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Review Article

Machinability of Ti6Al4V Alloy: Tackling Challenges in Milling Operations

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This study investigates strategies for improving the 3D milling of Titanium Alloy Grade 5 (Ti6Al4V) by optimizing machining parameters and cutting tool engagement techniques. Ti6Al4V presents significant machining challenges due to its low machinability index (20%), which directly impacts manufacturing efficiency. High temperatures during machining, often exceeding 882^{0}C, lead to phase transformations, creating a harder Beta lamellar equiaxed microstructure. This, coupled with the alloy's poor thermal conductivity, results in heat concentration at the cutting tool interface, accelerating thermo-chemical wear and potentially causing catastrophic tool failure. This study explores how controlled cooling methods, coupled with appropriate lubrication, can effectively dissipate heat and flush away chips, mitigating the detrimental effects of high temperatures. Furthermore, the selection of cutting tool materials and coatings with high thermal conductivity and chemical inertness, along with aggressive rake angles and higher relief angles, is examined as methods to improve shearing, minimize smearing, and enhance surface quality. By optimizing these parameters, this study aims to provide manufacturers with practical strategies to overcome the challenges of Ti6Al4V machining, ultimately increasing tool life and overall milling efficiency.

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1. Introduction

Titanium alloys, particularly Ti6Al4V, have emerged as indispensable materials across various industrial sectors, including aerospace, biomedical, and automotive, due to their exceptional properties. These include a remarkable strength-to-weight ratio, outstanding flexibility and durability, and the ability to maintain strength at elevated temperatures [1][2][3]. Furthermore, Ti6Al4V exhibits exceptional chemical inertness, rendering it highly resistant to oxidation, corrosion, and rust.

Despite these desirable attributes, Ti6Al4V presents significant challenges in machining processes, primarily attributed to its inherently low machinability [4][5][6][7]. Machinability, defined as the ease with which a material can be machined, significantly influences manufacturing efficiency and cost. It encompasses various factors, including tool life, tool wear, cutting force, chip formation, cutting temperature, surface integrity, and burr formation.

Several factors contribute to the poor machinability of Ti6Al4V [8][9][10][11]:

1. **Low Thermal Conductivity:** Ti6Al4V exhibits low thermal conductivity, leading to localized heat accumulation within the cutting zone during machining. This concentrated heat, often exceeding 882°C, induces phase transformations within the material, resulting in the formation of a harder Beta lamellar equiaxed microstructure. This harder phase significantly increases cutting forces and accelerates tool wear.
2. **High Chemical Reactivity:** At elevated temperatures, Ti6Al4V demonstrates increased chemical reactivity with cutting tool materials. This reactivity leads to chemical wear

mechanisms such as diffusion, adhesion, and abrasion, further accelerating tool wear and compromising surface integrity.

3. **Strain Hardening Tendency:** Ti6Al4V is prone to significant strain hardening during machining. The deformation induced by the cutting process strengthens the material ahead of the cutting tool, leading to increased cutting forces, higher cutting temperatures, and accelerated tool wear.
4. **Chip Adhesion and Built-Up Edge Formation:** The combination of high temperatures and chemical reactivity promotes chip adhesion to the cutting tool rake face. This adhesion can lead to the formation of a Built-Up Edge, a layer of workpiece material welded to the cutting edge. BUE formation negatively impacts surface finish, dimensional accuracy, and tool life.

The challenges posed by Ti6Al4V's low machinability necessitate the development and implementation of innovative machining strategies to enhance process efficiency and component quality. These strategies often focus on:

- **Optimizing Cutting Parameters:** Careful selection of cutting parameters, including cutting speed, feed rate, and depth of cut, is crucial to control cutting forces, temperatures, and chip formation [12][13].
- **Advanced Cooling and Lubrication Techniques:** Effective cooling and lubrication strategies are essential to dissipate heat from the cutting zone, reduce tool-chip friction, and minimize chemical interactions between the tool and workpiece. High-pressure coolant systems, cryogenic cooling, and minimum quantity lubrication are examples of advanced techniques employed in Ti6Al4V machining [14][15].

- **Cutting Tool Material and Geometry:** Selecting appropriate cutting tool materials with high hot hardness, wear resistance, and chemical inertness is critical for extending tool life. Additionally, optimizing tool geometry, including rake angle, clearance angle, and edge preparation, can significantly influence chip formation, cutting forces, and surface integrity [16][17].
- **Advanced Machining Processes:** Exploring and implementing advanced machining processes such as high-speed machining, laser-assisted machining, and ultrasonic machining can offer significant advantages in terms of improved material removal rates, enhanced surface integrity, and reduced tool wear [18].

This study delves into the key parameters influencing chip generation mechanisms during the machining of Ti6Al4V. By understanding these mechanisms and their implications, this research aims to provide insights into simplifying machining processes and enhancing overall efficiency. Furthermore, this study aligns with the growing emphasis on sustainable manufacturing practices by exploring strategies to minimize environmental impact during Ti6Al4V machining. This includes optimizing cutting parameters to reduce energy consumption, implementing eco-friendly cooling and lubrication techniques, and exploring the potential of near-net-shape manufacturing processes to minimize material waste.

1.1. High Tensile Strength

Titanium Alloy Grade 5 combines Titanium, Aluminum, and Vanadium with some chemical elements. It is not as robust as steel but has a high tensile strength of nearly 896 MPa and toughness even at higher temperatures [19]. So, this property restricts the shearing, and the cutting tool experiences shocks and vibrations during the initial entry for shearing. In addition, the work hardening property of Ti6Al4V needs higher cutting forces for shear, which may lead to generating a notch on the cutting tool edge.

