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Review Article

Improvement of machinability of Ti and its alloys using cooling-lubrication techniques: a review and future prospect

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ABSTRACT

Products made of titanium and its alloys are widely used in modern areas like the mechanical engineering, instrument making, aerospace and medical sector. High strength and low thermal conductivity are the causes of difficulties with the machinability of these alloys. It is important to find ways to increase machinability by cutting titanium alloys. One way to implement this is to apply various methods of cooling on workpieces of titanium alloys and on cutting tools during machining. In this review article, an extensive analysis of the literature on such cooling techniques as dry, conventional cooling system, minimum quantity of lubricant (MQL), minimum quantity cooling lubrication (MQCL), cryogenic lubrication, and high-pressure cooling (HPC) is performed. The following groups of Ti alloys

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Conventional cooling system
Minimum quantity of lubricant
Cryogenic cooling
High-pressure cooling

are considered: high-strength structural and high-temperature Ti alloys, intermetallic compounds, pure titanium, as well as composites CFRPs/Ti alloys. For the processes of turning, milling, drilling, and grinding, etc. it is shown how the type of cooling affects the surface integrity include surface roughness, tool wear, tool life, temperature, cutting forces, environmental aspects, etc. The main advantages, disadvantages and prospects of different cooling methods are also shown. The problems and future trends of these methods for the machining of Ti and its alloys are indicated.

1. Introduction

Titanium and its alloys are highly used structural materials in aerospace sector [1], shipbuilding and chemical industries [2], turbomachinery [3] in machine and instrument making, and medicine [4]. In terms of machinability, titanium alloys are close to corrosion and heat-resistant steels and alloys [5]. High strength and extremely low values of thermal conductivity and thermal diffusivity [6] (about 4–5 times lower than that of low-carbon steels) often become the causes of intense heat in the cutting zone, and consequently, structural-phase transformations in the surface layer of the material [7]. The low thermal conductivity of titanium alloys contributes to the occurrence of temperatures in the cutting zone – an average of 2.2 times higher than when machining AISI 1045 steel [8].

Machining of titanium alloys and its alloys are accompanied by oxidation of the chips and the machined surface [9]. Therefore, cutting fluids used in the processing of such materials should protect the chips and the treated surfaces from oxidation [10]. The machinability of titanium alloys by cutting is worse than that of steels [11], and titanium chips at high cutting speeds can ignite titanium dust explosive [12]. From the above classification, it can be seen that titanium alloys by machinability occupy an intermediate position between stainless and heat-resistant steels and alloys [13]. Their processing is hindered mainly by low thermal conductivity [14]. Compounds of titanium with iron, manganese, chromium, molybdenum, vanadium, tin and other alloying components form titanium alloys with improved strength properties [15] and better machinability by cutting compared to titanium [16]. In practice, the titanium machining is recommended to be carried out at low cutting speeds and with high feed [17].

A reliable condition for the possibility of increasing machinability and, in turn, improved cutting conditions is the use of cooling techniques [18]. For example, Klocke et al. [10] studied tool wear, cutting forces, chip morphology, and surface roughness during high-speed longitudinal turning of workpieces (heat resistant gamma titanium aluminides γ-TiAl). They have studied the effects of conventional flood cooling and the supply of high-pressure coolant (HPC), cryogenic liquid nitrogen cooling, and the minimum amount of lubricant (MQL). It is shown that HPC reduces flank wear, but the tool load increases. Conventional flood cooling provides better roughness than dry machining, but inferior to MQL. Cryogenic cooling also reduces tool wear and improves surface quality and defective layer [19].

Few reviews have been reported of different cooling lubrication methods, or on any specific cooling lubrication method by considering titanium alloys. Krolczyk et al. [11] presented a detailed and comprehensive report about by reviewing the advanced cooling lubrication technologies for machining, however, the main focus was on the ecological aspects than the productivity. Pervaiz et al. [20] in their review article showed the benefits of using minimum quantity of lubricant (MQL), and minimum quantity cooling lubrication (MQCL) using biodegradable vegetable oils for cleaner production. Sen et al. [21] reported the sustainability perception with the minimum quantity lubricants in machining. For mist assisted cooling lubrication in machining, a comprehensive review has been reported by Singh et al. [22] conventional machining processes like turning, milling, drilling, grinding were listed for mist assisted cooling system (MQL group).

However, a comprehensive review is needed that bridges the gap between the state-of-art cooling-lubrication and machining of Ti-alloys. This can give a guidance to researchers who are searching the knowledge about latest updates, and to industrial practitioners to have valuable information about cooling lubrication on the machining of Ti and its alloys. The scope of the current review is shown in Fig. 1. This review is divided as follows: firstly, described titanium and its alloys and their composition, classification, and properties - for following groups of Ti alloys: high-strength structural and high-temperature Ti alloys, intermetallic compounds, pure titanium, as well as composites carbon fiber reinforced polymers (CFRPs)/Ti alloys; secondly, a general methodology is described that covers the main methods of cooling techniques: Conventional Cooling System (CCS), Minimum Quantity Lubricant (MQL), Minimum Quantity Cooling Lubrication (MQCL), Cryogenic Lubrication (CL), High-Pressure Cooling (HPC). Then these methods are examined in the corresponding sections in more detail. The influence of various cooling methods on the parameters of surface roughness, temperature, tool wear, tool life, and productivity are considered. The application of these methods to the processes like turning, milling, drilling, and grinding, etc. in the literature and their advantages, disadvantages and prospects are considered. Finally, the last section discusses cooling techniques and their advantages and disadvantages with respect to facilitating their selection in accordance with the manufacturer's goals. The aim of this review is to analyze the trends in the application of cooling methods in machining of Ti and its alloys in terms of machinability, temperature,

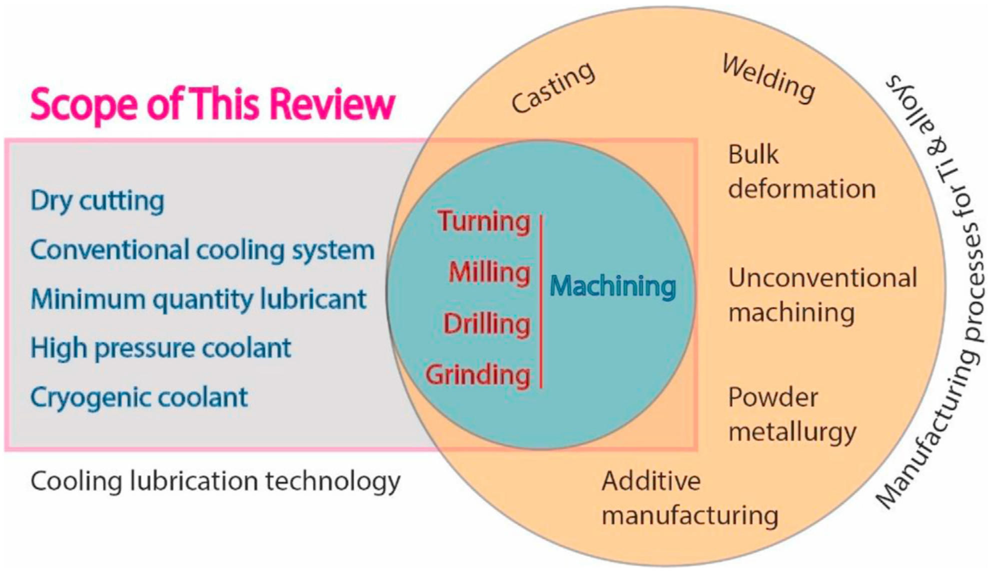

Fig. 1 – Scope of review article on cooling lubrication for Ti alloys.

cutting force, surface integrity, tool life, environmental aspects, productivity and accuracy to meet the requirements of modern manufacturing.

2. Titanium and its alloys: composition, classification, and properties

The density of titanium (Ti) is 4.54 g/cm^3. It is elastically rigid, about 115 GPa Young's modulus, strong, lightweight, and resistant to corrosion processes. Ti and titanium alloys have tensile strengths in the range of 210–1380 MPa, which is close to the tensile strength characteristic of many complex steels. It has an extremely low density of approximately 60.0% of that of iron (Fe). It can be hardened by alloying with a solute. Ti is non-magnetic and has excellent heat transfer properties. One of its important properties of titanium alloys is a high melting temperature of 1725.0 °C, that is, almost 200 °C more than steel, and 1000 °C more than aluminum (Al). Ti and its alloys are highly resistant to most mineral acids. It is non-toxic and compatible with biological tissues and minerals. Excellent corrosion resistance and biocompatibility [23] together with superior toughness have made them useful for the chemical and biomaterials industries.

Ti alloys are divided into the following groups: High-strength structural Ti alloys; High-temperature Ti alloys; Intermetallic compounds (Ti alloys based on a chemical compound).

Titanium grades 1, 2, 3 and 4 are commercially pure (99% titanium minimum). Each variety has a slight difference in chemical composition which affects the mechanical properties. Corrosion resistance is the same for all four classes. Titanium Grade 2 (Pure titanium) is most often used when good ductility and high corrosion resistance are required. Pure titanium is used in food, chemical industry, mechanical engineering, medicine, etc.

Table 1 shows the distribution of titanium alloys with their chemical composition, discussed in section 4. Machinability of Ti and its alloys under cooling-lubrication conditions.

High-strength structural Ti alloys are solid solutions which allows them to provide an optimal balance of strength and ductility characteristics.

Alloys of the Ti6A14V or Ti64 or TC4 (α+)-class are among the most widespread titanium alloys in the world which accounts for about 50% of all products made from titanium alloys, and in the aerospace industry and medicine this alloy accounts for up to 80% of products [24]. Aluminum in alloys of the TiAlV system increases the strength and heat–resistant properties, and vanadium is one of the few alloying elements in titanium that increase not only the strength properties but also the plasticity.

Ti6Al7Nb is an alpha-beta titanium alloy that has high strength and properties similar to the cytotoxic vanadium-containing alloy Ti6Al4V. In addition, it has additional useful mechanical properties, higher corrosion resistance and biotolerance in comparison with Ti6Al4V.

High-temperature Ti alloys are these grades of titanium alloys that differ in heat resistance, crack resistance and stability at T 400–550C.

Ti-6426 alloy has increased strength, ductility and low-cycle fatigue properties [25]. It also finds application in aerospace as well. Ti-6242S is a heat treatable alpha-beta alloy designed to combine increased temperature performance with high levels of strength. Alloy TC6 is classified as a two-phase titanium alloy that possesses high corrosion resistance, high strength and ductility. Therefore, it is used in aerospace, automotive and other industries. Beta-titanium alloy Ti-5Al-5V-5Mo-3Cr (Ti-5553) has high strength, temperature resistance and ductility, depending on the applied heat treatment. Compared to α-β-titanium alloy Ti-6Al-4V, a higher tensile strength can be achieved. As a result, Ti-5553 is used in the specialty aerospace industry. Ti-10V-2Fe-3Al or Ti-1023 is

Table 1 – Proportion and chemical composition of Ti and its alloys in the reviewed references in section 4. Machinability of Ti and its alloys under cooling-lubrication conditions.

Materials	Number of references	Proportion (%)	Chemical composition (almost) (%)														
			Titanium (Ti)	Aluminum (Al)	Niobium (Nb)	Molybdenum (Mo)	Vanadium (V)	Zirconium (Zr)	Tin (Sn)	Chromium (Cr)	Tantal (Ta)	Iron (Fe)	Carbon (C)	Nitrogen (N)	Oxygen (O)	Hydrogen (H)	Silicon v(Si)
Pure		titanium	7	6.4	99	–	–	–	–	–	–	–	–	to 0.3	to 0.08	to 0.03	to 0.25
to 0.015	–																
Ti6Al4V (TC4)	76	69.7	90	6	–	–	4	–	–	–	–	to 0.25	to 0.1	to 0.05	to 0.2	to 0.0125	–
Ti6Al7Nb	1	0.9	86	6	7	–	–	–	–	–	to 0.5	to 0.25	to 0.08	to 0.05	to 0.2	to 0.009	–
Ti-6246	2	1.8	84	6	–	6	–	4	–	–	–	to 0.15	to 0.04	to 0.04	to 0.15	to 0.0125	–
Ti-6242S	3	2.8	86	6	–	2	–	4	2	–	–	to 0.25	to 0.05	to 0.05	to 0.15	to 0.015	to 0.1
TC6	2	1.8	90	6.3	–	2.5	–	–	–	1.5	–	0.45	to 0.1	to 0.05	–	to 0.015	0.28
Ti-5553	6	5.5	81.9	4.85	–	5.14	5.17	–	–	3.36	–	0.29	–	–	–	–	–
Ti-1023	2	1.8	85	3	–	–	10	–	–	–	–	1.9	–	to 0.05	to 0.13	to 0.015	–
TiAl	5	4.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
CFRP/	Ti6Al4V	5	4.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–
–																	

a beta alloy with excellent hot formability, excellent high strength and deep quenching ability.

Intermetallic compounds (Ti alloys based on a chemical compound) are of interest as a heat-resistant material with a low density that can compete with heat-resistant nickel alloys in a certain temperature range. The properties of intermetallics are between that of ceramics and metals.

Titanium aluminides are TiAl based alloys [26]. Due to their low density (3.9–4.2 g/cm3), high specific yield strength and stiffness, good resistance to oxidation and ignition, combined with good creep characteristics up to high temperatures, these alloys are finding ever more widespread use. In particular, at temperatures from 600 °C to 800 °C, γ-based alloys (TiAl) outperform Ti-based alloys in terms of their specific strength. At the same time, TiAl exhibits low plasticity. Typical alloys in the gama phase have the following chemical composition: TNB type [Ti- (44–45) Al- (5–10) Nb- (0.2–0.4) C] is used at very high temperatures maintaining high values of resistance and oxidation; MoCuSi type [Ti- (43–46) Al- (1–2) Mo- (0.2) Si-Cu] for low temperatures with a high resistance below 650 °C [27]. This must be considered when designing components, and it is a major obstacle to widespread use in many applications.

In recent times, the multilayer stacks constituted by carbon fiber reinforced polymers (CFRPs) and titanium (Ti) alloys have advanced to find its usability in aerospace and other manufacturing areas. Since these structures are composed of different materials, the machinability of CFRPs is very difficult [28].

3. State-of-use of the cooling lubrication techniques in machining

Removing chips from machining zone, cooling, lubrication, and preventing welding between cutting tool, workpiece material and chips are the main functions expected from a coolant. Proper application of coolants maximizes efficiency, improves process safety, enhances tool performance and part quality. On the other hand, their cost, environmental damage, the problems experienced in the disposal and recycling are among the issues that are not clearly desirable [29]. Although dry cutting is the most effective way to prevent all these mentioned situations, due to the lack of very efficient cutting tools that can eliminate the possible heat-induced damages when cutting hard materials viz., titanium alloys, it is mandatory to use the cutting fluid [22].

