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Multi Objective optimization in micromilling of titanium alloy (Ti6Al4V) under Dry, Wet and MQL using gray relational analysis

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DEDICATION

To my Beloved Mother,

Without whom none of my success

Would have been possible

&

To my Respected Teachers,

Who acted like compass

that activated the magnets of

curiosity, knowledge and wisdom in me

Abstract

Micromilling is among the most significant and extensively employed types of micromechanical machining, attributed to its ability to reach higher precision requirements, even when machining high-strength materials. By its biocompatibility, titanium alloy Ti6Al4V has now been frequently utilized in industries such as the medical field as prosthesis & surgical instruments. Titanium alloys are notorious for having poor thermal conductivity and toughness at elevated temperature. Consequently their intrinsic mechanical and thermal qualities (which induce severe tool wear and limit tool life), lower surface quality, and reduced productivity. Because of cooling and lubricating effects, the use of various cutting conditions helps to the elevation of desired reactions, particularly in the case of difficult to cut materials like Ti6Al4V.

I investigate the best machining parameters for micromilling Ti-6Al-4V alloy under multiple cutting conditions in this research. Micromilling experiments were conducted with uncoated tungsten carbide tool in the dry, mql, and wet settings to optimize five response parameters: cutting forces (C.F), tool wear rate (R), Surface roughness Ra, up burr (UB), and down burr (DB). A multi-objective function was designed using grey relational analysis (GRA).

The created multi-objective function was optimized via response surface optimization, and the optimal cutting condition was determined. According to the ANOVA, cutting conditions were revealed to be the most significant aspect influencing the multi-objective function's grey relational grade (GRG).

Keywords: Micromachining, low speed, Ti-6Al-4V, Multi-objective optimization, burr formation, up and down burr, micro-milling, tool wear, surface roughness, ANOVA, GRA

List of figure and Tables

1 INTRODUCTION

Manufacturing operations and techniques are focusing their efforts towards small scale parts as technology advances and seeks to minimize size and shape as much as achievable. Micro and nano scale research is needed to keep pace with the growing for small scale products. Micro machining, including micro-scale milling, drilling, and turning is a set of procedures for removing material in the form of chips from 0.1 m to 100 m in size. To ensure the improvement in accuracy of small-scale components, highly precise tools and equipment are necessary. In terms of size and accuracy, Fig. 1 depicts the position of micro machining in comparison to other material removal processes. Macro machining equipment, methods, techniques, and materials has been the mouthpiece of much research over the last two decades, and transitioning to the micro domain is not as straightforward as lowering macro domain attributes. As a result, greater research is necessary to comprehend the intricacies of micro machining.

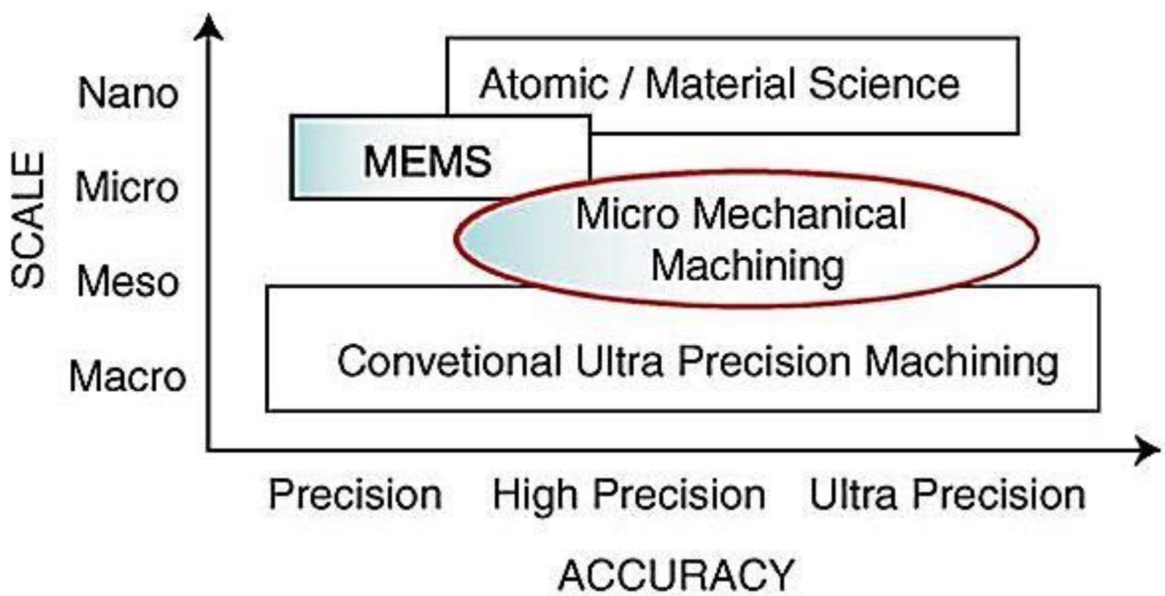


Figure 1 Accuracy vs scale for the micromechanical machining (Mian et al., 2014)

Cutting forces, elevated tool wear and surface roughness, and burr formation are always present in mechanical machining, whether it is macro or micro-machining. Cutting forces are critical to understand and monitor as they provide information on a variety of phenomena, such as chip formation, metal removal rate and mechanism, vibration, and tool condition (Balázs et al., 2021). The BUE's loose particles may be deposited upon the machined surface, increasing surface roughness. Micro cutting tools with a coherent BUE can be devised to machine titanium alloys with a long tool life and better surface quality (Oliaei & Karpat, 2017). Furthermore, enhancing tool diameter tends to produce a rougher surface, whereas increasing the number of flutes tends to smooth the surface (Bajpai et al., 2013). The most pressing matter in mechanical machining is burr emergence that also becomes more and more crucial for micro scale machining. Burr diminishes the machined product's quality and lowers its performance. Burrs are also prominent when micromachining hard materials, as a result of excessive tool wear. Burrs created in the micro-milling process along the final edges and surfaces have a major influence on final components and microstructures surface quality and operational performance. When the alloy is hard to cut, such as Ti6Al4V, the need increases much more. The high tool wear linked with titanium's reactivity with tool materials, as well as its low thermal conductivity, make machining Ti-6Al-4V titanium alloy challenging (Jaffery & Mativenga, 2009). Micromilling tool wear encompasses flank wear and rake face wear. Moreover, micromilling tool wear encompasses a decrease in nose edge radius in tandem with a reduction in tool diameter. During micro milling, a number of operations have a consequence on tool life. During operational conditions, micro-tools begin to wear out and lose their sharpness, affecting surface quality and cutting forces.

This study used carbide tools to micro-mill Ti-6Al-4V and multi-objective optimization method to find the best pairing of key operational variables (KPVs) to mitigate burr formation, cutting forces, surface roughness, and tool wear.

2 Objectives of the Study

The research's main goals are to:

• Analyze burr, T.W (R), C.Fs and Ra at various cutting parameters.

• To use the statistical analysis tool ANOVA, and to determine the impact of each parameter.

• Identify the optimal level of each parameter and perform experiment validation

• Utilizing Multi Objective Optimization to identify the best overall conditions for the best output.

3 Research Objectives

The scope of this study is restricted to micro milling Titanium Alloy Ti-6Al-4V with tungsten carbide tools at less than 8000 rpm.

4 LITERATURE REVIEW

4.1 Manufacturing

Manufacturing is a amalgamation of the Latin words manus (hand) and factus (make), which meaning "made by hand." T he English word "manufacturing" was first coined around 1567 A.D "made by hand" properly defined the manual processes utilized at the time. In 1683, the word "manufacturing" was first used. The gross domestic product, or GDP, is the total value of all final goods and services produced in a country in a given year, and it is used to estimate the size of the country's economy. To get at a total monetary worth, GDP is calculated by putting together the creation of a range of different things and services—smart phones, automobiles, music downloads, computers, steel, bananas, college educations, and any other new commodities and services generated in the current year. Manufacturing makes a considerable contribution to the country's gross domestic product (GDP). Manufacturing is a method of acquiring material riches for a country. In the United States, manufacturing accounts for around 20% of GDP. Manufacturing contributes greatly to the strength of the American economy. According to the National Association of Manufacturing, every penny spent on manufacturing, which includes commerce, transportation, and commercial services, adds $2.74 to the economy. The manufacturing industry supports a great amount of people. In January 2021, the Bureau of Labor Statistics (BLS) reported that there were 12.22 million manufacturing employment in the United States.

There are two types of manufacturing. Converting bauxite ore to aluminum or timber to lumber are examples of primary manufacturing. Aluminum rod to fuel valve conversion and lumber to furniture conversion are examples of secondary manufacturing. The majority of contemporary production is done by autonomous and computer-controlled machinery and is manually supervised in today's industrial world. Advanced manufacturing combines science, engineering, and information technology with high-precision techniques and technologies, as well as a high-performance workforce and imaginative business or organizational structures, to improve or develop entirely new materials, products, and processes. Advanced manufacturing is concerned with complicated, yet simple-to-use and cost-effective technologies capable of producing geometrically simple and light-weight objects with better functionality, reliability, environmental friendliness, and resilience.

4.2 Miniaturization of products

Miniaturization of items is a contemporary mega trend that offers a wider range of manufacturing industry opportunities. It presents novel low-cost, high-accuracy, and high-quality manufacturing processes for miniaturized items. Micro and miniature parts with precise dimensions and accuracies have been highly popular in recent years, leading to the development of micro and nanotechnology (Gao & Huang, 2017). In the health field, bioengineering, microelectronic, and communication areas, products varying in size from a few microns to a few millimeters have grown massively since the 2000s. Micro-mechanical machining is the cutting process that uses miniature tools (less than 0.5 mm). The rate of production of this manufacturing process is higher than that of non-traditional micro-manufacturing methods.

4.3 Micromachining

Because of the rising requirements of modern industry, micromachining has now become a key technology in today's society. Only micro mechanical machining can fulfil this need greater accuracy and precision, including for features on the finished product (which may have very small dimensions). The micro machining process is a manufacturing activity whereby the tool size varies between 1 and 1000 micrometres. Whereas most machine tools have rotating rates of less than 10,000 revolutions per minute (rpm), some advanced micro - machining systems can surpass 1,000,000 rpm (Group, 2006). Because machining shape is not constrained, some unique characteristics, such as arbitrary curvatures, or high aspect ratio features , 3D cavities and, such as long shafts and micro-channels, can be created. As a result, mechanical micro machining has become a prominent choice for small-scale manufacturing (Lee & Dornfeld, 2005). Moreover, mechanical micromachining has no constraints on the variety of workpiece materials which can be used. The benefits of micro machining over other micro-device manufacturing processes including such as silicon etching, energy beam, and chemical are less material limits and the ability to manufacture real three-dimensional features in comparison with other methods.

4.4 Micro-machining advantages

Micro-machining also has a wide range of benefits in terms of environmental, economic, and technological elements of manufacturing.

4.4.1 Environmentally

• Energy and material resources are saved, which is good for the environment.

• Minimal lubrication is required, and no masking materials are required.

• Reduced vibration and noise for workers.

• Waste materials are easier to monitor because the eliminated material is limited in the machine.

4.4.2 From a financial standpoint

• Requires less capital investment in terms of land, facilities, and power, and does not require clean room maintenance.

• Reduced operating costs

• Small energy consumption; no high-energy laser or x-ray technology is needed. Configurability and portability

• Machine size facilitates mobility

4.4.3 Technically

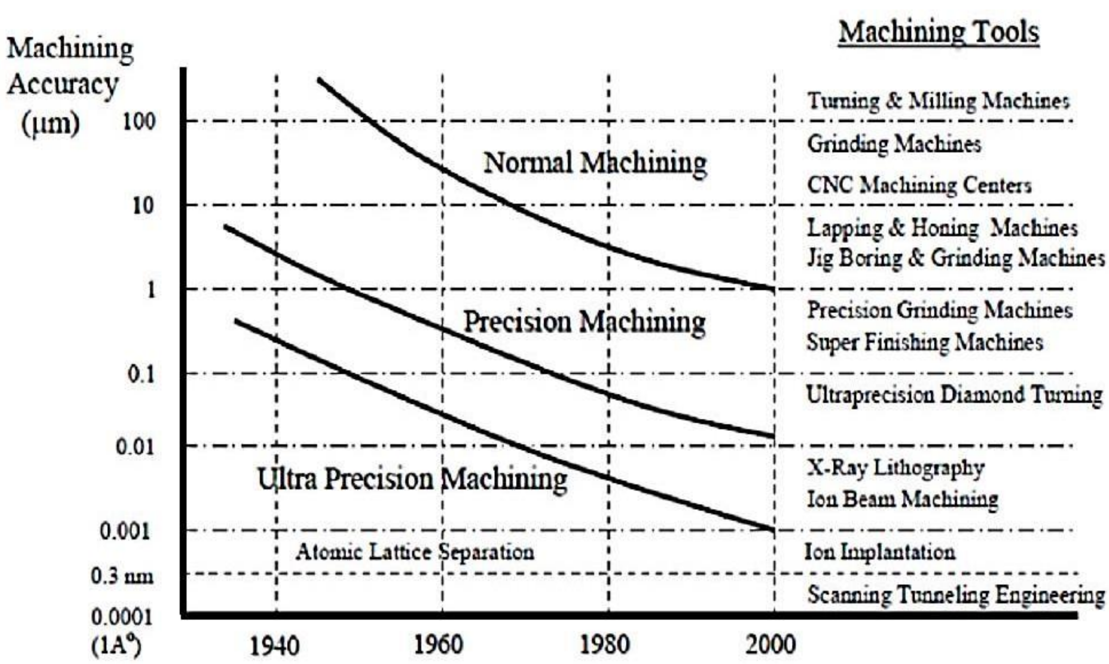
• Micro- and nano-scale precision because machines take up a lot of area, they have high productivity allocations.

• Piece-by-piece process advantage: Because batches don't rely on a single mould, the likelihood of errors may be checked and addressed immediately without causing batch losses.

