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Recent Advances on Cryogenic Assistance in Drilling Operation: A Critical Review

Drilling operation with cryogenic assistance is beneficial toward solving critical issues in machining difficult-to-cut materials and structures, especially in terms of improving surface integrity, elongating tool life, sustainability, and so on for providing high-performance components in aerospace industries. This article presents an overview of the state of the art on this technique in recent years. It aims at analyzing its requirements and orient future directions. It starts with a summary concerning its application for different categories of work materials, including metals, composites, and hybrid stacks. Then, the main methodologies of numerical modeling and experimental characterization toward understanding the fundamentals are reviewed. The goal is to present a general view of current approaches, discuss their advantages, and disadvantages to understand the requirements toward future work. In addition, impacts of cryogenic drilling on cutting performance are reviewed in terms of thermomechanical loadings, surface integrity, tool wear, and sustainability. Finally, a brief summary is presented from different perspectives, and an outlook is recommended for future orientations. [DOI: 10.1115/1.4054518]

Keywords: drilling, cryogenic machining, numerical modeling, experimentation, machining process, sustainable manufacturing

1 Introduction

Industrial technologies always develop toward integration of high efficiency, high performance, high sustainability, and low costs [1–3], especially following the permanent pursuit of both lightweight and high strength in aerospace and aeronautics industries. As a result, large amounts of high-performance metals, composites, and stacks [4–7] are required for structural components of aircrafts (Fig. 1). Meanwhile, titanium alloys [6,8–10] and nickel-based alloys [11–15] are also highly required for aeroengines (Fig. 2). These work materials are difficult to cut due to their severe thermal and abrasive conditions during machining. It requires a significant amount of metalworking fluids (MWF) to avoid high temperatures, which introduces some environmental burdens [16] due to their toxicity and waste. This is contradictory to the eco-friendly and sustainable requirements of modern industries [17,18]. As a result, advanced techniques need to be developed to balance increasing demands among efficiency, performance, and sustainability.

Cryogenic machining is an advanced technique with good performance in improvement of surface quality, decrease of tool wear, and reliable sustainability [19–21]. Reitz [22] first reported to use liquefied gas as coolants in machining in 1919, where carbon dioxide (CO_2) was used. Then, cryogenic processing was introduced by CryoTech company in 1966, and a prominent increase of tool life was reported. This technique was first described with the term "cryogenic machining" by Uehara and Kumagai [23] in 1968.

Although cryogenic machining is raised at an early stage of the 20th century, a rapid increasing number of academic research related to this topic comes out until 2000, with a series of publications concerning further development by Hong et al. [24–27] from 1999 to 2001. Their work is regarded as a milestone in this realm from the authors' point of view as the number of publications increases dramatically following their research. They introduced liquid nitrogen (LN_2) as a coolant into machining of Ti6Al4V, and it characterizes excellent performance in restraining tool wear and therefore attracts large amounts of interests from both academic communities and industries.

Currently, two kinds of liquids are used as cryogenic coolants, which are LN_2 and liquid carbon dioxide (LCO_2), respectively. Both of the liquids can provide extremely low temperatures (−196 °C for LN_2 and −78.5 °C for LCO_2). Both liquids show an excellent performance in improving cutting performance compared to dry and flood conditions, especially in terms of the surface quality. Generally, LN_2 can reduce more heats, while LCO_2 can save more energy [28,29].

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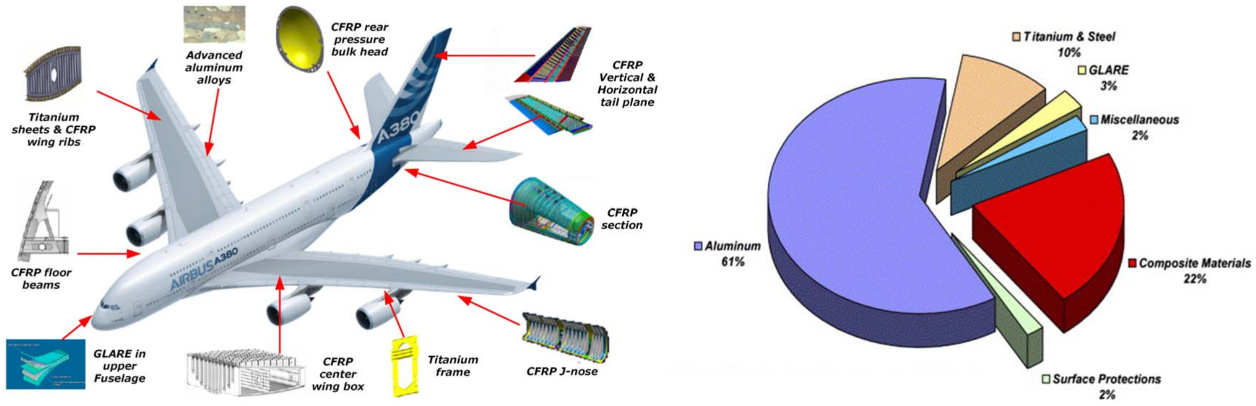


Fig. 1 Difficult-to-cut materials used in structural components of aircrafts [4]

Cryogenic assistance has been widely adopted in different machining operations like turning [30–33], milling [34–37], and drilling [38–41]. During the last two decades, cryogenic machining becomes a practical tool toward machining of difficult-to-cut materials, as reported by Wohlfeil [42] in a case study of milling operation for 5ME company. However, among these operations, it is more essential and beneficial for drilling, as drilling is executed within fully confined areas. The first trial of cryogenic assistance in drilling operation was performed by Bhattacharyya and Horrigan [43] in 1998, and then the topic remained silent, as more concerns are focused on the fundamentals involved in cryogenic machining in the following decade through turning and orthogonal cutting tests.

Cryogenic drilling returns to the eyesight of academic community since the comparative study performed by Venkatesh et al. [44] in terms of cryogenic assistance in drilling, turning, and grinding of Ti6Al4V. In 2012, the publication of Biermann and Hartmann [45] showed a good performance of cryogenic assistance toward eliminating burr formation during drilling hardened and tempered steels. Since then, a large amount of publications concerning cryogenic drilling starts to raise due to its excellent performance toward solving thermal issues involved in drilling operations, especially in terms of heat-resistant superalloys [46–50]. Figure 3 summarizes the timeline of evolution of cryogenic machining techniques with a rough statistics on academic publications. It shows that an outbreak of interests on cryogenic assistance in drilling operation increases in the last decade.

Meanwhile, in drilling operation, cooling efficiency of MWF is significantly reduced due to the difficulties in accessing cutting zones and the mean performance. Drilling is used as a semi-finish operation that will be executed before assembling, which has a higher demand for precision [52]. As a result, there is a more essential requirement in improving the efficiency of thermal dissipation during drilling process. Hence, cryogenic assistance is becoming a suitable solution, which can also present a good performance in reducing costs and enhancing sustainability simultaneously.