The most popular way of applying a cutting fluid is the overhead flood cooling. The abundant application of cutting fluids to the cutting zone during machining is called conventional cooling. In this type of application, a flow amount of approximately 600 L/h is taken for single point cooling tools. Moreover, it is worth noting that this value is higher if multiple tools are used (as in milling operations) or if cooling is applied from multiple points to the cutting area [30]. From the wide variety of coolant available in the market, the water-based liquids have widely been utilized for conventional cooling because of their good heat transfer abilities, quick and easy application without the need for additional equipment such as cooling setup and less costly [31]. The use of

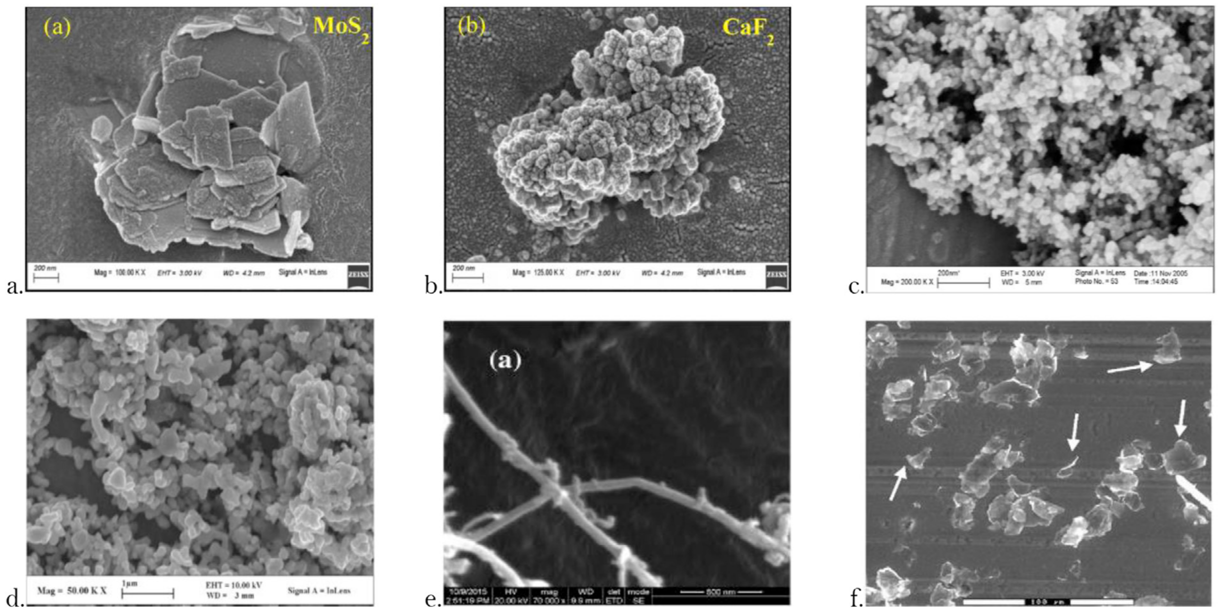

Fig. 2 – SEMs images of the nanoparticles. a. molybdenum disulfide [46], b. calcium fluoride [46], c. titanium oxide [47], d. copper [48], e. multi-walled carbon nanotubes [49], f. graphite nanoplatelets [50].

conventional cooling is used quite often, in turning [32], drilling [33], milling [34], etc.

The use of alternative lubrication techniques has been studied in the last few years and the motivation relies on two main factors: The development of sustainable manufacturing processes which reduce energy consumption and the use of substances such as petroleum-based oils while keeping high quality and productivity standard and the cutting of hard-to-cut materials in which the traditional lubrication method is not able to deliver the desired surface quality and productivity [35,36]. Notable approaches for cooling and lubricating the cutting zone includes the minimum quantity lubrication (MQL) [37], cryogenic cooling [38], and high-pressure coolant [39].

MQL is the use of small amount of cooling and lubricating agent, as such, it is called the small quantity lubrication (SQL), and if cooling effect is added it is called minimum quantity cooling lubrication (MQCL), or small quantity cooling lubrication (SQCL) [40]. Typical flow of 50–500 ml/h is practiced in this technology. Herein, the irrespective of the nuances, the whole group is called MQL. Critically reported, the bulk amount of cutting fluids in the conventional or wet cooling system is unable to reach at real cutting area; therefore, less heat is transferred as compared to MQL condition. Various types of emulsifiable oils, synthetic and semi-synthetic oils, and vegetable oils as cutting fluids have been supplied through the MQL system. However, the utility of bio-based fluids contributes to the environmental friendliness of the MQL practice. Therefore, it is worthy to claim that the MQL is an effective and green method used to improve the machining performances along with the less cutting fluid [41–43].

Research efforts have been shifted from traditional wet cooling system to the minimum quantity lubrication (MQL) system – to make it more sustainable and economical. Advantage of MQL system is that a small quantity of coolant with the combination of pressurized compressed air is directly transferred to cutting zone. In return, fruitful results with regard to cutting forces, surface roughness, tool wear and cutting temperature have been achieved [41,44,45]. The cooling medium is supplied in the form of an aerosol (often called mist), which is a combination of cutting oil and pressured air. A mixing chamber is used for the purpose. Alternatively, it is produced by the atomization process [42] – a bulk liquid is transferred into a spray or mist (i.e. a series of tiny droplets), often by going through a nozzle. Heat transfer is primarily in evaporative manner for MQL which is more effective than the convective heat transfers of conventional cooling assisted machining processes. It contributes to the more efficient utilization of machining floor space, removes additional equipment and procedures i.e., coolant pump, inspection, treatment and final disposal of the fluid, and allows the worker to monitor output during processing. Coolant pump, refrigerant inspection, refrigerant treatment, and coolant disposal, and allows the operator to monitor output in cutting processes. Coolant is directly in contact with the hot tool and chip surface; consequently, heat is transferred by evaporation. Most of the heat is conducted to the chips and evacuated from interface as the chips separate. Comparatively, lower amount of coolants is needed – this reflects the potential cost saving capability of this technique. Nanoparticles (i.e. size <100 nm) have added a new dimension to the MQL group. Based on this, the MQL can be classified as i. MQL without nanofluid, ii. MQL with nanofluid. Figure 2 shows the SEM images of the notable nanoparticles. The thermal conductivity is enhanced by the inclusion of nanoparticle, so is found with convective heat transfer, in addition, the anti-friction and wear properties are notable to ensure a good application of nanoparticle.

For intensive chilling of the tool, chips and work material, the application of cryogenic cooling has been practiced. The use of cryogenic lubrication in machining process have been investigated and stands out from other alternatives techniques when its applied in the machining process of hard-to-machine materials like Ti alloys [51,52].

The pioneering method of application of cutting fluids under high-pressure was proposed by Piggot and Colwell [53], directing the jet of cutting fluid (mineral lard, sulfurized mineral and soluble oil) among the main clearance surface of the cutting insert and the workpiece. The best fluid pressure was 400 psi (2.76 MPa), allowing increase in the tool life up to 17 folds when turning SAE 3156 steel and SAE 416 stainless steel using high speed steel tools as compared to the conventional overhead flood cooling. Approximately two decades after the pioneering work, Sharma et al. [54] experimented the high-pressure coolant jet during the cutting of SAE 1040 steel, using three different cutting fluid (straight mineral oil, same oil with chlorine and the same oil with sulphur) this time the jet travelling through hole in the body of HSS tools, reaching the rake face where the chips make contact with the tool at about 6000 (41.4 MPa). Albeit clogs happened in some tests, the authors concluded that a decrease in cutting temperature and friction coefficient was the most important benefits provided by the high-pressure jet. Nagpal and Sharma [55] confirmed the efficiency of applying the cutting fluid (water soluble, straight mineral oil, chlorinated oil and sulpho-chlorinated oil) under high-pressure (up to 500 psi or 3.4 MPa) in among the main clearance surface of the cutting insert and the workpiece. In their experiments in turning of SAE 1035 steel with HSS tools, they registered reductions on the cutting temperature, specific energy, friction coefficient, shear angle, surface roughness and cutting force when the high-pressure system was compared to flooding and dry cuttings. Mazurkiewicz et al. [56] have directed the high-pressure coolant jet among the rake side of tool and the chip being formed when orthogonal machining of UNS 1020 steel with cemented carbide inserts with promising results. They compared the high-pressure water jet system (with pressure up to 280 MPa) with dry cutting and soluble oil applied under low-pressure (overhead and among the rake side of tool and the chip being formed). The high-pressure system was able to decrease the machining forces components and the friction among the chip and the tool significantly in comparison with other lubri-cooling conditions tested, besides having the chips completely broken.

4. Machinability of Ti and its alloys under cooling-lubrication conditions

4.1. *Dry machining of Ti and its alloys*

Dry machining refers to the machining or cutting without using any fluids neither for cooling nor for lubricating. Dry machining of titanium alloys and the effect of this process on machinability parameters has been investigated by several scientists. Jawaid et al. [57] in their article showed the behavior of the alloy Ti ± 6% Al ± 2% Sn ± 4% Zr ± 6% Mo (Ti-6246) when dry turning in the range of cutting speeds of 60–100 m/min, cutting depth 2 mm and feed 0.25 and 0.35 mm/rev. It was shown that high cutting speeds lead to catastrophic wear of flank face and chipping of flank edge, with a predominance of abrasive wear. Using a chip breaker can be effective to increase tool life when dry turning. López de lacalle et al. [58] in their article investigated machinability from the point of view of increasing the productivity of the milling process of titanium based Ti6Al4V alloy, and nickel-based 718 alloy, having studied the influence of the tool on its geometry and coating, as well as on cutting conditions. Che-Haron [59], for the Ti-6246 titanium alloy, in addition to tool life tests, showed for dry turning the influence of the cutting process on the condition of the machined surface. The machined surfaces are significantly plastically deformed and hardened because of continuous cutting of tool wear. The surface of the titanium alloy is damaged due to poor machinability. Che-Haron and Jawaid [60] for dry turning of the Ti6Al4V alloy with carbide cutting tools in the range of cutting speeds of 45–100 m/min, a cutting depth of 2 mm and a feed rate of 0.25 and 0.35 mm/rev measured the roughness of the machined surface, microhardness and work hardening. For a catastrophically worn tool, a strong plastic flow was observed, a rupture and deformation of the microstructure were found. The upper layer to 0.1 mm was hardened, and under it is a softer layer due to aging of the material. Ginting and Nouari [61] for the dry ball-end milling of the Ti-6242S titanium alloy investigated the behavior of uncoated cemented carbide tools. Tests were carried out for cutting speeds of 60–150 m/min, for axial depths of 2 mm and radial 8.8 mm, for feeds of 0.1 and 0.15 mm/tooth. Flank wear and excessive cutting-edge chips result in tool failures. Ginting and Nouari [62] proposed the Taylor formula and optimal dry ball-end milling regimes for the Ti-6242S titanium alloy. The FEM model in the article makes it possible to evaluate chip morphology and temperature. Ginting and Nouari [63] for dry face milling of Ti-6242S titanium alloys investigated the lay, defects, roughness, microhardness and microstructure machined surfaces. As a result, it was found for fine and semi-dry machining that an uncoated carbide tool gives better roughness than a CVD coated tool. Sun et al. [64] in their work investigated the cutting forces and chip formation for different feeds, speeds and cutting depths of dry turning of a Ti6Al4V titanium alloy. The article shows the features of the formation of continuous and segmented chips. Lebaal et al. [65] in their work proposed a method for optimizing cutting conditions that provide high productivity and the required machining quality for dry turning of Ti6242S titanium alloys. The objective function is taken to maximize volume of material removal as tool life, and the limiting function is designed to provide an acceptable value for the machined surface roughness. Li et al. [66] investigated chip formation during high-speed dry milling of Ti-6Al-4V titanium alloy in the range of cutting speeds of 150–450 m/min, axial 1.0 and 1.5 mm, and radial 5.0 mm cutting depth and feed rates of 0.02 and 0.06 mm/tooth (see Fig. 3). Authors found jagged shape of chips for a given range of cutting conditions. An increase in chip serration ratio (CSR) contributes to efficient chip crushing.

Attempts have been made to research and find tool inserts and coatings for more efficient machining of titanium alloys. Niu et al. [67] for the high-speed dry face milling of TC6

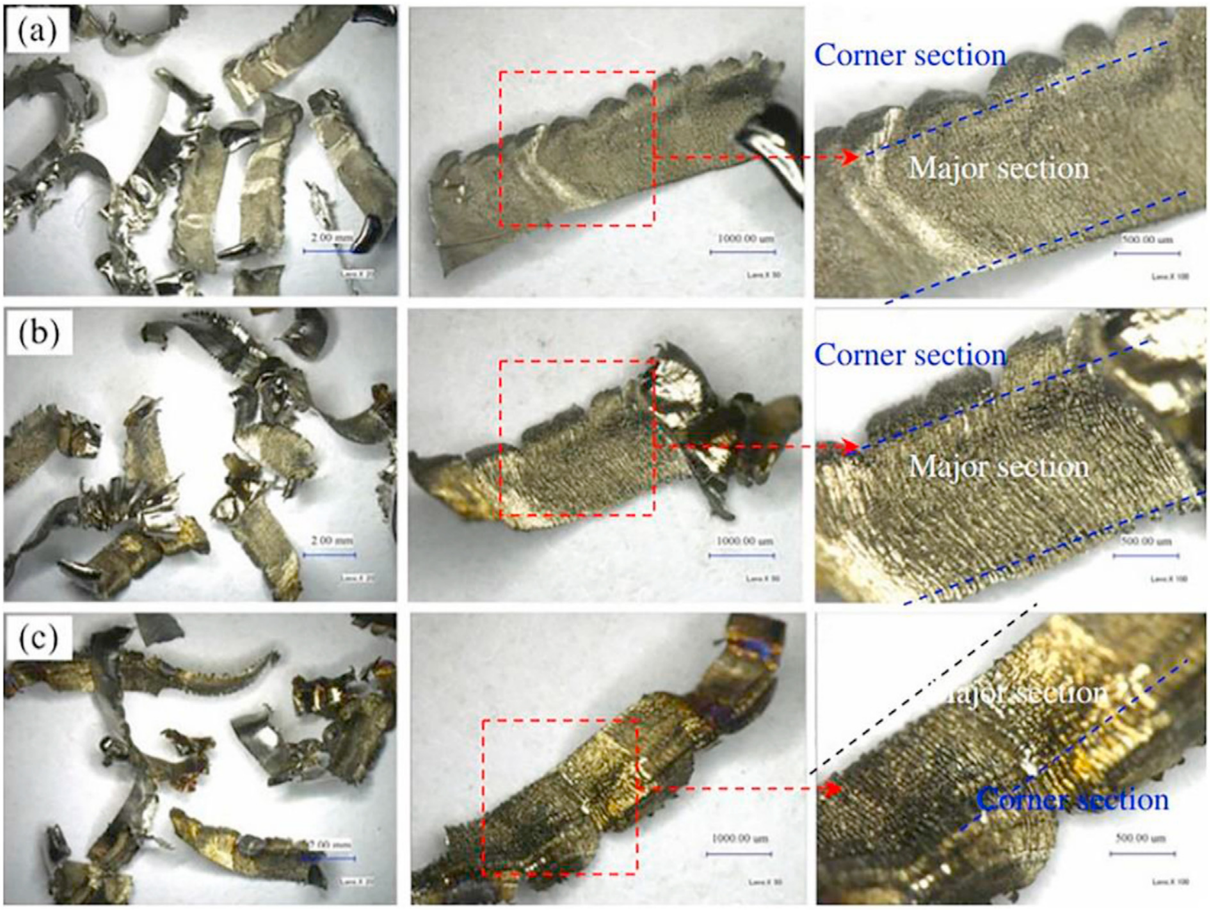

Fig. 3 – Chip morphologies (feed per tooth $f_z = 0.06$ mm/z, axial depth of cut $a_p = 1.5$ mm, radial depth of cut $a_e = 5$ mm). Cutting speeds: (a) $v_c = 150$ m/min; (b) $v_c = 300$ m/min; (c) $v_c = 450$ m/min [66].

titanium alloy, the performance of chemical vapor deposition (CVD) coated (TiN/Al_2O_3/TiCN) and physical vapor deposition (PVD) coated (TiN/TiAlN) carbide inserts were compared. The work compared the roughness of a machined surface, chip formation, cutting forces, wear mechanism, and tool failure condition. The result shows the advantage of PVD coated tools. Chang and Lai [68] investigated the wear process and cutting properties of tungsten carbide insert with different coatings TiAlN, CrAlSiN and TiAlSiN for dry milling of Ti6Al4V alloy. They showed an advantage in wear resistance and the best cutting properties of CrAlSiN coatings over TiAlSiN and TiAlN coatings. For example, at a cutting speed of 350 m/min tool life of insert with a CrAlSiN coating is higher than tools with a TiAlSiN and TiAlN coating and without a coating 2.9, 4.2 and 9.5 times, respectively. Liang et al. [69] investigated the effect of binder Ni3Al on WC-based cemented carbides obtained by spark plasma sintering (SPS) on the dry conditions of Ti6Al4V titanium alloy. As a result, WC-10Ni3Al showed better cutting performance than WC-8Co, especially at high cutting speeds (see Fig. 4). The synergistic mechanism of high hardness and chemical inertness of Ni3Al at high temperatures ensured high wear resistance of flank and crater wear.

