Review Article

Machinability of Ti6Al4V Alloy: Tackling Challenges in Milling Operations

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This study extensively elaborates the approach towards making ease in 3D milling of Titanium Alloy Grade 5; by adapting the controlled parameters and specific strategies in cutting tool encroachment in milling. Every manufacturer is anxious about the machinability index (20%) of Ti6Al4V, which affects the machining efficiency proportionally. During machining, Phase alteration above the 8820C produces a Beta lamellar equiaxed microstructure, which is hard; also, limited thermal conductivity allows the generated heat towards the cutting tool to lead the Thermo-assisted wear. Higher temperatures also initiated chemically eagerness of Ti6Al4V and reacted with cutting tool edge and escorts towards catastrophic failure. The difficult Machinability demonstrates the detrimental notable effect on the cutting tool's health and follows the Ti6Al4V surface quality. The Cooling methods can flush out chips and frictional heat with ample lubrication, desirably controlling the worse effect of Machinability to some extent blissfully. The cutting tool material and coating, has chemically inert and excellent thermal conductivity with an aggressive rake angle with higher relief angle, improves the shearing tendency of Ti6Al4V by avoiding smearing, ultimately speculated surface quality with desired Tool life through higher Machining efficiency in milling.

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1. Introduction

As per rigorous study, [1][2] Machinability is the ability to form chips by shearing. Typically, factors including tool life, tool wear, cutting force, chip formation, cutting temperature, surface integrity, and burr size are used to assess a material's Machinability [3]. Ti6Al4V is one of the essential alloys in the Industrial sector; however, there are good arguments for selecting titanium. It possesses a remarkable

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strength-to-weight ratio, outstanding flexibility and durability, and the capacity to sustain strength at high temperatures. Additionally, because of its exceptional chemical inertness, it can withstand oxidation, including corrosion and rust. Unfortunately, Ti6Al4V has limited Machinability due to owing inherent properties explained below. The reason Ti6Al4V is so well-known for difficult machining is that it has poor machinability. Because of the beta lamellar structure and higher temperature at the phase change cutting zone caused by increased thermal conductivity, the machinability is poor [4][5]. Furthermore, Ti6Al4V exhibits sticky material behavior at higher cutting zone temperatures. Higher cutting stresses are produced on the tool edge, which significantly slows down chip evolution and raises BUE. In addition, Ti6Al4V exhibits thermochemical reactivity with the cutting tool and shortens tool life by chemical etching and galling. The gradual wear of milling tools, temperature rise, and fracture of cutting tools are also caused by incorrect shearing settings. When all of these factors are considered, Ti6Al4V's machinability becomes quite complicated [6][7][8]. The 3D milling of Ti6Al4V can be made more efficient in terms of machining by managing the shearing parameter value, using adequate lubrication and cooling procedures, and selecting the right type of cutting tool for sequential chip evacuation. Ti6Al4V is need to machine with green manufacturing concept under the sustainability approach [9].

The present study focuses on the key parameters contributing to the chip generation mechanism in the machining of Ti6Al4V. It provides insights to simplify machining processes and their implications.

1.1. High Tensile strength

Titanium Alloy Grade 5 combines Titanium, Aluminum, and Vanadium with some chemical elements. It is not robust as steel but has a high tensile strength of 896 MPa nearly and toughness even at higher temperatures [10]. So, this property restricts the shearing and cutting tool experiences shocks and vibration during 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

Ti6Al4V alloy has a limited ability to conduct heat with poor thermal conductivity of 6.6 W/m°C [11]. During shearing through 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 hard to shear.