This article aims at presenting a summary of recent progress in drilling operations with cryogenic assistance, which has more urgent requirements of effective cooling approaches. It mainly focuses on the problems, methodologies, and targets involved in investigations of cryogenic drilling. A detailed review and discussion regarding the newly developed modeling and experimental approaches are presented with respect to different work materials, and the impacts on thermomechanical loadings, surface integrity, tool wear, and sustainability are also addressed. Conclusions are drawn through the analysis of the current research with an outlook for future orientations.

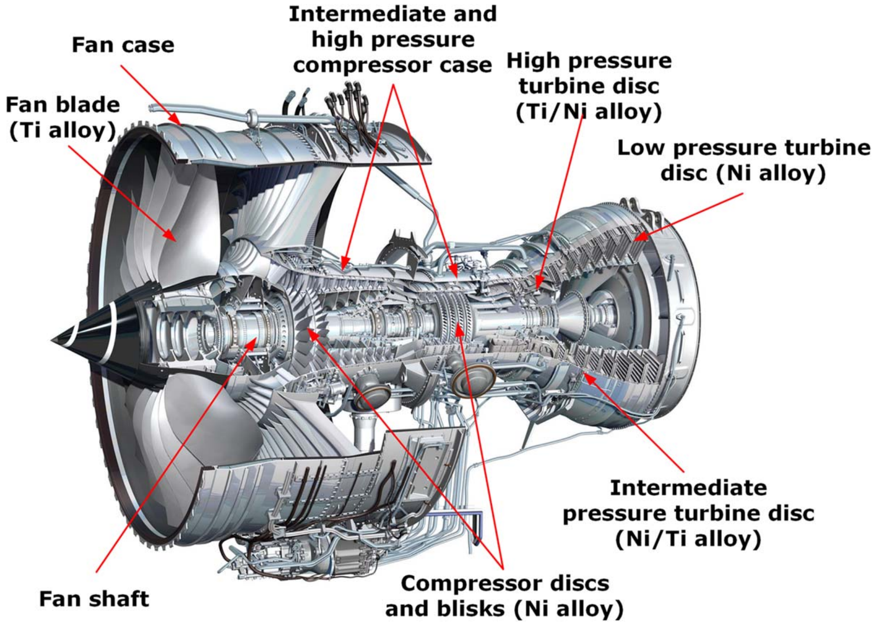


Fig. 2 Difficult-to-cut materials used in aeroengines [6,13] (Reprinted with permission

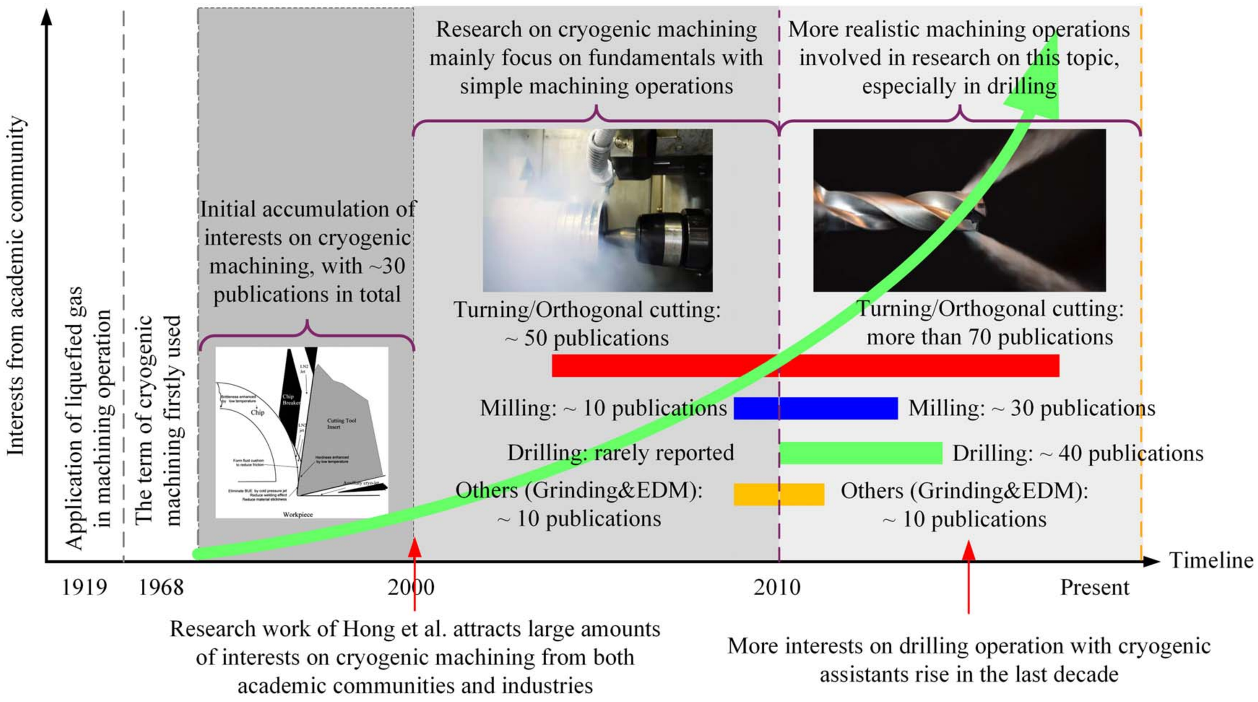


Fig. 3 Timeline of investigations on cryogenic machining toward academic community for different operations, where rapid increasing interests on drilling operation appear in the last decade. Images adopted from Refs. [26,51].

2 Applications of Cryogenic Drilling in Different Work Materials

Turning, milling, and drilling are the most commonly used operations in machining. Among these machining techniques, heat, abrasiveness, and hardness are the dominant enemies. These difficulties are more prominent in drilling compared to other two approaches. First, during drilling operation, chips continuously contact with cutting tool, which will produce more heats due to friction, and it makes chip evacuation more difficult, especially with the complex tool geometries and boundary conditions in drilling. Following, drilling is performed in a confined area; thus, coolants are difficult to access the main cutting zones through regular delivering methods externally, especially during a high aspect ratio drilling or deep-hole drilling process, the effectiveness and performances of coolants will be significantly reduced.

As a result, advanced cooling techniques with higher effectiveness and better performance are essential for drilling other than turning and milling. Cryogenic assistance is one of the best choices, which is being used more and more commonly. Moreover, applications of cryogenic assistance in drilling operation of aerospace industries can be mainly divided into three sections according to different work materials, which are difficult-to-cut metals, composites like carbon fiber-reinforced polymer (CFRP), and hybrid stacks as Ti6Al4V/CFRP stack. Following reviews are presented through these three categories.

2.1 Metals. Difficult-to-cut metals in aerospace industries mainly refer to heat-resistant superalloys, including titanium alloys and nickel-based alloys. These materials always show good mechanical properties and high thermal resistance [8–12], which provides high strength and the ability to serve at extreme conditions like high temperatures, high pressures, and high speeds. However, these excellent thermal and mechanical properties also introduce low machinability.

Normally, during machining of Ti6Al4V, the temperature at tool–chip interface can be higher than 500 °C [53,54], which can be even higher than 800 °C with higher feeds and negative rake angles [55,56], as shown in Fig. 4. Under this condition, serrated chips are easily formed with periodically adiabatic shear banding [57,58], which can induce nano-grains formation and therefore the change of mechanical properties [59]. These modifications finally introduce some periodical distributions of physical and mechanical properties [60] in machined surfaces instead of unique properties, which is harmful during the service of components and should be well prevented.