Safari et al. [70] studied the high-speed dry milling of alloy Ti6Al4V to find the influence of various cutting conditions of the tool and its wear on the integrity of the machined surface. For cutting speeds of 100–300 m/min, and feeds of 0.03 and 0.06 mm/tooth and TiAlN + TiN PVD-coated carbide tool values of the roughness and microhardness of the machined surface were obtained. Using a new tool and higher cutting speeds allows to get better roughness (see Fig. 5).

Beranoagirre et al. [71] investigated the machinability of titanium aluminides (TNB type [Ti-(44–45)Al-(5–10)Nb-(0,2–0,4)C] and MoCuSi type [Ti-(43–46)Al-(1–2)Mo-(0,2)Si-Cu]) for the dry milling process. Investigations of specific cutting forces showed when milling of TNB alloy showed the highest values than Ti6Al4V, and also the smallest tool life. As a result of research of chip morphology, wear and tool life, roughness, cutting forces, the most acceptable cutting conditions have been proposed.

Sun et al. [72] investigated the dry turning of the Ti6Al4V alloy with cutting tools made of superhard materials: polycrystalline cubic boron nitride (PCBN) and polycrystalline diamond (PCD). They studied the effect of cutting condition on the roughness and microhardness of machined surfaces, cutting temperature, tool life. For failure of tool mechanism with PCBN, labels, chips, crater, and adhesion correspond, and for tool with PCD, adhesion, crater and dissolution-diffusion correspond. Zhu et al. [73] studied the quality and integrity of holes, axial cutting forces, chip formation for various drilling modes for the dry drilling process of Ti6Al4V alloy. Le Coz

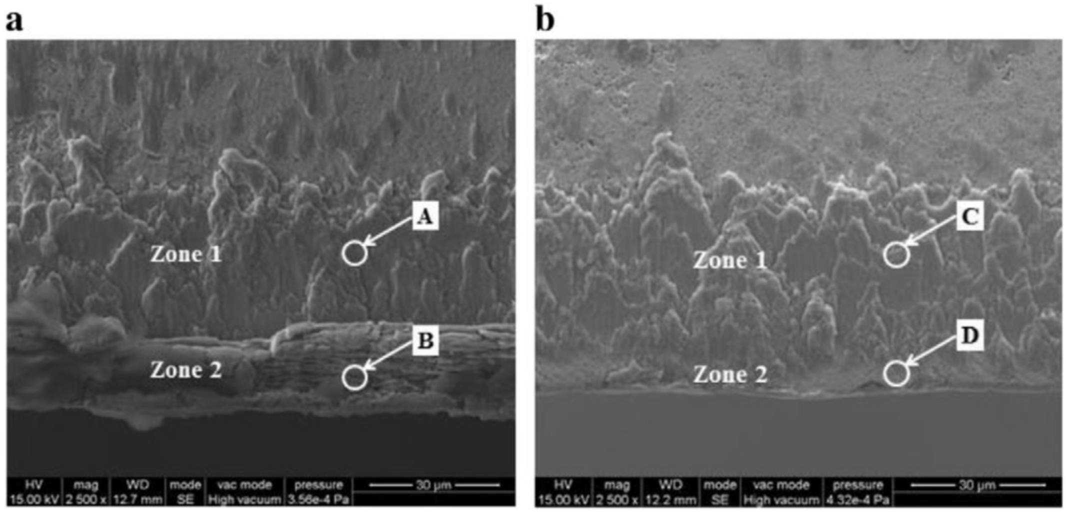

Fig. 4 – Two different carbide tools having different degrees of wear shown in SEM, a. WC-8Co, b. WC-10Ni$_3$Al [69].

et al. [74] investigated the dry cutting temperature, thrust force, microhardness and integrity of machined surfaces for dry drilling of AA7075 aluminum and titanium Ti6Al4V alloys for cutting forces of 30 m/min, feed 0.1 mm/rev, drilling depth 16 mm. It was found that the temperature during drilling of the Ti6Al4V alloy is higher than the drilling temperature of the AA7075 alloy by 450–540 °C along the main cutting edge. Festas et al. [75] investigated the arithmetic average height (Ra), the maximum height of the profile (Rt), the average peak to valley height (RzDIN), chip formation and the geometric deviation of holes in dry helical milling and drilling of Ti6Al4V and Ti6Al7Nb alloys. It was shown that Ti6Al7Nb has better machinability than Ti6Al4V, besides, it is less toxic and a good alternative to Ti6Al4V. Liang and Liu [12] examined the predetermined flank wear (VB) of tool on integrity of machined surfaces for dry orthogonal Ti6Al4V cutting. As a result of experiments, it was found that 3D surface roughness for wear 0–0.2 mm increases but decreases with wear 0.3 mm. The depth of the hardened layer increased from 20 to 60 microns with flank wear of 0 and 0.3 mm, respectively. This suggests that the best conditions for integrity of surface are flank wear up to 0.2 mm. Dargusch et al. [76] for dry turning of a titanium alloy Ti6Al4V showed that for a new tool and a worn tool, the microstructure of the segmented chip and the deformation mechanism change significantly. The end of the tool life during machining is characterized by strong friction between the rake face and chip and significant plastic deformation of the machined surface and shear chip. Liu et al. [77] investigated the morphology of chip, a model of tool wear depending on the radial depth of cut, for the dry trochoidal milling process of the Ti6Al4V alloy. The authors showed the advantages of trochoidal milling for clean production and the possibility of tool condition monitoring as chip.

Jamil et al. [78] have established relationships between stability (process time, cutting energy, energy efficiency, carbon emissions) and machining characteristics (tool wear, surface roughness, cutting temperature) when milling Ti6Al4V, comparing minimum quantity lubrication (MQL), CO2-snow, and cryogenic- LN2, and dry machining. As a result, they showed superior CO2 snow performance, followed by cryogenic LN2, MQL and dry cutting conditions for sustainability measures and machinability characteristics. The up-milling of 420 helix angle cutter CO2-snow allowed to achieve the highest productivity and reduce roughness by 47%

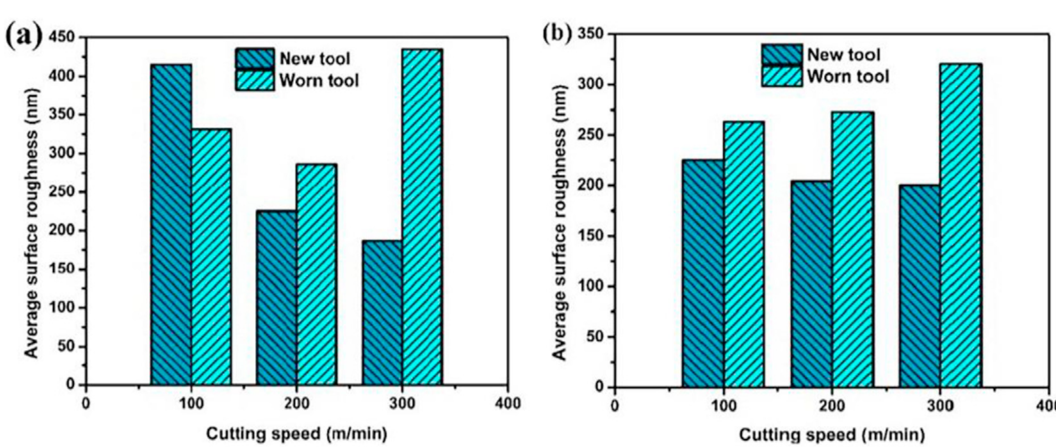

Fig. 5 – Surface roughness values with cutting speed for different feeds: (a) 0.03 mm/tooth and (b) 0.06 mm/tooth [70].

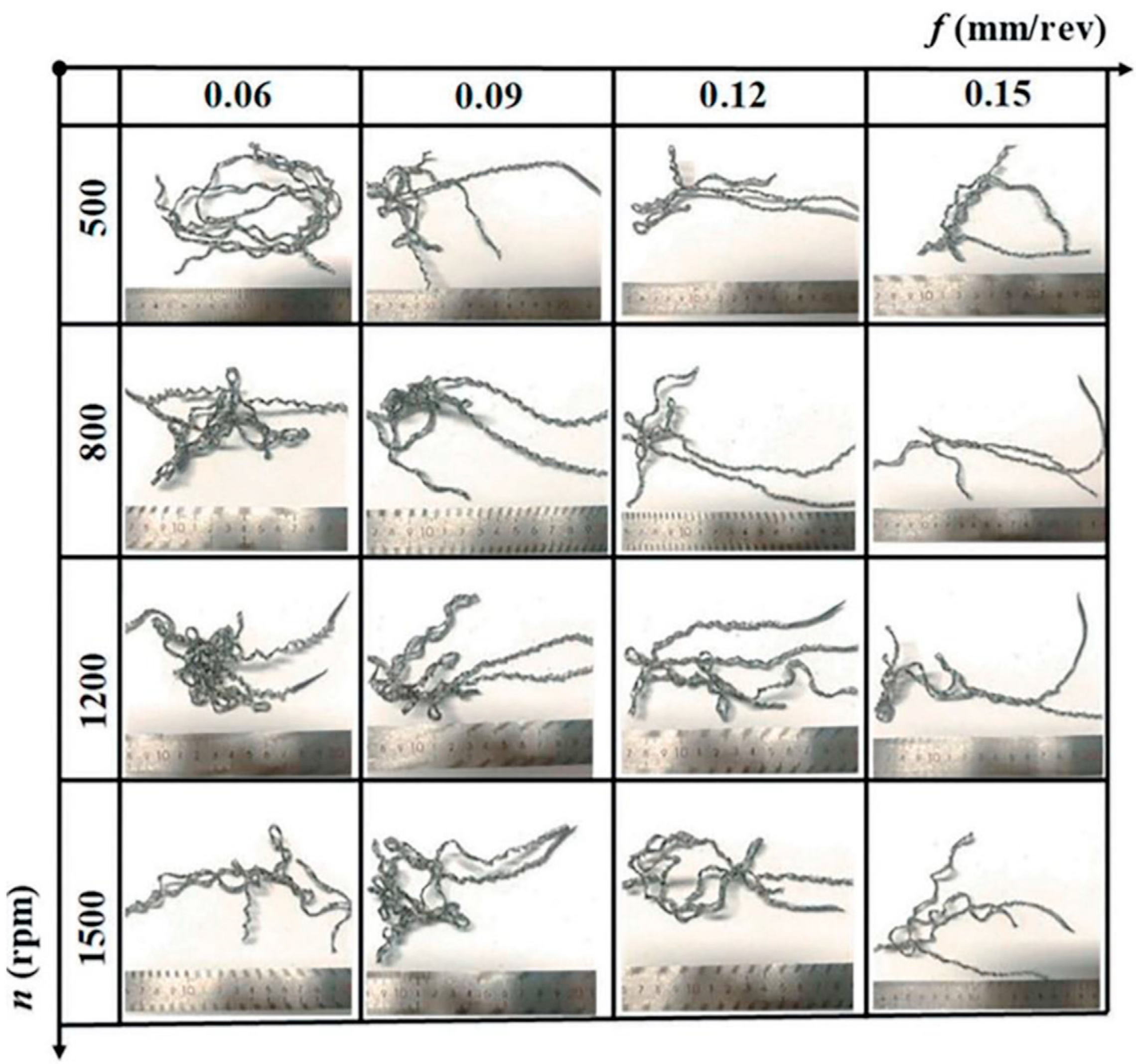

Fig. 6 – Parametric effect of chip morphology for different drilling modes of additive manufactured Ti6Al4V [80].

and increase tool life by 50% compared to dry cutting. And the minimum cutting temperature with cryo LN2.

In recent years, the problem of machining titanium alloys produced by additive manufacturing (AM) has become relevant. Such AM parts, as compared to the parts manufactured by conventional forging processes, as a rule have even more outstanding physical and mechanical properties that impede machining. Zhang et al. [79] investigated dry milling using the solid ceramic instrument of Ti6Al4V manufactured by Direct Metal Laser Sintering (DMLS) technology. The objectives of study were temperature fields of cutting, cutting forces, chip morphology, integrity of machined surface, and wear tool. Studies have shown that the feed has a greater effect on temperature and cutting forces compared to cutting speed. Ming et al. [80] investigated the dry morphology of the Ti6Al4V alloy manufactured by DMLS technology for the chip morphology and surface integrity of machined holes. Depending on the drilling mode, chip had different morphologies (see Fig. 6). Traces and scratches were observed on the machined surface due to tangled chips on the drill.

Dang et al. [81] investigated dry drilling of Ti6Al4V parts obtained in three ways (Direct Metal Laser Sintering (DMLS) AM technology with (i.e. HTDMLS), without (i.e. DMLS), heat treatment whilst the commercial wrought (HTDMLS)). The low thermal conductivity and high mechanical strength of these materials make it difficult to cut. DMLS alloy has a very high hardness due to the martensitic microstructure. DMLS also has the lowest thermal conductivity, and hence the highest cutting temperature.

Xu et al. [82] investigated for dry drilling of CFRP/Ti6Al4V stacks cutting forces, damage caused by drilling, and hole surface morphology. The paper uses the orthogonal cutting process to explain the drilling process on CFRP/Ti6Al4V stacks. This paper shows the benefits of drilling from Ti to CFRP, providing lower forces, lower burr extents and better surface morphology compared to CFRP to Ti drilling strategies. Xu et al. [83] this article explores the mechanisms on the orthogonal cutting (dry planing) characteristics of CFRP/Ti6Al4V stacks using PCD – tipped tools, such as the chip removal process and its features, cutting forces, bouncing-back phenomenon, machined surface morphology.

Table 2 – Dry machining of titanium alloys – investigated process, material, environment, and characteristics.