4.5 Micromilling

Micromilling is one of the most significant and extensively used types of micro machining because of high precision levels which can be accomplished while machining high-strength materials. The micro milling process is defined as a manufacturing process where the tool size ranges from 1 to 1000mm (Cardoso & Davim, 2012). The micro milling process is defined by the need to control a large number of machining parameters while creating tiny features and components with high aspect ratios and complex geometries. Micro machining is less expensive to install and removes more material than other methods, such as micro-electro-mechanical systems. The demand for small and compact components is increasing in modern businesses. Manufacturing technology to manufacture sophisticated 3D micro features must be developed to meet this requirement (Mittal et al., 2018). Micro milling methods provide a number of advantages in the production of high-precision 3-D goods, including flexibility, increased material removal rates, and cheaper costs (Malekian et al., 2009)(Balázs et al., 2021) employ metallic alloys, ceramics, and polymeric materials to construct three-dimensional things with high aspect ratios and geometric intricacy. When compared to traditional processes, its flexibility and efficiency allow for higher productivity and lower pricing for micro-parts. Micro-milling, in addition to direct part machining, can be a significant part of the manufacturing chain for moulding, tamping, and embossing, and thus play a key role in profitability. Researchers looked at mechanical micro-machining processes for manufacturing because of the growing need for micro-featured components in numerous applications, as well as strict quality rules. Micromilling has the potential for being the most cost-effective material removal process given the ease of use and availability of the tools. Micro milling is also used for micromachining of hard metals and alloys, which is difficult to achieve at low speeds. Micro-milling is a tool-based process; therefore progress is dependent on the development of micro-cutting tools.

Figure 2 Development of achievable machining accuracy (Thepsonthi & Özel, 2013)



4.6 Titanium and Ti alloys

Titanium and titanium alloys are used for a variety of micro-feature based applications in the medical field, turbine blades, aerospace industry, chemical industry, and other industries because of their excellent properties such as high specific strength, excellent strength-to-weight ratio, excellent physical and mechanical properties, low density, low corrosion resistance, reasonable mechanical resistance, higher wear resistance, longer lifespan, and high biocompacity (Rack & Qazi, 2006)(Sataloff et al., n.d.) Titanium alloy micro-milling is used in the manufacturing of implants in comparison to other metallic implants.

Tables below show the chemical composition, mechanical characteristics, and physical properties, respectively.

Table 1 Chemical composition of Titanium Ti6Al4V (wt %)

Material	Ti	V	Al	Cr	Cu	Fe	Mn
Titanium 6Al4V	89.4	4.30	6.15	.0027	.0045	.0510	.0055

Table 2 Mechanical properties of Titanium Ti6Al4V

Material	Tensile Strength (MPa)	Yield Strength (MPa)	Poisson's Ratio	Elastic Modulus (GPa)	Shear Modulus (GPa)	Hardness Brinell (HB max)
Titanium 6Al-4V	≥895	≥828	0.31	105-120	41-45	334

Table 3 Physical properties of Ti6Al-4V

Material	Density (g/cm^3)	Melting Point (°C)	Thermal Conductivity (W/m.K)	Specific Heat Capacity (J/g.°C)	Co-eff of Thermal Expansion 0-500°C (µm/m.°C)
Titanium 6Al-4V	4.43	1674	6.7	0.5263	9.7

4.7 Conundrum in machining of Titanium and Ti alloys

Veiga and Niinomi categorize titanium and its alloys as difficult-to-machine materials (Veiga et al., 2013) (Niinomi, 2019). Titanium exhibits some machining issues owing to its low elastic modulus, high toughness, low thermal conductivity, and chemical reactivity at high temperatures, which together lead to accelerated tool wear and asymmetrical micro burr creation (Niinomi, 2019), (Veiga et al., 2013). High cutting temperatures and severe tool wear are other issues in the machining of these alloys. The significant tool wear coupled with titanium's reactivity with tool materials, as well as its limited heat conductivity, make machining Ti-6Al-4V titanium alloy challenging (Jaffery & Mativenga, 2009). Due to the size impact, vibrations, and other uncontrollable elements, complicated issues arise. Decline in material removal rates, low machined microstructure quality, premature tool failures, and delayed machining efficiency are all consequences of high aspect ratios in micro-machining domains (Xia et al., 2019).

4.8 Ti-6Al-4V titanium alloy

With its outstanding physical and chemical qualities, robust corrosion resistance, enhanced specific strength, chemical inertness, low elastic modulus and biocompatibility, Ti-6Al-4V titanium alloy is one of the most popular functional materials for aerospace and biomedical applications (Bajpai et al., 2013). Ti-6Al-4V titanium alloy offers a better mechanical resistance than other titanium alloys while yet maintaining the characteristics required for implantation. Because of its small weight, it is ideal for aircraft applications (Bajpai et al., 2013).

Tool wear, which is frequently connected with workpiece material, is a key concern in micro-milling (Miranda et al., 2018). low surface quality, severe burr formation, speedy tool wear, and tool breakage are the most common issues faced in the micro-milling process (irfan Ucun et al., 2013), (I. Ucun et al., 2015). The aforementioned issues are frequently compounded by other factors such as size effect, ploughing, vibration, deflection, and workpiece microstructure, all of which worsen problems in the micromilling process. The challenges of micromilling titanium alloys are similar to those of the musicale process, but with the addition of the size effect**.**

4.9 Tool wear

During machining, tool wear is defined as a change in the tool's form from its original shape. It is induced by the progressive decline of the tool material. In high-speed machining, tool wear is a limiting constraint. Because of the high precision required in micromachining, it is vital to keep track of tool wear. In micro-machining, the identification of tool conditions presents different challenges than in traditional machining.

Tool wear on micro mill cutting edges is a serious problem that has an impact on process outputs such, dimensional, and geometrical tolerances, tool deflections , surface quality, and roughness. Understanding the relationships between tool wear, tool deflections, and machining forces, and surface roughness is crucial for meeting component quality standards. When difficult-to-cut materials like titanium alloys, stainless steel, and other materials are machined at the micro scale, excessive tool wear during the processing of hard and brittle materials has a major impact on cutting performance.

In machining, this is a common occurrence. It is crucial in the case of micromilling since it reduces tool and work piece life and generates numerous changes. The importance becomes even greater when the material is tough to cut, such as Ti6Al4V. Machining Ti-6Al-4V titanium alloy is challenging due to significant tool wear caused by titanium's reactivity with tool materials, as well as its poor heat conductivity (Jaffery & Mativenga, 2009). Flank wear and rake face wear are 2 types of micromilling tool wear. Furthermore, micromilling tool wear involves a decrease in tool diameter and a decrease in nose edge radius. Tool life is influenced by a number of processes during micro milling. Micro-tools wear out and lose its sharpness rapidly under working settings, impacting surface properties and cutting forces. Although the machining force has been the most evident cause of tool wear and breakage, it is connected to a range of other elements such as vibrations, stress, temperature, and other (Mandal, 2014)

Tool wear is minimized under MQL, for example, resulting in a longer tool life. MQL extends tool life, especially flank wear, which has a significant impact on surface quality. MQL enhances micro channel achieved dimensions, surface finish, and tool wear during micro milling of Ti6Al4V because cutting fluid has the ability to minimize friction and dissipate the heat created between the micro tools and the work piece. Under MQL, tool wear in the feed direction has a loss value of 1.6 percent, compared to 6.15 percent in the opposite direction (Vazquez et al., 2015). In micro-milling, the MQL method will also improve tool life and reduce material adhesion. This is due to the MQL oil mist's ability to reduce wear due to its lubricating properties. It can also reduce the tool-chip contact length, resulting in even better tool wear. Using the MQL technique, cutting temperature in the cutting zone can be successfully decreased (Zheng et al., 2013). Micro-milling titanium alloy, material adhesion is the primary source of tool wear. Dry machining offers a longer tool life than wet machining. This is related to the formation of BUE, which in this case preserves the tool's cutting edge (Ziberov et al., 2016).

Micromachining, in particular, of hard and difficult-to-cut materials, results in a short tool life. Hard coatings have a reputation for extending tool life and reducing tool wear (Aramcharoen et al., 2008). In addition, tool wear varies depending on whether or not the tool is coated. In terms of tool wear and cutting temperature, (Thepsonthi & Özel, 2013) discovered that cBN coated carbide tools outperformed uncoated carbide tools. Due to tool dynamics and material tool wear, cutting forces will vary in different passes of the cutting edge. As the number of cutter rotations grows, so does the cutting force. This could be due to the high cutting temperature created during microend milling of Ti6Al4V alloy, which causes rapid tool wear and edge rounding (Pratap et al., 2015). After machining, the tool's condition was evaluated, with a focus on tool damage and edge extension. Abrasion and adhesion were discovered to be the key phenomena affecting tool status under the specified cutting parameters.

Material adhesion induces tool coating delaminating in some zones, as is evident. As a consequence, the tool substrate is in direct contact with the work piece's material, accelerating tool degradation. As the feed-per-tooth increases, the burr diameters become larger (Attanasio et al., 2013). For both Inconel 718 titanium alloy and Ti6Al4V titanium alloy, the ideal micro-milling parameters for surface roughness, tool wear and cutting forces were discovered, and tool edge wear in Ti6Al4V HSM developed faster than in Inconel 718 HSM. Because of its high strength and large number of embedded hard particles in the matrix, Inconel 718 produced much higher wear than Ti6Al4V in another investigation. A Vc of 12,000 rpm, a *f*z of 50mm/min, and a DOC of 50mm were employed to reduce tool wear during micro-milling of Ti6Al4V titanium alloy. During micro-milling of Ti6Al4V titanium alloy, tool wear decreased as spindle speed rose, but increased in general with *f*z rate and D.O.C increased.

When the V_C was increased, the temperature at the tool's workpiece contact zone risen, and the increased cutting temperature caused the tool to lose its strength. Tool wear occurred as a consequence of the greater spindle speed. It was observed that keeping the feed low for micro-milling reduced tool wear. At first, tool wear decreased as the D.O.C was increased, but as the D.O.C was increased further, tool wear increased. The depth of the cut, on the other hand, had no effect (Kuram & Ozcelik, 2017). As a result, as the *f*z and/or V_C increase, the tool wear rate increases. The most typical types of tool wear were nose, flank, and rake wear, and improper tool structural modifications could lead to tool failure. As the adhesion layer deteriorated, exposed micro-end mills were more susceptible to fracture failure.

When paired with the restricted thermal conductivity of titanium alloy, the aforementioned characteristics resulted in even higher workpiece material adhesion to the tool flank surface. Cutting heat and uneven loading on the cutting edge and flank face are further factors (Bai et al., 2018). Built-up edge formation is observed under micro machining settings to protect the cutting edge from crater and flank wear, and the effect of built-up edge on Ra varies depending on the V_C and uncut chip thickness. During the break-in stage, the cutting edge radius increases, enhancing BUE generation and safeguarding the tools from flank and crater wear (Oliaei & Karpat, 2016).

To help increase tool life by reducing wear, new approaches are being developed. When it came to removing the oxide layer, for example, the tool wear rate in LOMM was significantly lower than in traditional approaches. In LOMM, coating spalling was observed as a tool wear mechanism, whereas in standard tool nose breaking, coating spalling and adhesive wear was observed. When compared to traditional approaches, the tool service life in LOMM was considerably extended. A large area of cemented carbide tool substrate materials falling at the tool nose exacerbates tool failure, producing further tool failure as well as breakage or fracture (Xia et al., 2019)

4.10 Burr formation

Burr formation is the most challenging problem in mechanical machining, and it is significantly more difficult in micro scale machining. Burr decreases the quality and performance of the machined product. The ductility of the workpiece material, cutter geometry, cutting parameters, tool wear, and workpiece shape all have a role in burr formation. Depending on the application, these burrs may or may not be necessary, but because of their size and bonding with the remainder of the workpiece, they frequently store microscopic fractures and cause later complications during assembly, inspection, or product operation. Micromachining hard materials, burrs are common as a result of increased tool wear. During the micro-milling process, burrs that develop along finished edges and faces have a considerable influence on the surface quality and operational performance of finished components and microstructures. Burrs are almost always unavoidable during micro-milling because an excess of material overhangs outside of the appropriate geometrical shape of the workpiece edge. It's significantly more difficult to get rid of a micro burr than it is to get rid of a macro burr.

Entrance, top, and exit burrs are the three types of milling burrs. Based on their shape, they can also be classed as knife-type or curl-type (Chern, 2006). The entry of the micromilling tool, the exit of the micro milling tool, and the top burr creation near the machined groove's edge have all been identified as significant places for burr formation. Variations in top burr forms can be found on both sides of the walls. When down milling is done on one side of the wall, burring is more evident than when up milling is done on the opposite side of the wall. Burr height affects tool wear (Lee & Dornfeld, 2005). Top burrs are produced by both up and down milling. Lee and Dornfeld investigated burr development in micro-slot milling of aluminum and copper using milling tests. They developed a range of standard burr types depending on the location and task shape (Lee & Dornfeld, 2005). Up milling's reduced burr creation can be explained by the fact that chip thickness begins out small, meaning that just a little amount of material is deformed and removed. The top burr is formed by a greater quantity of formerly deformed material when the tool is in the down milling position (De Oliveira Campos et al., 2019). As tool edge roundness rises owing to tool wear, top burrs, burr height and breadth dimensions, and chip curling all grow (Gao & Huang, 2017). Weinert found that the material's excessive ductility causes poor chip production and lengthy, tangled chips, which interfere with tool contact and burr, resulting in poor surface quality (Weinert & Petzoldt, 2008)

Burr creation mechanisms display smaller burrs on the down milling side and larger burrs on the up milling side at normal and high speed cutting speeds. The up milling region has a higher burr height and a smaller burr breadth than the down milling region (Bajpai et al., 2013). Higher feed rates lead to better surface finishing, whereas higher cut D.O.C lead to less burr formation (Thepsonthi & Özel, 2012). The burr diameters appear to be greater as the f_Z increases. The micro channel and burr quality are influenced by the material structure. Lower burrs were discovered when working with a bimodal structure (Attanasio et al., 2013). The axial D.O.C is determined to be the critical process parameter that induces top burr development. According to (Thepsonthi & Özel, 2012), achieving a Ra and low burr development is highly dependent on a practical axial D.O.C and *f*z, both of which result in high productivity. Burr development is reduced when the MQL technique is used and coupled to nozzle orientation. When the nozzle is oriented in the feed direction, burr formation is not visible, but it is similar to the dry method outcomes when the nozzle is orientated against the feed direction (Vazquez et al., 2015).