1.2. Poor Thermal Conductivity

The Ti6Al4V alloy has a limited ability to conduct heat with poor thermal conductivity of 6.6 W/m°C [20]. During shearing through a milling operation, the generated latent and frictional heat does not rapidly dissipate, and most of the heat is concentrated on the cutting tool edge and face. Cyclic heat accumulation is responsible for the thermal degradation of cutting tools and chip evolution problems during milling. Figure 1 illustrates the heat accumulation during

Ti6Al4V milling. Furthermore, this non-dissipated heat under insufficient lubri-cooling is responsible for metallurgical phase changes in the material, leading it to be hard to shear.

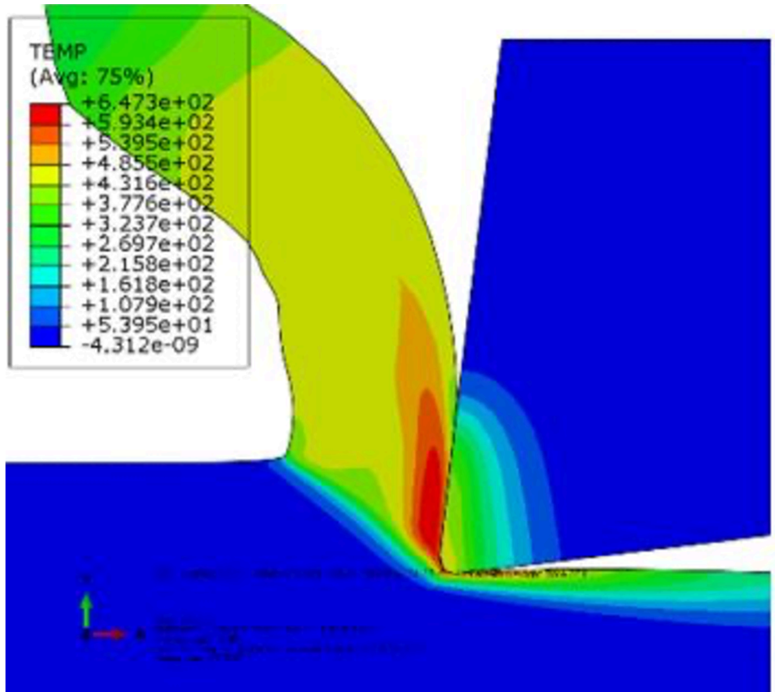

Figure 1. Heat distribution in cutting tool and chip during milling [21]

1.3. Chemical Reactiveness

Titanium alloys have strong chemical reactivity, leading the chip to weld to the tool, producing cratering and early tool failure. These materials' poor thermal conductivity prevents the heat produced during machining from escaping from the tool edge. This results in severe tool wear and distortion, as well as elevated tool tip temperatures, leading to galling, welding, and smearing. The higher temperature at the tooltip enhances the chemical affinity and, resultantly, terms-associated catastrophic failure of the cutting tool. The details are given below [22][23][24]:

- **Welding at the Tool-Chip Interface:** Ti6Al4V exhibits a strong affinity for reacting with cutting tool materials at elevated temperatures. This leads to a phenomenon known as "chip welding," where the chip material adheres to the tool rake face instead of flowing freely. This adhesion disrupts the cutting process and initiates a cycle of detrimental wear.
- **Cratering and Tool Failure:** As the welded chip material builds up, it forms a "crater" on the tool rake face. This crater alters the tool geometry, increasing cutting forces and accelerating wear. In extreme cases, the welded chip can break off erratically, taking chunks of the tool material with it, leading to premature tool failure.

1.4. Lower Modulus of Elasticity

Additionally, Ti 6Al-4V has a low modulus of elasticity, making it highly springy. During the milling of thin wall structures, spring back causes a vibration in the cutting tool, leading to chatter and poor surface quality. In milling solid sections, minute vibrations are produced in the cutting tool. The lower modulus of elasticity makes the Ti6Al4V shearing tricky and time-consuming, adversely affecting surface texture under insufficient workpiece clamping [25][26].

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1.5. Shearing Mechanism

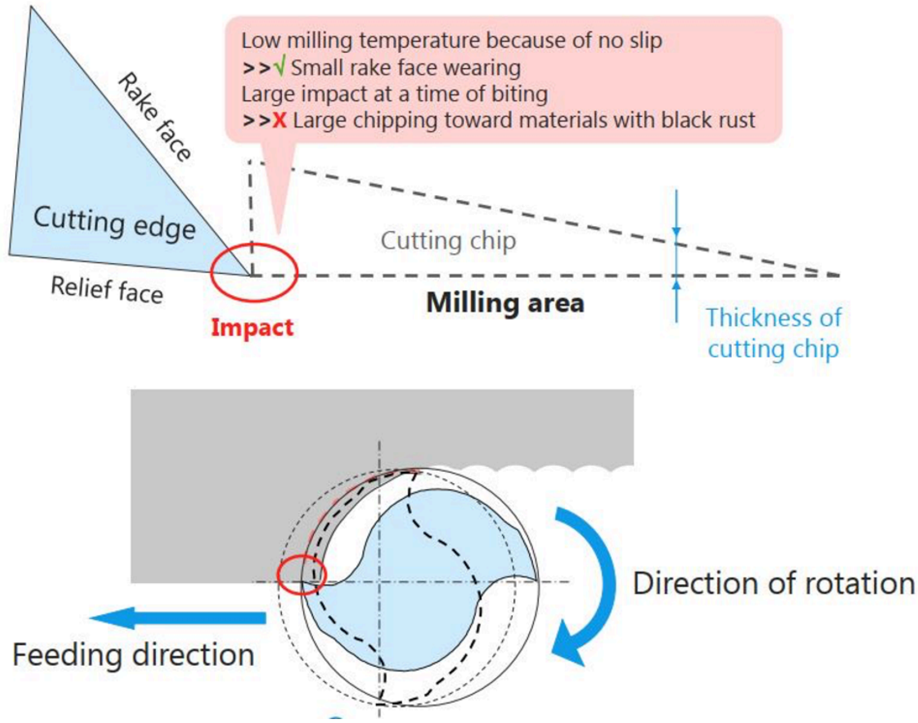

Figure 2. Down milling physics in milling [27]

Ti6Al4V does not fracture as many steels and irons do. In order to prevent built-up-edge conditions on the inserts, they must be sheared away similarly to gummier materials like aluminum or magnesium.

