

Establishing The Scientific Basis for An Experimental Model to Study the Effects of Minimum Quantity Lubrication in Internal Grinding of Ti-6Al-4V Alloy

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ABSTRACT

Ti-6Al-4V alloy is a critical engineering material widely utilized in aerospace, biomedical, and precision mechanical industries due to its high specific strength-to-weight ratio, excellent corrosion resistance, and relatively high thermal stability. However, it is classified as a difficult-to-machine material characterized by low thermal conductivity and high chemical reactivity, which lead to significant heat generation in the cutting zone, resulting in surface integrity degradation and accelerated tool wear. In finishing operations, internal grinding plays a vital role in ensuring surface roughness and geometric accuracy; however, this process faces additional challenges due to the confined machining space, which hinders the delivery of lubrication-cooling media into the contact zone and complicates heat dissipation. In this context, Minimum Quantity Lubrication (MQL) is considered a technological solution to improve lubrication and cooling conditions while enhancing machining quality in an environmentally friendly manner. Based on this premise, this paper focuses on establishing an experimental model to evaluate the effects of MQL during the internal grinding of Ti-6Al-4V alloy components. The research scope includes defining the sets of input and output parameters; proposing the relationships between grinding technological parameters, MQL parameters, and machining quality indicators; and outlining the experimental design and data processing methods for subsequent research phases. The proposed model serves as a scientific foundation for experimental implementation, quantitative analysis of MQL effects, and the development of optimization studies for the Ti-6Al-4V internal grinding process.

Keywords: Ti-6Al-4V; internal grinding; minimum quantity lubrication; MQL; experimental model.

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I. INTRODUCTION

Ti-6Al-4V is the most prevalent $\alpha+\beta$ titanium alloy, widely utilized due to its favorable combination of mechanical and chemical properties—notably its high strength-to-weight ratio, excellent corrosion resistance, and reliability in demanding environments [2]. However, it is classified as a difficult-to-machine (DTM) material due to its low thermal conductivity, a high tendency for heat concentration in the machining zone, and a strong chemical affinity for tool materials. These characteristics lead to localized heat buildup, accelerated tool wear, and adverse effects on the post-machining surface quality [1], [2].

In studies concerning the machinability of Ti-6Al-4V alloy, surface quality is consistently regarded as one of the most critical evaluation criteria, as it directly influences the functional performance and durability of the finished component [2]. Inappropriate machining conditions can lead to surface integrity degradation, such as increased roughness, surface hardening, unfavorable residual stresses, plastic deformation zones, and sub-surface damage [2], [4]. These trends are particularly pronounced in finishing operations like grinding, where the heat in the contact zone is high and the interaction mechanism between the abrasive grains and the workpiece surface is intense. This heightens the risk of phase transformations and surface layer alterations if the technological parameters and lubrication-cooling conditions are not appropriately selected [1], [3], [4].

Grinding is a widely used finishing process aimed at ensuring high precision and superior surface quality, especially for DTM materials. Due to the cutting mechanism involving a vast number of randomly distributed abrasive grains on the wheel surface, the grinding process is subject to highly complex simultaneous

mechanical, thermal, and frictional phenomena. Literature reviews indicate that grinding forces are closely linked to machining accuracy, system deformation, grinding zone temperature, and surface layer conditions; thus, they serve as a fundamental metric for analyzing the grinding process [3].

For Ti-6Al-4V alloy, experimental grinding studies demonstrate that machining quality is strongly influenced by input parameters such as wheel speed, depth of cut, and coolant delivery conditions. Correspondingly, output parameters typically used for process evaluation include surface roughness, grinding forces, vibration, and post-machining surface topography. Results from these studies indicate that variations in surface quality depend not only on the grinding regime but also significantly on the capacity for friction reduction, heat dissipation, and the mitigation of material adhesion in the contact zone [1], [4], [8].

Compared to surface or cylindrical grinding, internal grinding possesses distinct technological characteristics due to the machining zone being confined within a narrow space, the small diameter of the grinding wheel, and the restricted accessibility for delivering media into the contact zone. These features make heat dissipation, chip evacuation, and maintaining stable machining quality more challenging, particularly when processing DTM materials like Ti-6Al-4V [1]. Research into internal grinding and grinding cycles also shows that factors related to the contact state of the wheel significantly affect productivity and machining accuracy, confirming that internal grinding must be treated as a specialized technological case [5], [6].