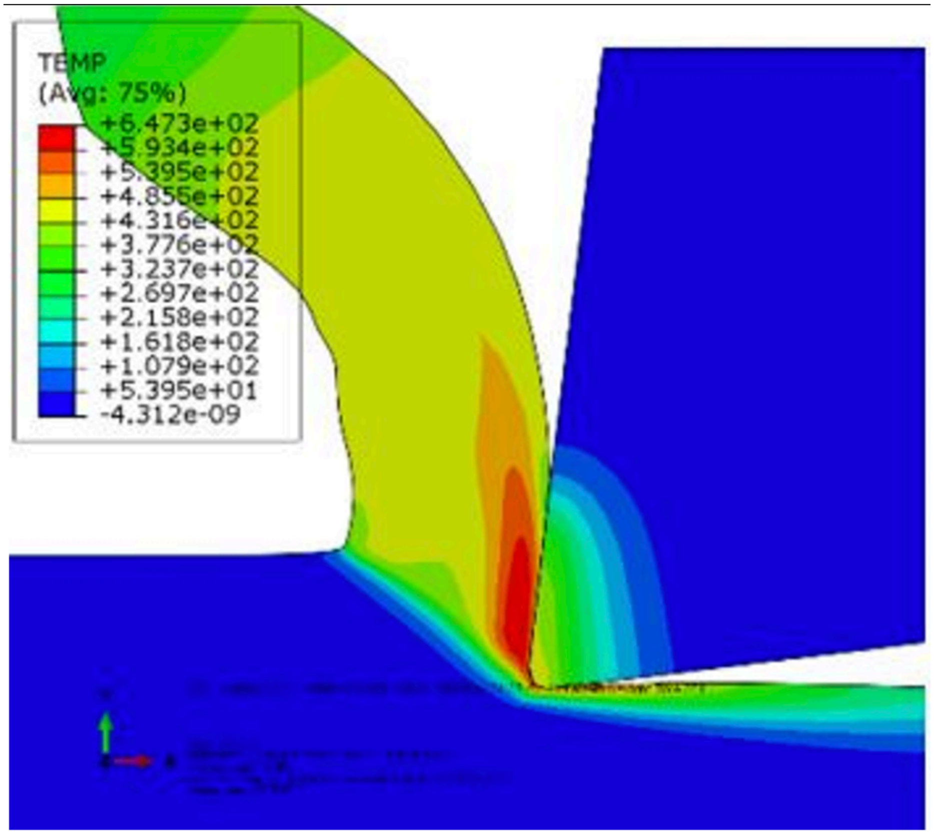

Figure 1. Heat distribution in cutting Tool and chip during milling [12]

1.3. Chemical Reactiveness

Titanium alloys have a 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.

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 experiences 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.

1.5. Shearing Mechanism

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) [3].

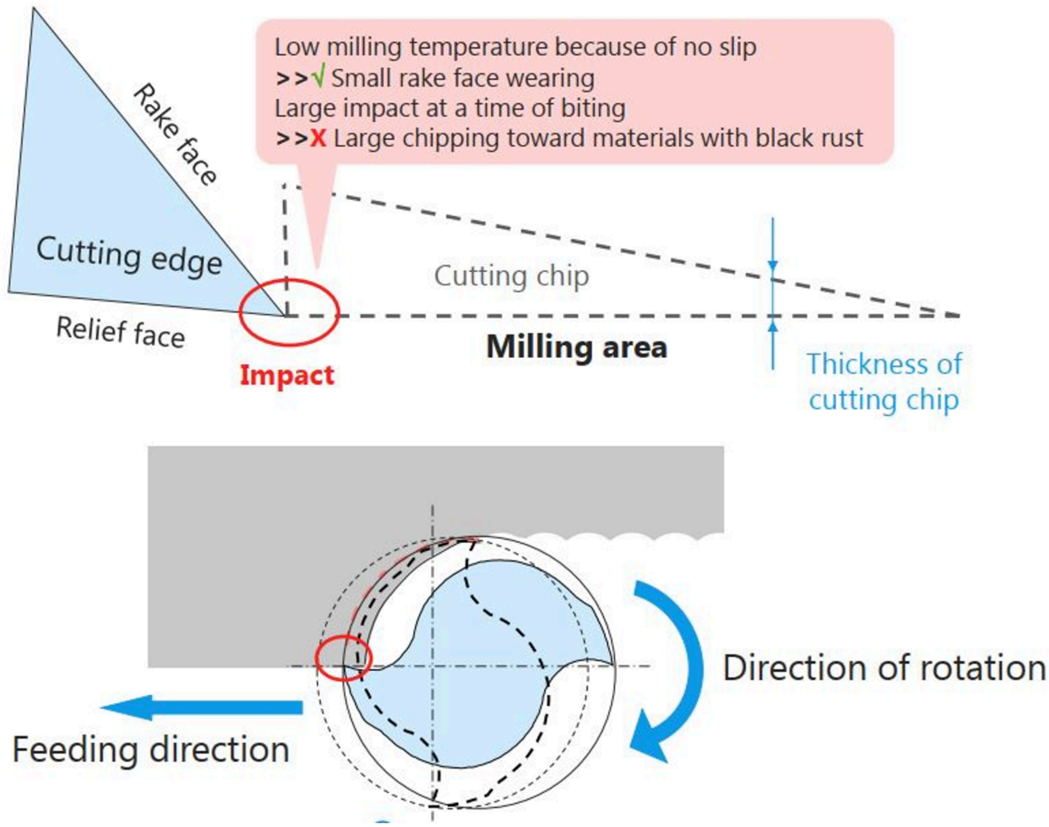

Figure 2. Down milling Physics in milling [13]