Reference	Year	Process	Material	Environment	Chip Morphology	Cutting Force	Cutting Temperature	Size accuracy	Surface integrity	Tool Life	Tool Wear
[12]	2017	Turning	Ti6Al4V	Dry					•		•
[57]	1999	Turning	Ti-6246	Dry						•	•
[59]	2001	Turning	Ti-6246	Dry					•	•	•
[60]	2005	Turning	Ti6Al4V	Dry					•	•	•
[58]	2000	Milling	Ti6Al4V	Dry	•					•	•
[61]	2007	Milling	Ti-6242S	Dry	•		•			•	•
[62]	2007	Milling	Ti-6242S	Dry	•		•			•	•
[63]	2007	Milling	Ti-6242S	Dry					•		•
[64]	2009	Turning	Ti6Al4V	Dry	•	•					
[65]	2011	Turning	Ti6Al4V	Dry					•	•	•
[66]	2011	Milling	Ti6Al4V	Dry	•						
[67]	2013	Milling	TC6	Dry	•	•			•	•	•
[68]	2014	Milling	Ti6Al4V	Dry						•	•
[69]	2015	Turning	Ti6Al4V	Dry	•					•	•
[70]	2015	Milling	Ti6Al4V	Dry					•	•	•
[71]	2011	Milling	TiAl	Dry	•	•			•	•	•
[72]	2015	Turning	Ti6Al4V	Dry	•		•		•	•	•
[73]	2017	Drilling	Ti6Al4V	Dry	•	•		•	•		
[74]	2017	Drilling	Ti6Al4V	Dry	•	•			•		
[75]	2020	Drilling, Milling	Ti6Al4V, Ti6Al7Nb	Dry	•				•		
[76]	2018	Turning	Ti6Al4V	Dry	•						•
[77]	2019	Milling	Ti6Al4V	Dry	•						•
[78]	2020	Milling	Ti6Al4V	Dry, MQL, CO2-snow, cryogenic			•		•	•	•
[79]	2020	Milling	Ti6Al4V	Dry	•	•			•		•
[80]	2020	Drilling	Ti6Al4V	Dry	•				•		
[81]	2020	Drilling	Ti6Al4V	Dry	•	•	•		•		•
[82]	2019	Drilling	CFRP/Ti6Al4V	Dry	•	•		•	•		
[83]	2019	Planing	CFRP/Ti6Al4V	Dry	•	•		•	•		

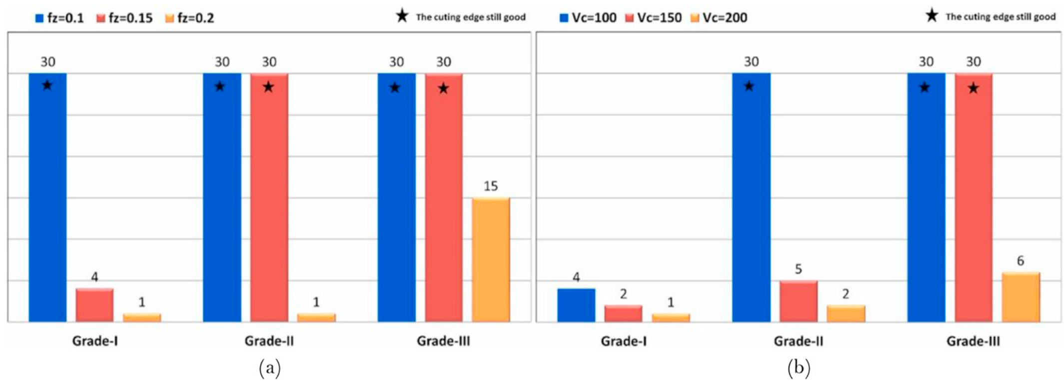

Fig. 7 – Tool life versus a) feed rate b) cutting speed in turning of Ti5Al5V5Mo3Cr under conventional cooling [84].

The literature sources considered in the section devoted to the analysis of dry machining are summarized in Table 2.

4.2. *Conventional cooling system for Ti and its alloys*

In the cutting of Ti alloys, it is desirable to obtain the final part with the desired properties without too much testing, due to the costs of titanium alloys, cutting tools and other additional accessories. Considering all these, conventional coolant application is one of the ways used by manufacturing engineers in cutting of Ti alloys from past to present. Some of the scientific studies on which titanium alloys are machined under conventional cooling are summarized as follows: Sadik et al. [84] have focused on machining of β-titanium alloy (Ti5Al5V5Mo3Cr) with PCD cutting tools under wet cooling condition. They reported that choosing the appropriate PCD quality is among the critical factors to enhance the performance of these tools with regard to wear development and tool lifespan as shown in Fig. 7.

Muthukrishnan and Davim [85] investigated the impression of coolant effect in machining of Ti6Al4V alloy. For this aim, they have employed different machining inputs i.e., cutting speed-45, 90, 135 m/min, feed rate-0.10, 0.20 and 0.32 mm/rev and depth of cut-0.5 and 0.75 mm on lathe machine in turning Ti6Al4V alloy using ceramic tools under emulsion with water and non-coolant. Consequently, the researchers stated that (i) cutting using traditional cooling offers more reasonable surface quality as compared to non-coolant machining; (ii) poor tool wear occurred under the coolant with the most appropriate operating parameters (in addition, approximately 30% improvement has been achieved with conventional cooling in comparison with dry cutting); (iii) adhesion wear was observed under both cutting conditions, diffusion wear was less under wet cooling. Another study conducted by Palanisamy et al. [86], they showed the relation among vibration and surface condition which occurred when cutting commercially available pure-Ti and Ti6Al4V alloys under both conventional cooling and dry cutting environments. Their outcomes revealed that the machined work material surfaces generated by traditional cooling are mostly better than corresponding surfaces generated by dry machining environment at similar machining parameters when cutting both titanium alloys.

Taylor et al. [87] explored the effect of cutting environments such as wet cooling at 60 bar pressure, wet cooling at any pressure and dry (without any coolant) during turning of Ti6Al4V and Ti10V2Fe3Al alloys. It was reported by researches that while conventional cooling methods cannot provide sufficient positive effects, disabling the coolant presents significant advantages in terms of operational, environmental and health benefits. On the other hand, when machining titanium without any coolant, the risk of fire should also be eliminated. Dawood et al. [88] purposed to compare the test conditions when machining Ti6Al4V under traditional wet cooling and dry cutting environments. In experiments, cutting speed, feed rate and depth of cut have been considered to evaluate performance outputs viz., tool wear patterns and chip morphology under each machining environment. They found out that the cutting time and surface finish is less in dry machining than conventional machining. For tool wear, no significant difference was observed under dry and wet cutting, while cutting tools were subjected to more chip adhesion during dry environment. Moreover, while flank wear and chipping are more prominent under conventional cooling, crater wear and BUE are more clearly observed under dry mode. In another work for machining of light metal titanium alloy with water-based emulsion cooling conducted by Narutaki et al. [89], it was emphasized, cooling fluids have critical tasks on machining operations and the cutting speeds of 3.33 m/s are possible, thanks to their applications. An interesting conclusion highlighted by Revuru et al. [31] carried out in a review paper on machinability studies of Ti alloys under cutting fluids that although fluids have good cooling properties, they cannot perform effective cooling and lubrication since most coolants are not directed to the cutting zone.

Mathew and Vijayaraghavan [90] conducted a study on drilling of intermetallic titanium alloy under conventional and dry cutting environments. The efficiency of both cutting environments was evaluated by considering various outcomes viz., thrust force, torque, burr formation, work-material surface quality, drill aspects and chip morphology. The researcher emphasized that the inclusion of conventional cooling method is beneficial in terms of force and torque and product surface finish. Moreover, lower burr and BUE formations in wet environments were observed than dry drilling as illustrated in Fig. 8. In general, their study showed that drilling

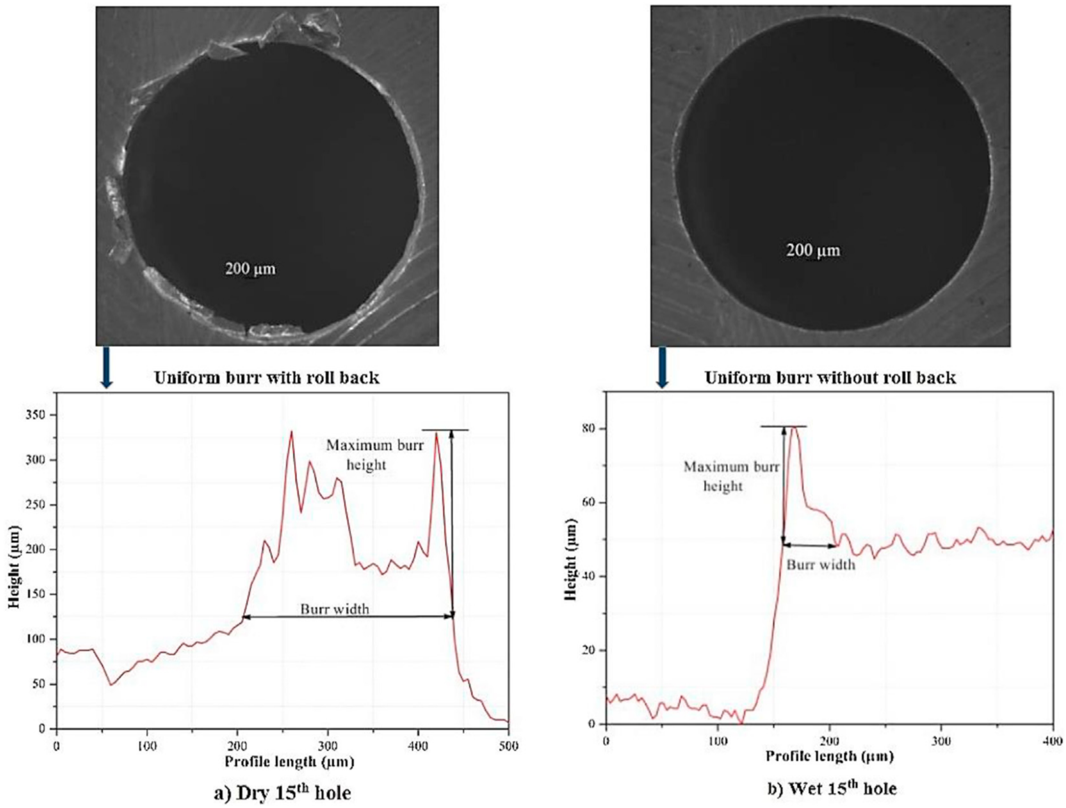

Fig. 8 – Burr formation and its profile under a) dry drilling b) wet drilling at 15th hole [90].

holes with high aspect ratios is not suitable for dry environment in drilling of intermetallic titanium alloy.

Beranoagirre et al. [91] investigated the drilling process with carbide drill using an internal coolant (8.5 bar) of gamma TiAl alloys (titanium aluminides), extruded MoCuSi, ingot MoCuSi, and TNB type in relation to cutting conditions and wear and tool life. Beranoagirre et al. [92] conducted a study of cutting forces and torque when drilling with a carbide tool using internal coolant pressure is set to 8.5 bar for Ti6Al4V and three different γ-TiAl alloys (TNB, extruded MoCuSi and ingot MoCuSi). The authors note the high brittleness of titanium aluminides; for all three intermetallic γ-TiAl alloys, the cutting forces and torque were significantly different and higher compared to Ti6Al4V in accordance with the mechanical properties of the materials, the highest hardness was in MoCuSi alloys.

The literature sources considered in the section devoted to the analysis of conventional machining are summarized in Table 3.

4.3. *Minimum Quantity Lubrication (MQL) group for Ti and its alloys*

The MQL system has showed significant results when machining of Ti and its alloys, and it is considered that further benefits can be achieved in the future. An et al. [105] practiced the turning experiments on TC9 alloy under flood and mist environments. The surface quality, heat transfer, chip morphology was discussed and compared under both cooling conditions. The outcome reveals that the cold-water mist jet (CWMJ) shows the highest heat transfer as compared to the cold air and flood cooling system (refer Fig. 9a). The acceptable surface roughness (Fig. 9b) and chips were produced under CWJM conditions [105]. In another work on Ti6Al4V alloy, the tool wear phenomena under dry and MQL environments was analyzed by Liu et al. [9]. The authors claim that the MQL conditions help to protect the tool coating while machining Ti6Al4V alloy. On the contrary, the dry mode disturbs the coating of tool with the chipping and fracture action during turning operation (refer Fig. 10). Moreover, the adhesive wear is noted under both cooling conditions [9]. Liu et al. [106] conducted the machinability research on Ti6Al4V under MQL environment to observe the cutting forces and surface roughness values. The outcomes reveal that the MQL condition greatly influenced the responses and improved the machining performance as compared to other traditional cooling conditions [106]. On same context, Raza et al. [107] observed the progression of tool wear in Ti6Al4V machining. The cooling conditions used were dry, wet, MQL, cooled air lubrication, cryogenic cooling (with LN_2), vegetable oil plus cooled air/MQCL environments, respectively. The outcome reveals that the application of vegetable oil with MQL is suitable at low cutting parameters value and the cryogenic cooling is best suited for elevated cutting speeds and feed rates [107]. Sun et al. [108] used the cryogenic cooling, MQL and flood conditions in turning of Ti-5553 alloy. The tool wear, cutting forces and surface roughness were explored under these cooling conditions. The responses indicated that the cryogenic assisted cutting provides to lower cutting forces and tool wear values, whereas the MQL cooling is helpful to achieve

Table 3 – Conventional cooling assisted machining of titanium alloys – investigated process, material, environment, and characteristics.

Reference	Year	Process	Material	Environment*	Chip Morphology	Cutting Force	Cutting Temperature	Size accuracy	Surface integrity	Tool Life	Tool Wear
[84]	2019	Turning	β-titanium alloy (Ti-5553)	CCS						•	•
[85]	2011	Turning	Ti6Al4V	Dry, CCS					•		•
[86]	2011	Milling	Ti Grade 2 and 5	Dry, CCS					•		
[87]	2018	Turning	Ti6Al4V, Ti-10V-2Fe-3Al	Dry, CCS	•				•	•	•
[88]	2015	Milling	Ti6Al4V	Dry, CCS	•				•		•
[89]	1983	Turning	Ti6Al4V	Dry, CCS		•	•		•	•	•
[90]	2016	Drilling	TiAl	Dry, CCS	•	•			•	•	
[91]	2019	Drilling	TiAl	Dry						•	•
[92]	2018	Drilling	Ti6Al4V, TiAl	Dry		•					
[93]	2007	Grinding	TC6	CCS		•		•	•		•
[94]	2011	Grinding	Ti6Al4V (TC4)	Dry, CCS		•			•		
[95]	2012	Grinding	Ti6Al4V	Dry, CCS		•			•		
[96]	1999	Drilling	Ti6Al4V	Dry, CCS					•		
[97]	2017	Drilling	Ti6Al4V	Dry, CCS					•		
[98]	2017	Drilling	Ti6Al4V	Dry, CCS		•			•		•
[99]	2017	Drilling	Ti6Al4V	Dry, CCS					•		
[100]	2013	Milling	Ti6Al4V	CCS							•
[101]	2020	Turning	Ti6Al4V	Dry, CCS					•		
[102]	2010	Turning	Ti6Al4V	Dry, CCS	•						•
[103]	2020	Turning	Ti6Al4V	CCS					•		•
[104]	2015	Milling	Ti-1023	CCS					•		

*CCS – Conventional cooling system.

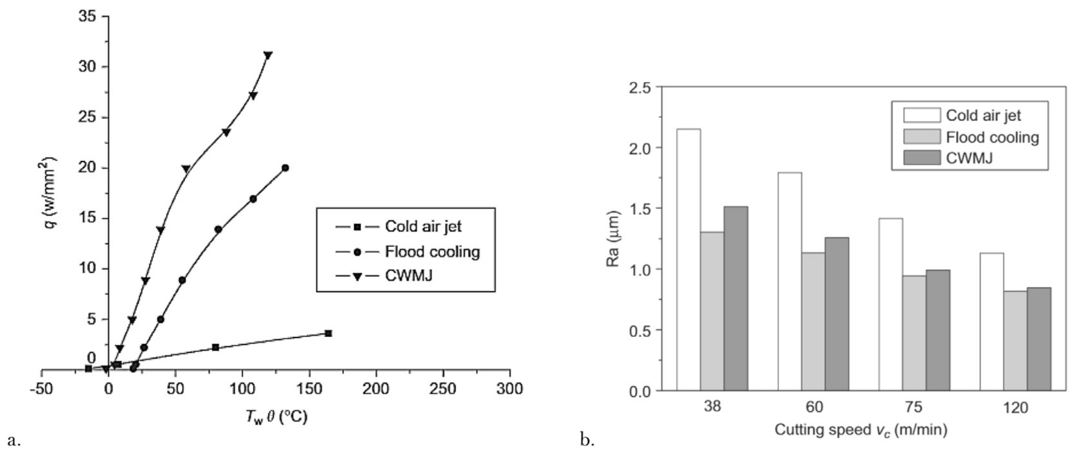

Fig. 9 – a. Heat transfer curves, b. Resulted surface roughness of the different cooling methods. Adopted from [105] with permission.

good surface finishing during turning of titanium alloys [108]. Singh and Sharma [109] used the commercially pure titanium alloy for machining experiments. The new feature i.e., Ranque-Hilsch vortex tube (RHVT) was introduced in MQL condition. With this method, the cutting forces, power, surface roughness and flank wear were analyzed. RHVT exhibited remarkable developments in the outcomes. In addition, it was also recommended as an efficient alternative way for machining environment [109].