Air pressure has an impact on tool vibration and burr formation. The burr size is greater at 0.45 MPa than at normal air pressures (Zheng et al., 2013). There is no correlation between the BUE and burr parameters (Oliaei & Karpat, 2017). The burr height increases by a factor of ten as the D.O.C increases, and the burr breadth increases as the cutting length increases. The tool corner radius enlarges due to the abrasive wear mechanism's action. Tools that were uncoated or NCD-coated were worn more than TiN- and AlCrN-coated tools (Bajpai et al., 2013). It was discovered that using a cBN coated tool can cause top-burr growth. Changing the feed per tooth has a significant impact on the surface roughness value and total top burr width, according to (Thepsonthi & Özel, 2013). Micro-ball end milling operations on Ti6Al4V produce massive slot base burrs, as well as entrance, exit, and top burrs, which is a major difference in burr formation compared to micro-milling with a flat end cutting tool. Significant burrs are formed at the slot's entrance and exit. When the mill's cutting edge fails to chop the material down, chip separation fails and an exit burr forms (Chen et al., 2012). 3-D micro-ball end milling operations on Ti6Al4V have been designed using FEM models. As a result, on the slot base, a new type of burr has been discovered.

The four types of burrs found in the simulation, based on their generating sites, are entrance burrs, exit burrs, top burrs, and slot base burrs. Adopting a short axial D.O.C to mill radius ratio in micro-ball end milling processes has a substantial impact on decreasing top burr production. The effect of cutting fluid on micromill tool performance in terms of burrs, machined surface, and tool wear when machining Ti-6Al-4V titanium alloy. According to the findings, cutting fluid has a significant impact on machined product quality, both in terms of machined surface and quality burr development (Ziberov et al., 2016).

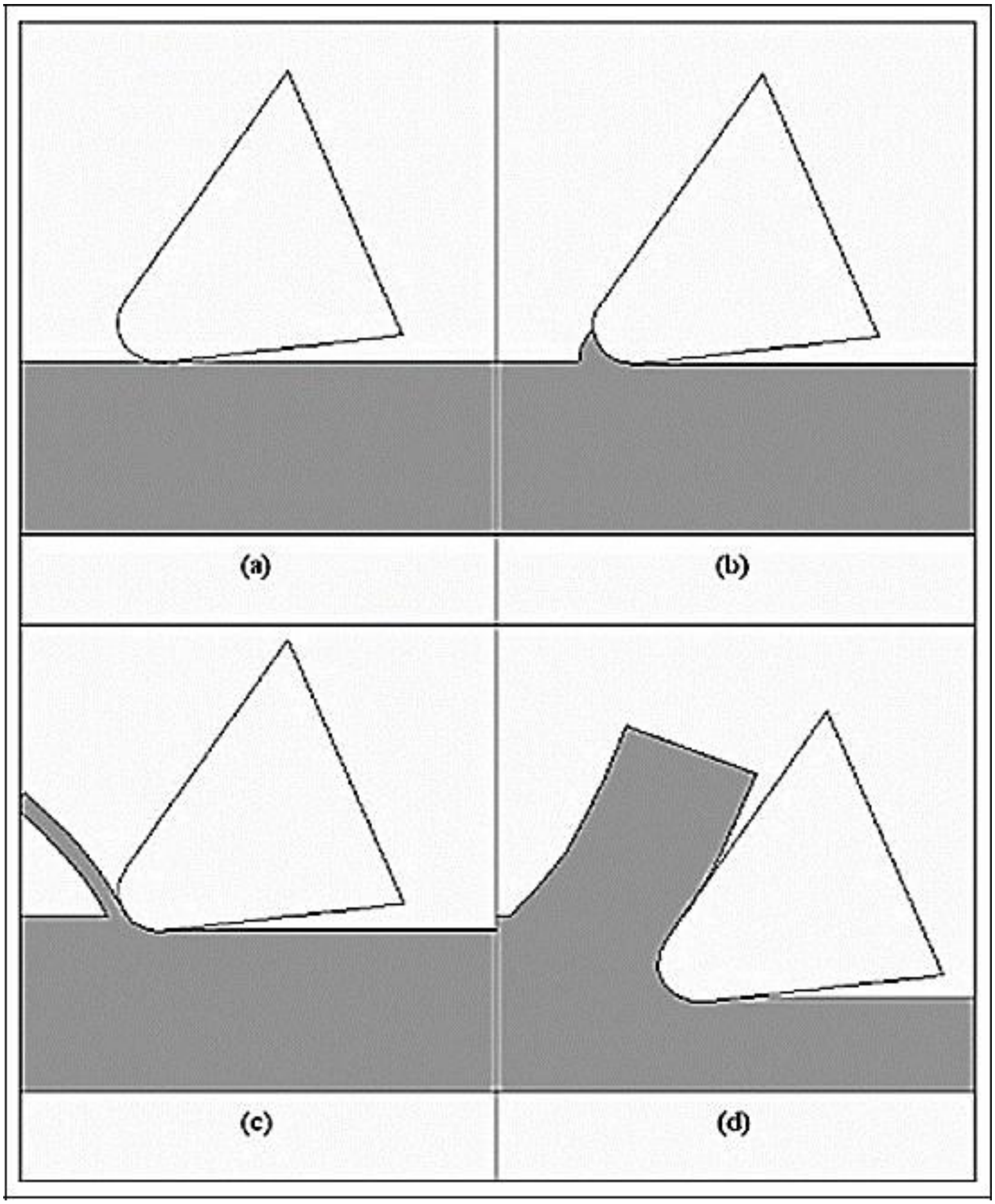


Figure 3 Micro-milling tool workpiece interactions

4.11 Number of Flutes and Tool Diameter

The number of flutes and tool diameter has an impact on the surface roughness of the work piece in micromilling procedures. Although increasing the number of flutes tends to smooth the surface, increasing the tool diameter causes the surface to become more rough (Bajpai et al., 2013). The burr size does not change much when the spindle speed is adjusted from 10,000 to 90,000 rpm and the feed rate is changed from 1 to 5 mm/sec, however the side exit burr on the up milling side decreases by 62 percent and 53 percent, respectively (Bajpai et al., 2013).The influence of various combinations, machining zone overlapping on equilibrium contact angle and geometry variations (diameter, pitch, and depth), were investigated, the researchers discovered that the surface roughness of all micro-textured surfaces increased as the roughness factor increased due to the increased machined surface area. Moreover, the dynamic wetting of the nano droplet was assessed in terms of advancing and retreating contact angles, which were used to calculate the micro-textured surface's Young's equilibrium contact angle (Pratap et al., 2015)

4.12 Cutting forces

Cutting forces are important to understand and monitor because they provide information on a variety of phenomena, including chip formation, material removal process, vibration, and tool condition (Balázs et al., 2021).

During the micro-milling of Ti6Al4V alloy, Pratap studied the C.Fs. They discovered that enhanced cutting pressures are mostly caused by accelerated tool wear rates (larger cutting edge radius), which are produced by higher cutting temperatures. The increase in force in this case is due to the stronger ploughing phenomenon, which occurs when the chip thickness is less than the minimum chip thickness (Pratap et al., 2015). Cutting forces are significantly reduced when TiAlN is coated with a dry lubricant (WS2) (Mittal et al., 2018). Furthermore, edge radius and feed per tooth effect cutting pressures in micro-end milling (Thepsonthi & Özel, 2013). Cutting forces are reduced when the cutting tool is laminated. When working with totally lamellar microstructures, for example, lower cutting forces and tool wear were seen compared to other microstructures (Attanasio et al., 2013). Because of the limited heat conductivity of the cutting zone, the cutting pressures vary, resulting in increased tool wear. Cutting force increases as the *fz* and Vc increase.

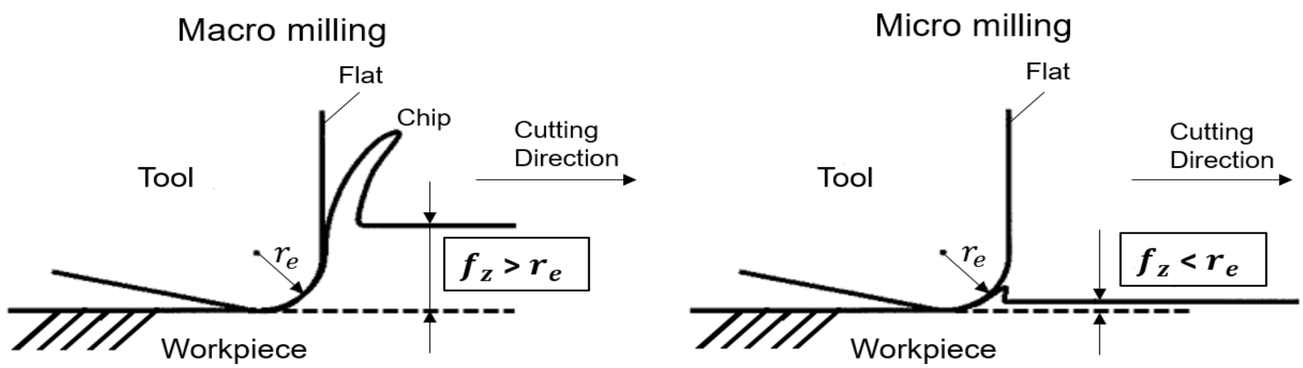


Figure 4 Micro vs. Macro In Burr formation

4.13 Cutting speed

When compared to feed/tooth, V_C has a large impact on temperature. The micro hardness beneath the machined surface was measured, and it was discovered to be a function of cutting force and temperature. The cutting insert's tool life is likewise discovered at the ideal cutting speed. The surface roughness decreases as the V_C is raised. The temperature at the cutting zone gradually rises as the cutting speed rises. Cutting force and temperature have an impact on the work piece’s micro hardness. Micro hardness increases below the machined surface when cutting force and temperature are high (Krishnaraj et al., 2016).

Despite the fact that the machining force is the most visible parameter, quantity that leads to Ra and breakage, it is linked to a number of other factors that contribute to tool wear, such as vibrations, stress, temperature, and others (Mandal, 2014)

4.14 Surface Quality

The work piece's surface roughness has an impact on surface quality. It is a crucial feature of micromilling because greater surface quality leads to a longer work piece life. In the micro milling process, a built-up edge (BUE) produces surface polish issues. The BUE's loose particles may be deposited on the machined surface, increasing R. Micro cutting tools with a consistent BUE can be created to mill titanium alloys with a long tool life and good surface quality (Oliaei & Karpat, 2017). Surface finish is increased by increasing V_C, *f*, and D.O.C. Furthermore, increasing tool diameter provides a rougher surface, but enhancing the number of flutes helps to smooth the surface (Bajpai et al., 2013)

Cutting fluid, also known as MQL, increases the quality of the machined surface. This improvement is due to the lack of BUE in MQL machining (Ziberov et al., 2016). Cutting with a cBN coated tool resulted in a smoother surface, according to (Thepsonthi & Özel, 2013). Micromilling with MQL produced improved Ra and burr formation, as well as reduced R, than dry milling (Li & Chou, 2010). When cutting speed is compared to feed per tooth, the experiment demonstrates that cutting speed has a considerable impact on surface roughness. This could be related to the cleaning of slot milling inserts (Krishnaraj et al., 2016). Higher feed rates result in better surface finishing, and deeper cuts result in fewer burrs. The size of the built-up edge is influenced by the MPI (uncut chip thickness, cutting speed, and clearance angle), which effects the process outputs. Under micro machining settings, built-up edge development is observed to protect the cutting edge from flank and crater wear, and the influence of built-up edge on Ra varies depending on the V_C and uncut chip thickness.

During the break-in stage, the cutting edge radius increases, enhancing BUE generation and safeguarding the tools from crater and flank wear (Oliaei & Karpat, 2016). The axial depth of cut is determined to be the critical process parameter that induces top burr development. The axial D.O.C and *f*z, both of which contribute to high productivity, are crucial in achieving a high Ra and low burr growth (Thepsonthi & Özel, 2012).

4.15 Chatter

Tolerances, Tool life, machining quality are all affected by chatter in the micromachining process. Macro-machining and its chatter theory does not apply to micro-machining operations (Novakov & Jackson, 2010)

4.16 Micro-milling Applications

Nowadays, emerging miniaturisation technologies are essential future technologies that will provide completely new methods for humans and machines to interact with the actual environment. In the coming decades, it is predicted that the manufacturing of miniaturized components and their use will rise at an exponential rate.

Micro-milling technique can address the needs of miniature components in a variety of industries, including aerospace, biomedical, information technology, jewellery, telecommunications, automotive, electronics, and watch making.

4.16.1 Biomedical

Moulds for medical components (micro dosage systems), orthodontics (dental brackets), and surgical micro tools, bio-technology applications (microchip electrophoresis devices, polymeric BIOMEMS devices, and cataract lenses.

4.16.2 Information technology

For example, membrane for PC chips manufacturing.

4.16.3 Watchmaker and jewelry

Moulds for rings and pendants, manufacturing and engraving of watch base plates, etc.