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 for 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. Cutting speed rate influences the tool life and surface quality in milling Ti6Al4V. On abutment of literature

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study [3][14][15][16][17][18] and practical results during research, at Higher rate of cutting speed above 120 m/min in the Ti6al4V milling; material becomes slightly softer and lowers the cutting forces initially, but after Built of Edge increases the shear edge area, which acts as tool bluntness. Finally, the high cutting stresses accumulated 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 suffering from cracking, chipping, and excessive rubbing. In this way, Higher cutting forces escort to catastrophic failure of 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 will shorten the tool's life. The Cutting speed selection in Ti6Al4V milling depends upon cutting tool material and their coating with the type of coolant used for milling. Generally, carbide cutters' cutting speed is between 50 m/min to 80 m/min. It is also distinguished by finishing and roughing operations with a combination of feed rates [19][20][21].

2.2. Effect of Feed/tooth

The cutting tools of each tooth advanced in 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 feed rate value. In general, 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. High feed rate increases Material Removal Rate (MRR) with lots of vibrations due to strain hardening as well as evaluated temperature creates thermal softening, which further leads BUE along with cutting forces in milling of Ti6Al4V [2][22][23]. The feed rate and spindle speed combination effectively control the chip load, tool life, and surface roughness in Ti6Al4V. A higher feed rate with high spindle speed gives ample MRR but too much chip load with feed marks on the surface. Lower feed rate and higher spindle speed invites bad MRR with rubbing action might lead to vibrations and catastrophic cutting tool failure by excessive thermal degradation.

At least recourse is a moderate feed rate and balanced spindle speed for better tool life and surface quality in Ti6Al4V milling. During rigorous study [3][21][24][25][26][27][28], for Titanium Alloy Grade 5 shearing in

Finish milling feed rate per tooth should be ≤ 0.07 mm/tooth, and for Rough milling 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 shear 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 operation [26][29][30][31].

Axial DOC is more integral than Radial DOC in the milling of Ti6Al4V. Higher Axial DOC proportional to MRR but prone to higher cutting stresses on the shearing edge and 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 notch on the leading edge and propagates cracks on the cutting tool. Higher Axial DOC in Ti6Al4V milling starts burning the chips and sticking on edge (BUE), finally disturbing surface quality with high cyclic stresses. On the abutment of experimental data [3][16][25][32], Axial DOC should be less than 2 mm in roughing operation and 0.1 to 0.4 mm in finishing mode, with ample cooling recommended.

2.4. Chip Evolution and Morphology in Ti6Al4V Milling

In the milling of Ti6Al4V, material removal by application of shearing parameters through a cutting tool with Orthogonal or Oblique type of cutting under a specific cooling environment [13][33][34]. The resultant effect of cutting material undergoes plastic deformation and shear at the shear plane and evolves into chips [35][36][37]. In general machining, four types of chips were observed: Continuous, Discontinuous, Continuous with Built-up-edge, and Segmented Saw tooth type. The type of chip mostly depends upon metallurgical properties and tool rake angle; 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. [36] 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 [35]. In saw-tooth chips, there are two critical steps in producing the segments [2][35][36].

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 primely 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 initiation of segmented chip at Vc = 800 m/min produce lot of heat at primary shearing zone and dominant on strain hardening which initiates the Adiabatic shear band.