When evaluating machining quality in internal grinding, relying solely on a single output parameter like surface roughness is insufficient. In addition to parameters such as Ra or Rz, indicators reflecting the geometric accuracy of the hole—such as roundness, cylindricity, and dimensional deviation—must be considered simultaneously, as these directly characterize the functional quality of the internal surface. Furthermore, output parameters like grinding forces, vibration, and surface state are valuable for elucidating the influence mechanisms of technological parameters and lubrication-cooling conditions on the internal grinding process [3], [5], [8].

Based on the reviewed publications, it is evident that research into grinding and internal grinding processes must not only consider input technological parameters but also select a system of output parameters capable of reflecting surface quality, geometric accuracy, and the technological state of the process simultaneously. This is an essential prerequisite for establishing an experimental model to evaluate the effects of Minimum Quantity Lubrication (MQL) in the internal grinding of Ti-6Al-4V alloy in subsequent sections [3], [8], [9].

Minimum Quantity Lubrication (MQL) is a method that delivers a very small amount of lubricant, usually in the form of oil, carried by a compressed air stream and injected directly into the machining zone as a fine mist. Compared to traditional flood cooling, MQL offers the advantages of significantly reducing fluid consumption, minimizing waste generation, and aligning with sustainable manufacturing goals. Recent reviews of green machining technologies and advanced lubrication-cooling techniques show that MQL has become a key approach to balancing technological efficiency, environmental impact, and occupational safety requirements [2], [7], [9].

In the study of DTM material machining, MQL is of particular interest due to its ability to improve lubrication conditions at the contact interface, limit friction, and support enhanced surface quality. For titanium-based alloys, numerous publications have indicated that the use of MQL or its variants can contribute to improved surface roughness, reduced machining forces, and higher media efficiency compared to traditional delivery methods [2], [7], [11]. This trend demonstrates that MQL possesses not only environmental significance but also clear practical value in enhancing the machinability of DTM material groups [2], [11].

Research by Sadeghi et al. [1] has shown that MQL can be a successful near-dry application for Ti-6Al-4V grinding. Subsequent studies, including comparative analyses of MQL, flood cooling, and nano-MQL in titanium alloy grinding, continue to reinforce the finding that coolant delivery conditions significantly influence surface quality and surface damage phenomena. Nevertheless, existing literature suggests that the effectiveness of MQL depends heavily on the method of distributing the media into the grinding zone—a point that must be explicitly incorporated into the research model.

Analysis of the published literature reveals three noteworthy points. First, Ti-6Al-4V is a difficult-to-machine material where the grinding process is strongly affected by heat, friction, material adhesion, and lubrication conditions in the contact zone [1], [3], [10]–[12]. Second, Minimum Quantity Lubrication is a technological direction aligned with sustainable manufacturing trends and has shown potential in various studies related to titanium alloy machining [10]–[14]. Third, for internal grinding, the technological process involves additional specificities regarding the contact zone, chip evacuation, coolant delivery conditions, and high requirements for geometric accuracy [2], [4], [5], [15], [16].

From these observations, it is clear that the current research gap lies not only in the limited number of studies on Ti-6Al-4V internal grinding under MQL conditions but also in the lack of a clearly structured experimental framework to simultaneously evaluate the influence of technological factors and lubrication

delivery conditions on machining quality. In many existing publications, the focus is primarily on surface grinding, while investigated parameters often concentrate on individual factors like oil flow rate, air pressure, lubricant type, or cooling environment, whereas the interactive relationship between these parameters and the specific characteristics of the internal grinding process has not been fully considered [10]–[16]. This highlights the urgent need to establish a specialized experimental model for the internal grinding process of Ti-6Al-4V alloy under MQL conditions.

On this basis, the experimental model should be developed by integrating three core content groups. The first group comprises input parameters of the grinding process, reflecting cutting conditions and material removal. The second group consists of input parameters specific to the MQL delivery process, reflecting the capability to deliver media into the machining zone for lubrication and cooling support. The third group includes output parameters used to evaluate machining quality, focusing on indicators that directly reflect the surface state and the precision of the part post-grinding. This approach allows for the establishment of a logically structured research framework, ensuring a clear link between the MQL action mechanism and the resulting machining quality in internal grinding.