4.16.4 Automotive

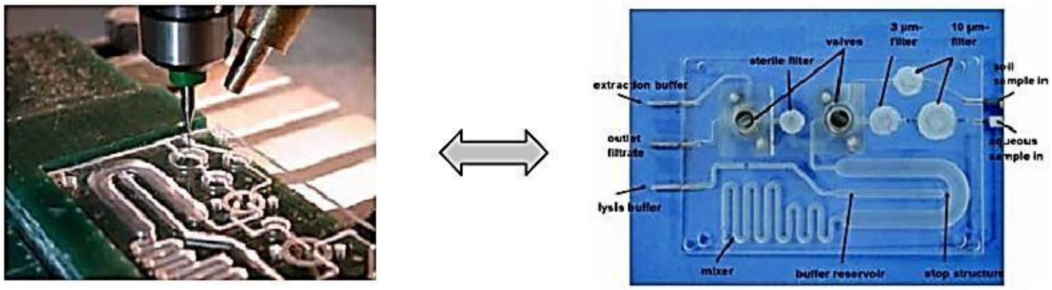
Electrodes for cutting insert, injection nozzles, etc.

4.16.5 Telecommunications

Multi-fiber connectors for single and multimode applications, as well as connecting parts and an easy-assembly mould are available.

4.16.6 Aerospace

Small planetary gear wheels attached to a turbine, miniature equipment for rockets, and other aerospace moulds.



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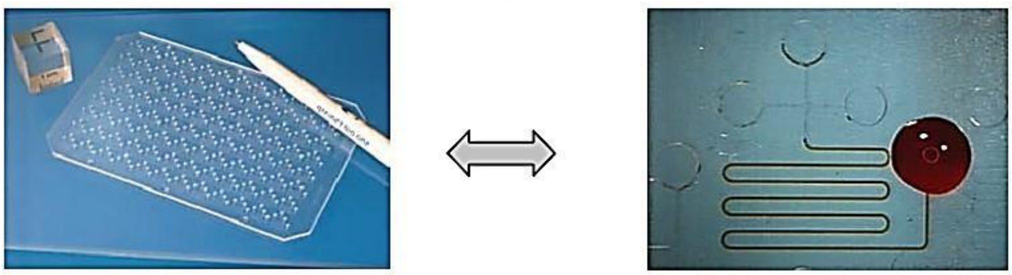

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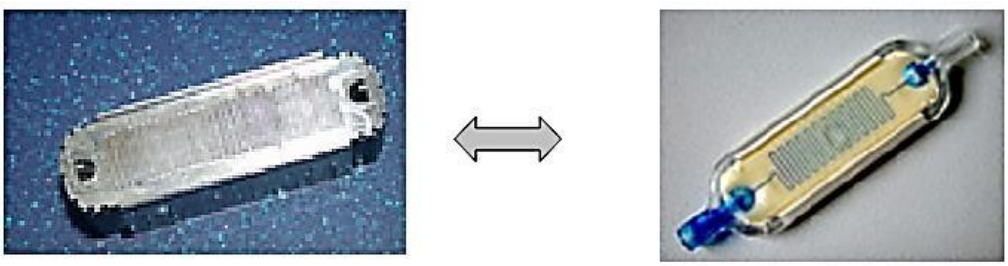

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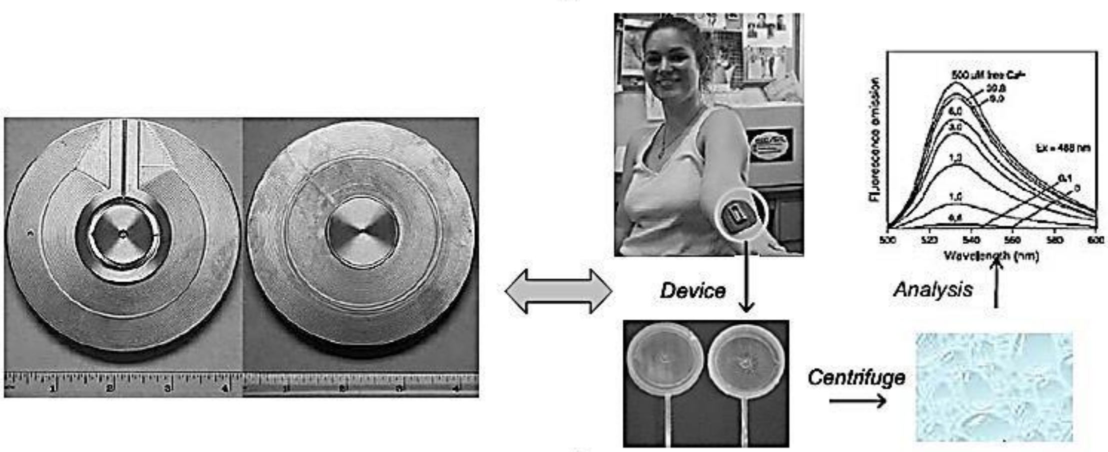
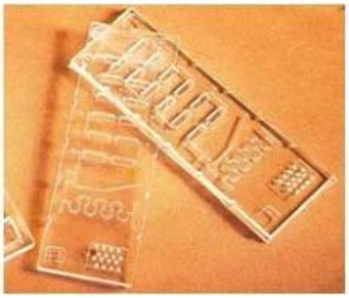


d

Figure 5 (a) Lab-on-a-chip; (b) Microplate with 96 capillarity electrophoresis system (vacuum hot-embossing plate from micro-milled mould) and filling of one structure; (c) Medicine micro-dosage system; (d) Sweat-stick for collecting human sweat (Kim & Lee, 2021)



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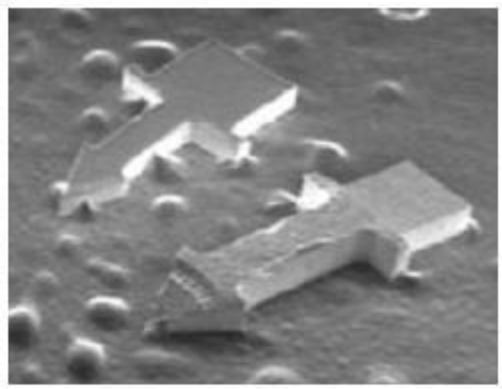


Integrated polymer micro-fluidic stacks (chemiluminiscence experiment); (b) Dental brackets; (c) Tissue removal tools for endoscopy; (d) Cataract lenses; (e) Fabrication of Ti retinal microcap

a

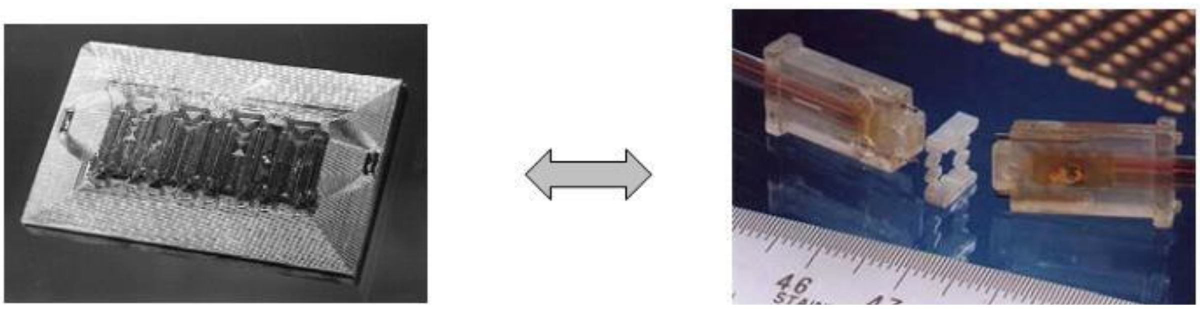
b

c

(a) Engraving watch base plate; (b) Watch parts; (c) Pendant mould

a

(a) Injection nozzles for diesel engines; (b) Electrodes for cutting inserts



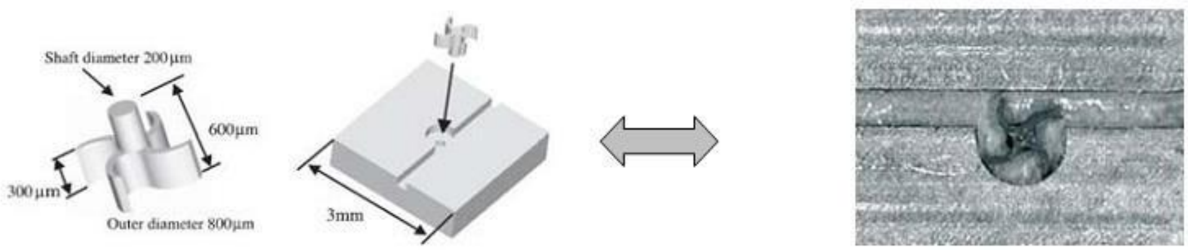
a

b

c

(a) Multi-fibre connector (micro-milled mould for X-ray mask fabrication and microinjected connector); (b) Joining element for optical fibre connector; (c) Computer chip manufacturing

a b c



(a) Disc of a rocket motor; (b) Turbine wheel for micro fluidic pump; (c) Micro-mould of a planetary gear wheel; (d) Assembled micro impeller and base block

5 METHODOLOGY

Ti-6Al-4V was used in micromilling tests. A FANUC MV-1060 conventional speed machining centre was used for the tests. The experimental setup is shown in the diagram. The FANUC MC Motion controller was used to govern relative motion between the workpiece and micro endmilling tool.

Micromilling tools utilized in Ti-6Al-4V micro-milling studies were ultrafine tungsten carbide tools (North Carbide Tools). Flat end mills with a diameter of 500 mm, a helix angle of 30^o, and two flutes were employed. Micro-tool edge radii were determined to be 3.5 micrometers on average, with a standard deviation of 0.5 3.5 micrometers.

The block that was mounted on the fixture was 10 x 20 x 10 mm in size. In complete immersion milling, several axial depths of cuts were used. To limit the impact of tool wear on the measured data, 10 mm long slots were cut in each session. Each experiment was repeated 3 times in order to determine error variation. The exp. conditions are shown in Table 4..

Table 4 Exp. Conditions

W. piece	Ti-6Al-4V (Grade 5)
Milling Tool	2 flute Tungst. Carbide micro mill T. dia = 500 µm
C. Conditions	Dry, wet, mql
Leng. of cut	10 mm
Milling Type	Full immersion

5.1 Experimental Design

Taguchi's L9 orthogonal array with four factors and 3-levels was used to design micro-milling experiments. Cutting conditions, such as *f*, V_C, and axial DOC, were all examined separately. Table 5 lists the process parameters and level information.

Figure 6 Exp. Setup

(1) Spindle (2) Micro-end mill (3) Workpiece (4) Machining vise

(6) Dynamometer and view of tool and workpiece

Serial No.	*Vc* (m/min)	*fz* (µm/tooth)	*Ap* (µm)	*Cutting Conditions*
1	5.0	3	50	Dry
2	5.0	6	100	Wet
3	5.0	9	150	MQL
4	7.5	3	100	MQL
5	7.5	6	150	Dry
6	7.5	9	50	Wet
7	10	3	150	Wet
8	10	6	50	MQL
9	10	9	100	Dry

Table 5 Experimental Conditions

5.2 Selection of Parameters

The levels of *f*, V_C and DOC (Table 5) have been selected according to the following criteria:

5.2.1 V_C

Cutting speeds recorded in the literature range from 16 m/min (10,000 rpm) to 141 m/min (90,000 rpm) (Bajpai et al., 2013). The focus of this study is on machining at speeds lower than the reported minimum cutting speed. As a result, the cutting speed in this study was set to be less than 16 m/min (10,000 rpm) and between 5 m/min (3183 rpm) and 10 m/min (10,000 rpm) (6366 rpm). Table 6 shows the actual numbers for RPM and *f*, V_C.

$$N = V c \pi \ x \ D \qquad (1)$$
$$V f = f \ x \ N \ x \ z \qquad (2)$$

5.2.2 DOC

As Niagara Cutter suggests, there is a recommended DOC for each instrument according on its diameter. (Niagara Cutter, n.d.)

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Serial No.	*Vc* (m/min)	N (rpm)	*fz* (µm/tooth)	*ap* (µm)	Cutting Conditions
1	5.0	3183	3	50	Dry
2	5.0	4774	6	100	Wet
3	5.0	6366	9	150	MQL
4	7.5	3183	3	100	MQL
5	7.5	4774	6	150	Dry
6	7.5	6366	9	50	Wet
7	10	3183	3	150	Wet
8	10	4774	6	50	MQL
9	10	6366	9	100	Dry

5.3 Experimentation

• Experiments are carried out in dry, wet, and mql machining conditions.

• A multi-meter was used to measure the precise and accurate tool offset.

• 3-7 slots were machined with a 3-5 mm gap between slots and a cut length of 10 mm.

Tool Offset measuring devices

6 RESULTS AND DISCUSSION

Each experimental run included measurements of cutting forces, top and down burr, Ra and tool R. In the table below, the findings are presented as a L9 array. Different forms of burrs, such as top, exit, entry, and down burr, are generated in micro-milling depending on the cutting direction and tool-workpiece contact (Rehman et al., 2018).

