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# Sustainable Precision: Unveiling the Potential of PVD and CVD Coated Carbide Inserts in Machining α-β Titanium Alloy (Ti–6Al–4V)

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**Abstract**

With a primary focus on green machining techniques, this review study offers a thorough overview of the machining of α (alpha) -β (beta) titanium alloy, specifically Ti6Al4V, using PVD and CVD coated carbide inserts. Using knowledge from studies using the Taguchi technique, the examination synthesizes previous research findings on Ra (surface roughness), energy efficiency, power factor, and total cutting energy required for machining. Depth of cut (DOC), Cutting speed and Feed rate are taken into consideration when we examine Ra (surface roughness), a crucial machining quality indicator, in different scenarios. The effect of PVD and CVD coatings on carbide inserts, which are intended to improve wear resistance, on obtaining the best possible surface finishes in Ti–6Al–4V machining applications is investigated. In the context of green machining, the review highlights the importance of power factor and energy efficiency. A summary of previous studies on the effects of machining operations on the environment is provided, with an emphasis on tactics and innovations that support environmentally friendly production methods.

**Keywords:** α-β titanium-alloy, Ti–6Al-4V, green machining, PVD coating, CVD coating, carbide inserts, Ra (surface roughness), energy efficiency, power factor, total cutting energy, Taguchi method, sustainable manufacturing

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## Introduction

The extensive application of α-β titanium alloy, in particular Ti–6Al-4V, in the aerospace, medical, and other high-performance industries has placed this alloy's machining at the forefront of modern manufacturing difficulties. Studying green machining methods becomes essential as industries shift more and more toward sustainable practices[1,2]. With a particular emphasis on the use of coated carbide inserts for green machining made via Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD), this paper attempts to thoroughly analyze and summarize the body of knowledge currently available on the machining of Ti–6Al-4V. This review's main goals are to clarify the complex relationships that exist between machining settings and important performance metrics including power factor, total cutting energy, energy efficiency, and Ra (surface roughness). In particular, Ra (surface roughness) must be thoroughly investigated because it affects the performance and quality of machined parts. Additionally, the investigation explores the effectiveness of PVD and CVD coatings on carbide inserts in enhancing wear resistance and tool life, hence promoting improved surface polish and sustainable tool usage.

Green machining considers the wider environmental impact of machining operations in addition to surface quality and tool performance. Therefore, the purpose of this review is to examine the factors related to power factor and energy efficiency when milling Ti–6Al–4V. Additionally, the study summarizes research using the Taguchi method to optimize machining parameters, providing a methodical way to improve energy efficiency and lower the overall amount of cutting energy needed.

This review attempts to consolidate information, identify research gaps, and offer a roadmap for future endeavors in green machining of α-β titanium alloys by critically reviewing the current literature. In order to fulfill the changing needs of precision machining in critical applications and advance sustainable manufacturing practices, it is imperative to synthesize insights on Ra (surface roughness), energy efficiency, power factor, and total cutting energy.

## Study of Ra (Surface Roughness)

Through experimentation, the authors discovered that the machining tool's nose radius had the biggest impact on the workpiece's Ra (surface roughness)[1]. Through experimentation, it was discovered that when turning titanium alloy, feed rate had the biggest effect on Ra (surface roughness). It was discovered that during the first few machining cycles, Ra (surface roughness) decreased with increased feed rate but rose with successive feed rate increases[2]. The impact of a variety of lubrication techniques and machining fluid on Ra (surface roughness) during titanium alloy turning was examined. In comparison to dry and flooded situations, the MQL state was determined to have the least amount of Ra (surface roughness)[3]. With a drop in feed rate and a little rise in cutting speed, the Ra (surface roughness) diminishes. Cryogenic conditions proved to be the most successful in achieving decreased Ra (surface roughness) at greater feed; only at low feed was flooding cooling found to be beneficial in delivering an acceptable surface during machining[4]. An investigation on the impact of different metalworking fluid concentrations on Ra (surface roughness) during titanium alloy machining was carried out using an ACF spray system. The lowest Ra (surface roughness) and best surface smoothness were obtained at 10% MWF concentration[5].

The most significant influences on Ra (surface roughness) were found to be feed rate, machining speed, and depth of cut, according to experimental studies. It was found that the physician vapor deposition coated tool performed superior at higher speeds and the non coated cutting tool performed better at lower speeds when PVD coated and uncoated tools were used to measure surface smoothness during machining[6]. Ra (surface roughness) is a crucial measure for the machinability of any cutting operation. Because surface finish is highly valued in every manufacturing business, a lot of research has been done on the machining parameters that impact the work specimen's Ra (surface roughness)[7]. An increase in cutting edge radius causes a built-up edge that creates exceptionally less Ra (surface roughness) and protects the cutting tool surface from cutting tool flank wear and cutting tool crater wear. A very low Ra (surface roughness) value was obtained by spinning titanium alloy at a speed of 62 m/min, according to experimental research[8].