Meanwhile, these high temperatures and high pressure at tool–chip interface promote chemical diffusion of material elements from workpiece to cutting tool. This diffusion significantly weakens the strength of cutting tool materials to introduce crater wear and decrease tool life, as presented by Jianxin et al. [61] and shown in Fig. 5. Moreover, the diffusion between work materials and cutting tools also leads to the formation of built-up edges (BUEs) [50], which can prominently increase cutting forces and accelerate the collapse of cutting tools. Cryogenic assistance shows an

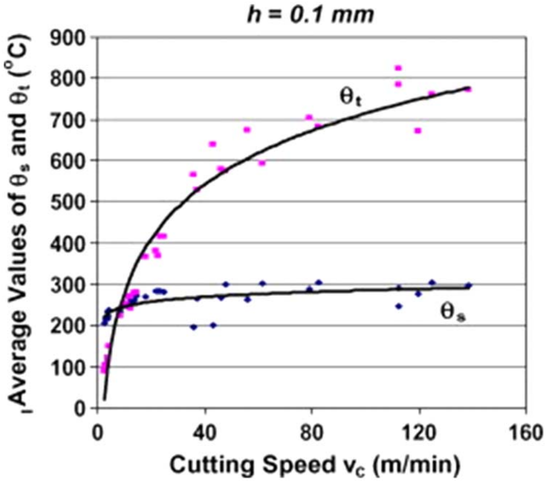


Fig. 4 Predicted temperatures during machining of Ti6Al4V with different cutting speeds [55]

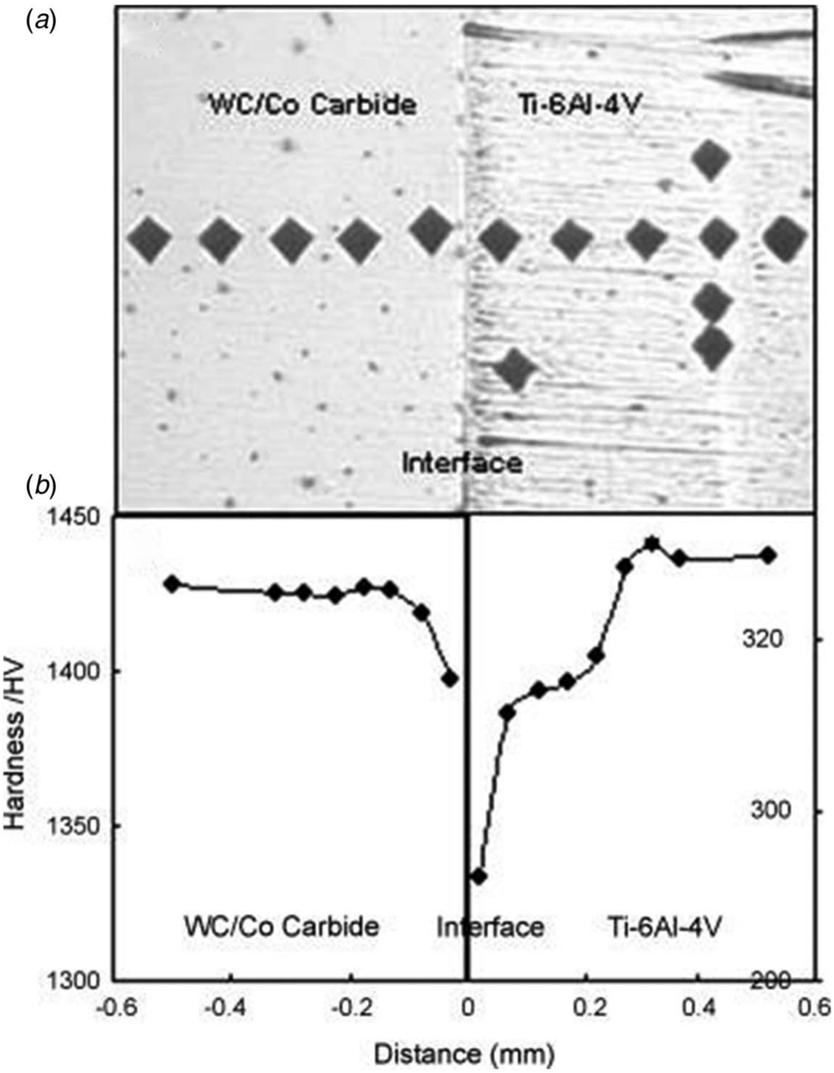


Fig. 5 Hardness values along the interface of diffusion couple between Ti6Al4V and WC/Co carbide tool [61]: (*a*) hardness testing positions and (*b*) profile of hardness values

excellent performance in reducing BUEs formation and diffusion wear during machining Ti6Al4V compared to both dry and flood cutting conditions, as reported by Liu et al. [51].

As a result, a large quantity of heats should be removed during the machining process to restrain these issues to improve tool life and surface quality, especially for the drilling process. Thus, effective cooling strategies are always required to boost heat dissipation. Currently, the most commonly used cooling approaches in machining superalloys are MWF, high pressure jet-assisted machining, minimum quantity lubrication (MQL), and cryogenic assistance. These assistances help to reduce high temperature mainly in terms of two aspects: increase the cooling rate and decrease the friction coefficient. This reaction is also different with respect to different work materials.

Courbon et al. [62] investigated influences of cryogenic coolants LN_2 on titanium alloys and nickel-based alloys. The results show that the cooling performance is excellent for both materials, while the lubricating effects are negligible for Ti6Al4V and a slight improvement for nickel-based alloy Inconel 718, especially at low cutting speeds. Table 1 summarizes a detailed comparison of different cooling strategies on drilling difficult-to-cut superalloys.

To conclude, although cryogenic assistance is not always a satisfying technique toward some work materials due to chipping of tools at low temperatures [67], it still shows an excellent performance in drilling difficult-to-cut alloys, including steels, titanium-based alloys, and magnesium-based alloys, especially in terms of improving surface quality. Moreover, the main issues encountered in machining of these materials are always thermal related, which make the materials very sticky to the cutting tools at high temperatures and pressures. As a result, degradations of tool life and surface quality always occur, and cryogenic assistance can perfectly solve this problem. Although some fundamentals regarding to its controlling mechanisms are still unclear, it is very attractive toward industries concerning cutting performance and sustainability.

2.2 Composites. Composites are composed of matrix and reinforcement, such as metal matrix composites and fiber-reinforced polymers (FRPs). In aerospace industries, FRPs, including CFRPs, glass fiber-reinforced polymers (GFRPs), and glass aluminum reinforced epoxy (GLARE), are of wide use. Recently, fiber metal laminates (FMLs) also become popular due to its excellent performance with combination of both metal phase and composite phase, which can be manufactured together with either CFRP or GFRP, or even both of them. These materials provide extremely low mass and excellent mechanical properties of specific orientations due to their heterogeneity, which is beneficial as structural components of aircrafts [4,72].