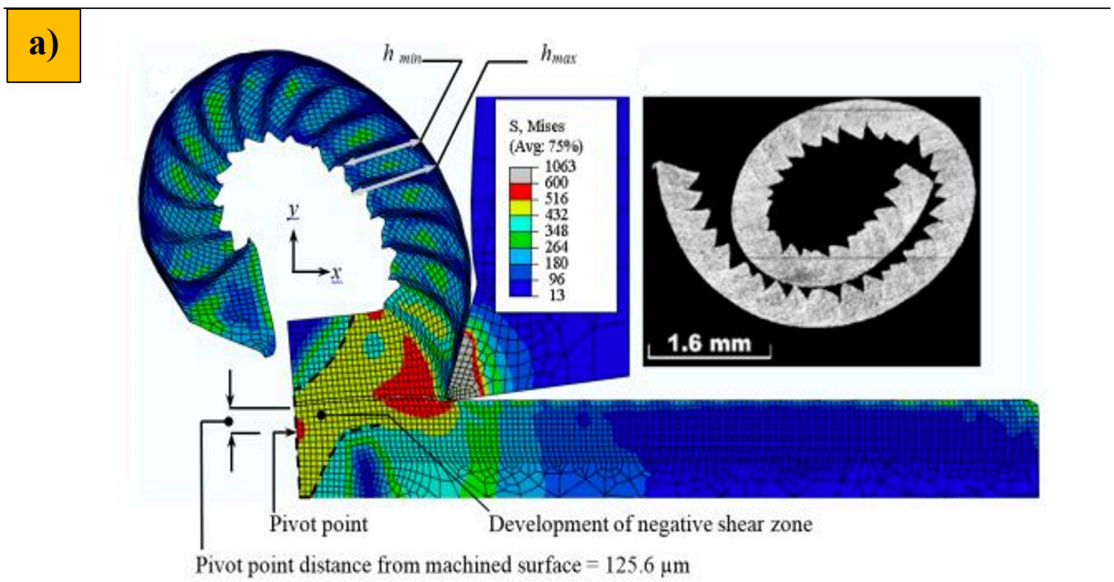

Figure 3(a). Initiation of Segmented chip generation

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)).

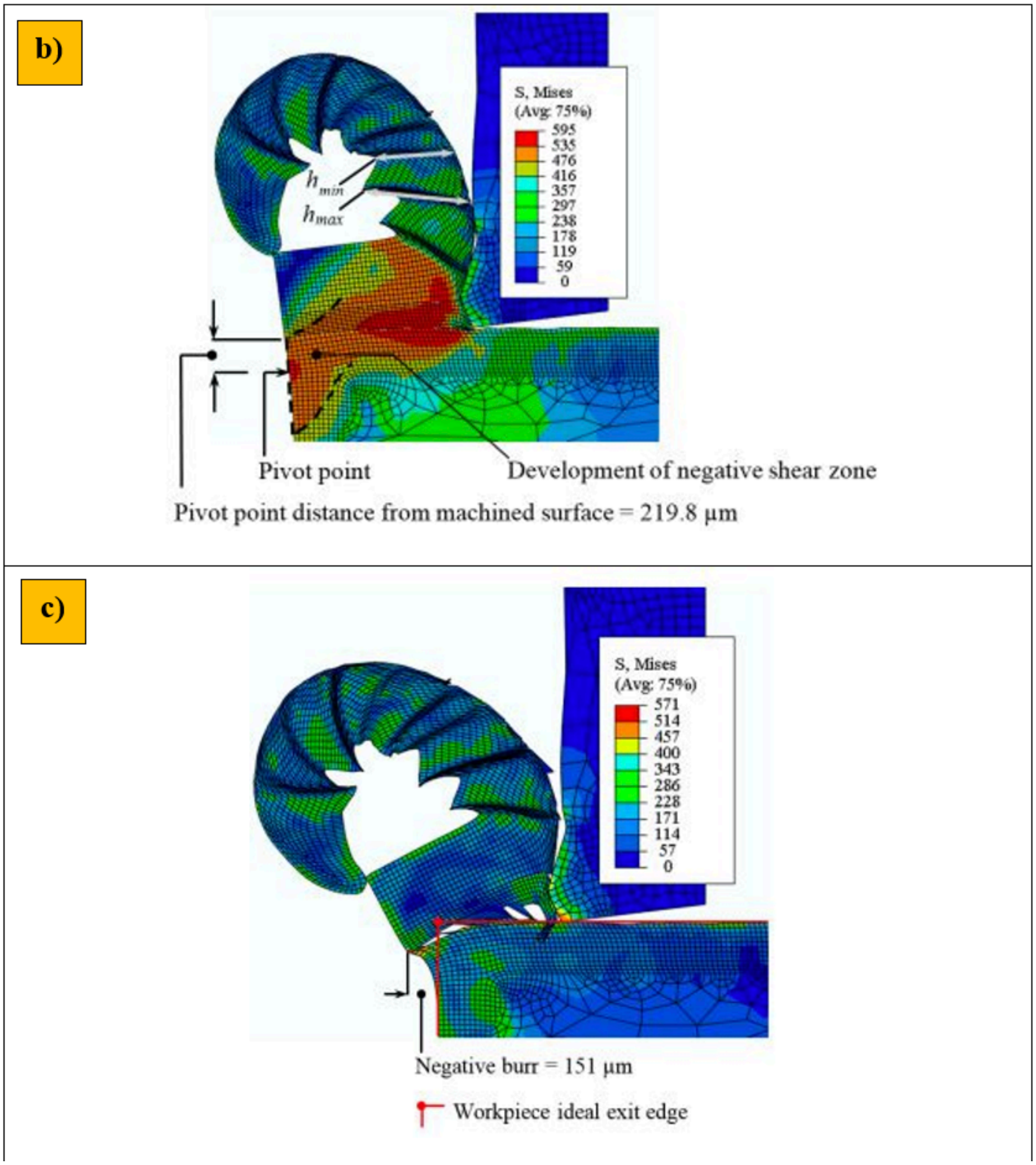

Figure 3(b-c). Chip formation and Segmentation in Ti6Al4V machining **b)** Initiation of fracture at primary shear zone **c)** Fracture of a chip with negative burr [38]

Figure 4 indicates the strain distribution in the serrated chip in the milling of the Ti6Al4V. The low to high strain creates dynamic stresses that create non-homogeneous chips [2].