Among the researches with nanoparticles and MQL, Gupta et al. [110], executed the turning trials on pure Ti alloys. Several type of nano-fluids i.e., alumina, graphite, and molybdenum disulfide were introduced in the MQL condition. The outcomes clearly reveal that the graphite based nano fluids are producing smoother surface as compared to other nano fluids (refer Fig. 11) [110]. Jamil et al. [111] presented an interesting study wherein hybrid nanoparticles were used with MQL. Here, hybridization was made by combined use of Al_2O_3 and multi-walled carbon nanotube. In fact, the comparison of the performance with cryogenic cooling, showed a reduction of roughness and force as 8.72% and 11.8% respectively, and increase of tool life by 23%.

As nanofluid caused improved machining performance, it was necessary to investigate the wear condition of textured tools under the graphene doped nanofluid mist spray cooling during the cutting of Ti6Al4V, and Singh et al. [112] conducted that study. The excellent thermal conductivity of graphene has caused the promotion of the tool performance. The flank and crater wear were found with adhesion and abrasion wear mechanisms. 1% graphene showed the best results. In another study, the graphene enriched nanoparticles were used in the lubrication medium of MQL to explore its usability on the machining of the Ti-6Al-4V [112]. The excellent combination of nanofluid with vegetable oil was supported better tool life by more than 170%. To establish a sustainable machining (milling) for Ti6Al4V alloy, the use of hybrid nanofluids was reported by Jamil et al. [113] wherein the energy consumption, product quality and productivity have been considered to be benefited from nanofluid MQL. For grinding application of Ti6Al4V, the combined outcome of optimization and use of nanofluid caused an interesting benefit for the machining, as reported by Liu et al. [114]. The depth of cut was found to be highly influential to grinding performance, and the combined use of optimization and MQL with nanofluid showed superior results. They have explained the nanofluid actions in MQL grinding as shown in Fig. 12.

For advanced use of MQL, hybrid system was investigated, one such hybrid system is the use of RHVT tube and MQL's combined use. Though it has found its usability in machining of other materials (Al alloy, steel), Gupta et al. [115] have investigated its efficacy for the Ti6Al4V alloy. It was reported that the hybrid cooling system provided lowest specific

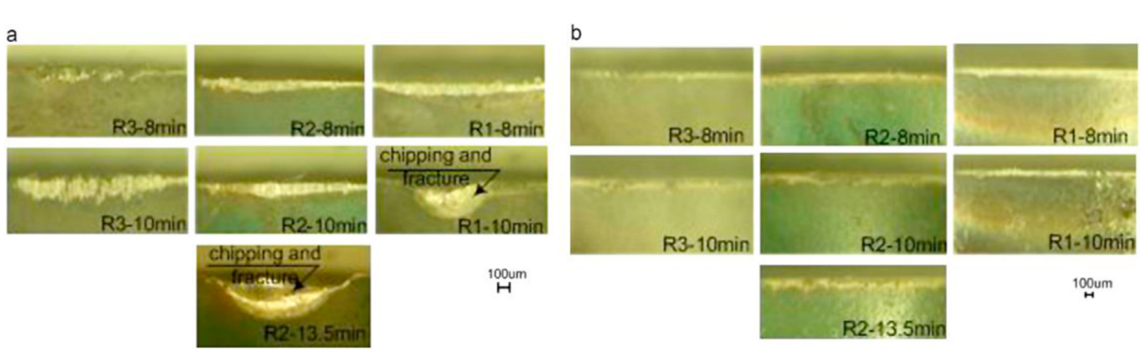

Fig. 10 – Wear morphology of uncoated insert (R1) and two coated inserts (R2 and R3): (a) flank face wear under dry condition (optical images) and (b) flank face wear under MQL conditions. Adopted from [9] with permission.

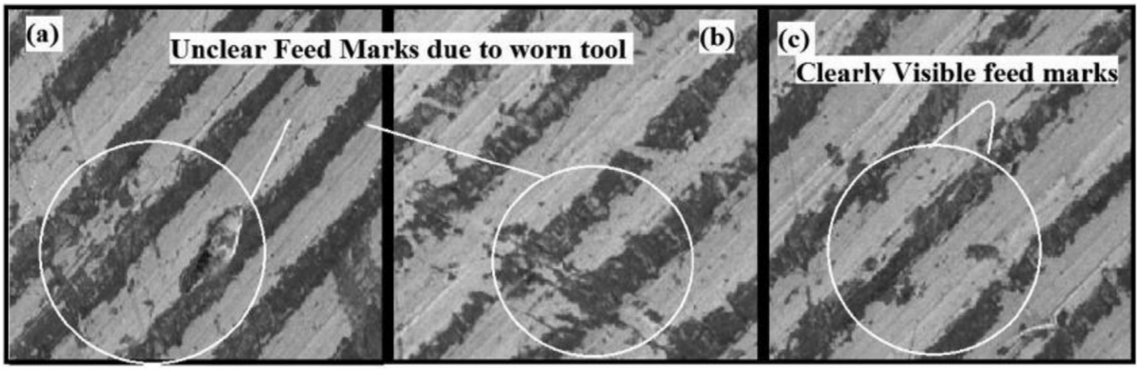

Fig. 11 – Workpiece condition after machining process at cutting speed: 250 m/min, feed rate: 0.2 mm/rev and approach angle 75 (a) Al_2O_3 added nano-fluid (b) MoS_2 added nano-fluid (c) Graphite added nano-fluid. Adopted from [110] with permission.

cutting energy and hardness but highest surface quality. For hybridization with cryogenic cooling system, Sokrani et al. [116] reported, recently, a study on the MQL + cryogenic cooling for milling of Ti6Al4V, and compared it with pure MQL, pure cryogenic cooling, and flood cooling – the improvement of 50% productivity and 30 times tool life. Singh et al. [117] investigated the surface quality, force and tool wear values when turning of pure titanium alloys using evolutionary algorithms and showed that RHVT improved the results by almost 15% for all parameters studied. Gupta et al. [118] investigated the process of turning of pure titanium alloys using Ranque-Hilsch Vortex Tube assisted Minimum Quantity Cutting Fluids (RHVT-MQCF). And showed high performance of RHVT-MQCF conditions in terms of processing characteristics compared to MQL under the same conditions. The study of Madarkar et al. [119] showed hybridization with ultrasonic MQL wherein the MQL was dependent on the oscillation of ultrasonic vibration. The application area was grinding of Ti6Al4V alloy with sunflower oil, and improvement was noteworthy – a good surface quality and reduced grinding force.

Mathew and Vijayaraghavan [120] in their work, they studied the low and high aspect ratio drilling with a carbide drill of intermetallic titanium aluminide alloy (Ti-48% Al-48% Cr-2% Nb-2%) with dry, wet environments and minimum quantity lubrication environment. Thus, Fig. 13 shows the thrust force and torque during LAR from which it can be seen that MQL gives the lowest values in comparison with Wet and dry drilling. Thus, MQL has shown its effectiveness.

Although MQL has been successfully used for titanium alloys, the experience of using MQL in machining of the composite titanium stacks is interesting. So Xu et al. [121] investigated axial drilling forces, composite phase delamination and tool wear during drilling with tools using TiAlN-coated and diamond coatings for MQL and dry conditions on CFRP/Ti6Al4V stacks. The CFRP laminate was an epoxy (FRD-YZR-03) thermosetting plastic reinforced with T700 carbon fibers, subjected to a stacking sequence of [(0°/-45°/45°/90°) 4] sec (Fig. 14). The authors stated that MQL does not contribute to the reduction of axial drilling forces and the reduction of delamination damage on the composite phase, They also identified a slight difference in tool life and tool life between MQL and dry drilling on CFRP/Ti6Al4V stacks, and showed advantages in wear resistance and breakage of drills with PVD TiAlN coatings compared to diamond coated drills for dry drilling on CFRP/Ti6Al4V stacks. Xu et al. [122] conducted a comparative study of the machinability of CFRP/Ti6Al4V stacks for MQL and dry drilling using uncoated tungsten carbide twist drills in order to quantify the potential of MQL. By examining the drilling forces, the surface morphology of the cut composite holes, the dimensions of the hole defects, the geometric accuracy of the holes, and the tool wear signatures. As a result, they showed that MQL is not required when drilling CFRP/titanium stacks if the delamination damage is the key concern. However, if the surface morphology of the cut hole composite and the wear rate of the drill are most important, MQL is useful. Xu et al. [123] for the drilling process using the TiAlN-coated and diamond-coated drills, he CFRP/Ti6Al4V stacks showed minimization of specific cutting energy consumption and improved machining qualities and CFRP surface morphology for MQL conditions.

The literature sources considered in the section devoted to the analysis of MQL machining are summarized in Table 4.

4.4. *Cryogenic Lubrication of Ti and its alloys*

Cryogenic cooling method consists of applying cryogenic gases, usually liquid nitrogen (LN_2) and carbon dioxide (CO_2), on the cutting zone to reduce the temperature. As other lubrication methods discussed in this work, cryogenic lubrication is clean and environmental friendly [137] but different from the other methods. It deeply reduces the temperature in cutting zone which locally modifies the mechanical properties of the workpiece surface and subsurface [138]. The cryogenic temperature generated in the cutting interface avoid the heat induced problems which are major problems in the machining process of materials such as Ti alloys [139,140].

The cryogenic machining can be performed using different techniques such as cryogenic bath (Fig. 15), in which the workpiece submerged in liquified gas before or during the machining process, application of emulsified cryogenic fluid on the cutting zone (Fig. 16), which is the mostly used method, and the injection of pressurized liquified gas which abruptly

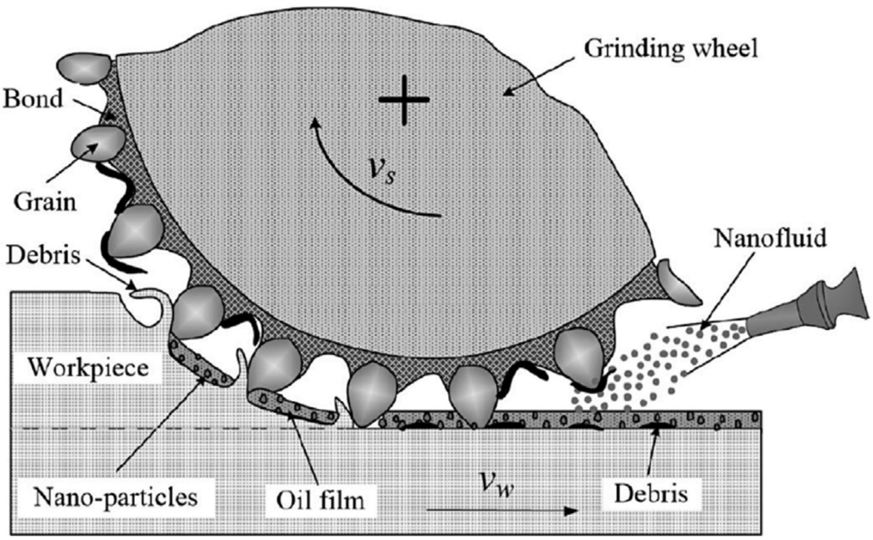

Fig. 12 – Nanofluid in grinding Ti-6Al-4V. Reprinted with permission [114].

expands in the exit of application nozzles resulting in a combination of gas and solid particles (CO_2 snow) (Fig. 17).

The surface integrity improvement by the use of cryogenic lubrication in the machining process of titanium alloys have been recently reported by many authors who investigated the use of cryogenic cooling in different machining processes (turning, milling, grinding and drilling) and its effects on parameters such as surface and sub-surface hardening, microstructural and phase transformations, surface roughness and residual stresses, etc. [144].

One of the challenges of implementation of cryogenic cooling in shop floor is the integration or retrofit of regular

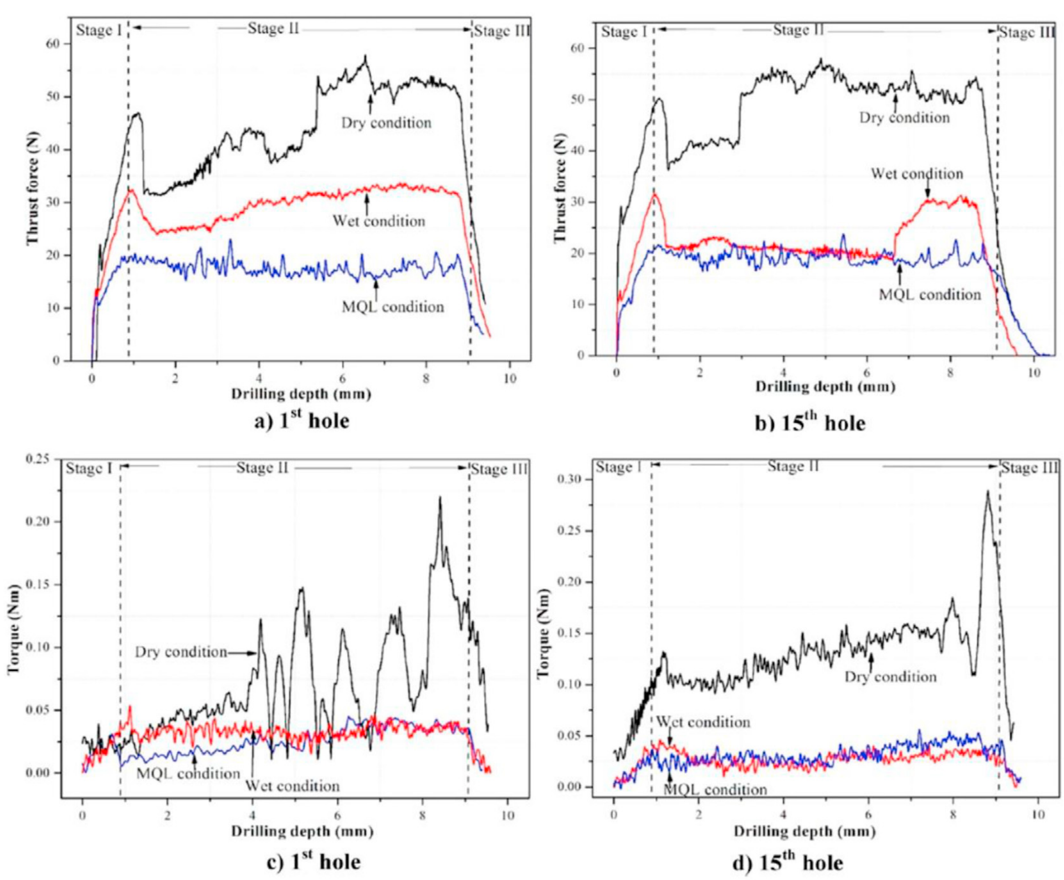

Fig. 13 – Thrust force and torque during LAR drilling. a) for the 1st hole, b) for the 15th hole, c) for the 1st hole, d) for the 15th hole.