In line with this orientation, the present study focuses on establishing an experimental model as a foundation for the subsequent experimental design and data processing phases. This model serves not only to identify the impact levels of individual input parameters but also to provide a basis for analyzing the interaction between the grinding regime and MQL conditions on specific output parameters. Therefore, constructing a specialized experimental model for Ti-6Al-4V internal grinding under MQL conditions is necessary from both a scientific and an applied perspective.

II. SCIENTIFIC BASIS FOR ESTABLISHING THE EXPERIMENTAL MODEL

2.1. Mechanism of Surface Quality Formation in Grinding

Surface quality after grinding is formed under the combined effects of various mechanical and thermal phenomena occurring at the contact zone between the grinding wheel and the workpiece. At the microscopic scale, each abrasive grain participates in plowing, micro-cutting, rubbing, and localized plastic deformation of the surface layer. The collective series of successive impacts from a large number of abrasive grains—possessing heterogeneous geometries and varying depths of cut—creates the micro-topographical state of the post-machined surface, characterized by specific roughness and grinding patterns [1], [2], [4].

For Ti-6Al-4V alloy, the mechanism of surface quality formation becomes more complex due to the material's inherent difficult-to-machine characteristics. Low thermal conductivity prevents heat generated in the contact zone from dissipating effectively, while high chemical reactivity at elevated temperatures increases the tendency for material adhesion onto the abrasive grains and the wheel surface. Furthermore, the low elastic modulus and surface hardening capacity of titanium alloys make the near-surface layer susceptible to localized plastic deformation, material side flow, smearing, and surface defects if machining conditions are not appropriately selected [1], [3], [10]–[12].

During grinding, surface quality formation depends not only on the cutting action of the grains but is also significantly influenced by sliding friction and plowing friction between the wheel and the workpiece. As friction increases, energy consumption in the contact zone rises, leading to increased grinding forces and a tendency for surface integrity degradation. Thus, the post-grinding surface is essentially the result of simultaneous interactions between the material removal mechanism, contact friction, and localized heat accumulation within the machining zone [2], [4], [5].

In internal grinding, this mechanism is further influenced by specific technological constraints. Compared to surface or external cylindrical grinding, internal grinding involves a relatively narrow contact zone, confined machining space, more difficult chip evacuation, and less favorable conditions for delivering media precisely into the contact zone. These features increase the risk of thermal buildup, material adhesion, and geometric deviations of the finished hole. Consequently, surface quality in internal grinding reflects not only the material properties and grinding regime but also the suitability of the lubrication method employed in the machining zone [2], [4], [5], [15], [16].

From a mechanistic perspective, it is evident that surface quality in the internal grinding of Ti-6Al-4V is governed by three primary factors: the mechanical characteristics of the material removal process, the friction conditions at the contact interface, and the ability to limit localized heat accumulation. This provides an important scientific basis for evaluating the role of Minimum Quantity Lubrication (MQL) in the research model.

2.2. The Role of Minimum Quantity Lubrication in Ti-6Al-4V Internal Grinding

Minimum Quantity Lubrication is a method that delivers a very small amount of lubricant as a fine mist into the machining zone using a compressed air stream. Unlike flood cooling, the effectiveness of MQL relies

not on providing a large volume of media but on its capacity to form a lubrication film at the contact interface and the ability of the mist droplets to penetrate the tool-workpiece interface. Therefore, during grinding, MQL acts primarily through two mechanisms: reducing friction at the contact zone and providing a degree of localized cooling [10], [12], [14].

For Ti-6Al-4V, the role of MQL is particularly noteworthy as this material is highly sensitive to friction and heat. When a lubrication film is effectively formed at the contact interface between the grains and the material, the tendencies for adhesion and sliding/rubbing can be mitigated, thereby reducing grinding forces and improving the post-machining surface state. Simultaneously, the oil-carrying air stream assists in chip evacuation, partially reducing wheel loading (clogging) and improving tool working conditions [10]–[13].

However, the effectiveness of MQL in internal grinding is not identical to other machining processes. In the narrow space of an internal hole, the ability to distribute oil mist precisely to the contact zone depends heavily on spray conditions, the geometry of the machining zone, and the penetration capability of the oil-carrying air stream. Thus, the actual efficiency of MQL depends not only on the lubricant type itself but is also closely tied to the delivery parameters of the MQL system. This is a crucial distinction that necessitates approaching MQL research in internal grinding as a separate problem, rather than directly extrapolating from studies on surface grinding or other cutting processes [11], [12], [15], [16].