Among these composites, FRPs are the most widely used, especially as parts of high-performance components. Thus, they are

Table 1 Review on comparison of cooling strategies in drilling difficult-to-cut alloys

Researchers	Material	Cooling approaches	Description
Venkatesh et al. [44]	Ti6Al4V	Flood Cryogenic	Cryogenic assistance provided excellent roundness compared to flood condition, and the value of roundness keeps good even with a doubled or quadrupled feed.
Biermann and Hartmann [45]	34CrNiMo6 AlMgSi1	Dry Flood (emulsion) Cryogenic (CO_2 snow)	Both burr heights of 34CrNiMo6 and AlMgSi1 are reduced by cryogenic assistance due to its impact on ductility, as well as surface quality. However, roundness of drilled holes is not improved.
Outeiro et al. [63]	Inconel 718	MWF Cryogenic (LN_2)	Tool wear generated during cryogenic drilling of Inconel 718 is higher, as the drill is optimized for MWF. Specific tool design should be developed to improve the performance of cryogenic drilling.
Ahmed et al. [38,40,64,65]	Ti6Al4V AISI1045	Flood (emulsion) Cryogenic (LN_2)	In both cases of Ti6Al4V and AISI1045, cryogenic assistance can provide lower temperature, higher cutting forces, better roughness, and cylindricity.
Perçin et al. [66]	Ti6Al4V	Dry Flood (emulsion) MQL Cryogenic (LN_2)	For micro-drilling process, tool wear with respect to tool corner radius is at a minimum when cryogenic assistance is used.
Shokrani et al. [52]	Grade5 ELI Ti alloy	Flood (emulsion) MQL Cryogenic (LN_2)	Cryogenic assistance helps to improve tool life for about 20%, and surface roughness using cryogenic cooling is reduced 43% on average.
Uçak and Çiçek [67]	Inconel 718	Dry Flood Cryogenic (LN_2)	Cryogenic assistance can provide better machining accuracy, including hole diameter and cylindricity. However, compared to flood condition, tool wear is not improved due to chipping at low temperatures, which also introduce decrease in surface roughness.
Koklu and Coban [68]	AZ31 magnesium alloy	Dry Cryogenic (LN_2)	Thrust forces are increased by 32–39% with supply of LN_2. Adhesion of AZ31 magnesium alloy is common under dry condition, while it is almost negligible with cryogenic assistance.
Merzouki et al. [69]	Ti6Al4V	Dry Cryogenic (LN_2)	Hole shrinkage can be well prevented by using cryogenic assistance with a unique cylindricity. Under dry condition, tool breakage will occur after drilling 22 holes, while for cryogenic, drill is still in good shape after 126 holes.
Khanna et al. [70]	Inconel 718	Dry Cryogenic (LN_2)	When cryogenic assistance is applied, tool life is improved by 87%, required torque decreases up to 30%, and surface quality is also significantly improved.
Shah et al. [29,71]	Ti6Al4V	Dry Flood (emulsion) Cryogenic (LN_2) Cryogenic (LCO_2)	LCO_2 produces lower thrust forces and surface roughness compared to LN_2, which shows a better performance in modifying the machinability of work materials.

usually assembled with other metallic parts through bolting or riveting, which requires a considerable number of holes to be drilled [73]. When drilling FRP composites, there are mainly two general concerns: delamination and tool wear. Delamination always occur at the drill entry due to peeling effects and at the drill exit due to push-out [74], as FRPs are typically heterogeneous with lower strength along the feed direction of the drill; thus, delamination easily occurs once thrust forces exceed the strength of ply interface. This phenomenon is harmful as it can induce a larger hole diameter and introduce excessive damage under the hole surface, which decreases the fatigue life of assembled components drastically [75].

Moreover, tool wear in drilling FRPs shows different characteristics with respect to superalloys as material behaviors of FRPs are totally different with metals, where diffusion and adhesion occurred are not the main concerns. In general, the temperature in drilling CFRP lies within an acceptable range below 200 °C [76,77]. As a result, abrasiveness induced by carbon or glass fibers turn to the dominant issues, which makes the rounding of cutting edges and evolution of flank wear (VB) increase quickly, so that both tool life and surface integrity will decrease. Meanwhile, with increasing tool wear, delamination is more liable to appear due to the increase of thrust forces [78], and a linear relationship between tool life and delamination was reported by Gaugel et al. [79]. As a result, delamination can be avoided from two aspects: adopting better machining strategies and decreasing tool wear.

Generally, cutting fluids will dip FRPs and induce degradation of mechanical properties due to the hydroscopicity of carbon/epoxy system, so flood condition is always avoided in FRP machining. As a result, the most commonly adopted strategies in drilling FRPs include: (1) dry condition with specifically designed or optimized drill bit geometry [80]; (2) vibration-assisted machining; (3) MQL; and (4) cryogenic machining. For MQL and cryogenic conditions, some liquids will also be introduced into the machining process, while their effects on degrading material properties can be ignored, as MQL only provides a very tiny amount of liquids for lubricating at the tool–work interface, and cryogenic liquids easily evaporate at room temperature, where the dipping effects can be neglected.

Among these methods, cryogenic machining is taking an increasing attraction from both academic communities and industrial societies due to its excellent performance in improvement of hole quality and sustainable concerns. However, its effects on machining FRPs are still unclear, and it shows some negative impacts on delamination. The first application of cryogenic drilling was performed by Bhattacharyya and Horrigan [43] in 1998 for Kevlar fiber-reinforced plastic (KFRP). Their results show that tool wear-rate was significantly decreased with the help of cryogenic coolants, and delamination increased. However, they also pointed out that the application of the back plate is effective toward reducing delamination, or the phenomenon will always occur even if without cryogenic assistance.

Afterward, several publications compared performances of dry and cryogenic conditions with LN_2 in drilling CFRP, which show that the surface quality improves with the increase of delamination factor when cryogenic coolants are applied [81–83]. It is attributed to the increase of thrust forces induced by the higher stiffness and hardness of materials at low temperatures. Figure 6 shows the hole surface obtained in drilling CFRP under dry and cryogenic conditions.