Table 7 Combine summary of all experiments in first and second set of experiments

Run	Factors				Values				
	Speed (rpm)	Feed (µm/ tooth)	DOC (µm)	C.COND.	TW (µm)	UB (µm)	DB (µm)	SR (µm)	CF (N)
1,10	5	3	50	Dry	13.79	51.962	57.065	0.037	0.46925
2,11	5	6	100	Wet	7.74	19.785	22.52	0.0295	0.90997
3,12	5	9	150	MQL	5.99	24.5805	29.7305	0.0127	1.8584
4,13	7.5	3	100	MQL	10.49	28.0355	33.0005	0.039	0.7291
5,14	7.5	6	150	Dry	15.87	43.805	65.641	0.041	1.5702
6,15	7.5	9	50	Wet	8.92	21.307	25.069	0.024	0.4418
7,16	10	3	150	Wet	11.46	27.221	31.261	0.0236	1.0505
8,17	10	6	50	MQL	10.91	26.86	31.3805	0.0402	0.47033
9,18	10	9	6	Dry	9.37	32.9	48.58	0.043	0.8977

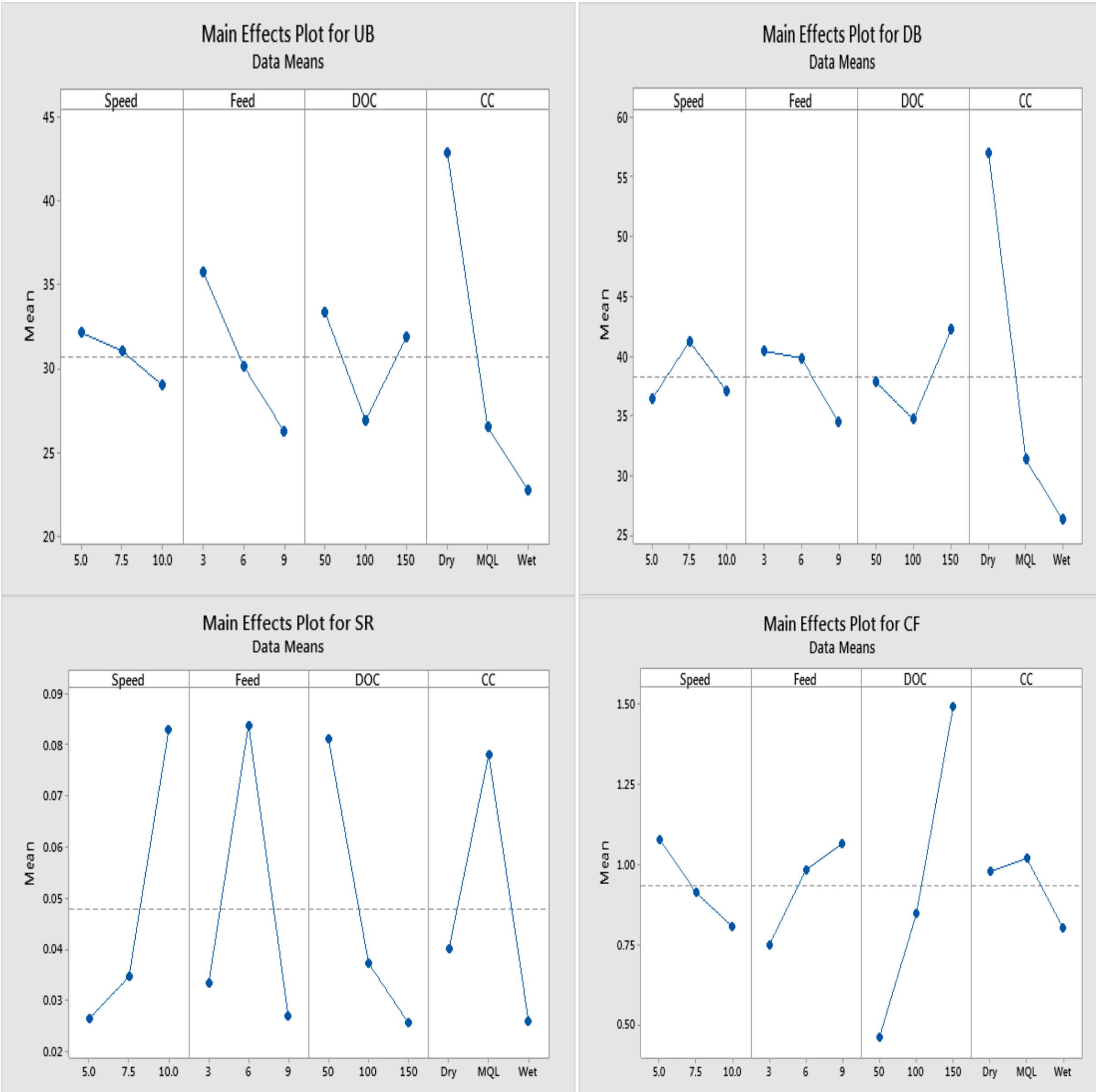
6.1 ANOVA (Analysis of Variance)

ANOVA was utilized for statistical analysis of the results after obtaining results for top and down burr, tool wear, and surface roughness using an optical microscope. AN.OVA is a statistical tool for determining the impact of process parameters on output responses.

6.2 Experimental Results

Cutting parameters (V_C, *f*, doc, and varied cutting conditions) had an effect on the response parameters (cutting forces (C.F), T.W rate (R), Surface roughness Ra, up burr (UB), and down burr (DB).

Each response parameter's trend is depicted in the main effect graph. The best UB response was at low V_c (10 m/min), DOC (100 micrometers), and *f* (9 micrometers) in wet conditions, while the worst response was at high V_C (5 m/min), DOC (50 micrometers), and *fz* (3 micrometers) in dry conditions. Under wet conditions, the best response for DB was at V_C (7.5 m/min), whereas the worst response was at V_C (5 m/min). The best response for Ra under MQL was V_C (5 m/min), DOC (150 micrometers), and *fz* (9 micrometers); the worst response was V_C (10 m/min), DOC (50 micrometers), and *fz* (6 micrometers). (6). Under dry conditions, the best response for R was V_C (5 m/min), DOC (100 micrometers), and *f* (9 micrometers) under MQL, whereas the worst response was V_C (7.5 m/min), DOC (50 micrometers), and *f* (3 micrometers).


Main Effects Plot for UB
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Main Effects Plot for DB
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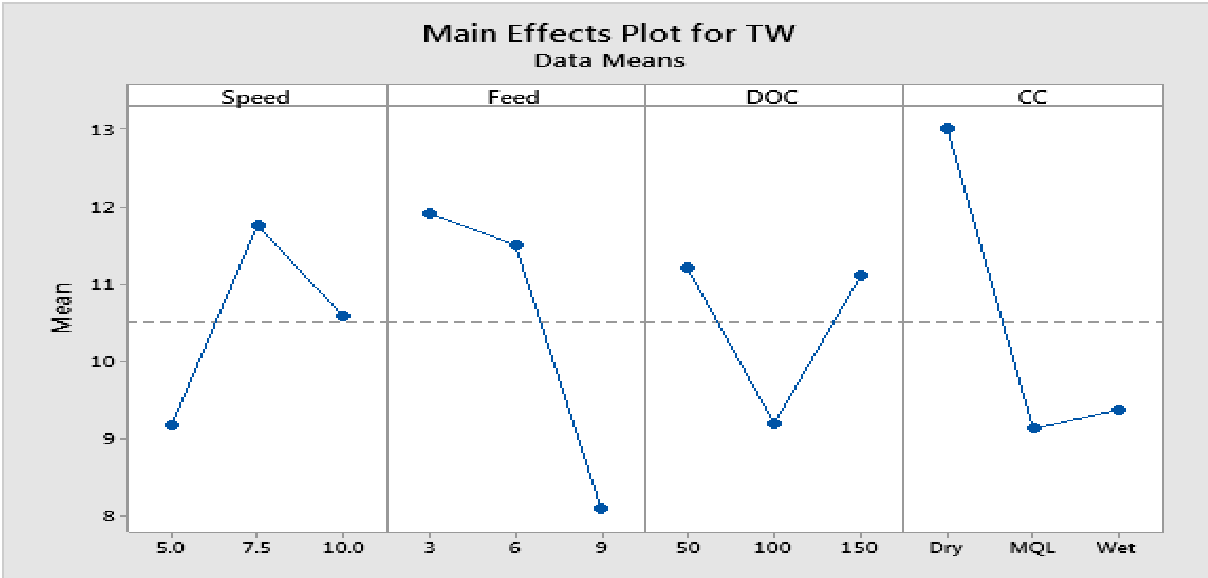
MQL
Wet



Mean Effect plots of results

6.3 Effect on Up and Down Burr

Using the above equations, ANOVA was used to determine the impact of factors on burr formation. Cutting conditions are the most important characteristic, accounting for 71 percent of the variance in burr creation, and feed per tooth is another important factor, accounting for 13.08 percent of the variance. Cutting conditions are the most important characteristic, accounting for 77.15% of the down burr generation, and feed per tooth is another important factor, accounting for 9.45 percent of the total. This diagram depicts how different cutting conditions, such as dry, wet, and MQL, affect the machining of TI6Al4V. MQL is one of the most effective ways to decrease burr formation in the interim. The reason for this is that in a flooding way, the airflow combined with the lubricant is low, and so the oil drops cannot reach the tiny cutting zone properly, causing them to erupt out of the cutting zone. The MQL approach, on the other hand, allows for lubrication and cooling because the flow can reach the cutting zone. The traditional cooling condition reduces the accuracy of the micro-channels, resulting in a 20 percent inaccuracy (Taylor, Vazquez, et al., n.d.). During dry machining, the most important parameter impacting top-burr production is the feed per tooth. Due to tool wear, burr height and width dimensions, as well as chip curling, increase as tool edge roundness increases, which may be predicted pretty well using an analytical model (zel et al., 2017). The burr does not damage the material, but it has a significant impact on the part's quality and performance.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	2	30.11	1.45%	30.11	15.06	0.51	0.619
Feed	2	272.34	13.08%	272.34	136.17	4.57	0.043
DOC	2	137.50	6.60%	137.50	68.75	2.31	0.155
CC	2	1374.88	66.01%	1374.88	687.44	23.08	0.000
Error	9	268.02	12.87%	268.02	29.78		
Total	17	2082.84	100.00%				

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	2	81.52	1.92%	81.52	40.76	0.62	0.557
Feed	2	130.33	3.07%	130.33	65.17	1.00	0.406
DOC	2	170.75	4.02%	170.75	85.38	1.31	0.317
CC	2	3274.05	77.15%	3274.05	1637.03	25.10	0.000
Error	9	586.96	13.83%	586.96	65.22		
Total	17	4243.62	100.00%				

6.4 Effect on Tool wear

Using the above equations, ANOVA was used to determine the impact of factors on tool wear. Cutting conditions are the most important characteristic, accounting for 32.75 percent of tool wear, and feed is another important factor, accounting for 30.51 percent of tool wear. The mql produced the best results, followed by wet and dry. This demonstrates that changing cutting conditions has a major impact on tool wear. MQL extends tool life considerably (Zheng et al., 2013). The tool used with typical coolant by jet application wears out quickly, but the greatest results were obtained with MQL in the feed direction (Vazquez et al., 2015). Cutting fluid usage is significantly reduced while switching from MQL to micro-milling. Furthermore, chip adhesion at the tool tip can be detected under dry cutting conditions, whereas this behavior is not observed under MQL conditions. Oil mist has a good potential to reduce wear in MQL because to its lubricating capabilities. It can also reduce the tool-chip contact length, resulting in even better tool wear.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	2	20.10	11.61%	20.10	10.049	3.21	0.088
Feed	2	52.81	30.51%	52.81	26.407	8.44	0.009
DOC	2	15.34	8.86%	15.34	7.671	2.45	0.141
CC	2	56.68	32.75%	56.68	28.340	9.06	0.007
Error	9	28.15	16.26%	28.15	3.127		
Total	17	173.08	100.00%				

6.5 Surface roughness

Surface polish is a crucial criterion for judging machining quality. Poor surface polish reduces micro-component tolerance and exposes subsurface surface cracks (leads). Surface roughness is a reflection of surface polish. The lower the surface roughness, the better the surface polishes. Micro-machining is supposed to have a lower surface roughness in order to minimize machining time on subsequent finish processes. Using the above equations, ANOV.A was used to study the impact of factors on tool wear. Fz & V_C are the most important characteristic, accounting for 14. 21% & 14.90 % percent of R. Cutting fluid is used to increase the quality of the machined surface. This enhancement is due to the lack of BUE in MQL machining (Ziberov et al., 2016). The surface becomes rougher as the tool diameter increases, while the surface becomes smoother as the number of flutes increases (Bajpai et al., 2013). The experiment was carried out using a.5 mm tool and two flutes.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	2	0.011169	14.21%	0.011169	0.005585	1.37	0.302
Feed	2	0.011713	14.90%	0.011713	0.005856	1.44	0.287
DOC	2	0.010345	13.16%	0.010345	0.005172	1.27	0.327
CC	2	0.008723	11.10%	0.008723	0.004362	1.07	0.383
Error	9	0.036653	46.63%	0.036653	0.004073		
Total	17	0.078603	100.00%				

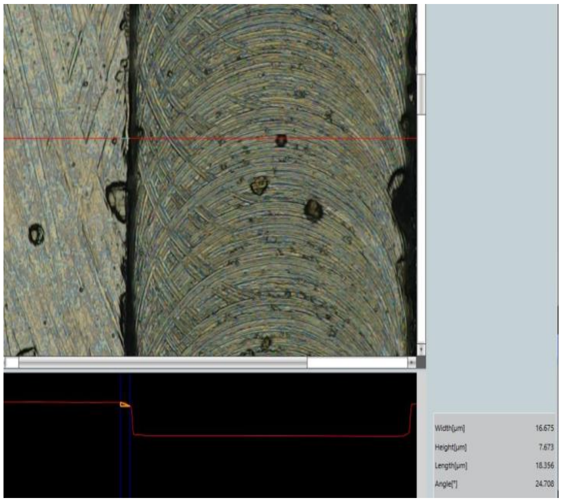
6.6 Cutting forces

Cutting forces are important to understand and monitor because they provide information on a variety of phenomena, including chip formation, material removal mechanisms, vibration, and tool conditions. The magnitude of the C.Fs in micro-milling is substantially smaller than in macro-milling due to the size decrease. D.O.C has a considerable influence on cutting forces, accounting for 73.23% of total cutting conditions. Cutting forces are the second most important element, accounting for 3.65% of total cutting forces. The data can be verified, and their research demonstrates that cutting force increases as feed rate and cutting speed increase(Hassanpour et al., 2016) (Pratap et al., 2015)

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	2	0.2272	5.09%	0.2272	0.11360	2.13	0.175
Feed	2	0.3236	7.25%	0.3236	0.16178	3.03	0.099
DOC	2	3.2665	73.23%	3.2665	1.63325	30.59	0.000
CC	2	0.1626	3.65%	0.1626	0.08129	1.52	0.269
Error	9	0.4806	10.77%	0.4806	0.05340		
Total	17	4.4604	100.00%				