Published research indicates that MQL and its variants, such as cryo-MQL or MQL combined with CO₂, can improve machining forces, surface roughness, and various indicators related to surface integrity when machining titanium alloys [13]–[16]. However, the degree of improvement depends significantly on the synergy between the grinding technological conditions and the media delivery conditions. This underscores the need for an experimental model capable of simultaneously reflecting the influence of these two groups of factors on machining quality.

2.3. Rationale for the Proposed Experimental Model Structure

Based on the preceding analysis, it is clear that machining quality in Ti-6Al-4V internal grinding under MQL is not the result of a single factor, but rather the interaction between the grinding process and the lubricant delivery process at the contact zone. In other words, for identical grinding conditions, if the ability to deliver oil mist into the machining zone varies, the resulting friction state, grinding forces, and surface quality may also differ. Conversely, for a given MQL condition, changes in the grinding regime will alter the effectiveness of the lubrication film. Therefore, the experimental model must be constructed to integrate factors from both groups simultaneously.

On this basis, the proposed experimental model structure consists of three main components:

Input parameters of the grinding process: reflecting the degree of mechanical impact of the wheel on the workpiece surface.

Input parameters of the MQL delivery process: reflecting the capacity to form and deliver the lubricant into the machining zone.

Output parameters: used to evaluate machining quality and the process response under various investigated conditions.

Organizing the model according to this structure has a clear scientific foundation. The grinding input parameters represent the material removal mechanism and mechanical load generation; the MQL system input parameters represent the friction reduction and localized cooling mechanisms; and the output parameters reflect the combined result of these two mechanisms on machining quality. This approach allows for the consideration of not only the individual influence of each input parameter but also their interactive effects on the characteristic output metrics.

In conclusion, the scientific basis for the experimental model in this study stems from the very nature of the Ti-6Al-4V internal grinding problem under MQL: machining quality is determined by the interaction between grinding conditions and MQL delivery conditions within a machining space constrained by contact, chip evacuation, and geometric accuracy requirements. This serves as the foundation for specifically defining the input and output parameters used in the experimental design in the following section.

III. ESTABLISHING THE EXPERIMENTAL MODEL STRUCTURE AND SELECTING RESEARCH PARAMETERS

3.1. Experimental Model Structure

Based on the literature review and research objectives, the experimental model for the internal grinding of Ti-6Al-4V alloy under MQL conditions is developed to simultaneously reflect the influences of the grinding process and the MQL delivery process on machining quality. Prior studies on MQL grinding of Ti-6Al-4V indicate that the commonly considered variable groups include grinding wheel speed, workpiece speed or feed rate, depth of cut, MQL flow rate, and air carrier pressure [10], [12]. Furthermore, several publications have

shown that abrasive material, the wheel surface state post-dressing, and the efficiency of delivering media into the contact zone significantly affect grinding forces, surface integrity, and process stability [10], [12], [15].

From this perspective, the experimental model is organized into four interconnected blocks: the Workpiece block, the Grinding Tool and Dressing block, the Technological Impact block, and the Output Response block. Specifically:

Workpiece: Ti-6Al-4V alloy specimens with a length of 23 mm and an initial hole diameter of 17.9 mm, ground to a nominal diameter of 18 mm. Choosing a small-hole geometry aligns with the characteristics of precision internal grinding and highlights the role of MQL in confined spaces where coolant delivery is more restricted than in surface grinding.

Grinding Tool: Two wheel variants are selected—Silicon Carbide (SiC) and Cubic Boron Nitride (CBN). The selection of CBN is based on studies applying MQL to Ti-6Al-4V grinding that evaluated MQL parameters' effects on force and roughness [10]. For SiC, recent research suggests it is a suitable choice for titanium based on abrasive-material compatibility principles and has been effectively used to improve the grindability of Ti-6Al-4V [15]. The wheels are selected with a grit size of F100, vitrified bond, porous structure, diameters of 13–14 mm, and widths of 6–9 mm to fit the 18 mm hole diameter.

Dressing: The working state of the wheel is maintained using a single-point diamond dresser. This choice follows studies indicating that a small dressing lead (approx. 20 μm) can create a wheel surface favorable for titanium machining [15]. In this model, the dresser geometry is fixed based on actual equipment conditions, and the dressing regime is held constant throughout the study to avoid noise when evaluating the primary input parameters.