Khanna et al. [82] differentiated delamination factors at drill entry and exit, respectively, which shows that cryogenic assistance can help to reduce delamination factor at the entry. However, the

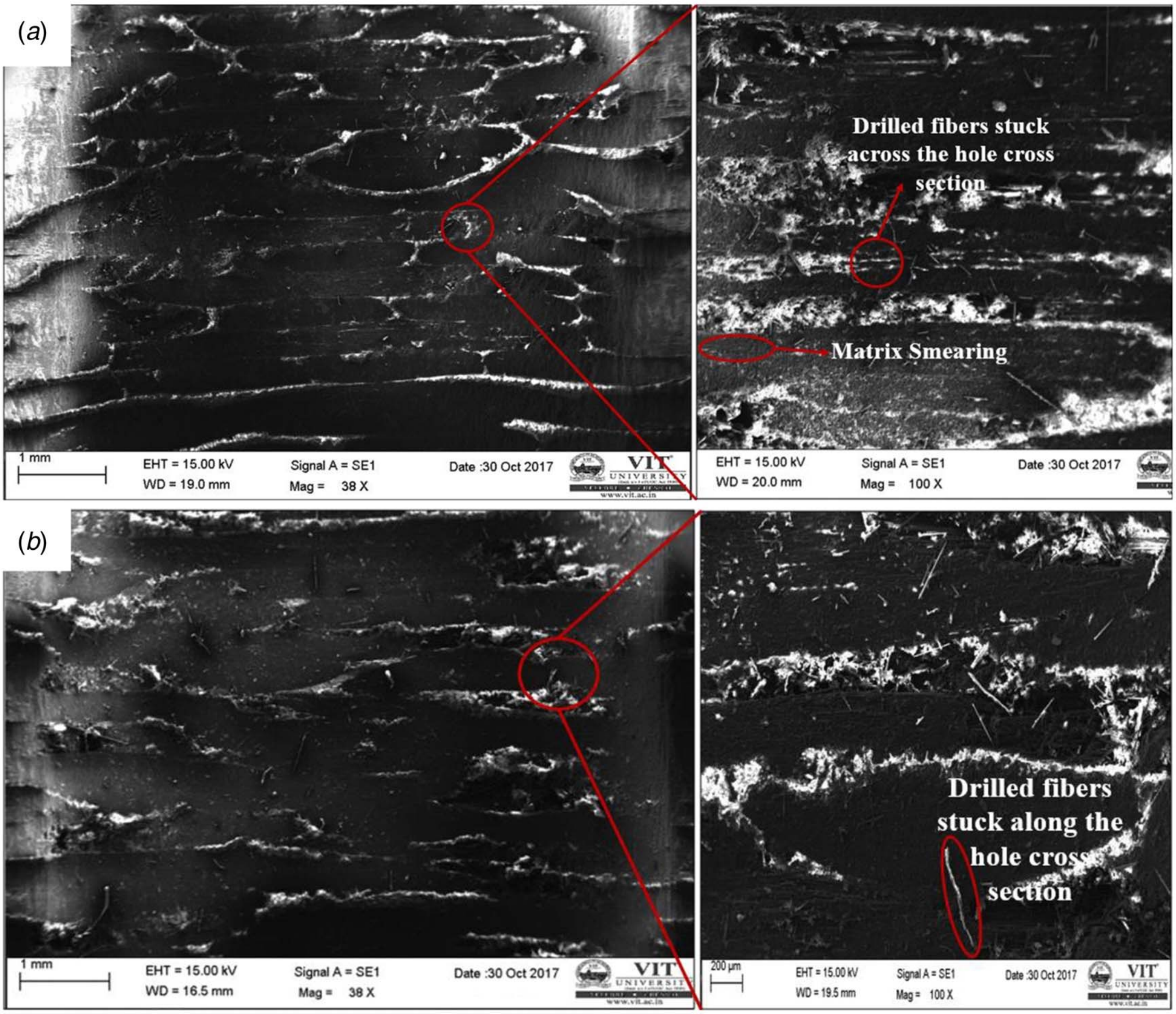


Fig. 6 Hole surface quality of drilling CFRP [81] under different conditions: (*a*) dry condition and (*b*) cryogenic condition (Reprinted with permission from Elsevier © 2018)

factor increases at the exit. Moreover, in recent researches, both Joshi et al. [81] and Iqbal et al. [83] reported that although cryogenic assistance generally increases delamination factors compared to the dry condition, it is controllable through adjusting cutting parameters. It shows the same performance in terms of several different criteria and therefore characterizes a higher potential for applications in industries. Dalle Mura and Dini [84] proposed a method to use cryogenic precooling instead of continuous cooling toward drilling CFRP. They used LN_2 to cool down the specimen before the drilling operation. The results show that precooling can effectively decrease delamination compared to both dry and cryogenic conditions; however, tool wear is accelerated in this case, even with respect to dry condition. Table 2 presents a summary on recent advances in drilling composites with cryogenic assistance.

To summarize, cryogenic assistance shows a negative influence in terms of delamination factors compared to dry condition, especially at the exit, which is attributed to its higher thrust forces induced by higher stiffness and hardness of materials at cryogenic temperature. However, these disadvantages are controllable through adopting appropriate cutting parameters like low feeds and high speeds, and optimized drill geometries. Meanwhile, better hole qualities, including surface roughness, dimension accuracies of circularity, and cylindricity, are always reported when cryogenic assistance is applied. Moreover, it is also an effective method in restraining tool wear, although the mechanisms are still not well understood. As a result, interests on this topic are increasing rapidly in recent years due to the illustrated characteristics and its excellent eco-friendly performance. It also shows a high potential to be used in drilling hybrid stacks, which will be introduced in Sec. 2.3.

2.3 Hybrid Stacks. In many cases of aerospace industries, metals and composites will not appear individually as they require to be assembled through bolting or riveting to construct high-performance components, which can enlarge the advantages and compensate the disadvantages of each individual material, such as Ti6Al4V/CFRP stacks. For these stacks, a major concern is to maintain dimensional accuracy for assembling, and as a result, these holes are always drilled in a same operation with a same drill.

However, as illustrated in Secs. 2.1 and 2.2, these superalloys and FRP composites also present their individual issues. To overcome these issues, different recommendations of cutting parameters and cooling strategies are proposed. For example, Ti6Al4V requires low cutting speeds, high feeds, and flood cutting condition, while CFRP requires high cutting speeds, low feeds, and dry cutting condition, which are totally contradictory. In this case, some strategies like optimizing drill geometries are not eligible, as this kind of specialized geometry is not suitable for both materials [97–99].