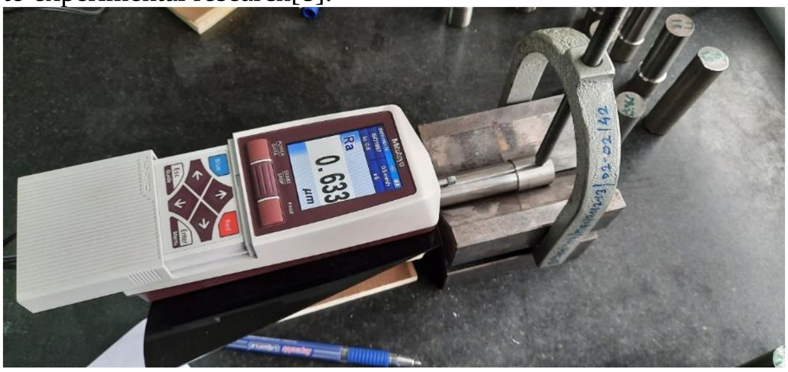


***Figure 1*** *Roughness measurement by Ra (surface roughness) Tester*

***Dry machining environment***

Estimating the heat generated between the tool and the workpiece interface is crucial since it directly impacts the machined workpiece's dimensional correctness, residual stress, and tool wear experimental observations[9]. Chowdhury et al. found that the cutting tool's life may be significantly extended by using a self-lubricating TiB2 PVD coating on its surfaces. Comparing this form of coating to uncoated and TiAlN-coated inserts, it was discovered that the surface finish was superior[10]. Research, feed rate primarily influences machining and feed forces, while machining speed significantly affects machining tool temperature [11].

The segmentation and chip morphology during Ti6Al4V alloy machining. It was discovered during machining that fracture initiation had a significant impact on chip formation. At low machining speeds, discontinuous chips were produced; at higher machining speeds, serrated chips were produced [12]. The dry turning operation was developed in response to the increasing need for hard and tough steel machining due to its superior machining performance when turning materials that are challenging to machine. Harder materials are machined by dry turning operation, which uses largely coated inserts and doesn't require the use of coolants or lubricants [13]. Nouari and Makich looked into how material microstructure affected tool surface wear. Experimental observations have shown that the microstructure and machinability of the workpiece have a significant impact on tool wear. When dry machining, low machinability leads to significant and early tool surface wear [14]. According to research, feed has the biggest impact on surface finish, followed by machining speed and depth of cut [15].

**The performance examination of several cutting tools is the main topic of the study.**

The researchers looked at the harm that physical vapor deposition could do to cutting tools when turning a titanium alloy. The coating on the tool's rake face deteriorated due to the stress created by the attached materials on the grain boundary of the damaged coating surface, resulting in fracture without plastic deformation [16]. The testing findings confirmed that flank and crater wear is the primary wear mechanism when cutting Ti6Al4V alloy with PCD inserts under cryogenic, hybrid, and flood machining conditions. Lower forces were observed in the cryogenic coolant supply scenario during machining[17,37].

Researchers found that at 100 bar of pressure, HP assist machining could increase tool life by up to nine times. Furthermore, it has been shown that pressures greater than 100 bar result in surface scratches on the workpiece [18]. Research indicates that uncoated tools can only be used during machining at lesser feeds, speeds, and depths of cut in comparison to coated tools, which can be used at high machining speeds and depths of cut[19]. Because of its, low heat conductivity, low modulus of elasticity, high chemical reactivity, extreme hardness titanium alloy is particularly difficult to machine. Therefore, depending on the need and the machining conditions, different kinds of cutting tools are employed during titanium alloy cutting operations [20]. Tool life was improved by around 60% when utilizing TiB2 coated tools during rough turning operations of titanium alloy, and by more than 70% when using TiAlN coated tools. Better surface polish was produced as a result of the coated layer's self-lubricating quality, which also improved heat decapitation at the tool-workpiece interface[21]. The researchers examined tool wear during the turning of a titanium alloy for commercial aerospace using an

RCMT 10T300 MT TT3500 round cutting tool. The key factor that altered the surface finish, based on the trial results, was feed[22]. Because of its increased toughness and resistance to cutting tool wear, the tool with CVD coating performed better than the tool with PVD coating. Using a CVD coated tool was found to reduce Ra (surface roughness) and tool wear compared to a PVD coated tool[23]. Armendia et al. used a WC-Co tool to compare the various machinability characteristics of several titanium alloys during turning operations. During high speed cutting, The material of the workpiece was found to be adhering to the tool surface., creating a built-up edge[24].

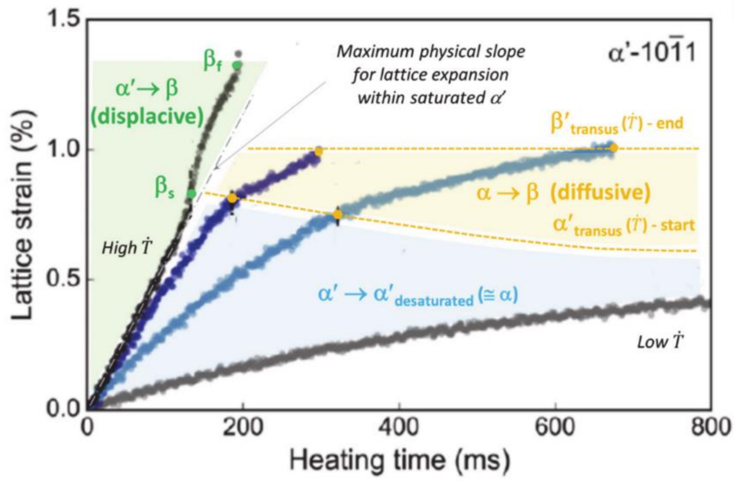


**Figure 2.** Influence of heating rate as indicated by the evolution of the lattice parameters on the mechanism and transition sites of the reverse transformations of α′ (modified with permission from ref. [36]). 2017 by Springer Nature (copyright).