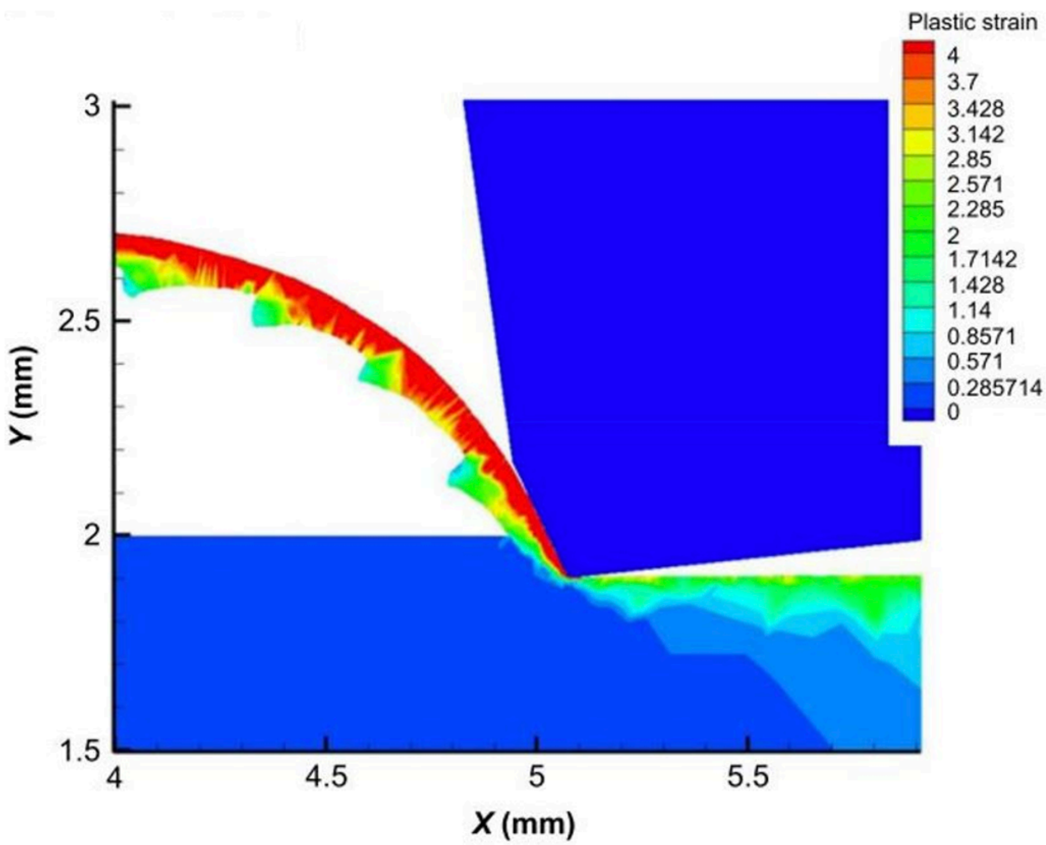

Figure 4. Instability in Plastic strain in milling of Ti6Al4V [2]

Typically, localized shear deformation and thermal softening overstrain 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 [39].

- 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 softens 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.