When the Ti6Al4V being machined begins to weld or connect to the cutting edge, it is known as a built-up edge (BUE). The cutting pressures are increased by a built-up edge, which eventually damages the cutting edges when parts of the carbide break off along with it. In general practice, Titanium Alloy Grade 5 is sheared by down milling for acceptable machinability compared to up milling. The chips produced during down milling are thick at the beginning of the cutting process and thin at the conclusion. As speed changes from conventional to high speed, the burr development is reduced by 50%, so the initial heat will be dispersed with the chips. This milling technique also has the advantage that the thin section of the chips does not stick to the cutting edge (refer to Figure 2) [28].

2. Discussion

Shearing parameters, cutting speed, feed per tooth, and depth of cut produce the chip by plastic deformation of the material at the expense of cutting force in a particular fashion. The Ti6Al4V is notoriously known for machinability and phase alteration. The shearing parameters are mainly responsible for chip formation, surface quality, and tool life in Ti6Al4V milling. Tool wear is a significant concern in milling because the economics of machining is highly dependent upon it. These shearing parameters combined apply to machining and show an impressive effect on the machinability of Ti6Al4V in the following way.

2.1. Effect of Cutting Speed

Cutting speed is the movement of the cutting tool against the workpiece material in m/min. The cutting speed rate influences the tool life and surface quality in milling Ti6Al4V. On the abutment of literature study [28][29][30][31][32][33] and practical results during research, at a

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higher rate of cutting speed above 120 m/min in the Ti6Al4V milling, the material becomes slightly softer and lowers the cutting forces initially, but after the built-up edge increases, the shear edge area acts as tool bluntness. Finally, the high cutting stresses accumulate at the cutting zone. Further, it leads to the pulling action of material from the upper surface that gives the distorted surface quality. Also, a higher rate of cutting speed rivals the thermo-mechanical stresses at the shearing edge, resultantly the cutting edge suffers from cracking, chipping, and excessive rubbing. In this way, higher cutting forces escort a catastrophic failure of the cutting tool. In addition, high cutting speed increases the chip evolution rate; flank face rubbing also initiates the crater and flank wear, respectively, with vibrations. The lower cutting speed below 40 m/min in Ti6Al4V milling makes the material tensile shear due to higher tensile strength and strain hardening, producing a pulling effect with a worse surface texture. This action creates shock and vibrations in the cutting tool, which will shorten the tool's life. The cutting speed selection in Ti6Al4V milling depends upon the cutting tool material and their coating with the type of coolant used for milling. Generally, carbide cutters' cutting speed is between 50 m/min and 80 m/min. It is also distinguished by finishing and roughing operations with a combination of feed rates [34][35][36].

2.2. Effect of Feed/tooth

The cutting tools of each tooth advanced into the workpiece in a revolution direction to form an equal thickness chip in an equal amount said as feed/tooth. It is highly appreciable in shearing Ti6Al4V because cutting tool life and surface quality are mainly influenced by the feed rate value. In general, the feed/tooth value depends upon the number of teeth or flutes and the type of operation in Ti6Al4V milling, like finishing and roughing. The cutting forces are proportional to the feed rate. A high feed rate increases the Material Removal Rate (MRR) with lots of vibrations due to strain hardening, as well as the evaluated temperature creates thermal softening, which further leads to BUE along with cutting forces in the milling of Ti6Al4V [37][38][39]. The feed rate and spindle speed combination effectively control the chip load, tool life, and surface roughness in Ti6Al4V. A higher feed rate with a high spindle speed gives ample MRR but too much chip load with feed marks on the surface. A lower feed rate and higher spindle speed invite bad MRR with rubbing action that might lead to vibrations and catastrophic cutting tool failure by excessive thermal degradation [40][41][42][43][44].

At least, the recourse is a moderate feed rate and balanced spindle speed for better tool life and surface quality in Ti6Al4V milling. During rigorous study [28][36][45][46][47][48][49], for Titanium Alloy Grade 5 shearing in finish milling, the feed rate per tooth should be ≤ 0.07 mm/tooth, and for rough milling, it should lie between 0.2 to 2.2 mm/tooth in the combination of ≤ 60 m/min cutting speed.

2.3. Effect of Depth of Cut

Depth of Cut is the material sheared per movement of the cutting tool passing against the workpiece and decides the chip width. In the milling of Ti6Al4V, both types of DOC are axial and radial, essential for cutting force and tool life. The depth of the cut strongly influences the cutting force more than the feed rate. Also, it affects the machined surface microhardness through instantaneous frictional heat. Radial DOC is preferred as a stepover many times in milling; it should be 60 to 75% of the diameter of the cutting tool. If its value exceeds the prescribed limit, higher vibrations are induced in the cutting tool due to a higher amount of material coming in contact with the cutting edge. The regular radial DOC for Ti6Al4V milling is up to 1 mm in finishing and roughing operations [47][50][51][52].

Axial DOC is more integral than Radial DOC in the milling of Ti6Al4V. A higher Axial DOC is proportional to MRR but is prone to higher cutting stresses on the shearing edge, and the temperature at the cutting zone will lead to thermally enhanced cutting tool wear. The exact amount of DOC in a recurring cycle induces repetitive stresses and a notch on the leading edge and propagates cracks on the cutting tool. A higher Axial DOC in Ti6Al4V milling starts burning the chips and sticking on the edge (BUE), finally disturbing surface quality with high cyclic stresses. Based on the abutment of experimental data [28][31][46][53], Axial DOC should be less than 2 mm in roughing operations and 0.1 to 0.4 mm in finishing mode, with ample cooling recommended.