Table 2 Review on recent advances in drilling FRPs with cryogenic assistance

Researchers	Material	Cooling approaches	Description
Bhattacharyya and Horrigan [43]	KFRP	Dry Cryogenic (LN_2)	Tool wear-rate is significantly decreased through cryogenic assistance, while delamination turns to be worse due to the increase of thrust forces. However, this drawback can be reduced through usage of back plates.
Xia et al. [85]	CFRP	Dry Cryogenic (LN_2)	Cryogenic cooling presents profound effects in reducing tool wear, improving hole surface and quality compared to dry condition. However, the delamination factor is increased due to its higher thrust forces.
Giasin et al. [86–89]	GLARE	Dry MQL Cryogenic (LN_2)	Both LN_2 and MQL show good performances in improving surface quality and reducing tool wear, while thrust forces and micro-hardness produced by cryogenic cooling are higher than that of MQL. Waste formation on machined surface can be well prevented by both MQL and LN_2.
Basmaci et al. [39]	CFRP	Dry Cryogenic (LN_2)	Cryogenic assistance is effective in both cooling and lubrication, which produces better surface quality, less tool wear, and higher efficiency; however, thrust forces are increased due to the increase of material stiffness at low temperature.
Joshi et al. [81]	CFRP	Dry Cryogenic (LN_2)	Thrust forces, delamination factors and surface roughness all decrease with the increasing cutting speed under cryogenic condition. Higher feed rates introduce higher thrust forces and delamination factors for both dry and cryogenic conditions.
Shokrani et al. [90]	CFRP	Dry Cryogenic (LN_2)	Cryogenic assistance reduces delamination at exit by 8% and improves surface roughness with an average of 25%. Geometry of drill also influences the performance of cryogenic assistance.
Nagaraj et al. [91]	CFRP	Dry MQL Cryogenic (LN_2)	Highest delamination factor is found under cryogenic condition due to its high thrust forces, and adopting variable feeds could be beneficial for that. Better hole qualities concerning diameter and roundness are produced by cryogenic condition, which shows a good performance in maintaining the sharpness of drill bit.
Ferreira Batista et al. [92]	CFRP	Dry Cryogenic (LN_2)	Hole quality is improved under the cryogenic condition, which is partially attributed to the increase of stiffness for laminates. At entry, more cracks and delamination are produced, while at exit, uncut fibers always appear. Cryogenic assistance shows more significant influences on the matrix of thermoplastic than that of thermoset.
Khanna et al. [82]	CFRP	Dry Cryogenic (LN_2)	Application of cryogenic assistance improves drilling performance for surface roughness by 14–38% and entry delamination by 5–68%. However, the delamination is worse at the exit under cryogenic condition.
Janakiraman et al. [93]	CFRP/GFRP/ Al FML	Dry MQL Cryogenic (LN_2)	Cryogenic assistance performs higher thrust forces, while less delamination and surface roughness compared to dry and MQL conditions.
Kumar et al. [94]	Ti/CFRP/Ti FML	Dry Cryogenic (LN_2)	Lower damage factor and higher surface quality were reported with the application of cryogenic assistance. Meanwhile, interlayer burr formation and associated damage were also reduced under cryogenic condition.
Bertolini et al. [41]	Magnesium-based FML	Dry Cryogenic (LN_2)	Modification of drill geometry can reduce cutting temperatures, and application of LN_2 can significantly improve the surface quality and accuracy of machined holes.
Giasin et al. [95]	GFRP	Dry Cryogenic (LN_2)	Hardness, cutting forces, and delamination factors are all higher under cryogenic condition, while surface roughness is significantly decreased.
Iqbal et al. [83]	CFRP	Dry MQL Cryogenic (compressed CO_2, LN_2)	Throttle cryogenic cooling with CO_2 performs best combination of low surface roughness, coaxiality, and circularity of holes. The issues of delamination and fiber fraying can be controlled by using cryogenic coolants at high cutting speeds.
Dalle Mura and Dini [84]	CFRP	Dry Cryogenic (LN_2)	Delamination can be reduced in cryogenic drilling through precooling of CFRP; however, tool wear can be also accelerated in this case. Some effects may also be influenced by different compositions and structures of CFRP.
Koklu et al. [96]	GFRP	Dry Cryogenic (LN_2)	Both hole circularity and cylindricity are reduced significantly under the cryogenic condition; however, deviation of hole size at top and bottom is higher when using cryogenic bath.

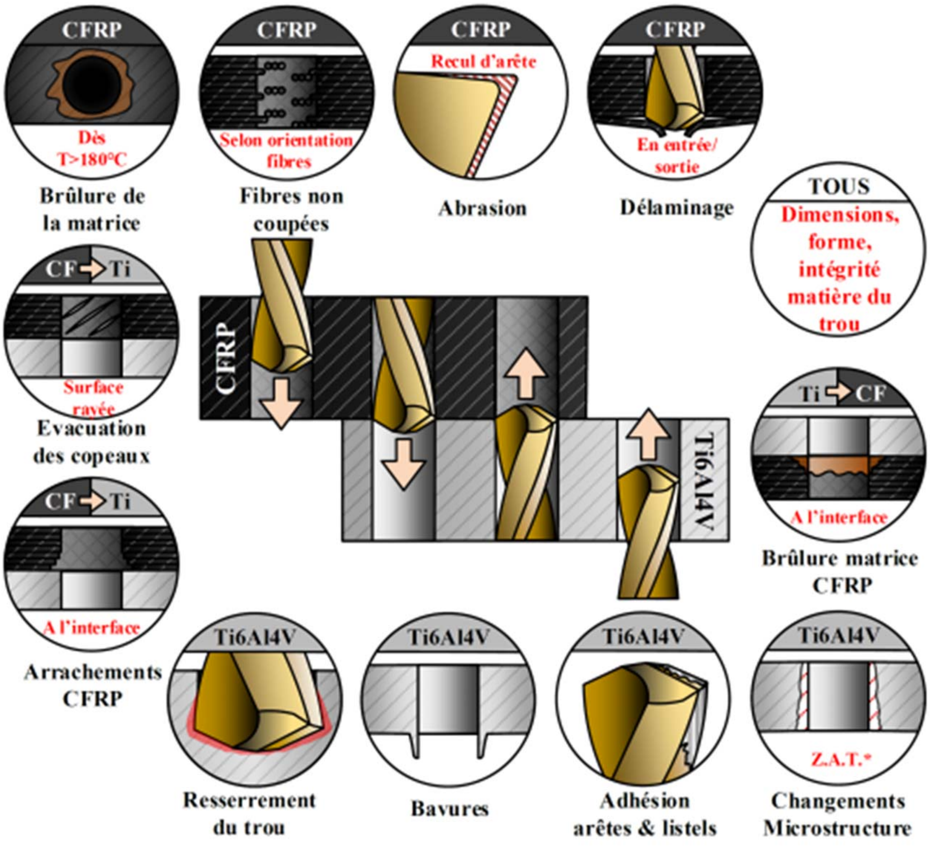
Moreover, although variable parameters can be applied through computer numerical control (CNC) machines to fit different requirements on cutting speeds and feeds, cooling strategies are still opposite for different materials. Besides related problems of individual material, some new issues also appear when they are combined as a hybrid structure, especially at the interface depending on the different sequences, as shown in Fig. 7.

Currently, to suit the contradictory requirements of different materials in drilling hybrid stacks, there are mainly three catalogs of methods.

The first is to drill under dry cutting condition, which is the easiest way to be applied. However, tool wear can progress very fast and surface quality is difficult to be maintained. Moreover, high temperature induced by drilling Ti6Al4V also introduces some burning damage at the interface with the sequence of drilling from titanium to composite.

The second is to use vibration-assisted drilling. This method also provides the dry cutting condition, which is perfect for CFRP, and vibration assistance is also effective in reducing delamination through decreasing thrust forces. However, cutting temperature was still reported to show a higher value than conventional drilling process for CFRP [101], which may also lead to property degradation once it hits the glass transition point. The advantage toward Ti6Al4V phase by vibration assistance is to reduce the interaction at tool–chip interface and improve chip ejection ability, so that thermal loads can be effectively decreased [102]. Normally, this method should be applied together with forced air cooling to improve cutting performance and decrease tool wear [103].

The last is to apply controllable amounts of cutting fluids that can improve cutting performance without degrading properties of CFRP induced by hydroscopicity, such as MQL and cryogenic coolants. For MQL, although it shows some effects in improving surface quality [104], its main contribution to lubrication may be still limited due to the hydroscopicity of carbon/epoxy system, which absorbs the liquids instead of forming a protective lubricating film at the interface [105]. As a result, it can only benefit for the



* Z.A.T. : Zone Affectée Thermiquement

Fig. 7 Overview of general issues in drilling hybrid stacks Ti6Al4V/CFRP [100]

Ti6Al4V phase. For cryogenic coolants, it is beneficial for drilling both superalloys and composites, especially in improving surface quality. Thus, it is believed to have a good performance in drilling metal/composite stacks with increasing numbers of researches in recent years.