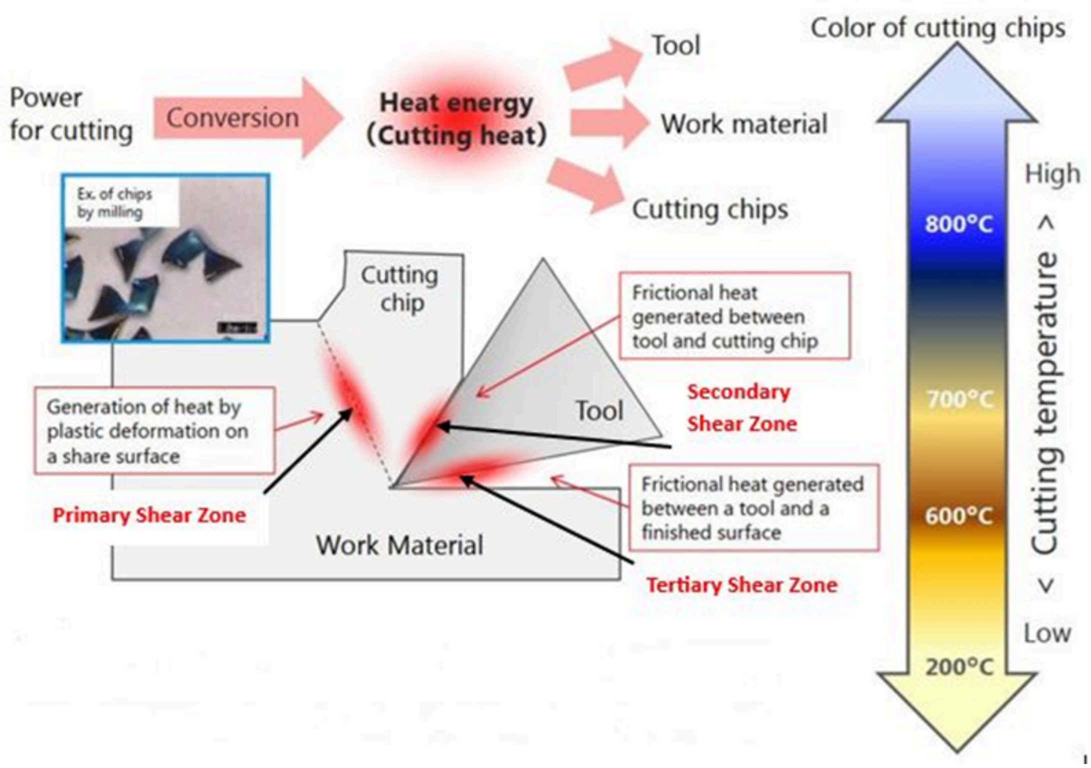

Figure 5. Heat generation junction in Chip generation in Ti6Al4V milling [13][39]

Cooling media also plays 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 restrict the chemical reaction with tool coating and enhances the tool life. Ample lubrication quickly sides the evolved chip from the tool's rake face, minimizing the crater wear in milling.

2.5. Cutting Tools

The Machinability of Ti6Al4V is important in measures of Tool Life. Limited tool life was observed in Ti6Al4V milling due to their 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 exact geometry along with proper shearing parameters enhances the Machinability of Titanium Alloy Grade 5 in milling operation.

On the view of throughout research [15][40][41][42][43], Carbide PVD, CVD multilayered/nanolayered (PVD TiAlN, CVD Al_2O_3+TiCN, and PVD TiAlN+TiN) cutting tools are popular in milling than other tools. They have high- Hot hardness, ample inertness about thermo-chemical reactions, and better thermal conductivity. Also, it exhibits a toughness against abrupt contact with material means capable of avoiding mechanical wear up to a particular sustain. Basically, cutting tool material with high wear resistance against Fracture failure, Temperature failure, and Gradual wear (Crater and Flank) in the machining of Ti6Al4V is expected to improve the Machinability. The geometry should reduce the 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 the surface integrity [14][15][44][45]. Table 1 exhibits keen requirements of Cutting tool properties and Geometry and their effect on the Machinability of Ti6Al4V based on recent study.

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Sr. No.	Property of Cutting Tool Material	Effect on Machinability
1	High Thermal Conductivity	Improved tool life, Restrict the metallurgical alterations, and Avoid Thermo-Assisted wear.
2	High Hot Hardness	Ability to shear material efficiently at high temperatures without melting, Improves Tool life, lower cutting stresses, and Improves surface quality.
3	Ample Toughness	Avoids abrupt fracture, Reduces Mechanical Wear, Limited Notching at cutting edge
4	High Bending strength	Increase ability to work under high cutting pressure, maintain dimensional accuracy, and Sustain high Depth of Cut shocks and vibrations.
5	High Abrasive resistance	Minimize the Gradual wear rate (Crater and Flank wear)
6	High Chemical Inertness	Avoid chemical wear, oxidation, and diffusion. Restrict the etching of the cutting tool at elevated temperatures.
7	Ability to withstand at high thermal gradient environment	For capable of surviving under cryogenic temperature coolant in the cutting zone, Avoid cold cracking and shrinkage
Sr. No.	**Tool Geometry**	**Effect on Machinability**
1	Positive Rake angle	Improved chip flow, Reduces the vibrations
2	Sharp cutting edge	Ease shearing with lower cutting stresses with minimum power consumption. Avoid 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	Affect the cutting force and surface quality in general Nose angle should be 0.2 to 0.8 mm. Higher value increase strength but improves friction. Lowe value improves stress concentration and porn to breakage.