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2.4. Chip Evolution and Morphology in Ti6Al4V Milling

In the milling of Ti6Al4V, material removal occurs by the application of shearing parameters through a cutting tool with an Orthogonal or Oblique type of cutting under a specific cooling environment [27][54][55]. The resultant effect of cutting material undergoes plastic deformation and shear at the shear plane and evolves into chips [56][57][58]. In general machining, four types of chips are observed: Continuous, Discontinuous, Continuous with Built-up-edge, and Segmented Saw tooth type. The type of chip mostly depends on metallurgical properties and the tool rake angle; the cooling media is one of the noticeable parameters in chip generation. Ti6Al4V has poor thermal conductivity and low ductility, responsible for the generation of segmented chips with serrations. Ducobu et al. [57] well acknowledged that the development of thermo-plastic instability inside the primary shear zone is the basis for the mechanism of saw-tooth chip production. The cutting speed affects the brittleness and ductility of the chip material and its mechanical properties, which also impacts the friction condition of the machining process and the cutting temperature. As a result, the free surfaces and back surfaces of the chips can vary geometrically and morphologically [56]. In saw-tooth chips, there are two critical steps in producing the segments [39][56][57].

1. Thermo-Plastic instability by tolerating the additional shear strain inside the "failed" shear zone.
2. Squeezing the wedge-shaped material volume immediately ahead of the tool.

The increment of cutting speed is primarily significant for segmentation by adiabatic shear. When cutting Ti6Al4V, adiabatic shear and breaking are caused by dynamic stress. Through the recrystallization of nanograins into the equiaxed microstructure, the high cutting speed propagates the shear fracture. On the other hand, the columnar grain structure results in tensile fracture at low cutting speeds. Figure 3(a) indicates that the initiation of a segmented chip at Vc = 800 m/min produces a lot of heat at the primary shearing zone and is dominant over strain hardening, which initiates the adiabatic shear band.

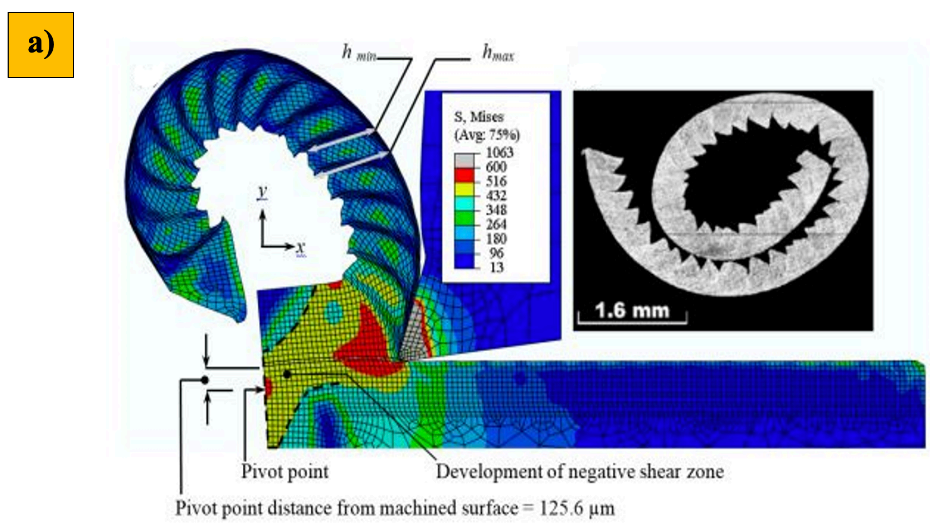

Figure 3(a). Initiation of segmented chip generation

After that, the penetration of the tool continuously stresses degraded, and the possibility of fracture developed in the primary shear is illustrated in Figure 3b). Furthermore, the bending force that the workpiece-free end experiences during tool advancement in the cutting direction is especially responsible for creating the negative shear zone. The material suffers increased stresses in this deformation zone as the tool moves forward, the bending load rises, and a pivot point forms (refer to Figure 3c)).

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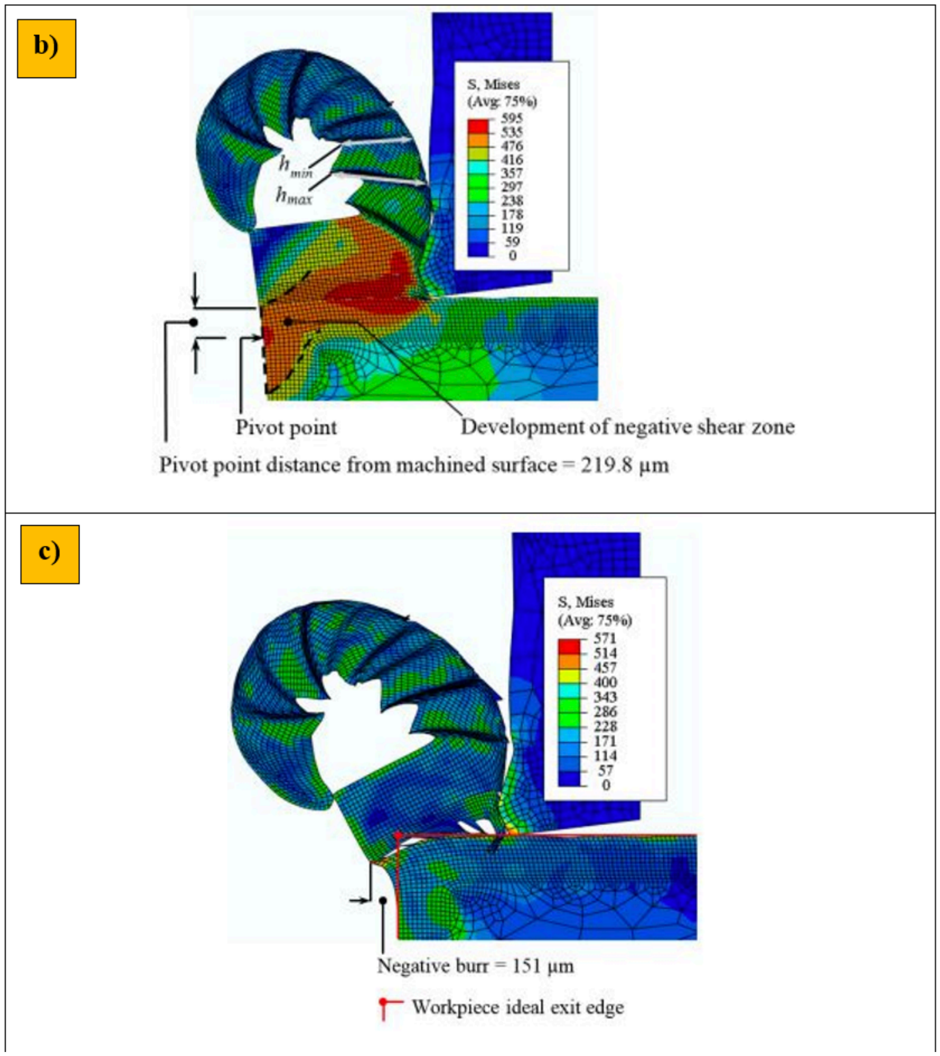