Seeholzer et al. [106] carried out studies regarding to drilling CFRP/Al7175 stacks, where they compared four different conditions of dry cutting, compressed air cooling, cryogenic LCO_2 cooling, and combination cooling with compressed air and LCO_2. Both cooling strategies with compressed air and LCO_2 are effective during this process; however, chip accumulation cannot be totally avoided by either method. One of the major reasons for the limited contribution of cryogenic coolants is attributed to the metal phase, which is aluminum alloy in this case. It does not show a significant issue of temperature but the difficulty in chip evacuation. As a result, cryogenic assistance cannot show prominent effects in terms of drilling this type of stack.

In contrast, stacks composed of heat-resistant superalloys and composite have a higher requirement of cryogenic coolants. Impero et al. [107] and Prisco [108] investigated drilling CFRP/Ti6Al4V stacks under wet and cryogenic conditions, which show that more steady cutting can be obtained with the supply of cryogenic coolants. Another benefit is the reduction of global thrust force and torque needed, which makes the process energy saving. Meanwhile, chip evacuation becomes easier due to the embrittlement of chips at cryogenic condition. According to a comparison between dry condition and cryogenic LCO_2 cooling condition toward drilling CFRP/Ti6Al4V performed by Rodríguez et al. [109], a dramatic improvement of surface quality was obtained when cryogenic assistance is applied, which makes the geometrical values close to the nominal data. A visible improvement of the hole quality can be observed, as shown in Fig. 8. Tool wear is also significantly reduced, especially in terms of adhesion, which does not occur even after drilling 160 holes.

However, researches pertinent to drilling metal/composite stacks with cryogenic assistance are still limited, which require further investigations to understand the performances and fundamentals and also in terms of different drilling sequences. Thus, as the realistic operation of drilling in aerospace industries, investigations of cryogenic drilling hybrid stacks are increasing promptly due to the successful utilization of cryogenic assistance in individual materials of both superalloys and FRPs. Although interactions between different materials will introduce new issues, some preexisting issues of cryogenic drilling single material may also be reduced. It is an interesting topic that requires further studies, which is also challenging in understanding the fundamentals to present predictive models.

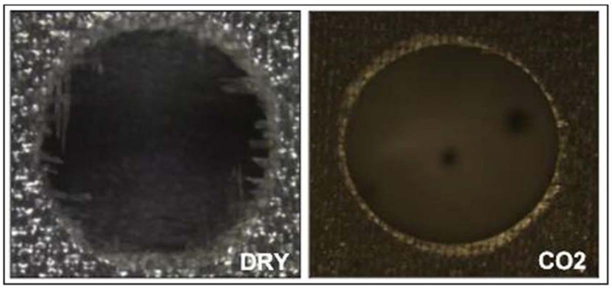


Fig. 8 Hole quality of drilling CFRP/Ti6Al4V stacks under dry and cryogenic conditions [109]

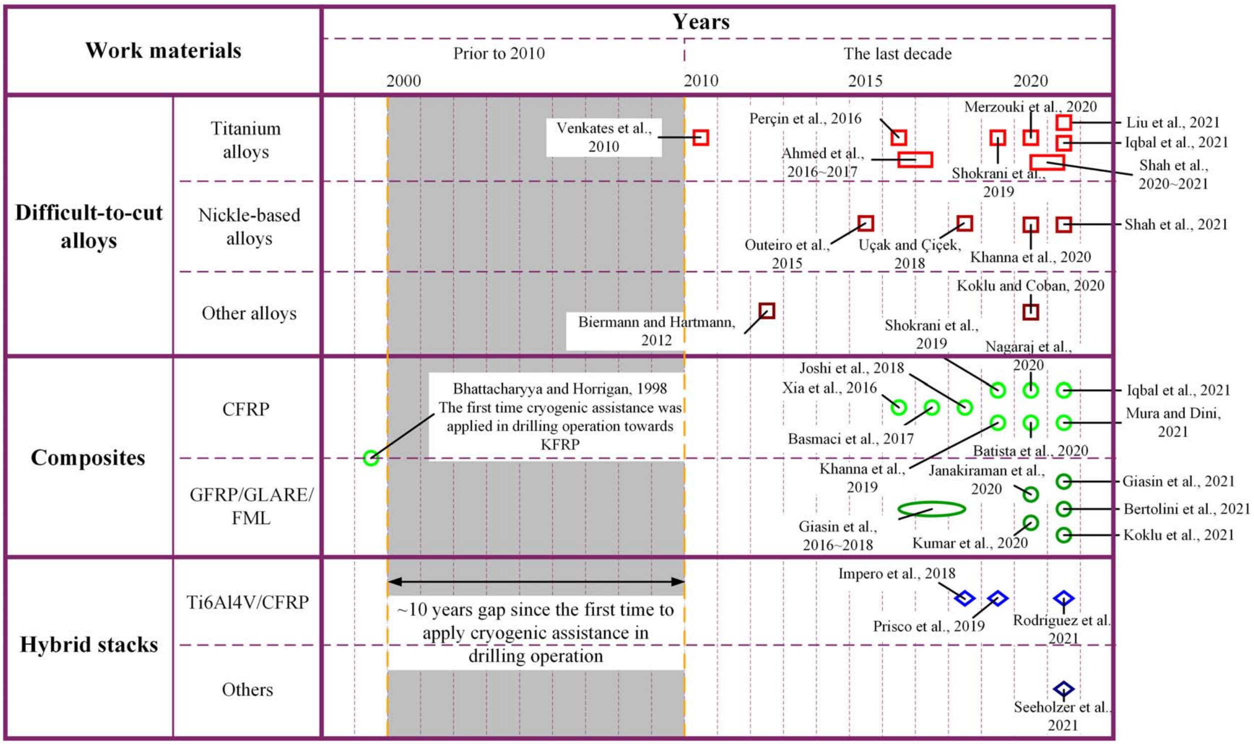


Fig. 9 Summary of evolution of cryogenic drilling with respect to different work materials

2.4 Summary. To summarize, the application of cryogenic drilling is first raised toward decreasing severe tool wear induced by machining of difficult-to-cut materials, especially in terms of Ti6Al4V. Then, it becomes attractive due to the excellent performance of elongating tool life and improving surface quality. As a result, this technique is further extended to be applied for composite materials. However, with respect to composites like CFRP, although tool wear is decreased and surface quality is improved, the performance of delamination turns worse, which is a major concern in terms of drilling. Further investigations show that the delamination induced by cryogenic assistance is controllable through adjusting cutting parameters, which gives higher potential of this technique to be used in industries. Thus, exploration in drilling hybrid metal/composite stacks becomes attractive in recent years due to the excellent performance of cryogenic assistance in terms of machining both materials, which is also working as the actual operation and has an urgent requirement in aerospace industries.