Sr. No.	Property of Cutting Tool Material	Effect on Machinability
6	Multi flues with variation in flute angle	Improves chip flow, Reduces frictional heat
7	Chip breaker	Improves the 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

Summary

Ti6Al4V is notoriously well-known for complex machining due of with poor Machinability. The Machinability is poor due to lower thermal conductivity, which raises the temperature at the cutting zone of the phase transformation and becomes too Hard due to the Beta lamellar structure. Furthermore, at higher cutting zone temperatures, Ti6Al4V behaves like sticky material. It creates higher cutting stresses on the tool edge, drastically decreasing chip evolution and increasing BUE. At the same time, Ti6Al4V shows thermo-chemical reactivity with the cutting tool and reduces the tool life by galling and chemical etching.

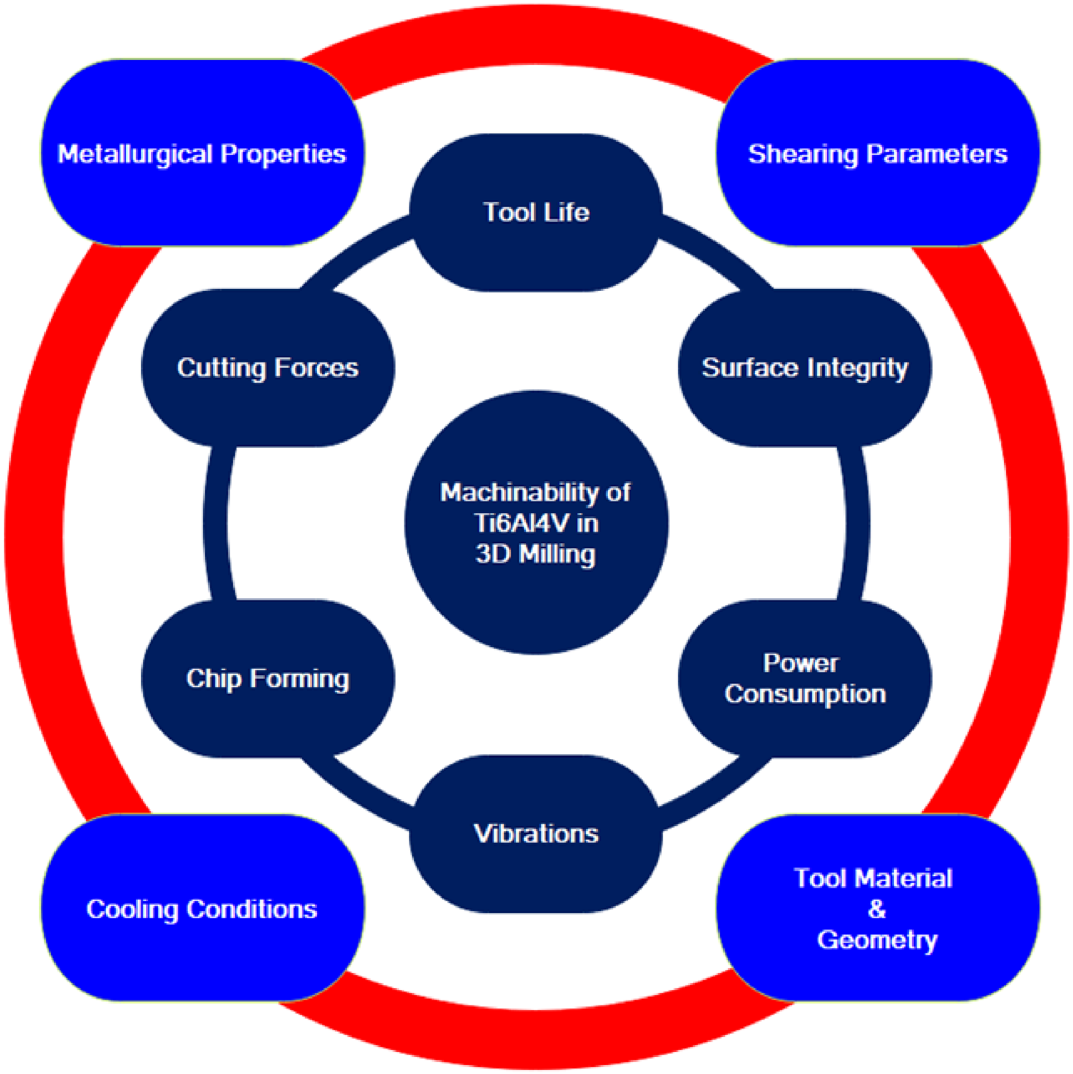

Figure 6(a). Machinability factors for assessing the Machinability of Ti6Al4V milling

The improper shearing parameters are also responsible for cutting tools' fracture, temperature increment, and gradual milling wear. In accumulating these reasons, the Machinability of Ti6Al4V is really complex. The improvement in Machinability by controlling the shearing parameters value, sufficient cooling techniques, and proper cutting tool type for successive chip evacuation is indeed for improving the machining efficiency in 3D milling of Ti6Al4V. Figures 6a) and b) illustrate the factors for assessing the Machinability and Quantitative importance based on practical and reviewed experimental studies [46][47][48][49][50][51][52] for the Titanium Alloy Grade 5 milling, respectively.