3.2. Selection of Input Parameters

Inheriting from prior publications and considering the specificities of internal grinding, input parameters are divided into two groups: grinding technological parameters and MQL delivery parameters.

Grinding Technological Parameters: While wheel speed is pre-set based on equipment limits, the primary investigated inputs are feed rate (f) and depth of cut (a_p). These two parameters directly influence material removal rates, grinding forces, surface state, and geometric deviations.

MQL Delivery Parameters: Literature [10, 12] identifies lubricant flow rate (Q) and air pressure (P) as core variables governing MQL effectiveness. Sadeghi et al. [12] directly selected flow rate and pressure variables in Ti-6Al-4V MQL grinding, while Biswojyothi et al. [10] investigated their impact on force and roughness using CBN wheels. Thus, MQL flow rate and MQL pressure are selected as the characteristic delivery parameters.

Categorical Variable: The wheel type (G) (SiC vs. CBN) is included as a grouping variable. This allows for an evaluation of how grinding regimes and MQL conditions interact within specific abrasive material contexts.

Thus, the primary input variables are feed rate (f), depth of cut (a_p), MQL flow rate (Q), and MQL pressure (P), with wheel type (G) acting as a categorical factor.

3.3. Selection of Output Parameters

Output parameters are selected to reflect the process's working state and the part's finished quality. In previous MQL grinding studies of Ti-6Al-4V, grinding force (F) and surface roughness (R_a) are the most common metrics used [10, 12, 15]. Grinding force reflects the mechanical load and friction at the contact zone, while surface roughness directly reflects the micro-geometric state.

However, since this study focuses on internal grinding, force and roughness alone are insufficient. Internal grinding requires a stricter focus on maintaining the dimensional and geometric accuracy of the hole. Therefore, the selected output parameters include grinding force, surface roughness, and geometric accuracy (e.g., roundness or cylindricity). Including geometric accuracy ensures the model fully reflects the technological objectives of precision internal grinding.

3.4. Proposed Experimental Model Framework

Based on the analysis above, the experimental model framework can be generalized as a relationship between the input and output parameter groups as follows:

$$Y = f(s, t, Q_{MQL}, p_{MQL}, G) \quad (1)$$

Where:

Y: The set of output parameters (Grinding force, Roughness, Geometric accuracy).

f: Feed rate (mm/min).

a_p : Depth of cut (mm).

Q: MQL flow rate (ml/h).

P: MQL air pressure (MPa).

G: Grinding wheel type (SiC, CBN).

This expression encapsulates the research perspective that machining quality in MQL-assisted internal grinding of Ti-6Al-4V results from the interaction between grinding conditions, media delivery conditions, and abrasive characteristics. This framework serves as the basis for defining the survey range, experimental levels, and the experimental matrix in the following section.

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IV. SELECTION OF EXPERIMENTAL DESIGN AND MATRIX

4.1. Rationale for Selecting Investigated Parameters

Based on the experimental model established in the previous section, the parameters selected for investigation include the grinding technological parameters and the MQL delivery parameters. This selection is based on prior research on Ti-6Al-4V alloy grinding under MQL conditions, where common variables include wheel speed, workpiece speed or feed rate, depth of cut, MQL flow rate, and air carrier pressure [10], [12]. Specifically, Sadeghi et al. [12] directly utilized variables v_s , v_w , a_e , and $Q_{\{MQL\}}$ to study Ti-6Al-4V grinding; similarly, Biswojyothi et al. [10] investigated the effects of flow rate and air pressure in Ti-6Al-4V grinding using CBN wheels. Therefore, for the present study, four input parameters were selected: feed rate (f), depth of cut (ap), MQL flow rate (Q), and MQL pressure (P).

Furthermore, the type of grinding wheel is considered a grouping factor. Literature [10] indicates that CBN wheels can perform effectively in Ti-6Al-4V grinding under MQL, while a recent study by Mukhopadhyay et al. [19] emphasizes the suitability of SiC wheels for titanium alloys and demonstrates improved grindability when using SiC wheels in conjunction with small-quantity lubrication methods. Consequently, this study adopts two distinct experimental branches corresponding to SiC and CBN wheels.