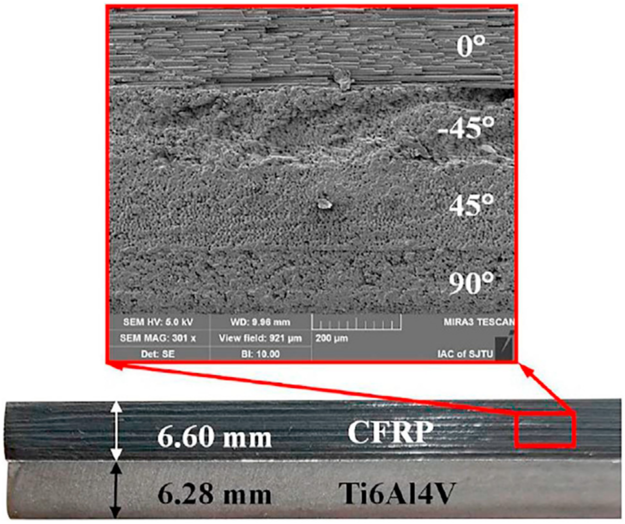

Fig. 14 – Morphologies of the used CFRP/Ti6Al4V specimen [121].

machine tool which must be adapted to avoid the freezing of machining system due to the ultra-low temperature. In this scenario, Aramcharoen [145] developed a customized modular cryogenic system that could be installed in regular CNC lathe. Using this modular system, they evaluated the influence of liquid nitrogen cooling on chip formation and tool wear of Ti6Al4V under high speed turning. The developed system was successfully integrated in the machine tool and the authors reported the improvement of machinability of titanium alloy associated with the reduction of friction in chip-tool interface and tool wear. For α-β titanium, the cryogenic cooling assisted machinability evaluation was conducted by Jamil et al. [146] who have claimed that cryogenic cooling is better performance oriented and economically beneficial. The thermal aspect, especially the heat transfer capability of cryogenic cooling was reported by Jamil et al. [135] for the machining of Ti-6Al-4V alloy wherein it was compared with that of sub-zero MQL. A significantly higher heat transfer capability was demonstrated by the cryogenic cooling system (Cryogenic: 1347 W/m^2C, sub-zero MQL: 486 W/m^2C) which was considered to be the key factor for cooling the cutting zone and ensuring a favorable machining.

In the study of Sun et al. [108], the authors investigated the use of liquid nitrogen cooling on the turning process of Ti-5553 alloy regarding machining forces, tool wear and surface roughness. The obtained results were compared with flood and MQL methods, and improvements in cutting forces and tool wear were reported when cryogenic coolant was used. However, the best surface finishing was obtained using MQL. The use of cryogenic lubrication methods in the turning process of β-titanium-alloy Ti–10V–2Fe–3Al was investigated by Machai and Biermann [147]. Authors concluded that carbon dioxide snow can reduce tool wear and improve surface integrity in comparison with flood technique. Along with machinability aspect, the sustainability and life cycle assessment for the cryogenic cooling assisted turning of Ti-6Al-4V was performed by Mia et al. [148]. Instead of single jet of cryogenic cooling, the use of dual jets for rake and flank surfaces showed superior performance, leading to industrial economic benefits. In another study, Mia et al. [149], optimized the machining characteristics under the implementation of cryogenic cooling jets. They have developed the mathematical models of responses (cutting force and surface roughness) and performed the statistical analysis by which they claimed that cutting speed should be limited to 110 m/min. It was a question of how many jets of cryogenic cooling should be used in machining of Ti alloy, and to find out that key answer, Mia and Dhar [150], performed a comparative study on the single and dual jet cryogenic cooling, and they concluded that dual jets were more effective in reducing forces, surface roughness, and specific energy, however, the chips showed no big difference.

In the work of Park et al. [151], the authors have investigated the application of cryogenic coolant on the milling process of Ti-6Al-4V alloy and compared the obtained results with other lubrication methods (flood, minimum quantity lubrication (MQL) with and without nano platelets) and dry machining. They reported that cryogenic cooling reduced tool wear in early stage but, on the other hand, led to increments in cutting force and tool wear for longer cutting time. According to the results, the most promising lubrication method is the combination of cryogenic cooling and MQL. The influence of cryogenic coolant in the milling process of Ti-6Al-4V alloy was also evaluated by Sadik et al. [152] who reported that CO_2 cryogenic application was able to reduce the lateral propagation of thermal crack delaying the chipping of tool cutting edge. Pereira et al. [153] in their work presented the technology of manufacturing prostheses thanks to cryogenic CO2 milling of Ti6Al4V. Cryogenic milling of Ti-6Al-4V alloy using LN2 was investigated by Zhao et al. [154]. In this work, the influence of lubrication method in residual stresses, microstructure, hardness, surface finishing and cutting forces were evaluated. Although the application of cryogenic coolant generated an increment in cutting forces, it promoted dramatical reduction in surface roughness. In addition, more compressive residual stresses were observed when cryogenic method was used.

Elanchezhian et al. [155] studied the effect the nozzle angle and the depth of cut on the grinding process of the Ti-6Al-4V alloy using cryogenic and conventional coolants. Grinding performance was substantially increased by the application of cryogenic coolant resulting reduction of machining forces, surface roughness, and grinding zone temperature. Nozzle angle of 45° was reported as the optimal angle. The uses of cryogenic CO_2 and conventional flood lubrication method in the grinding process of Ti-6Al-4V alloy were compared by Elanchezhian and Kumar [156]. The authors evaluated the machining forces, surface roughness and the grinding temperature during the process and observed great reduction in grinding force when CO_2 was used. The application of cryogenic coolant also contributed to the reduction of grinding temperature and surface finish generating a smother and free of defects surface.

Drilling process of Ti-6Al-4V under cryogenic lubrication condition was studied by Ahmed and Kumar [157] who used LN_2 as coolant. Author used an L18 orthogonal array and TOPSIS method. Better tool life and chip breakability were observed when LN_2 was used instead of flood method.

Table 4 – MQL groups in machining of titanium alloys – investigated process, material, environment, and characteristics.

Reference	Year	Process	Material	Environment	Chip Morphology	Cutting Force	Cutting Temp-erature	Power Consu-mption	Size accuracy	Surface integrity	Tool Life	Tool Wear
[9]	2013	Turning	Ti6Al4V	Dry and MQL							•	•
[106]	2013	Turning	Ti6Al4V	MQL	•	•				•		
[107]	2014	Turning	Ti6Al4V	Dry, flood, vegetable oil with MQL, Cooled Air Lubrication, Cryogenic Machining, Vegetable Oil + Cooled Air/MQCL conditions						•		•
[108]	2015	Turning	Ti-5553	MQL, Cryogenic and flood		•				•		•
[116]	2019	Milling	Ti6Al4V	Flood, MQL, cryogenic cooling, hybrid MQL						•	•	•
[117]	2019	Turning	Pure titanium	MQL		•		•		•	•	
[118]	2019	Turning	Pure titanium	MQL	•	•		•		•	•	
[120]	2017	Drilling	TiAl	Dry, Wet, MQL	•	•						
[121]	2020	Drilling	CFRP/Ti6Al4V	Dry, MQL	•	•					•	•
[122]	2019	Drilling	CFRP/Ti6Al4V	Dry, MQL		•			•		•	•
[123]	2020	Drilling	CFRP/Ti6Al4V	Dry, MQL		•			•	•	•	•
[124]	2009	Turning	Ti6Al4V	Dry, wet and MQL		•	•					
[125]	2014	Turning	Ti6Al4V	dry, MQL, cryogenic						•		•
[126]	2014	Turning	Ti6Al4V	Dry, cryogenic, MQL						•		
[127]	2015	Turning	Ti6Al4V	Dry, flood and MQL		•				•		•
[109]	2016	Turning	Pure titanium	MQL and RHVT + MQL		•		•		•		•
[128]	2015	Turning	Pure titanium	Dry and MQL	•	•						•
[129]	2015	Turning	Pure titanium	MQL	•	•				•		•
[130]	2016	Turning	Pure titanium	Dry, flood and MQL		•				•		•
[131]	2012	Grinding	Ti6Al4V	MQL		•				•		
[132]	2020	Milling	Ti6Al4V	Dry and CO2 with MQL conditions						•	•	•
[133]	2020	Turning	Ti6Al4V	MQL and nano-MQL environments	•	•						•
[134]	2020	Turning	Ti6Al4V	MQL		•				•		•
[135]	2020	Milling	Ti6Al4V	CO2-snow and subzero MQL	•	•	•			•		•
[118]	2020	Turning	Pure titanium	MQL and RHVT + MQL	•	•		•		•		•
[136]	2020	Turning	Ti6Al4V	MQL	•					•		•

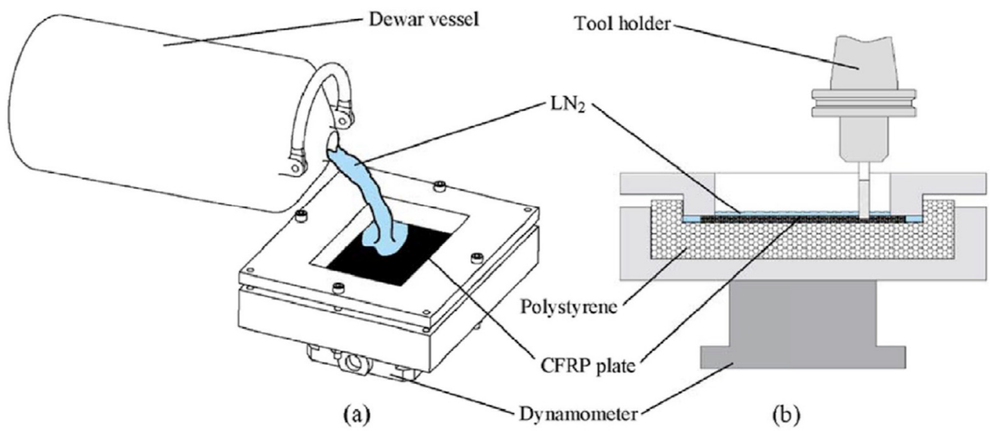

Fig. 15 – Cryogenic bath milling [141].

Considering the adopted multi objective optimization, cryogenic cooling was considered a better alternative than traditional lubrication method. Ahmed and Kumar [158] studied the application of cryogenic LN_2 coolant in the drilling process of Ti-6Al-4V alloy. The application of cryogenic coolant drastically reduced the temperature when compared to flood technique. Cutting force and torque were reduced and surface roughness was improved when LN_2 was used.

The literature sources considered in the section devoted to the analysis of Cryogenic cooling assisted machining are summarized in Table 5.

4.5. *High-Pressure Cooling for Ti and its alloys*

Because of the difficulties encountered when machining titanium alloys [13], any alternative method that can move a step ahead is worthy trying. The first work found that studied the application of the high-pressure coolant system in the machining of titanium alloy was the PhD thesis developed by Machado [159]. In his work a complete experimental investigation of the machinability of Inconel 901 and Ti6Al4V superalloys was carried out in turning, under different cutting conditions, with uncoated cemented carbide inserts, using a high-pressure coolant system with the jet (14.5 MPa) directed between the rake face of the tool and the chip being formed. An emulsion of water base cutting fluid was used as coolant and conventional overhead flood cooling was also tested for comparisons. Chip-tool contact length, chip morphology, tool life, tool wear mechanisms, cutting forces, cutting temperature as well as workpiece surface integrity were considered. Summary of the main results were published elsewhere [160,161].

The main results showed that the high-pressure coolant supply system significantly reduced the chip-tool contact length and cutting temperature as compared to flood cooling but did not affect the surface roughness and cutting forces. When machining the titanium alloy, the high-pressure coolant system considerably increased the tool life. On the other hand, when machining the Inconel 901, the high-pressure coolant jet accelerated the prevailing notch type of wear and reduced the tool life significantly. The authors concluded that in this case the higher amount of water base cutting fluid increased the formation of oxides on the tool notch wear areas, accelerating the pulling out process that

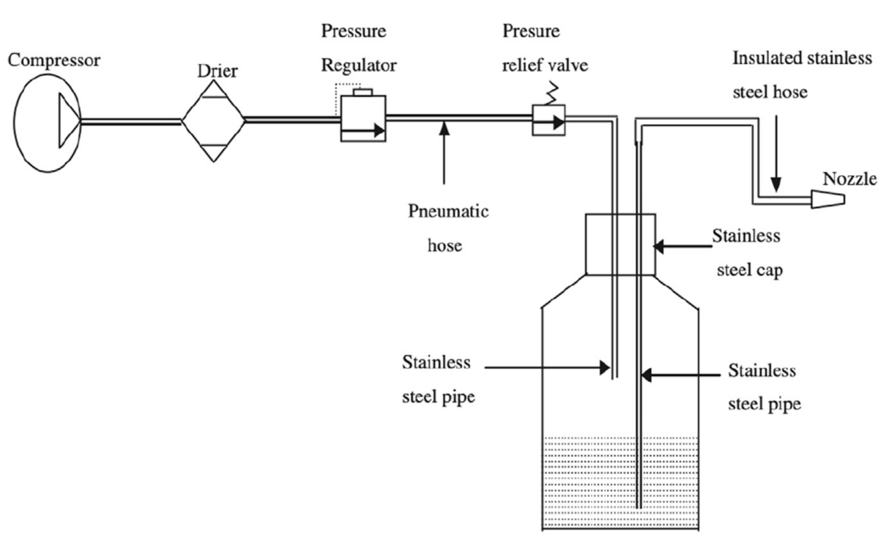

Fig. 16 – Application of cryogenic fluid on cutting zone [142].

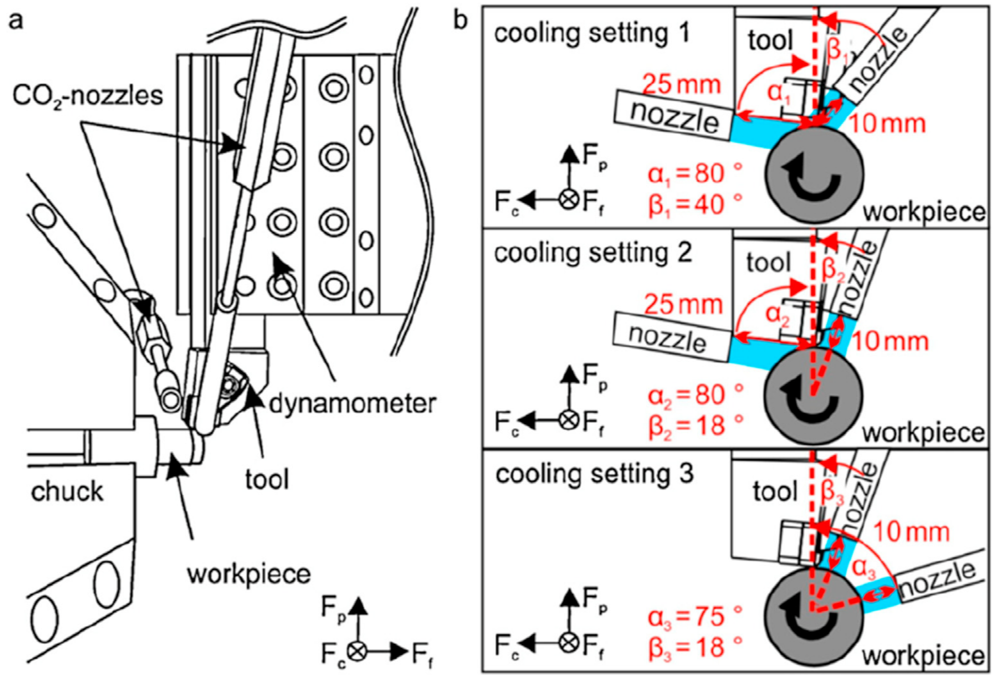

Fig. 17 – Application of CO_2 snow [143].

caused adhesive (attrition) wear. When machining the titanium, notch wear did not occur, but flank wear was the most important type of wear and the high-pressure coolant jet reduced the cutting temperature and the prevailing diffusion wear mechanisms, increasing the tool life considerably [159–161].

López de Lacalle et al. [162] in their research showed the possibility of doubling the cutting speed and increasing tool life when drilling and turning of alpha – beta type titanium alloy Ti6A14V and nickel-based superalloy of type 718 using High Pressure Coolant.

