abrasive waterjet cutting emerges as the most cost-effective solution for numerous applications.

5.4 Future Works

The current experimental study on surface roughness in abrasive water jet (AWJ) cutting has illuminated several intriguing avenues for future research. The complexity of the AWJ machining process, coupled with the nuanced effects of operational parameters, prompts the identification of key areas for further investigation.

5.3.1 Optimization Strategies

Future research endeavors should delve into the development of advanced optimization strategies for AWJ machining. Exploring the intricate relationships between operational parameters and their impact on surface roughness could lead to the formulation of robust optimization models. This could involve the integration of machine learning algorithms, statistical approaches, or artificial intelligence techniques to enhance the precision and efficiency of AWJ processes.

5.3.2 Advanced Materials

Expanding the scope of the study to encompass a broader range of materials would provide valuable insights into the versatility and limitations of AWJ machining. Investigating the effects of operational parameters on surface roughness in the context of advanced materials, such as composites or exotic alloys, could uncover novel challenges and opportunities. This exploration would be essential for adapting AWJ processes to the evolving landscape of materials engineering.

5.3.3 Hybrid Machining Techniques

Considering the growing trend toward hybrid machining approaches, future research could explore the integration of AWJ with other cutting technologies. Combining AWJ with complementary techniques, such as laser cutting or traditional milling, could offer synergistic advantages. Exploring the synergies and trade-offs in hybrid machining could pave the way for enhanced precision, efficiency, and versatility in material processing.

5.3.4 Environmental Considerations

In light of increasing environmental awareness, future studies could focus on the ecological footprint of AWJ machining. Exploring sustainable practices, optimizing abrasive material usage, and minimizing waste generation are essential aspects that align with contemporary environmental priorities. Investigating eco-friendly adaptations of AWJ processes would contribute to the sustainability of advanced machining technologies.

In conclusion, the identified future research directions underscore the dynamic nature of AWJ machining and its potential for continuous improvement. By addressing these areas, researchers can contribute to the advancement of AWJ technology, ensuring its relevance and effectiveness in the evolving landscape of precision machining.

References

- [1] Hoogstrate A.M., van Luttervelt A.M.;Opportunitirs in Abrasive Water-Jet Machining, Annals of the CIRP Vol. 46/2/1997
- [2] Janković P., Radovanović M., Parameters of Abrasive Waterjet Cutting Process, 6th International Conference ”Research and Development in Mechanical Industry”-RaDMI 2006, Budva, Montenegro, 2006, pp.343-346
- [3] Janković, P., Radovanović, M., Vicovac, N.: High-pressure pump - "Heart" of the machine for contour cutting by an abrasive water jet, 29. HIPNEF, 2004, Vrnjačka Banja
- [4] Radovanović M., Characteristics of Abrasive Waterjet, 3th International Conference "Research and Development in Mechanical Industry"-RaDMI 2003, Herceg Novi, Serbia and Montenegro, 2003, pp. 469-473
- [5] Radovanovic M., Dasic P., Stefanek M., Some Possibilities for Determining Abrasive Waterjet Cutting Parameters, 13. International Conference "Co-Mat-Tech 2005", Trnava, Slovakia, 2005, pp. 969-976
- [6] Radovanovic M., Determining of Cutting Data by Abrasive Waterjet Cutting, XII International Conference ”Machine-building and Technosphere of the XXI Century”, Sevastopol, Ukraine, 2005, pp.221-225
- [7] Radovanovic M., Estimate of Cutting Speed by Abrasive Waterjet Cutting, The 31st Internationally Attended Scientific Conference "Modern Technologies in the XXI Century", Bucharest, Romania. 2005, pp. 8.196-8.203
- [8] Radovanović M., Mathematical modeling of cutting speed by abrasive waterjet, Nadiinist instrumentu ta optimizacia tehnologičnih sistem, No.21 2007, ISBN 966-379-149-4, UDK 621.9: 658.3: 519.8, Sbornik naučnih trudov, Ministerstvo osviti i nauki Ukraini, Donbaska deržavna mašinobudivna akademia, Kramatorsk, Ukraina, 2007, pp. 273-279
- [9] www.kmtgroup.com - web site of "KMT Waterjet Systems Inc.
- [10] M. Roopa Rani & S. Seshan “AJM - Procees Variables And Current Applications”, Publication-Journal of Metals Materials& Process,1995 Vol.7 No. 4 PP.279-290