A schematic of the experimental setup is shown in Fig. 7. The Ti-6Al-4V alloy workpiece was mounted on an internal grinding machine, where the grinding wheel machined the inner surface of the hole, while the minimum quantity lubrication (MQL) fluid was delivered directly into the contact zone between the grinding wheel and the workpiece surface. The setup also ensured stable dressing conditions and enabled the evaluation of the output parameters, including grinding forces, surface roughness, and the geometric accuracy of the machined hole.

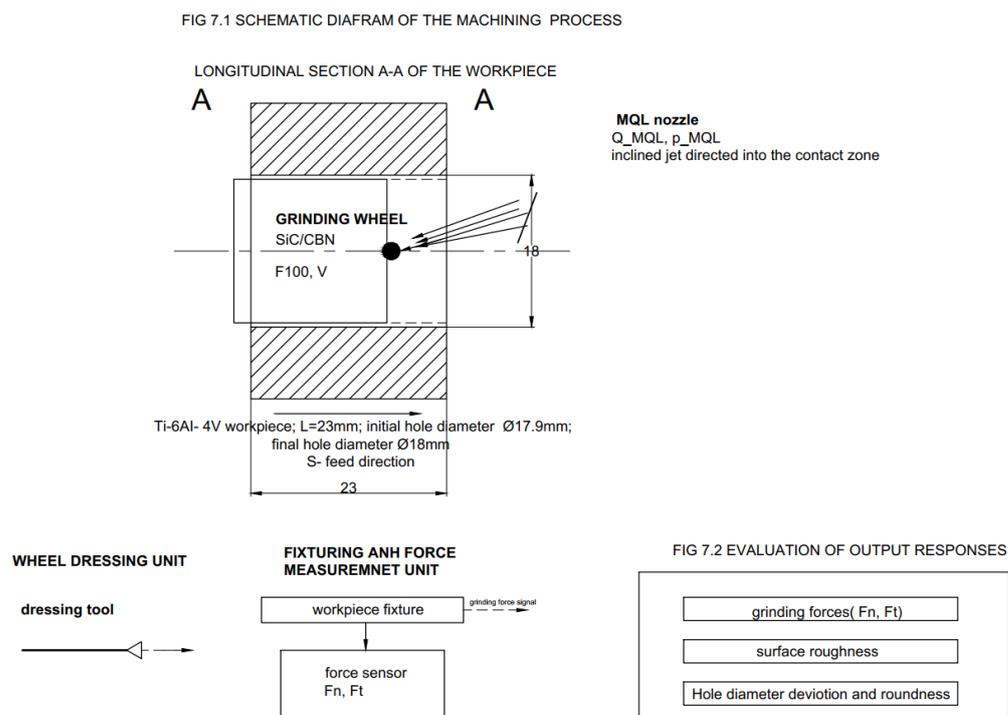


Fig. 7 schematic of the experimental of the machining process

4.2. Determination of Input Parameter Levels

The investigation levels were determined by inheriting data from published literature and adjusting them to suit the specificities of internal grinding, hole dimensions, and the technological capabilities of the experimental setup. In previous studies, Sadeghi et al. [12] investigated $v_s = 60$ m/s, $a_e = 5\text{--}15$ μm , $Q\{\text{MQL}\} = 30\text{--}150$ ml/h, and $P = 4\text{--}6$ bar. Meanwhile, Biswojyothi et al. [10] utilized flow rates of 60, 80, and 100 ml/h with pressures of 2, 4, and 6 bar. For SiC wheels, Mukhopadhyay et al. [19] investigated Ti-6Al-4V grinding with infeed levels of 5, 10, and 15 μm , noting that a 20 μm dressing depth with a single-point diamond dresser is appropriate for SiC wheels when machining this material.

On this basis, the grinding wheel speed in the current study is held constant to ensure stable working conditions and reduce model complexity. The primary investigated parameters and their levels are selected as follows: feed rate $f = 100\text{--}300$ mm/min; depth of cut $a_p = 0.005\text{--}0.015$ mm; MQL flow rate $Q = 50\text{--}150$ ml/h; and MQL pressure $P = 2\text{--}6$ bar. In essence, the ranges for Q and P are selected within values proven effective in prior research [10], [12], where the vicinity of $Q = 100$ ml/h and $P = 4$ bar showed trends of reduced grinding forces and improved surface integrity [12]. For the depth of cut, the range of $0.005\text{--}0.015$ mm inherits the $5\text{--}15$ μm levels used in [19], while providing sufficient variation for internal grinding conditions.