Another important contribution on the application of high-pressure coolant supply in the machining of Ti6Al4V was the PhD thesis developed by Da Silva (2006) [163], when twelve different tool materials (two uncoated and two coated cemented carbides, two polycrystalline diamond - PCD, three cubic boron nitride - CBN, SiC whiskers reinforced ceramic, Al_2O_3 mixed ceramic and Si_3N_4 base nano-grain size ceramic) where tested. The high-pressure pumping unit was a ChipBlaster, model CV26-3000, with 22 kW of power. The coolant jet (water-based emulsion HOCUT 3380 at 6% concentration) was applied between the rake face of the tool and the chip being formed, under different coolant pressures (7 MPa, 11 MPa and 20.3 MPa). Figure 18 shows details of the special tool holder used and the jet of cutting fluid directed to the rake face of the tool ready to perform a test.

Conventional overhead flood cooling was also tested for comparisons. Tool life and failure modes, wear mechanisms, machining force components, workpiece surface integrity and chip morphology were the output variables considered. The results showed that PCD and carbide inserts, particularly the uncoated grades, gave the best overall performance, in terms of tool life, which increased with increasing coolant pressure. With the PCD inserts, an amazing 8-fold increase in the tool life was achieved as compared to the conventional flood cooling with the uncoated cemented carbide insert. CBN and ceramic tools did not present satisfactory performance in terms of tool life and are not recommended for this application.

Three CBN grades (50% CBN + 50% TiC ceramic binder; 90% CBN + 10% Al ceramic binder and the same coated with TiAlN + TiN) were tested using a constant cutting speed of 150 m/min. Although the high-pressure coolant increased the tool lives when compared to conventional overhead coolant supply, the performance of the CBN tools was a disaster when compared to uncoated cemented carbide tools, particularly the 90/10CBN, when the tool lives were less than a minute, regardless the coolant pressure used. The 50/50 CBN performed better than the 90/10CBN but the tool life was lower than the cemented carbide insert. Accelerated crater and flank wear as well as chippings of the cutting edges occurred in the CBN tools [164], therefore CBN tools are not recommended to machining titanium alloys, even under high-pressure coolant supply.

On the other hand, when the Ti6Al4V was machined with PCD tools and cutting speed up to 250 m/min, the high-pressure was able to increase the tool lives considerably and the performance of the PCD tools were far better than the cemented carbide tool. Cutting speed could be increased 5-folds when machining with the PCD tools and over 20-folds increase in tool lives were observed under the coolant pressure of 20.3 MPa and cutting speeds of 175 m/min and 230 m/min relative to the conventional overhead coolant supply under the same cutting speeds [165].

Surface integrity is an important issue when titanium superalloys are used. The effect of the high-pressure coolant jet

Table 5 – Cryogenic cooling assisted machining of titanium alloys – investigated process, material, environment, and characteristics.

Reference	Year	Process	Material	Environment	Chip Morphology	Cutting Force	Cutting Temperature	Size accuracy	Surface integrity	Tool Life	Tool Wear
[51]	2017	Turning	Ti6Al4V	Cryogenic lubrication	•				•	•	•
[52]	2011	Turning	Ti6Al4V	Cryogenic lubrication	•	•					•
[108]	2015	Turning	Ti5553	Cryogenic lubrication		•			•		•
[139]	2001	Turning	Ti6Al4V	Cryogenic lubrication						•	•
[140]	2020	Turning	Ti6Al4V	Cryogenic lubrication		•			•		
[142]	2011	Turning	Ti6Al4V	Cryogenic lubrication		•	•		•		•
[145]	2016	Turning	Ti6Al4V	Cryogenic lubrication	•						•
[147]	2011	Turning	Ti10V2Fe3Al	Cryogenic lubrication		•					•
[151]	2017	Milling	Ti6Al4V	Cryogenic lubrication	•	•					•
[152]	2016	Milling	Ti6Al4V	Cryogenic lubrication						•	•
[153]	2019	Milling	Ti6Al4V	Cryogenic lubrication					•		
[154]	2020	Milling	Ti6Al4V	Cryogenic lubrication		•			•		
[155]	2015	Grinding	Ti6Al4V	Cryogenic lubrication	•	•	•		•		
[156]	2018	Grinding	Ti6Al4V	Cryogenic lubrication	•	•	•		•		
[157]	2016	Drilling	Ti6Al4V	Cryogenic lubrication		•	•	•	•	•	
[158]	2016	Drilling	Ti6Al4V	Cryogenic lubrication		•		•	•		

on the surface integrity of the Ti6Al4V workpieces machined with PCD tools was studied by Ezugwu et al. [166] and with uncoated cemented carbide tools by Da Silva et al. [167]. The authors did not observe any considerable amount of plastic deformation below the machined surface with conventional and high-pressure coolant. Microhardness analysis showed that the high-pressure coolant system has softened the subsurface layer of the work material due to the low heat generated, allowing tempering to occur. With the conventional overhead cooling hardening of the top machined surface was observed.

Besides showing that increasing the coolant pressure improved the tool lives and reduced work material adhesion on PCD tools when machining the Ti6Al4V, Da Silva et al. [168] showed that adhesion (attrition) and abrasion are the dominant tool wear mechanisms. Although adhesive wear is more frequently seen under low cutting speeds, they showed that it can also occur in relatively high cutting speeds. The authors comment that the segmented chip formation enhances the stick-slip process, that generates a plucking action effect, removing particles from the tool's surfaces, accelerating the tool wear. This plucking action effect is clearly seen on a tool used to machine the Ti6Al4V alloy with a cutting speed of 200 m/min and coolant pressure of 20.3 MPa in Fig. 19.

The efficiency of the high-pressure coolant jet in breaking the chips, which is another very important benefit of the system, is clearly showed in Fig. 20. The fragmentation process is schematically illustrated in Fig. 21. When few segments of the chip are formed, the mechanical action of the coolant jet immediately curls the chip, reducing the chip-tool contact length and with further curling as the chip grows, the pressure of the jet breaks it and the process repeats periodically.

Ezugwu et al. [169] have tested three types of cutting fluids applied under high pressure in the machining of Ti6Al4V alloy with uncoated cemented carbide tools. The fluids tested were dicyclohexylamine-based coolant (emulsion coolant containing alkanolamine salts of dicyclohexylamine and fatty acids), a triethanolamine-based coolant (semisynthetic), and an ester-based coolant (soluble oil). These fluids were applied under conventional overhead flooding and directed between the rake surface of the tool and the chip being formed with 11 MPa and 20.3 MPa of pressure. Under the higher coolant pressure, the dicyclohexylamine-based coolant was the more effective in increasing tool life. However, under the lower pressure of 11 MPa, the triethanolamine-based coolant was the most efficient coolant. The ester-based fluid gave the poorest performance due to its susceptibility to oxidation at elevated temperatures. Bermingham et al. [170] have compared the high-pressure coolant supply technology with cryogenic machining of Ti6Al4V, which is another encouraging strategy with positive response in this challenging process. The results showed that, although cryogenic machining showed positive response, the high-pressure coolant supply system showed superior performance and the coolant nozzle position plays important hole.

Surface integrity is an important requirement for titanium alloys, particularly the aeronautic grades, and the effect of the high-pressure coolant supply on surface roughness, surface defects, residual stress as well as work hardening of the machined surfaces was reviewed by Liu and Liu [171]. They

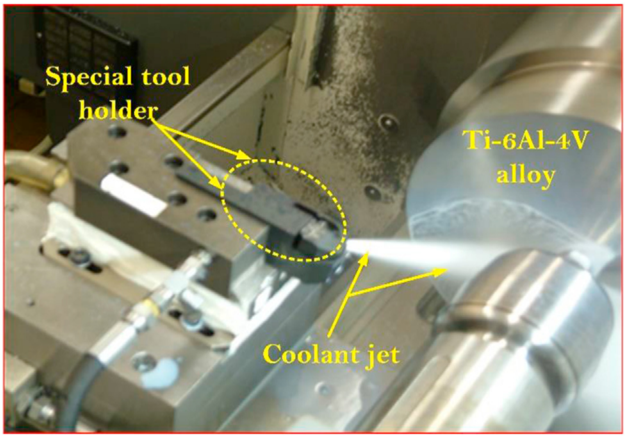

Fig. 18 – A view of the special toolholder and the coolant jet used to machine Ti6Al4V [163].

showed that the high-pressure coolant supply system generally improved the surface integrity parameters and pointed out that the fluid jet direction (rake surface and/or clearance surface) is an important variable and studies about its effect and the type of coolant used must be encouraged for future works. Mia and Dhar [172] have applied high-pressure coolant jet (8 MPa) simultaneously to the rake and flank surface of the TiCN/Al_2O_3/TiN coated cemented carbide inserts in turning of Ti6Al4V to study the chip-tool interface temperature, surface roughness, cutting force, tool ear and chip formation. The results revealed the positive response of using the double coolant jets, lowering cutting temperature, cutting forces, surface roughness and tool wear. Aa a consequence of these, tool life was increased 55–60% as compared to dry cut.

Machine learning and numerical modelling are also used in high-pressure coolant supply system to study and predict machining performance of titanium alloys. Mia et al. [173] have used artificial neural network (ANN) and support vector machines (SVM) to model the surface roughness, cutting temperature and chip thickness coefficient and Michaelis–Menten model for tool wear. Turning of Ti6Al4V experiments with TiCN coated cemented carbide inserts in dry and HPC (8 MPa) with jet directed to the rake face of the tool were performed to validate the models. Good fittings of the models with experimental results were found. In another work Mia et al. [174] have used mono and multi-objective optimization techniques and Taguchi method for cutting forces, surface roughness, cutting temperature and chip thickness coefficient in turning of Ti6Al4V under dry and high-pressure coolant supply, with the cutting conditions as the input variables. This time, the high-pressure jet (8 MPa) was simultaneously applied to the rake and flank surface of the tools.

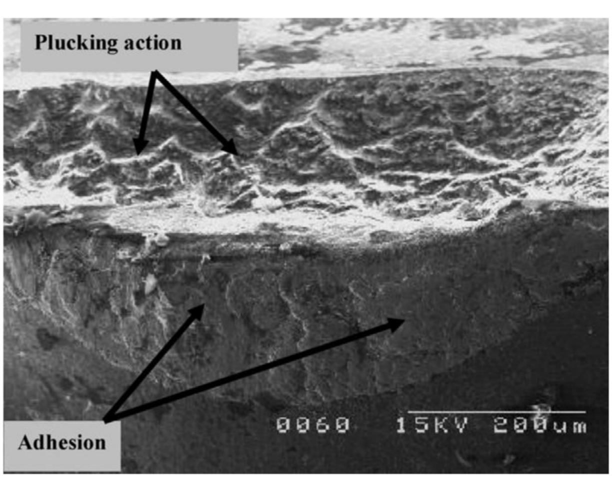

Fig. 19 – PCD tool after machining Ti6Al4V at 200 m/min and 20.3 MPa of coolant pressure [168].

Very recently, the high-pressure coolant supply (HPC) was tested in high-speed ultrasonic vibration cutting (HUVC) of Ti6Al4V alloy in turning operation with cemented carbide inserts in cutting speed ranging from 200 to 500 m/min [175]. Tool life result with the combined HUVC/HPC systems was impressively 7.3 times higher than the conventional coolant supply at the cutting speed of 400 m/min and coolant pressure of 20 MPa, besides increasing the surface quality and reducing the cutting temperature.

While several works in turning of titanium alloys under high-pressure coolant supply are available in the literature, in other cutting operations they are scarce. An exception of this is the work by Bermingham et al. [176], they investigated the application of high-pressure coolant (7 MPa) in a combination of milling and drilling operations. Three different cutting tools (milling cutter with TiCN + Al2O3 coated cemented carbide inserts; solid uncoated cemented carbide end milling cutter and uncoated cemented carbide drill) were used in the cycles to machine the Ti6Al4V alloy components presented in Fig. 22. The investigation produced positive results for the high-pressure coolant supply method, that increased tool lives, reduced cycle time by up to 43%, allowing an estimation of reduction of production cost of up to 64%.

The titanium alloy most investigated is the Ti6Al4V, justified by the high use of this a-b alloy in the medical and metal industries. However, recently the use of the Ti5553 alloy (5%Al, 5%V, 5%Mo and 3%Cr) has increased, particularly in the aerospace industry and research with this alloy start to appear in the literature. Braham-Bouchnak et al. [177] studied the use of high-pressure coolant (HPC) in turning of this alloy with CVD Ti(C,N)+Al_2O_3+TiN coated cemented carbide under several pressures (5, 10, 20 and 30 MPa) and compared to dry cutting and flood cooling. The results showed that, in general, the tool life and the surface roughness have improved significantly, and the residual stress has become more compressive in nature with increasing jet pressure of the HPC system, credited to the lower forces, lower friction coefficient and lower cutting temperatures generated. Another research in the Ti5553 alloy was presented by Kaynak et al. [178] under dry, cryogenic, minimum quantity lubrication (MQL), and high-pressure coolant (HPC) conditions, considering the chip-formation (chip-tool contact length, chip thickness and shear angle) and cutting forces. They found superior experimental performance of the cryogenic and HPC systems regarding the chip formation process and only the HPC was able to promote chip breakability efficiently.

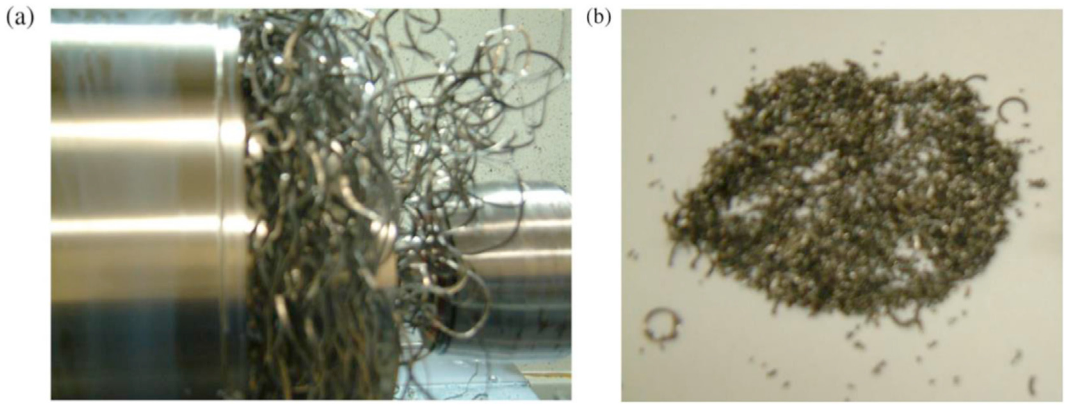

Fig. 20 – (a) Long ribbon type Ti6Al4V chip entangled on the chuck of the lathe after machining under conventional overhead flood cooling; (b) fragmented chips produced by 20.3 MPa of coolant pressure [168].

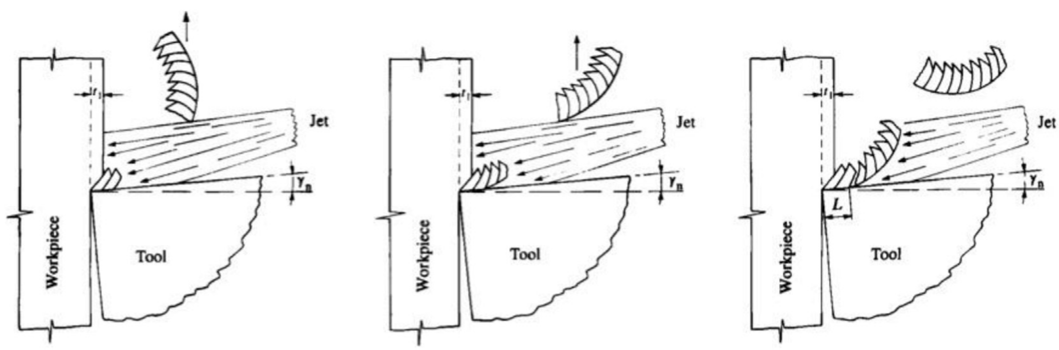

Fig. 21 – Schematic draw of chip fragmentation caused by the high-pressure coolant jet (Machado and Wallbank [160]).