Figure 3(b-c). Chip formation and segmentation in Ti6Al4V machining **b)** Initiation of fracture at primary shear zone **c)** Fracture of a chip with negative burr [59]

Figure 4 indicates the strain distribution in the serrated chip in the milling of Ti6Al4V. The low to high strain creates dynamic stresses that create non-homogeneous chips [39].

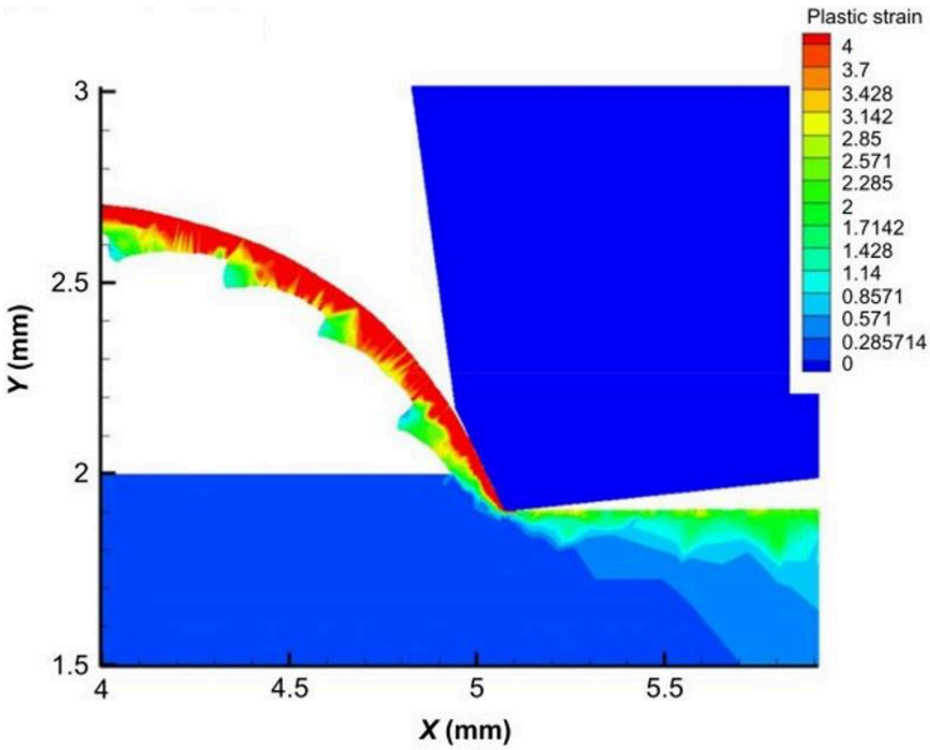

Figure 4. Instability in plastic strain in milling of Ti6Al4V [39]

Typically, localized shear deformation and thermal softening over strain hardening cause metallurgical change in the chip. Under low cutting speed and high feed rate, respectively, the continuous and segmented chip production processes were seen. The following points expose another concern about chip generation in milling. The machinability success depends upon the ease of chip generation with limited cutting power consumption and lower cutting stress. However, in Ti6Al4V milling, a contradictory effect is generated by metallurgical properties like poor thermal conductivity and springiness [60].

- Plastic deformation from shearing in the primary shear zone causes the principal cutting force to be applied to the tool rake face.
- As a result of shearing and friction on the tool rake face, the second deformation zone experiences plastic deformation and chip formation. Local heating in this zone causes exceptionally high temperatures, which soften the materials of both the workpiece and the tool.
- The rubbing contact between the tool flank face and the freshly cut workpiece surface causes friction in the tertiary deformation zone.

Figure 5 indicates the heat generation and dissipation at status in the milling of Ti6Al4V.