Table 8 These all response are summarized					
The best and worst response under different cutting conditions					
	Speed (m/ min)	Doc (µm)	Feed ((µm/ tooth)	Cutting Conditions	Results (µm)
Up Burr (µm)					
Maximum	5	3	50	Dry	58.76
Minimum	10	9	100	Wet	9.875
Down Burr (µm)					
Maximum	7.5	3	150	Dry	78.67
Minimum	5	9	100	Wet	12.44
Surface Roughness R_a (µm)					
Maximum	10	6	50	Mql	.061
Minimum	5	9	150	Wet	.04
Tool Wear R (µm)					
Maximum	7.5	3	50	Dry	19.32
Minimum	5	9	100	Mql	4.56
Cutting forces (N)					
Maximum	5	9	150	Mql	1.985
Minimum	10	3	5	Wet	.215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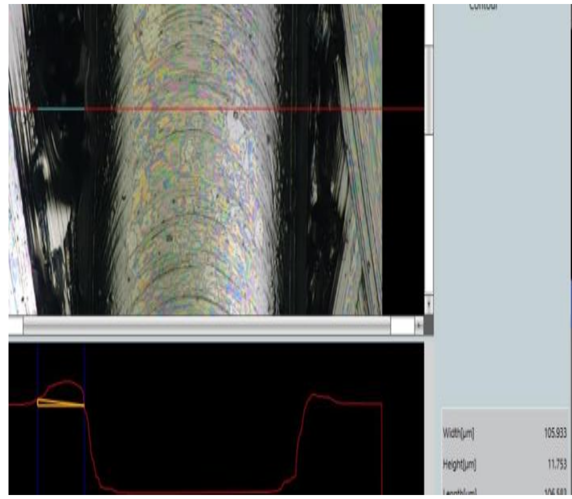
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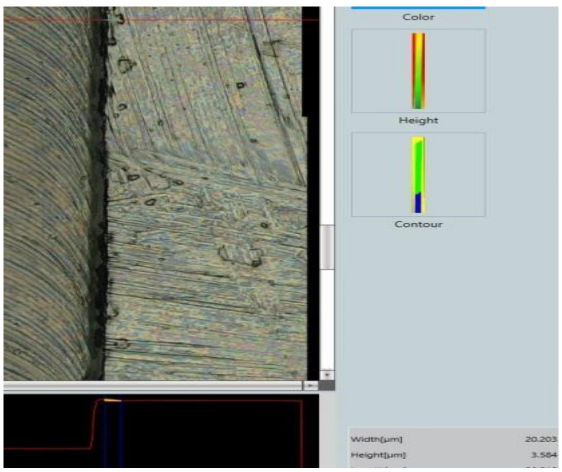
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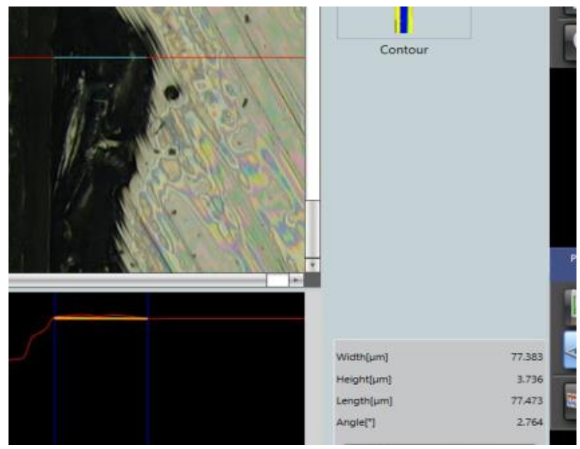
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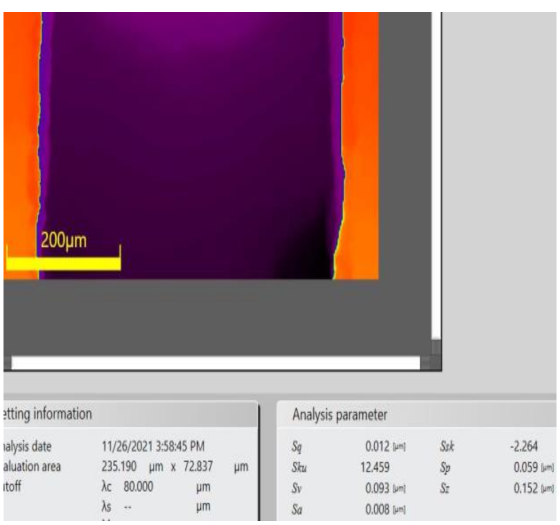
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toff λc 80.000 µm
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Analysis parameter
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Sv 0.093 µm
Sa 0.008 µm
Ssk -2.264
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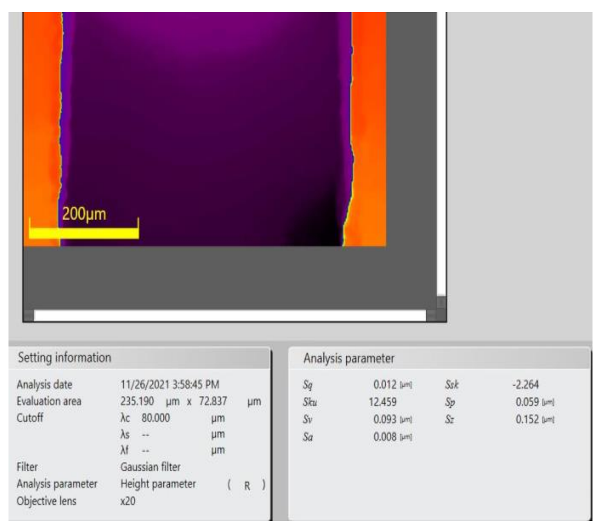
Sz 0.152 µm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λs -- µm
λf -- µm
Filter Gaussian filter
Analysis parameter Height parameter (R)
Objective lens x20
Analysis parameter
Sq 0.012 µm
Sku 12.459
Sv 0.093 µm
Sa 0.008 µm
Ssk -2.264
Sp 0.059 µm
Sz 0.152 µm

7 Grey relational analysis (GRA) for multi-objective optimization

In most machining techniques, improving one reaction without reducing the other is not achievable. Multi-objective optimization is extremely useful for making complex judgments involving competing replies. GRA, which is based on the Taguchi approach, reduces a multi-response problem to a single, distinct function (Taylor, Kuo, et al., n.d.)

GRA begins by standardizing all of the replies and converting each output response to a common scale (0–1). The degree to which responses are normalized is determined by the goal. Cutting forces (CF), wear rate (R), up and down burr, and surface roughness (Ra) should all be kept as low as possible. Thus, the target value was used to normalize the experimental data for five responses (CF, UB, DB, R, and Ra). Using Equation below, the values for are estimated as "smaller the better."

$$Zij = \frac{(yij, i=1,2,\ldots\ldots n) - yij}{(yij, i=1,2,\ldots\ldots n) - min(yij, i=1,2,\ldots. n)} \quad (3)$$

The maximum (yij) and minimum (yij) values of the experimental data for each response are represented by max (yij) and min (yij). True and normalized values are represented by Yij and Zij, respectively.

7.1 Calculation of grey relational coefficients

GRC are calculated using the normalized data using the equation below. GRC connects the optimal response value to the experimental values.

$$\gamma(Z_0, Z_{ij}) = \frac{\Delta min + \xi \Delta max}{\Delta oj(k) + \xi \Delta max} \quad (4)$$

$$0 < \gamma(Z_0, Z_{ij}) \leq 1$$

$$\Delta oj(k) = Z_0(k) - Z_{ij}(k)$$

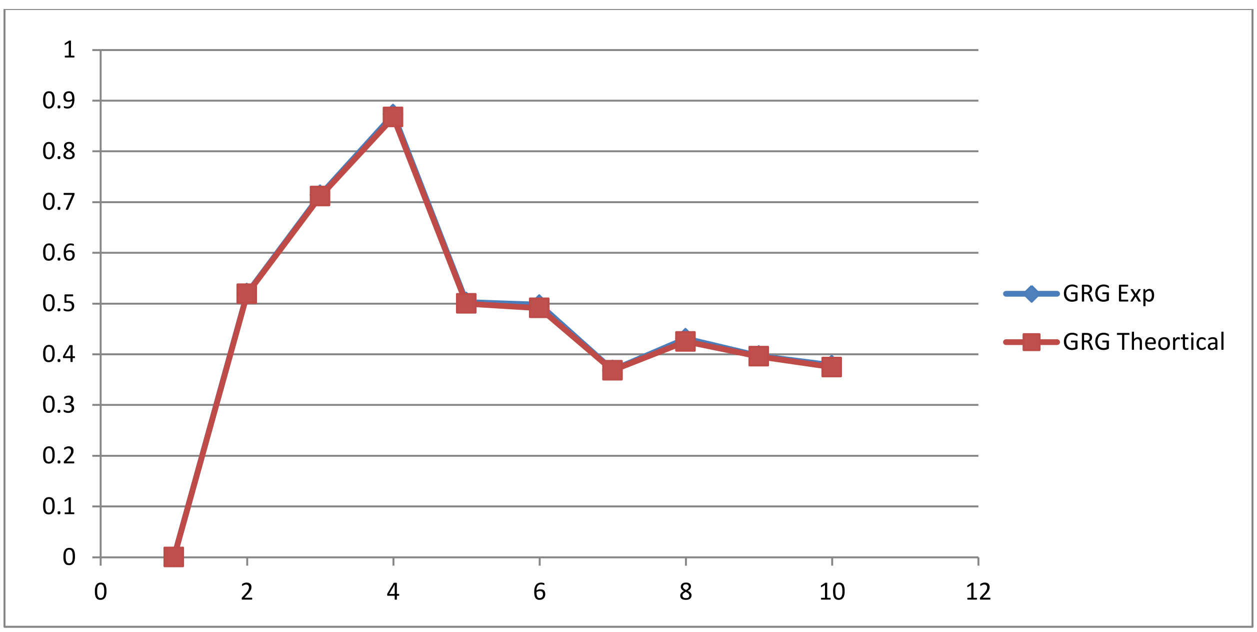
The reference and comparability sequences are represented by Zo (k) and Zij (k), respectively. The value of ξ (distinguishing coefficient) is 0.5 in this study, but it can range from 0 to 1. The estimated GRC values for the five replies are displayed..

7.2 Calculation of GRG

Using the specified weight value of each response, (GRG) turns numerous GRC into a composite factor.

$$\text{Grade}\,(Z_0, Z_{ij}) = \sum_{k=1}^{n} \omega_K\, \gamma(Z_0, Z_{ij}) \qquad (5)$$

$$\sum_{K=1}^{N} \omega_{K=1}$$



Results comparison between experimental GRG and theoretical GRG

Table 9 Gray Relational Co efficient (GRC)										
Speed (m/min)	*Feed (µm/ tooth)*	*DOC (µm)*	*C.Cond*	*Tool Wear (GRC)*	*Down Burr (GRC)*	*Up Burr (GRC)*	*Surface Roughne ss Ra (GRC)*	*C.Forc es (GRC)*	*GRG (Exp)*	*Rank*
5	3	50	Dry	0.38775	0.33333	0.38428	0.38403	0.96269	0.49041	8
5	6	100	Wet	0.49393	1	1	0.47417	0.60205	0.71403	3
5	9	150	MQL	1	0.77037	0.74938	1	0.33333	0.77061	2
7.5	3	100	MQL	0.52330	0.66101	0.67290	0.36550	0.38563	0.52167	6
7.5	6	150	Dry	0.33333	0.40112	0.33333	0.34867	0.38563	0.36042	9
7.5	9	50	Wet	0.6277	0.91357	0.89427	0.57277	1	0.80166	1
10	3	150	Wet	0.47454	0.68390	0.71153	0.58157	0.53781	0.59787	5
10	6	50	MQL	0.50101	0.69456	0.70873	0.35521	0.96128	0.64416	4
10	9	100	Dry	0.59375	0.55091	0.45275	0.33333	0.60840	0.50783	7

7.3 Regression modeling of multi-objective function

RSM is used to carry regression modeling and optimize it. Machining environment was a non-continuous categorical factor in this study, with three unique levels: dry, wet, and MQL. As stated in equation, a separate function was constructed for cutting each situation.