**MINIMUM LEVEL OF LUBRICANT**

In a MQL setting, the primary element influencing machining speed for both surface quality and machining force during micro milling[25]. Using nanofluid MQL dramatically lowers drilling torque, drill tool wear, and thrust forces experimental findings [26]. In order to investigate MQL's machining performance during grinding operations, Sadeghi et al. conducted an experiment. In a MQL context, less machining force and Ra (surface roughness) were produced. MQL considerably lowered the tangential and perpendicular forces in comparison to a flooded cooling environment [27]. However, this impact is more pronounced at low feed rates. According to the authors, MQL machining is superior than dry machining in that it requires less thrust force, machining heat or temperature, and cutting tool life. During MQL machining, it was discovered that palm oil lubricant performed better during machining than synthetic ester [28]. The friction between the tool and the work specimen surface during dry turning operation generates a significant quantity of heat at the machining zone. Coolant use thus becomes essential in order to maximise surface quality and reduce heat generation. In order to satisfy all requirements that could not be met during dry machining, MQL technology is employed. Multi-walled carbon nanotubes mixed in vegetable oil were discovered by Hegab et al. to minimise power consumption and flank wear by approximately 11.5% and 45%, respectively [29]

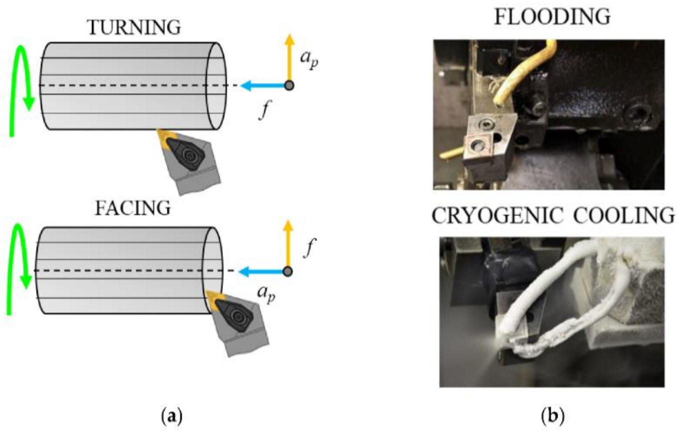

**Figure 3.** Scheme of the cylindrical turning and facing operations: (a) flooding and cryogenic cooling experimental setup (b)[35]

**An overview of coolant types and how they affect machining performance**

| Ref | Cutting Fluid | Depth of cut (DOC in mm) | Cutting Speed (m/min) | Feed rate (mm/rev) | Responses |
|---|---|---|---|---|---|
| 4 | Rapeseed oil | 0.8 | 90,120 | 0.1,0.2 | Tool wear, Ra (surface roughness) & Energy consumption |
| 30 | Liquid CO2 | 2 and 30 | 80 | 0.15 mm/tooth | Tool life and Tool wear |
| 31 | MWF S-100 | 1 | 80 | 0.2 | tool life, machining temperature |
| 32 | Liquid N2 | 0.25 | 80 | 0.2 | Ra (surface roughness), Tool wear, Ra (surface roughness) |
| 33 | Liquid N2 | 0.2 | 70,110,150 | 0.2 | Forces and Machining temperature |
| 34 | Sunflower oil | 0.6,1,1.6 | 63,79,99 | 0.2,0.27,0.34 | Ra (surface roughness) |

## CONCLUSION

In the endeavour to achieve sustainable precision machining, this research has conducted an extensive investigation into the use of PVD and CVD coated carbide inserts for the machining of α (alpha) -β(beta) Titanium Alloy (Ti6Al4V). The study has uncovered noteworthy progress in the domain, as these coatings exhibit remarkable ability to tackle the difficulties related to the machining of titanium alloys. For Ti–6Al–4V, the application of PVD and CVD coatings on carbide inserts has been crucial in prolonging tool life, reducing wear, and raising overall machining quality. The study's findings demonstrate the practicality of these cutting-edge coating technologies and point the way towards environmentally friendly precision machining procedures. In addition to improving machining operations' efficiency, the longer tool life and increased wear resistance also support industry objectives related to resource conservation and environmental responsibility. Practical insights into the integration of improved coatings for carbide inserts are offered by the results presented here, as industries continue to struggle with the competing goals of environmental sustainability and production efficiency. This study extends the discussion on green machining techniques in the industrial industry in addition to improving titanium alloy machining optimisation.

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