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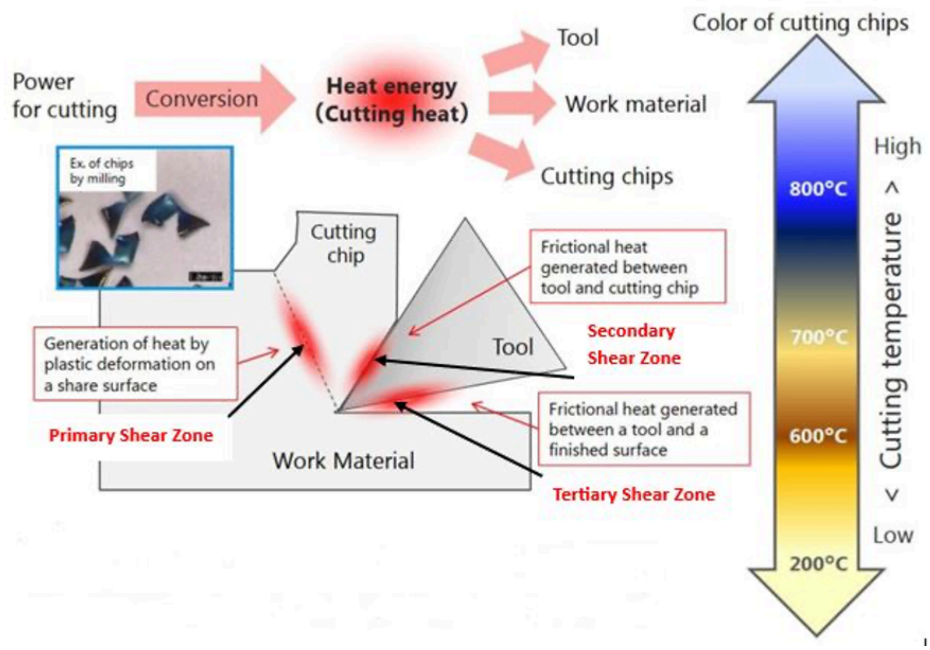

Figure 5. Heat generation junction in chip generation in Ti6Al4V milling [27][60]

Cooling media also play a vital role in segmenting chips in milling Ti6Al4V. It absorbs heat from the cutting zone and flushes the chips from the machining area. It avoids the burning of chips and restricts metallurgical alteration, as well as restricts the chemical reaction with the tool coating and enhances tool life. Ample lubrication quickly slides the evolved chip from the tool's rake face, minimizing crater wear in milling.

2.5. Cutting Tools

The machinability of Ti6Al4V is important in terms of tool life. Limited tool life was observed in Ti6Al4V milling due to its metallurgical properties and poor machinability index. Sometimes, tool life curves are considered to define the machinability of Ti6Al4V. Therefore, the proper selection of cutting tools with the exact geometry, along with proper shearing parameters, enhances the machinability of Titanium Alloy Grade 5 in milling operations.

On the view of thorough research [30][61][62][63][64], Carbide PVD, CVD multilayered/nanolayered (PVD TiAlN, CVD Al_2O_3+TiCN, and PVD TiAlN+TiN) cutting tools are more popular in milling than other tools. They have high hot hardness, ample inertness to thermo-chemical reactions, and better thermal conductivity. Also, they exhibit toughness against abrupt contact with material, meaning they are capable of avoiding mechanical wear up to a particular sustain. Basically, cutting tool materials with high wear resistance against fracture failure, temperature failure, and gradual wear (crater and flank) in the machining of Ti6Al4V are expected to improve machinability. The geometry should reduce cutting stresses, quickly break the evolved chips, and sharpen the cutting edge with a positive rake angle to minimize cutting power consumption and BUE, and enhance surface integrity [29][30][65][66]. Table 1 exhibits keen requirements of cutting tool properties and geometry and their effect on the machinability of Ti6Al4V based on recent studies.

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Sr. No.	Property of Cutting Tool Material	Effect on Machinability
1	High Thermal Conductivity	Improved tool life, Restricts metallurgical alterations, and Avoids Thermo-Assisted wear.
2	High Hot Hardness	Ability to shear material efficiently at high temperatures without melting, Improves Tool life, lowers cutting stresses, and Improves surface quality.
3	Ample Toughness	Avoids abrupt fracture, Reduces Mechanical Wear, Limited Notching at the cutting edge
4	High Bending strength	Increases ability to work under high cutting pressure, maintains dimensional accuracy, and Sustains high Depth of Cut shocks and vibrations.
5	High Abrasive resistance	Minimizes the Gradual wear rate (Crater and Flank wear)
6	High Chemical Inertness	Avoids chemical wear, oxidation, and diffusion. Restricts the etching of the cutting tool at elevated temperatures.
7	Ability to withstand at high thermal gradient environment	Capable of surviving under cryogenic temperature coolant in the cutting zone, Avoids cold cracking and shrinkage
Sr. No.	**Tool Geometry**	**Effect on Machinability**
1	Positive Rake angle	Improved chip flow, Reduces vibrations
2	Sharp cutting edge	Eases shearing with lower cutting stresses with minimum power consumption. Avoids Built-up Edge
3	Secondary relief angle	Performance improvement in Tool life
4	Clearance angle	It should be positive. Flank health of the tool increases
5	Nose angle	Affects the cutting force and surface quality. In general, the Nose angle should be 0.2 to 0.8 mm. Higher value increases strength but also increases friction. Lower value improves stress concentration and is prone to breakage.
6	Multi flutes with variation in flute angle	Improves chip flow, Reduces frictional heat
7	Chip breaker	Improves Machinability by reducing Crater wear, chip-tool contact, and cutting forces

Table 1. Effect of Cutting tool material and Tool geometry on Ti6Al4V Machinability in milling

2.6. Cooling Methods and Recent Trends in Ti6Al4V Machining

Efficient cooling and lubrication are critical aspects of Ti6Al4V machining due to the material's low thermal conductivity and high reactivity at elevated temperatures. Conventional flood cooling, while effective for many materials, often falls short in addressing the specific challenges posed by Ti6Al4V. This has led to the exploration and adoption of advanced cooling techniques to improve heat dissipation, reduce tool wear, and enhance the overall machining performance of this alloy [4][8][9][67][68][69][70][71].

Traditional Cooling Methods

- **Flood Cooling:** This method involves flooding the cutting zone with a large volume of coolant, typically an emulsion of water and oil. While it provides some cooling, it is often insufficient for Ti6Al4V due to the material's poor thermal conductivity. Additionally, flood cooling can lead to environmental concerns due to coolant disposal and potential contamination.