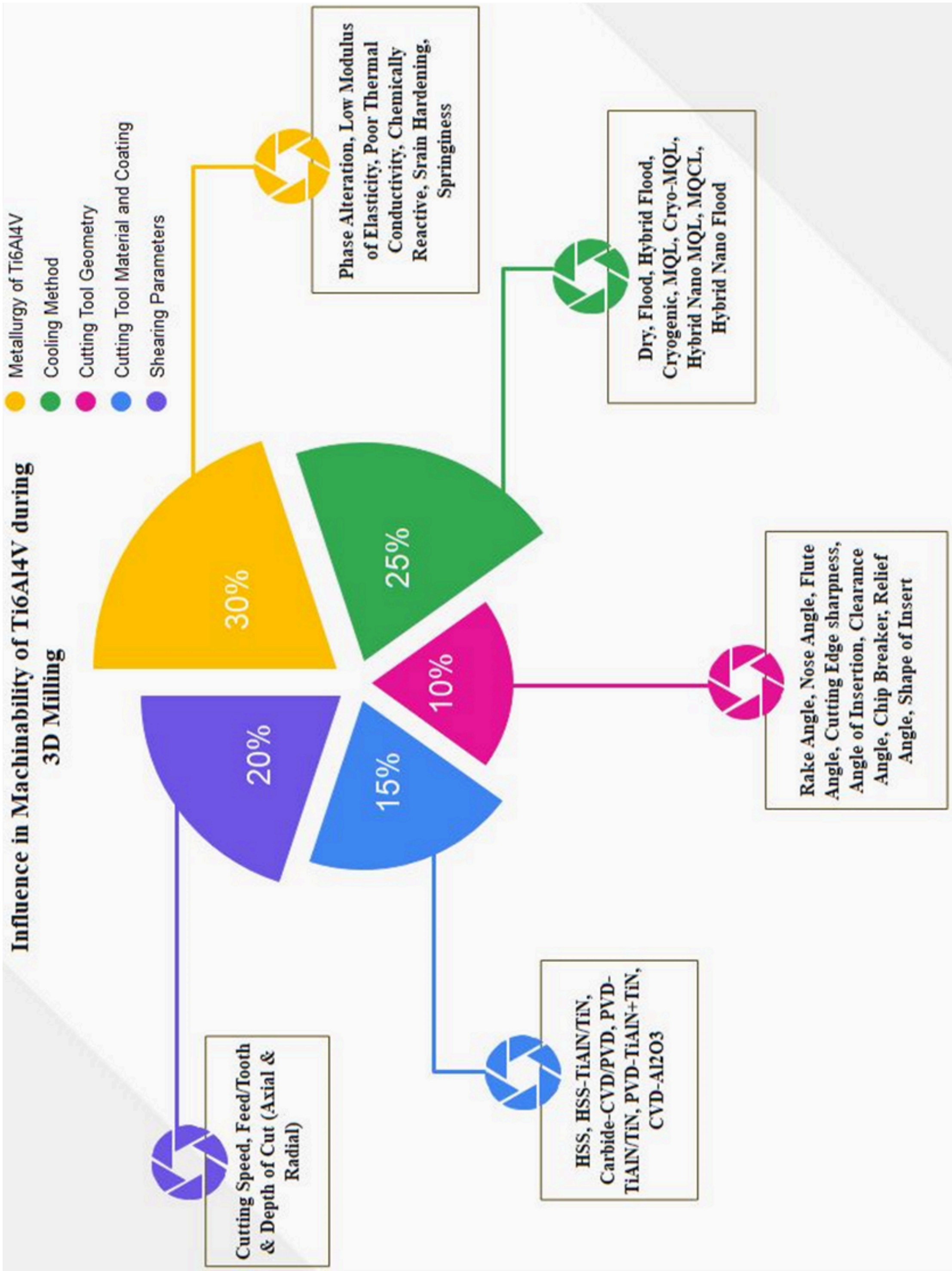

Figure 6(b). Quantitative Importance of Factors on Machinability of Ti6Al4V

Conflict of Interests

There is no conflict of interest. The authors are solely responsible for the content of this article.

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