The literature sources considered in the section devoted to the analysis of High-pressure cooling assisted machining are summarized in Table 6.

5. Challenges and future trends

Over the past decade, scientific articles have received even more attention to the study of machining processes of titanium alloys. Fig. 23 shows a graph of the number of publications in 2011, 2013, 2015, 2017 and 2019 for the Scopus (dated 12.09.2020) query for the keywords "Machining" + "Titanium" for different types of cooling: Dry; Conventional cooling (Flood); Minimum Quantity of Lubricant (MQL); Nanofluids (NF); Cryogenic Lubrication (CL); High-Pressure Cooling (HPC). The total number of publications on machining of titanium alloys has doubled since 2011.

Much research has been done on dry machining of titanium alloys and its comparison with other cooling methods. This cooling method attracts the least environmental impact. One of the main trends for increasing machinability here is the use of the latest materials of the cutting part of the tool,

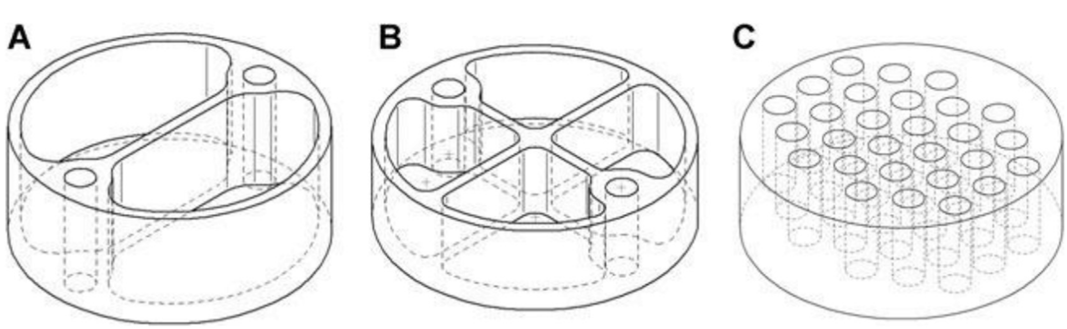

Fig. 22 – Details of the workpieces machined by Bermingham et al. [176] a) Pocket with insert milling cutter; b) pocket with end milling cutter and c) drilling.

Table 6 – High-pressure cooling assisted machining of titanium alloys – investigated process, material, environment, and characteristics.

Reference	Year	Process	Material	Environment*	Cutting tool used*	Chip morphology	Cutting force	Cutting temperature	Surface integrity	Tool wear	Tool life
[159]	1990	Turning	Ti6Al4V	HPCR	UCC	•	•	•	•	•	•
[160]	1994	Turning	Ti6Al4V	HPCR	UCC	•	•	•	•	•	•
[161]	1998	Turning	Ti6Al4V	HPCR	UCC	•	•	•	•	•	•
[162]	2000	Turning, Drilling	Ti6Al4V	HPCR	UCC	•				•	•
[163]	2006	Turning	Ti6Al4V	HPCR	Several	•	•		•	•	•
[164]	2005	Turning	Ti6Al4V	HPCR	CBN, UCC		•		•	•	•
[165]	2007	Turning	Ti6Al4V	HPCR	PCD, UCC					•	•
[166]	2007	Turning	Ti6Al4V	HPCR	PCD				•		
[167]	2017	Turning	Ti6Al4V	HPCR	UCC		•		•		•
[168]	2013	Turning	Ti6Al4V	HPCR	PCD	•	•			•	•
[169]	2019	Turning	Ti6Al4V	HPCR Various coolants	UCC	•			•	•	•
[170]	2012	Turning	Ti6Al4V	HPCR	UCC	•				•	•
[171]	2018	Turning	Ti6Al4V	HPCR, HPCF	PCD, UCC	•					•
[172]	2018	Turning	Ti6Al4V	HPCR, HPCF	CC		•				•
[173]	2017	Turning	Ti6Al4V	HPCR	CC		•		•	•	
[174]	2017	Turning	Ti6Al4V	HPCR, HPCF	CC		•	•	•	•	
[175]	2020	Turning	Ti6Al4V	HPCR + HUVC	UCC		•	•	•	•	•
[176]	2014	Milling, drilling	Ti6Al4V	HPCR	UCC, CC	•	•			•	•
[177]	2015	Turning	Ti555–3	HPCR	UCC	•	•		•		•
[178]	2018	Turning	Ti555–3	HPCR	UCC	•	•				

*CC – Coated carbide, UCC – Uncoated carbide, PCD – Poly crystalline diamond, CBN – Cubic boron nitride, HPCR – High pressure coolant at rake face, HPCF – High pressure coolant at flank face.

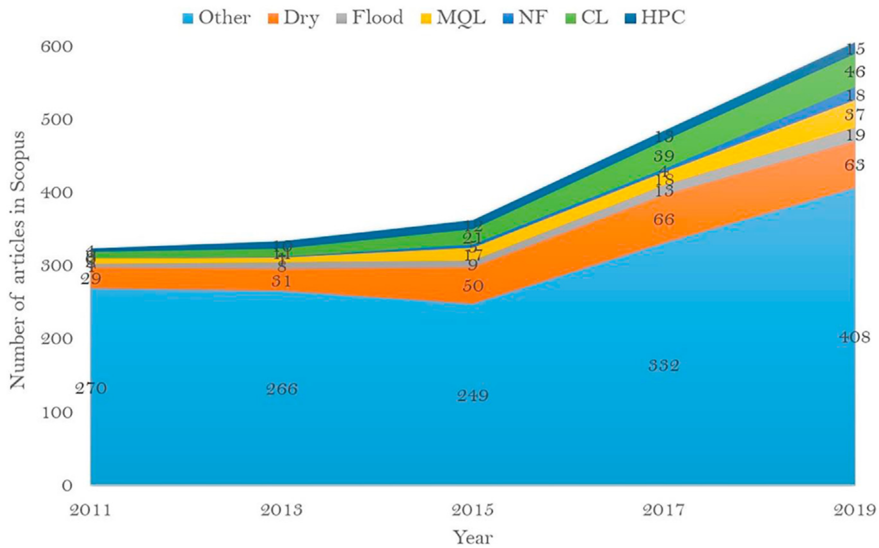

Fig. 23 – Growth dynamics of the number of articles in Scopus on machining of titanium alloys for 2011, 2013, 2015, 2017, 2019: Dry; Conventional cooling (Flood); Minimum Quantity of Lubricant (MQL); Nanofluids (NF); Cryogenic Lubrication (CL); High-Pressure Cooling (HPC).

which provide good wear resistance and allow to increase the resource of the cutting tool [179]. The use of texturing of cutting inserts for machining of titanium alloys also seems promising [180]. This method has been tested on other materials and has been shown to reduce the cutting temperature and reduce the frictional effect of the insert and chips, which means the cutting edges are reduced, which increases the energy efficiency of the operation by reducing the power and saving energy [181]. Also, the tendency of replacing traditionally sintered alloys with additively manufactured titanium alloys (Selective laser melting (SLM), Laser Metal Deposition (LMD), Direct Metal Laser Sintering (DMLS), etc.) may significantly bring the workpiece closer to the size of the finished part [182]. This means that finishing machining will be enough to provide the required accuracy parameters. However, the enhanced physical and mechanical properties of such alloy's present new challenges for machining AM Ti alloys. But the development trend of dry machining is towards sustainable manufacturing.

The most basic way to achieve easy deformation of titanium alloys during machining is to provide thermal softening by increasing the temperature [183]. Although this can be possible during dry cutting, excessive temperature rise also leads to thermal softening of the cutting tool, leading to a loosening of its mechanical properties. When machining titanium alloys with low thermal conductivity, the use of abundant coolant is a necessity to bring the balance between the workpiece and the cutting tool in favor of the thermal effect. Moreover, the complete absence of cutting fluid/coolant creates problems in chip evacuation and results in increased tool-to-chip and tool-to-workpiece friction [180–184]. This phenomenon can result in excessive tool wear and tear, thermal damages, and even tool breakage [115]. On the other hand, the use of conventional cooling system has advantages such as chip evacuation, effective transfer of heat from the environment, reduced friction, and tool wear rate. However, the use of abundant cutting fluid has severe constraints in terms of cost, environment and health aspects [181–185]. From an economic perspective, besides the own costs of cutting fluids, the necessary processes for their disposal create additional costs and increase the total cost. In addition, the increase in energy consumption due to the pump power in the machine tool affects the overall cost [186]. In terms of environment and health, processes like waste disposal, the release of chemical wastes to the environment and the indirect increase of carbon emissions play a role in disturbing the ecological balance. Moreover, skin contact and inhalation of cutting fluids are among the main causes of occupational diseases for machining operators [187]. Therefore, the employment of more economical, biodegradable, environmentally friendly and health-friendly cutting fluids together with high efficiency is one of the main future trends in the machining of titanium alloys as in other difficult-to-machine materials.

Despite MQL's outstanding benefits in laboratory environment, its actual application in industries are quite limited. Hence, the future trend of research should be identification of root-causes of MQL and its variant's unavailability in industries. Tool wear in general for MQL environment showed promising results with extension of tool life, however, literature showed that the evaporation of MQL agents at high temperature causes removal of tool's outer skin, hence, it can be investigated. The thermal and mechanical stress exerted on the tool and work surface need to be quantified for dry condition and MQL condition which can reveal the fraction of benefits of MQL on them. Another scientific study can be on the droplet's suspension in air of the machine shop and fix a threshold for industrial recommendation of safe working environment. From the nanofluid assisted MQL, the uniformity of the nanofluids, their distribution, penetration into the cutting zone need to be managed based on researched outcomes.

Analyzing all the presented results in the literature it is clear that cryogenic cooling and lubrication is one the most promising technologies regarding sustainable and clean machining processes. Apart from all the benefits related to economic, social and environment dimensions, cryogenic cooling is a great alternative to improve the machining process of difficult to cut material such as Ti alloys, eliminating premature tool wear and delivering high quality surface finishing. However, most of cryogenic lubrication systems reported in the literature are not commercial systems but tailor made systems which require machine tool adaptation and do not offer the proper conditions to industry applications in which robustness and high productivity are required. One of the challenges to be overcome is the development of robust commercial cryogenic pumping systems which are able to reach high productivity and can be easily installed in regular machine tools by simple and cheap retrofitting or upgrading.

The positive aspects offered by the use of high-pressure coolant system (HPCS) has encouraged companies to implement this technique in the shop floors, particularly in the aerospace industries in the machining of superalloy, principally in the machining of titanium alloys. The system demands a high-power unit (pump normally with over 20 KW of power) and special hose pipes and tooling. It also requires machine-tools with protective guards. These facts may refrain companies to implement it, although the most important machine-tool manufactures can offer new products with the HPCS unit incorporated to the machine tool, fact that in a very near past the units were adapted separately from the body of the machine.

From the literature on high-pressure coolant supply available the application on machining of steel is rather scarce, meaning that this most important engineering metal is not benefiting from it as it should. Steel produces long stringy chips and chip-breaker technologies do not always succeed in control them. With no doubt, HPCS technology is a very efficient candidate to solve this problem, with the bonus of having the tool life enhanced, the chip-tool contact length, the cutting force and cutting temperature reduced. Is the main reason for this the high cost of the equipment that may not trade-off positively? Or scientific research is lacking?

6. Conclusions

- Dry machining occupies a significant area in approaches to the production of titanium alloys. At the same time, one has to face great difficulties in the machinability of these alloys in production. From a physical point of view, this is a high strength alloy, which leads to large values of cutting force, a low thermal conductivity causes the appearance of high cutting temperatures. As a rule, the tooth morphology of the chip is present, which can cause problems with the need to clear the chip, especially when drilling and milling. The nature of tool wear typically extends to the flank face and cutting-edge profile of insert. The use of new cutting insert materials and their coatings can significantly increase tool life. The advent of new additive manufacturing methods for titanium alloys is even more difficult for machining. However, this requires a solution in the near future. Dry machining is very useful for sustainability and clean manufacturing, as it has minimal environmental impact.
- In the past, the success of a machining operation was only valued in terms of product quality and cutting tool life, whereas today the most important criterion for success of an operation is its sustainability. As mentioned above, excessive use of petroleum-based coolant in general cooling application can cause high costs, environmental damage, employee health deterioration, and disposal and recycling problems. As such, it is impossible to say that this method is sustainable. Therefore, the introduction of alternative methods that will respond to sustainability is among the main duties of actors operating in the field of machining today.
- The MQL system (or its variants) has shown its effectiveness in application of titanium and its alloys. The major benefits are that the cutting fluid consumption has been reduced and the good results in terms of cutting forces, tool wear, surface roughness are noted. In the future, more researches are expected in evaluating the trade-off of thermal benefits versus machining benefits, investigation of novel nanofluids for Ti-alloy machining, and cost benefit ratio analysis for overall economic benefits.
- The use of cryogenic cooling methods is a very promising technology which is able to promote improvements in surface integrity when applied to different machining process and stands out as an environmentally friendly and sustainable method. To overcome the present limitations and lack of information regarding cryogenic machining of Ti alloys some solutions such the combination of cryogenic coolant application and MQL have been investigated presenting great results.
- Robust studies on high pressure coolant supply for machining titanium started in the 1990's and the very positive results have spread investigations (experimentally and numerically) on the application of the system to help users to overcome the huge amount of practical problems faced when machining this superalloy. Tool lives could be significantly increased (up to 20-folds has been reported) when machining chiefly with uncoated cemented carbides and PCD tools and when directing the jet to the rake face of the tool as compared to flood cooling and dry cut although some works have shown positive results when directing it to the flank face of the tools. Reduction of the cutting forces, cutting temperature and surface roughness have been reported. Effective chip fragmentation makes the system a very efficient chip breaker. Most of the work accessed was in turning and this suggests the future works in expanding the system to other cutting process such as milling, drilling, and threading. Power consumption has not been studied, provided the machining of Ti-alloys consumes significant power and HPC uses pumps to circulate the coolant.

Author contributions

All authors contributed equally on the conceptualization, methodology, formal analysis, and writing-reviewing of this article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

AM	Additive manufacturing
CBN	Cubic boron nitride
CC	Coated carbide
CCS	Conventional cooling system
CFRP	Carbon fiber reinforced polymer
CL	Cryogenic lubrication
CSR	Chip serration ratio
CVD	Chemical vapor deposition
CWMJ	Cold-water mist Jet
DMLS	Direct metal laser sintering
HPC	High-pressure cooling
HPCF	High pressure coolant at flank face
HPCR	High pressure coolant at rake face
HPCS	High-pressure coolant system
HTDMLS	Direct metal laser sintering with heat treatment
LMD	Laser metal deposition
MQCL	Minimum quantity cooling lubrication
MQL	Minimum quantity lubricant
NF	Nanofluids
PCBN	Polycrystalline cubic boron nitride
PCD	Polycrystalline diamond
PVD	Physical vapor deposition
RHVT	Ranque-Hilsch vortex tube
SLM	Selective laser melting
SPS	Spark plasma sintering
SQCL	Small quantity cooling lubrication
SQL	Small quantity qubrication
UCC	Uncoated carbide
f_z	Feed per tooth
a_p	Depth of cut
a_e	Radial depth of cut
v_c	Cutting speeds

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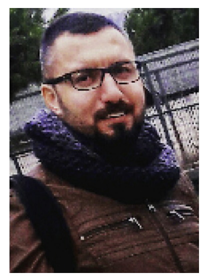

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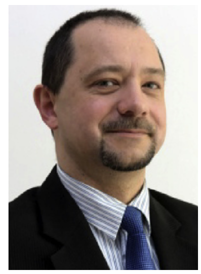

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