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Advanced Cooling Techniques

- **Cryogenic Cooling:** Cryogenic cooling utilizes cryogenic fluids, such as liquid nitrogen, to achieve significantly lower temperatures in the cutting zone compared to traditional coolants.

Merits:

- **Enhanced Chip Removal:** Cryogenic cooling causes thermal shock in the chip, making it brittle and easier to break, leading to improved chip evacuation.
- **Reduced Tool Wear:** The lower temperatures significantly reduce tool wear mechanisms like diffusion and adhesion, extending tool life.
- **Improved Surface Integrity:** Cryogenic cooling can lead to better surface finishes due to reduced thermal stresses and improved chip formation.

Demerits:

- **Cost:** Cryogenic cooling systems can be expensive to install and operate due to the cost of cryogenic fluids and specialized equipment.
- **Safety Concerns:** Handling cryogenic fluids requires strict safety protocols due to their extremely low temperatures.

- **Minimum Quantity Lubrication:** MQL is a near-dry machining technique that delivers a minimal amount of lubricant, often in aerosol form, directly to the cutting zone.

Merits:

- **Reduced Coolant Consumption:** MQL significantly reduces coolant consumption compared to flood cooling, minimizing environmental impact and cost.
- **Improved Tool Life:** The targeted lubrication reduces friction and heat generation, extending tool life.

Demerits:

- **Limited Cooling Capacity:** MQL's cooling capacity is limited compared to flood or cryogenic cooling, making it less effective for high-heat applications.
- **Chip Evacuation:** Effective chip evacuation can be challenging with MQL, potentially leading to chip re-cutting and tool wear.

- **Nano-Fluid Flood Cooling:** This technique involves suspending nanoparticles in conventional coolants to enhance their thermal conductivity and heat transfer properties.

Merits:

- **Enhanced Cooling Efficiency:** Nanoparticles improve the heat transfer capabilities of the base fluid, leading to more efficient cooling.
- **Potential for Improved Tool Life and Surface Finish:** The enhanced cooling can lead to reduced tool wear and improved surface integrity.

Demerits:

- **Long-Term Effects:** The long-term effects of nanoparticle accumulation in the coolant and their potential environmental impact are still being investigated.
- **Cost:** Nano-fluids can be more expensive than traditional coolants.

The selection of the most appropriate cooling method for Ti6Al4V machining depends on various factors, including the specific machining operation, desired surface quality, production volume, and economic considerations. While traditional flood cooling remains prevalent, advanced techniques like cryogenic cooling, MQL, and nano-fluid cooling offer significant potential for improving machining performance, reducing environmental impact, and enhancing the overall sustainability of Ti6Al4V machining processes.

- **Surface Quality in Titanium Alloy Grade 5 Milling**

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Achieving exceptional surface quality during the milling of Titanium Alloy Grade 5 (Ti6Al4V) is crucial for its successful application in demanding industries, particularly aerospace and biomedical. The surface texture of machined components directly influences their fatigue life, corrosion resistance, wear properties, and aesthetic appeal. However, the inherent properties of Ti6Al4V, such as its low thermal conductivity, high strength at elevated temperatures, and chemical reactivity, pose significant challenges to achieving pristine surface finishes [72][73][74][75][76].

Various machining factors intricately affect the surface texture in Ti6Al4V milling. Cutting speed plays a critical role, with higher speeds generally leading to smoother surfaces due to increased heat generation and localized annealing. However, excessively high speeds can induce tool wear and result in surface defects. The feed rate directly influences the surface roughness, with lower feed rates producing finer finishes. However, extremely low feed rates can lead to rubbing instead of cutting, increasing tool wear and deteriorating surface quality. The depth of cut also impacts surface texture; shallower cuts generally yield smoother surfaces, while deeper cuts can cause increased tool deflection and vibration, negatively affecting surface integrity [76][77][78].

Tool geometry significantly influences chip formation and heat dissipation, ultimately impacting surface quality. A larger rake angle promotes easier chip flow and reduces cutting forces, potentially improving surface finish. However, a larger rake angle can also weaken the cutting edge, making it prone to chipping or breakage. The selection of appropriate tool materials is equally critical. Tools with high hot hardness, wear resistance, and low chemical affinity to Ti6Al4V are essential for achieving superior surface quality.

Cooling and lubrication strategies play a vital role in controlling heat generation and tool-chip interactions, directly influencing surface texture. While traditional flood cooling is commonly employed, advanced techniques like cryogenic cooling and minimum quantity lubrication have shown promise in improving surface quality by enhancing heat dissipation and reducing tool wear.

Furthermore, the presence of residual stresses in the machined surface can significantly impact fatigue life and corrosion resistance. Machining parameters that minimize heat generation and mechanical stresses during cutting are essential for mitigating residual stress formation. Post-processing techniques like stress-relieving annealing can also be employed to improve surface integrity [79][80][81].

From the study, achieving optimal surface quality in Ti6Al4V milling necessitates a comprehensive understanding of the complex interplay between machining parameters, tool properties, and cooling strategies. Recent research emphasizes the importance of optimizing cutting speed, feed rate, and depth of cut, selecting appropriate tool materials and geometries, and employing advanced cooling techniques to mitigate the challenges posed by Ti6Al4V's inherent properties. By carefully controlling these factors, manufacturers can achieve superior surface finishes, enhancing the performance, reliability, and longevity of Ti6Al4V components in demanding applications.

Summary

Titanium alloy Ti6Al4V presents significant machining challenges despite its desirable properties. Its **low thermal conductivity** leads to elevated temperatures in the cutting zone, causing phase transformations that harden the material into a difficult-to-machine Beta lamellar structure. This, coupled with Ti6Al4V's tendency to become sticky at high temperatures, results in **increased cutting stresses, poor chip evacuation, and the formation of a Built-Up Edge** on the cutting tool.