Notably, the feed rate was adjusted downward compared to published surface grinding studies [12], as this research involves small-diameter internal grinding, characterized by a narrower machining zone, different technological stiffness, and more restricted coolant access. This adjustment ensures experimental feasibility while maintaining a scientific link to previous literature.

Dressing conditions are kept consistent throughout the study. The choice of a single-point diamond dresser is supported by research [19], [16], which successfully utilized this method with a dressing depth of approximately 20 μm for conventional wheels in Ti-6Al-4V machining.

Table 1. Input parameters and investigated levels

Symbol	Input parameter	Level 1	Level 2	Level 3
s	Feed-rate (m/min)	0,5	1,0	1,5
t	Depth of cut (mm)	0,005	0,010	0,015
Q_{MQL}	Flow rate MQL (ml/h)	40	50	60
p_{MQL}	Pressure MQL (bar)	4	5	6

4.3. Selection of Experimental Design and Matrix

With four continuous input parameters, each investigated at three levels, a full factorial design would require $3^4 = 81$ experimental combinations for each wheel type. When considering both SiC and CBN wheels, the total experimental volume would become excessively large and impractical. Therefore, a Taguchi L9 orthogonal array was selected for each wheel branch to reduce the number of basic experiments while ensuring the ability to evaluate the influence of input parameters on the outputs.

The wheel type is not included in the same orthogonal matrix as the continuous variables but is separated into two independent experimental branches. This organization aligns with the categorical nature of the "wheel type" variable and facilitates a distinct comparison of technological parameter influences under each tooling condition.

Table 2. Proposed experimental matrix for each wheel type (L9)

Trial	$s(\text{m/min})$	$t(\text{mm})$	$Q_{MQL}(\text{ml/h})$	$p_{MQL}(\text{bar})$
1	0,5	0,005	40	4
2	0,5	0,010	50	5
3	0,5	0,015	60	6
4	1,0	0,005	50	6
5	1,0	0,010	60	4
6	1,0	0,015	40	5
7	1,5	0,005	60	5
8	1,5	0,010	40	6
9	1,5	0,015	50	4

This matrix is applied separately to both SiC and CBN wheels, resulting in a total of 18 basic experimental combinations. To enhance reliability, each combination should be repeated at least three times, using the average values for analysis.

4.4. Selection of Output Parameters

The selected output parameters include grinding force, surface roughness, and the geometric accuracy of the hole. This selection is grounded in previous research where grinding force and surface roughness are the

primary indicators for MQL effectiveness in Ti-6Al-4V grinding [10], [12], [19]. Additionally, for internal grinding, geometric accuracy is particularly critical; thus, including this group of indicators is essential to accurately reflect the technological objectives of the study.

In conclusion, the parameters and levels selected for the current study both inherit a foundation from published literature and are calibrated to the practical conditions of internal grinding and the experimental setup. This provides the basis for subsequent experiments to establish the relationship between input and output parameters in the MQL-assisted internal grinding of Ti-6Al-4V alloy.

V. EXPERIMENTAL SETUP AND EVALUATION METHODS

5.1. Experimental System Setup

The experimental system is established on a TOYO T-11C internal grinding machine, integrated with a Minimum Quantity Lubrication (MQL) delivery unit capable of providing stable adjustments for oil flow rate and compressed air pressure within the ranges defined in Section 4. This configuration is selected to address the specific characteristics of small-diameter internal grinding, where the low stiffness of the grinding wheel and tool deflection can directly impact the actual depth of cut, surface roughness, and the geometric accuracy of the hole [17]. Furthermore, research on MQL in grinding indicates that lubrication efficiency depends heavily on the ability to direct the media jet precisely into the contact zone, as well as on jet parameters such as pressure and flow rate [12], [18], [20].

The grinding wheels are organized into two distinct branches—SiC and CBN—both with a grit size of F100 and a vitrified bond. This layout inherits from studies that utilized CBN wheels for MQL-assisted Ti-6Al-4V grinding, while incorporating the SiC branch as an abrasive material recently proven capable of effectively machining Ti-6Al-4V [10], [15], [21]. Dressing conditions are maintained using a single-point diamond dresser to minimize variations caused by the wheel surface state between experimental runs.