Regression Equation in Uncoded Units

CC

Dry GRG = 1.214 - 0.1580 Speed - 0.03007 Feed - 0.003066 DOC + 0.009531 Speed*Speed + 0.004682 Feed*Feed + 0.000012 DOC*DOC

MQL GRG = 1.406 - 0.1580 Speed - 0.03007 Feed - 0.003066 DOC + 0.009531 Speed*Speed + 0.004682 Feed*Feed + 0.000012 DOC*DOC

Wet GRG = 1.465 - 0.1580 Speed - 0.03007 Feed - 0.003066 DOC + 0.009531 Speed*Speed + 0.004682 Feed*Feed + 0.000012 DOC*DOC

Dry condition contours plot

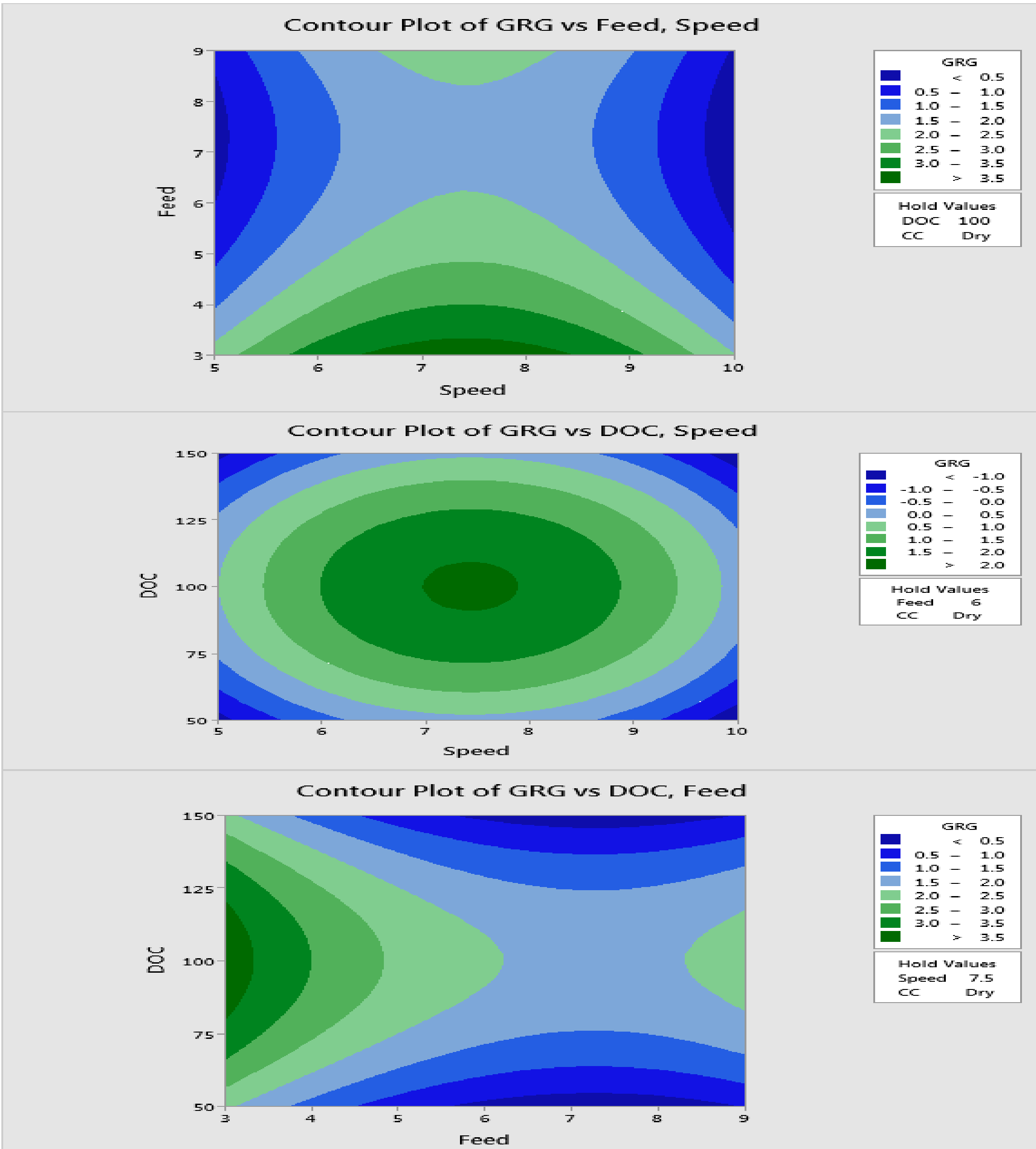


Figure 7 Contours plots for dry machining condition

Surface plot for dry conditions

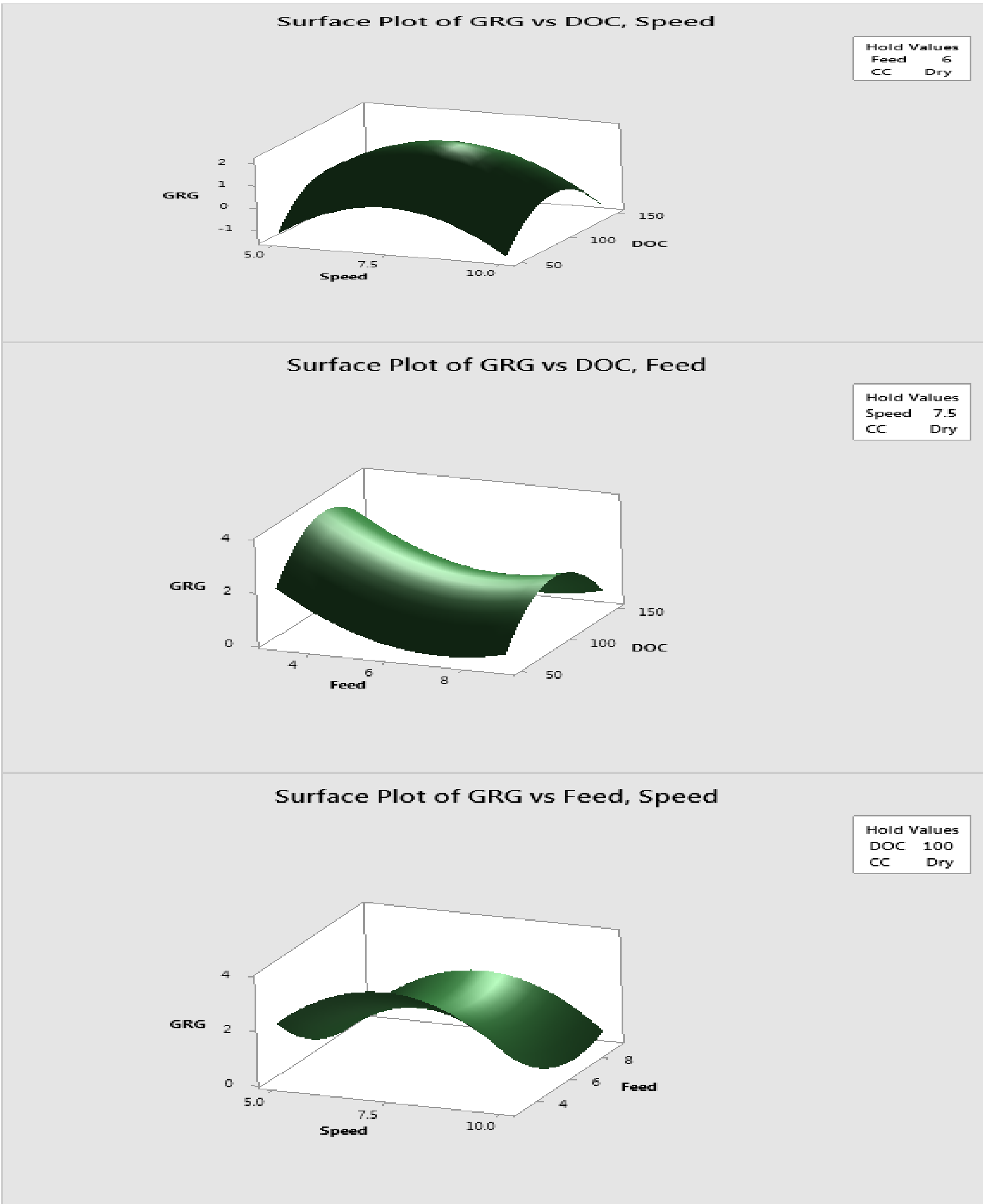


Figure 8 Surface plots for dry machining condition

MQL contours plot

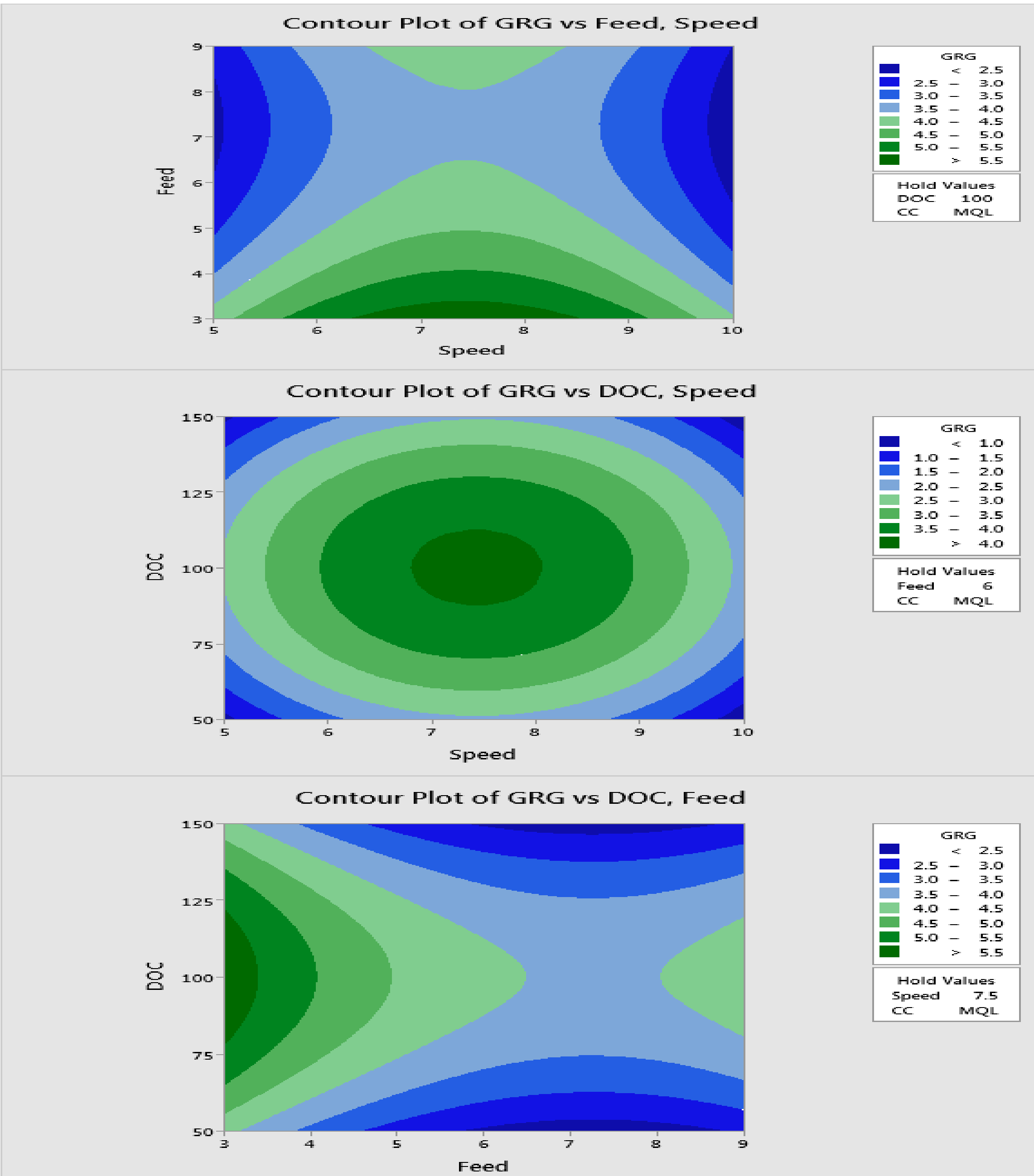


Figure 9 Contours plots for MQL machining condition

Surface plot for MQL conditions

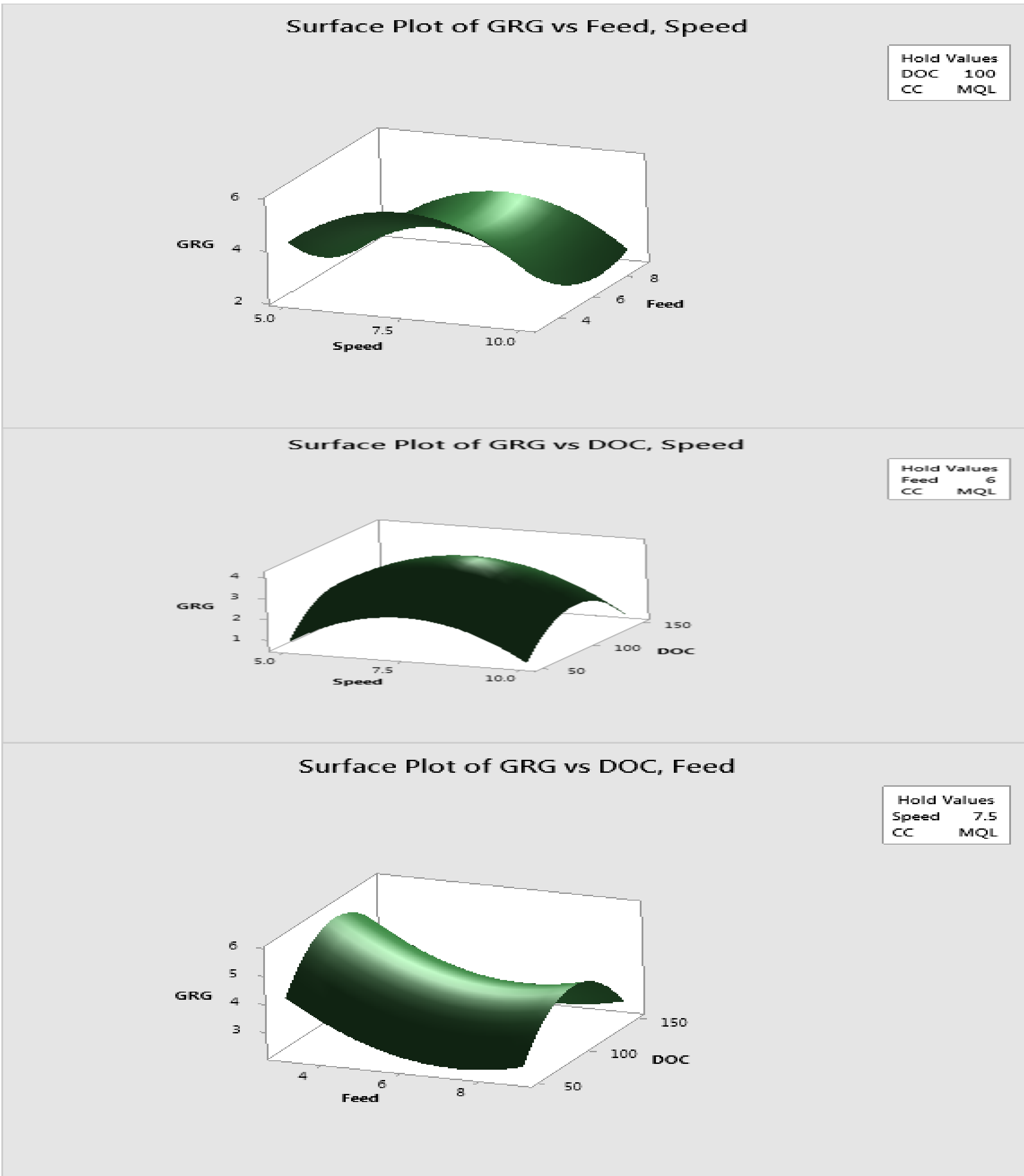


Figure 10 Surface plots for MQL machining condition

Wet contours plot

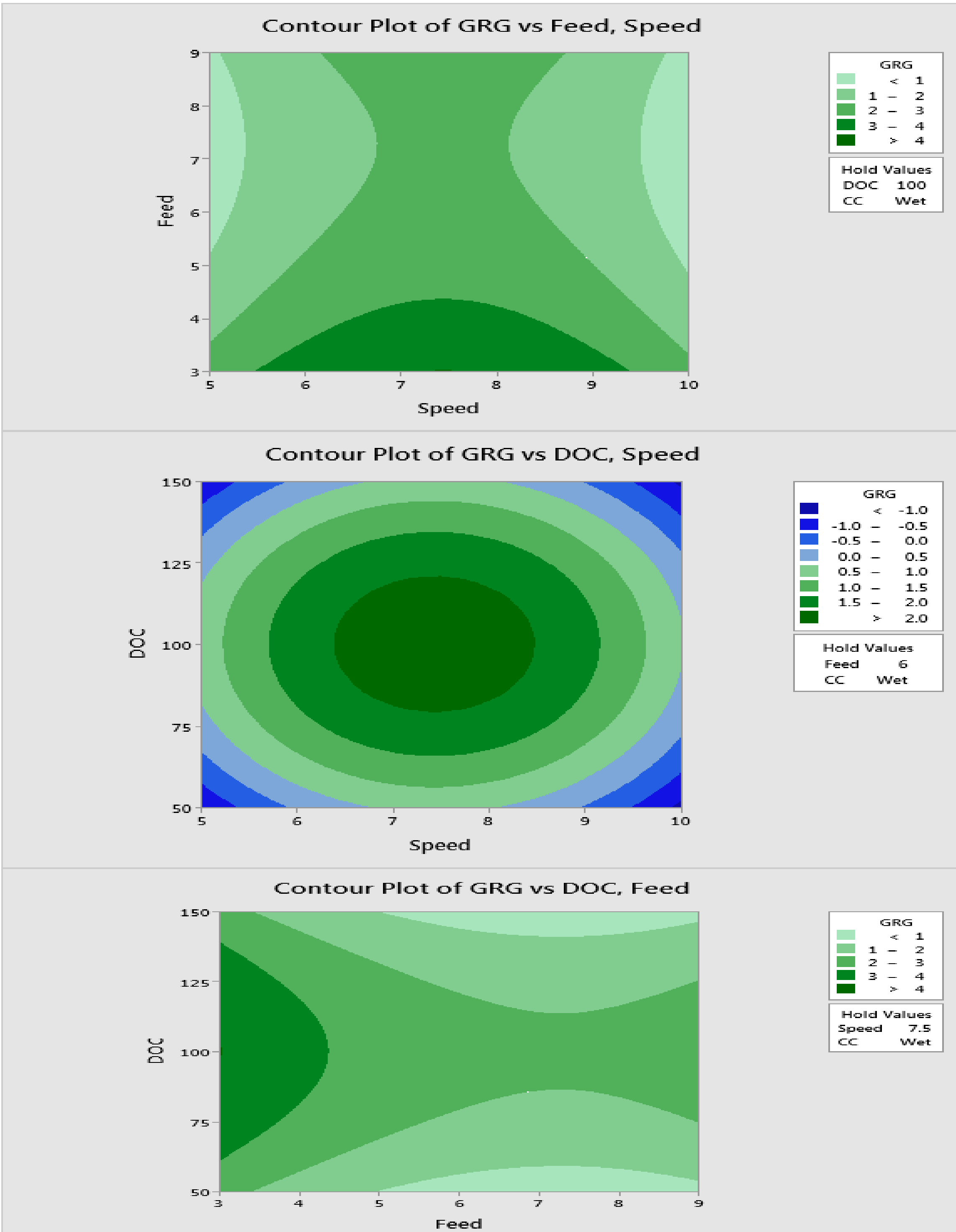


Figure 11 Contours plots for wet machining condition

Surface plot for Wet

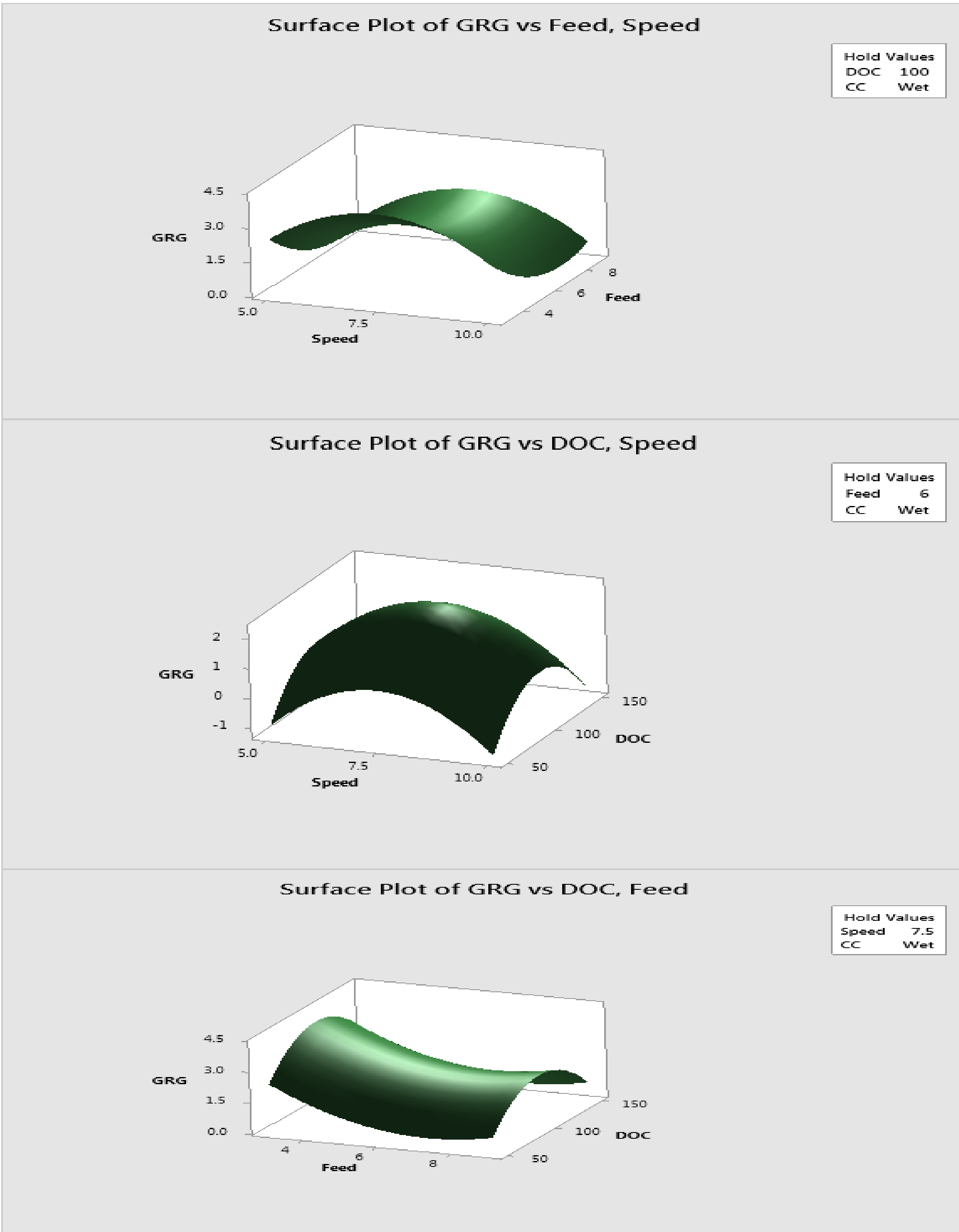


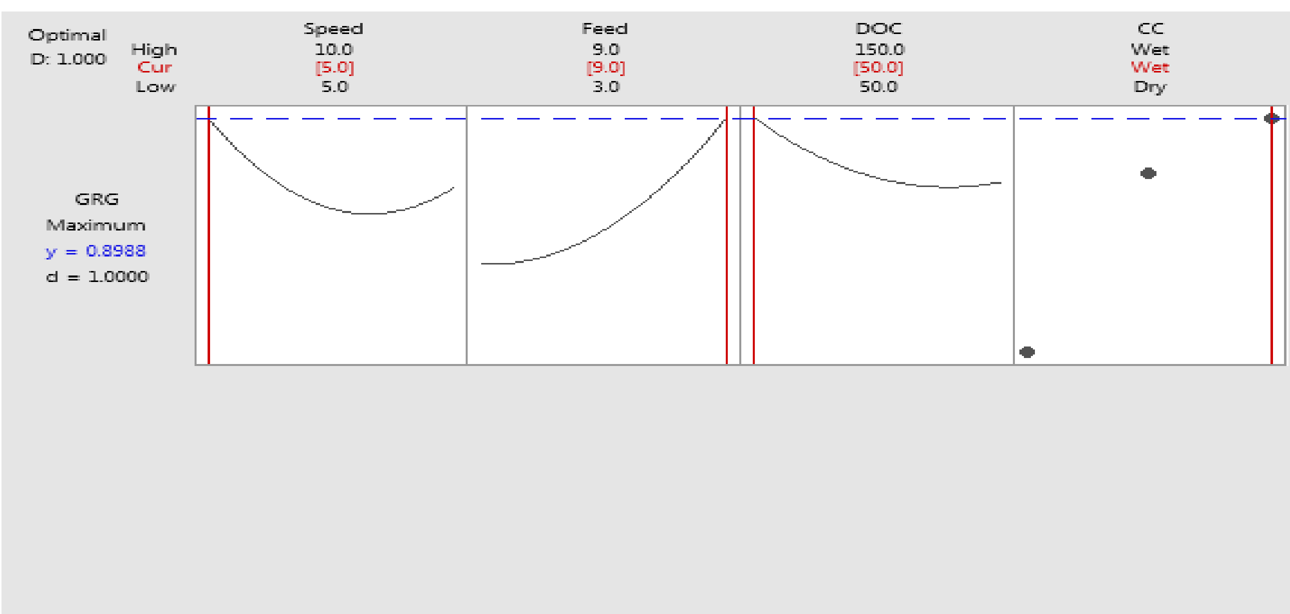
Figure 12 Surface plots for wet machining condition

ANOVA

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	8	0.224472	91.46%	0.224472	0.028059	12.04	0.001
Speed	1	0.011293	4.60%	0.004810	0.004810	2.06	0.185
Feed	1	0.030981	12.62%	0.001389	0.001389	0.60	0.460
DOC	1	0.006475	2.64%	0.000361	0.000361	0.16	0.703
CC	2	0.167262	68.15%	0.167262	0.083631	35.89	0.000
Speed*Speed	1	0.003535	1.44%	0.003535	0.003535	1.52	0.249
Feed*Feed	1	0.003976	1.62%	0.003976	0.003976	1.71	0.224
DOC*DOC	1	0.000950	0.39%	0.000950	0.000950	0.41	0.539
Error	9	0.020970	8.54%	0.020970	0.002330		
Total	17	0.245442	100.00%				

7.4 Analysis of variance (ANOVA)

The statistical analysis was carried out with MINITAB® software, and ANOVA was used to assess the significance of the cutting parameters (Vc, DOC, Fz, and Cutting conditions) at the 95 percent confidence level. The ideal fit was a quadratic model, which indicated great accuracy with R2 = 96.8%. According to the analysis of variance, speed has a greater impact on the outcome. In comparison to the interaction effect of these parameters, the machining reactions and GRG (f, V, and d). DOC appears to be the second most critical machining condition, with cutting conditions coming in third.



7.5 Regression model optimization

To identify the best combination of machining parameters for the best output response, response surface optimization was employed. The outcome is displayed in a table. They were also put to the test in the lab.