Figure 6(a). Machinability factors for assessing the machinability of Ti6Al4V milling

Furthermore, Ti6Al4V exhibits **thermo-chemical reactivity** with cutting tools at elevated temperatures, accelerating tool wear through galling and chemical etching. Improper selection of shearing parameters exacerbates these issues, leading to tool fracture, increased cutting temperatures, and accelerated milling wear.

Improving the machinability of Ti6Al4V requires a multifaceted approach. **Optimizing shearing parameters** (cutting speed, feed rate, depth of cut) is crucial to control cutting forces and temperatures. Employing **efficient cooling techniques**, such as cryogenic cooling or nano flood coolant systems, is essential to dissipate heat and prevent detrimental phase transformations. Finally, selecting **appropriate cutting tool materials** with high hot hardness, wear resistance, and low chemical affinity to Ti6Al4V is critical for extending tool life and achieving acceptable surface integrity.

By addressing these challenges through a combination of optimized parameters, advanced cooling, and appropriate tool selection, the machining efficiency and surface quality of Ti6Al4V components can be significantly improved.

Figures 6a) and b) illustrate the factors for assessing the Machinability and Quantitative importance based on practical and reviewed experimental studies [82][83][84][85][86][87][88] for the Titanium Alloy Grade 5 milling, respectively.

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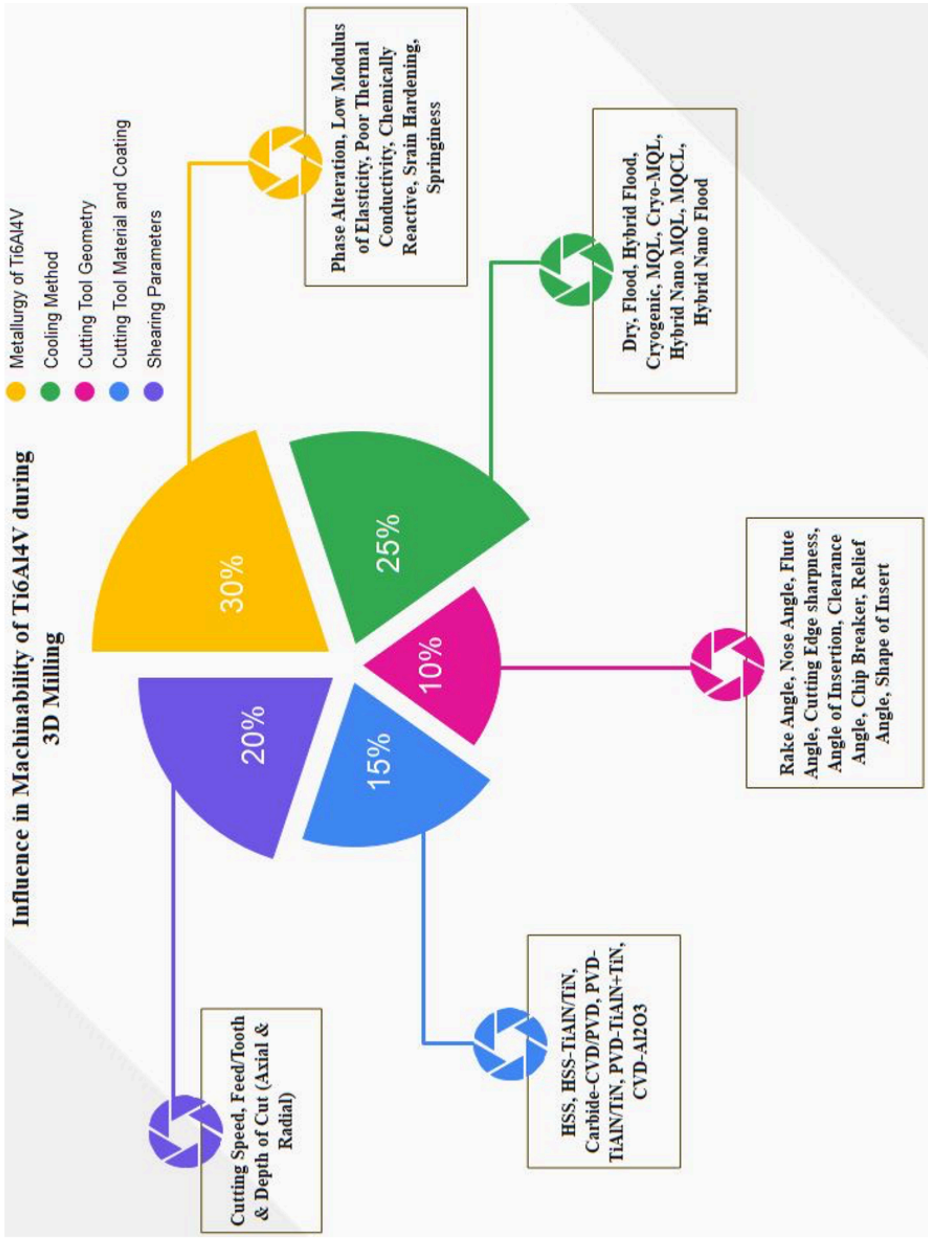

Figure 6(b). Quantitative Importance of Factors on Machinability of Ti6Al4V

Statements and Declarations

Author Contributions

Conceptualization: Amit S. Patil; Methodology: Amit S. Patil; Validation: Sushil V. Ingle; Formal Analysis: Deepak Singh; Investigation: Kiran S. Bhole; Resources: Deepak Singh; Writing – Original Draft Preparation: Amit S. Patil; Writing – Review & Editing: Kiran S. Bhole; Visualization: Deepak Singh; Supervision: Vivek K. Sunnapwar; Project Administration: Vivek K. Sunnapwar.

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