5.2. Establishment of Experimental Conditions

The experimental workpieces consist of Ti-6Al-4V alloy, with a length of 23 mm and an initial hole diameter of 17.9 mm, ground to a nominal diameter of 18 mm. The choice of a small-hole geometry is intended to accurately represent precision internal grinding, where the narrow machining zone increases requirements for kinematic stability and the penetration capability of the lubricant into the contact zone [17], [20]. The primary investigated parameters are feed rate, depth of cut, MQL flow rate, and MQL air pressure; other conditions such as workpiece material, grinding wheel characteristics, nozzle type, oil type, dressing regime, and fixturing methods are kept constant throughout the study to isolate the effects of the main input parameters [18], [19]. This organization aligns with the experimental logic of MQL grinding research, where technological and media delivery variables are chosen as investigated factors, while background conditions are controlled to ensure comparability across experimental combinations [18], [19]. For Ti-6Al-4V grinding, this approach is particularly essential as machining quality is simultaneously influenced by friction, localized heat, and the operational state of the grinding wheel [20], [21].

5.3. Measurement Methods for Output Parameters

For each experiment, the measured output parameters include surface roughness, three grinding force components, and three vibration components of the grinding wheel mandrel. The selection of these metrics has a clear scientific basis: surface roughness directly reflects machining quality; grinding forces reflect the mechanical load and friction at the contact zone; and vibration reflects the dynamic stability of the technological system—a factor of critical importance in internal grinding using small-diameter wheels [17], [18], [20].

Surface Roughness: Post-grinding surface roughness is measured using a Mitutoyo SJ-201 tester. In each experiment, the roughness value is determined following a consistent measurement protocol to serve as the primary indicator for surface quality [18], [19].

Grinding Forces: Three force components (F_x , F_y , F_z) are measured using a Kistler 9139AA force dynamometer. Simultaneous measurement of the three components allows for a more comprehensive evaluation of how the grinding regime and MQL conditions influence the interaction between the wheel and the workpiece [12], [18], [20].

Vibration: Three vibration components of the grinding mandrel are measured using a 4525-B-001 accelerometer. Including this parameter group is necessary because internal grinding involves lower technological stiffness and the process is more sensitive to oscillations, which directly affect surface quality and machining stability [17], [20].

Force and vibration signals are acquired during machining and processed within the stable working zone. This setup provides an experimental foundation for simultaneously evaluating surface quality and the operational state of the Ti-6Al-4V internal grinding process under MQL conditions.

5.4. Principles for Ensuring Experimental Reliability

To ensure data reliability, each experimental combination is repeated, and the results are processed based on average values. Regarding grinding forces, signals are selected from the stable phase of the process to limit the influence of the entry and exit stages of the tool. For surface roughness and geometric accuracy, measurements are taken at multiple positions on the same workpiece to reduce the impact of localized errors. This organization is consistent with experimental methodologies in published grinding research, where output responses are evaluated based on multiple measurement points or repetitions to increase statistical reliability [18], [19].

In conclusion, the experimental conditions and evaluation methods in this study are developed to both inherit established approaches in MQL grinding research and be specifically calibrated for Ti-6Al-4V internal grinding on an actual equipment system. This serves as the basis for executing experiments according to the selected matrix and analyzing the influence of input parameters on output responses in the subsequent sections [17]–[21].

VI. CONCLUSION

The paper has successfully established the scientific basis for an experimental model to study the effects of Minimum Quantity Lubrication (MQL) in the internal grinding of Ti-6Al-4V alloy. Based on a comprehensive literature review, the study indicates that internal grinding must be treated as a distinct problem due to its specific contact zone characteristics, media delivery challenges, and the dynamic sensitivity of the technological system.

The proposed experimental model integrates both grinding technological parameters and MQL delivery parameters. The selected input parameters include feed rate, depth of cut, MQL flow rate, and MQL pressure; meanwhile, SiC and CBN grinding wheels are organized into two separate experimental branches. On this basis, the experimental design was selected to ensure feasibility and the ability to evaluate the influences of the investigated factors.

The experimental evaluation system was also established in alignment with the research objectives. In each experiment, surface roughness is measured using a Mitutoyo SJ-201, the three grinding force components are captured via a Kistler 9139AA force dynamometer, and the three vibration components of the grinding mandrel are recorded using a 4525-B-001 accelerometer. This approach allows for the simultaneous assessment of machining quality and the operational state of the grinding process.

In summary, this paper has established a scientifically grounded experimental framework with a clear structure that is well-suited to practical research conditions. This serves as a fundamental basis for the subsequent stages of data analysis and processing.

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