7.6 Validation experiments

Table lists the machining parameters optimized by RSM, as well as the optimal run condition in the initial trials (experiment #6). These circumstances were validated, and the findings showed a significant improvement. Burr, C.F, R, and Ra all improved by 3 percent, 9 percent, and 5%, respectively. The best run (Exp. #6) to an optimized run, the only difference is the *f*; V_C and DOC, on the other hand, are the same in both runs. In order to solve multi-objective issues, it is necessary to analyze machining responses in relation to cutting parameters.

Table 10 Best Vs Optimize results	Machining conditions				Responses				
	Speed m/min	Feed µm/ tooth	DOC (µm)	Cutting Conditions	Tool Wear (µm)	UP Burr (µm)	Down Burr (µm)	Surface Roughness Ra (µm)	C.Forces N
Best run	7.5	9	50	Wet	8.92	21.307	25.069	0.024	0.4418
Optimized run	5	9	50	Wet	6.8172	12.8815	14.1278	.0208	.40303
% change					19 %	32%	37%	9%	3%

8 Conclusions

KPVs must be identified in order to improve product quality while simultaneously enhancing efficiency, which leads to cheaper production costs. By micromilling Ti-6Al-4 V in dry, wet, and MQL settings, the current study studied the long-term survival, productivity, and efficiency of the machining process. For machining process productivity, Burr, CFs, R, and Ra were chosen. Optimal settings were established by MOO of all of these responses in order to meet the ends of manufacturing goods for aeronautical, biomedical, and automobile applications. These findings can be taken from the experimental data analysis.

• The major effect of machining settings on burr formation, C.Fs, R, and Ra was investigated using the ANOVA technique on measured outputs. Machining under optimize conditions produced the best results in terms of top and down burr, surface roughness, tool wear, and cutting pressures on the slot's edges.

• Based on this research, it's easy to conclude that wet and MQL as lubrication has a positive impact on burr development, R, and Ra. This demonstrates how wet conditions can be used to improve the machining process as a whole. Wet machining out performed dry and MQL machining in terms of burr creation, R, and Ra.

• The optimize conditions for maximal GRG were a V_C of 5 m/min, *fz* of 9 micrometers, DOC 50 micrometers. The only difference with the best condition was Vc.

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