Although the concept of cryogenic machining was raised in the early stage of the 20th century [22,23], the rising of academic concerns of this technique starts from 1999, with the highlighted work following publications of a US patent [110] and a series of research papers by Hong et al. [24–27]. The first application of this technique on drilling was performed by Bhattacharyya and Horrigan [43] for KFRP materials in 1998. However, the interests were then mainly focused on the realm of turning and orthogonal cutting with simplified boundary conditions to understand the fundamentals involved in cryogenic machining during the following decade from 2000 to 2010. The restart of concerns on drilling operation was performed until 2010. Since then, due to the perfect suitability of cryogenic assistance with respect to drilling toward solving problems of severe tool wear of difficult-to-cut materials, interests on this research topic increase quickly. Meanwhile, due to its excellent performance of sustainability, it is believed to be an advanced technique toward future manufacturing. Figure 9 summarizes the evolution of cryogenic drilling with respect to different work materials.

3 Numerical Modeling and Experimentation

As reviewed in Sec. 2, researches regarding to cryogenic drilling are heavily dependent on the experimental study; however, some fundamentals cannot be thoroughly explained as some key variables are unmeasurable during the machining operation. These factors are essential to provide reliable guidance for improving and optimizing machining strategies. As a result, numerical modeling turns to be a practical tool toward providing some insights of in-depth understandings of the general process, which can supplement the vacancies in this area and also help to reduce the high costs from experiments. This section summarizes the prominent methodologies adopted in investigations of cryogenic drilling aiming at launching a good numerical simulation and executing experimental validation.

3.1 Numerical Modeling of Cryogenic Drilling Process. Drilling is a comprehensive machining process occurring in a confined area, where a large amount of details regarding thermomechanical conditions is unmeasurable. As a result, numerical simulation is essential in terms of analyzing material responses within drilling processes. When cryogenic coolants are introduced, the procedure turns to be more complicated due to the forced heat convection process. Normally, cryogenic flows are driven under turbulence condition at a high pressure due to the storage of cryogenic liquids, and depending on different delivery methods, the flow conditions are also variable. Delivery methods through external device and through internal holes characterize very different performances, especially in terms of high aspect ratio drilling. Moreover, cryogenic coolants easily evaporate during the interaction with work materials, which makes the cooling process at a multiphase flow condition, where heat transfer induced by phase transformation takes a large portion.

Thus, to develop a precise numerical model of cryogenic drilling, several key points should be highlighted. The first is to describe the interactions of coolant/tool system and coolant/work system, including both effects of heat transfer and lubrication. Hence, the

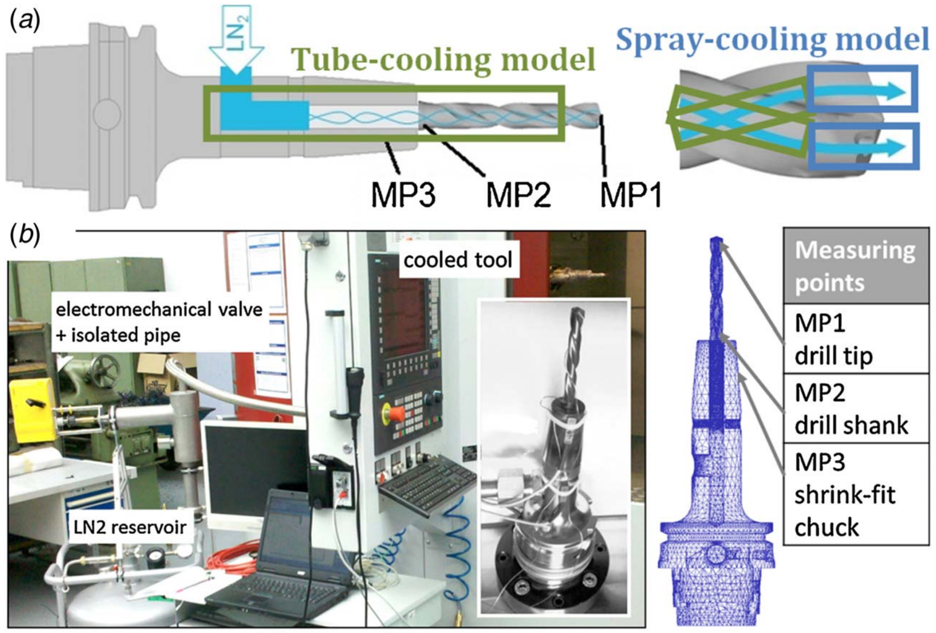


Fig. 10 Cooling conditions of the through-tool system [114]: (*a*) schematic of different cooling models and (*b*) experimental setup (Permission to reprint from Elsevier © 2014)

temperature-dependent material properties should be characterized, especially at the cryogenic range. Finally, these aspects should be merged into a unique numerical model, to carry out fully coupled thermomechanical simulations. This section reviews pertinent research outputs from this perspective.

3.1.1 Heat Transfer and Lubrication. As illustrated previously, heat transfer is a key factor involved in cryogenic machining, especially for the drilling process within a confined area. However, researches concerning heat transfer induced by cryogenic coolants are rarely reported specifically toward the drilling operation. Generally, to determine the heat transfer conditions in drilling, computational fluid dynamics (CFD) is the most commonly adopted approach. Oezkaya et al. [111,112] proposed a CFD model toward identification of heat transfer conditions in drilling with the supply of coolants. However, when referring to cryogenic drilling, the multiphase flow with evaporation of liquids makes it more complicated than conventional cutting fluids. As discussed by Golda et al. [113], a phenomenon of film boiling will occur at the hot surface of solids, where liquid turns into gas, and the related phase change is also a key factor in terms of heat convection. This approach highlights the physics of cryogenic multiphase flows and evaporation, which provides a stronger basis of the reality involved in cryogenic cooling. However, it is only applied to orthogonal cutting with simplified boundary conditions, which is not exactly the same as drilling.

In this case, depending on the physics and fundamentals of two-phase LN_2 flow in cooling, Dix et al. [114] developed a setup to analyze cooling performance with a through-tool cooling system with realistic drilling operation and complex boundary conditions. He divided cooling processes into two different stages: (1) tube cooling inside the tool channels and (2) spray cooling on the work material, as shown in Fig. 10. For tube cooling, a turbulence condition is assumed with a formation of gas film on the inner walls, and a function was proposed to describe heat convection coefficient as shown in Eq. (1):

$$h_c = 0.62\frac{\lambda_m}{d_k}\left(\frac{d_k^3 Q_m(Q_{fl}-Q_m)g l_d}{\lambda_m \eta_m}\left(1+0.4\frac{c_{p,m}\Delta T}{l_d}\right)^2\right)0.25 \quad (1)$$

where d_k is the tube diameter; Q_m, λ_m, η_m, Q_{fl}, $c_{p,\,m}$, and l_d are material properties of gas N_2 layer; and g is the gravitation.

While for spray cooling-interacted between cryogenic coolants and work material, although it occurs within a confined area in drilling, the convection condition is assumed to be the same as in an open area. This is mainly due to the difficulty to characterize pertinent parameters directly through a drilling operation with tool rotation, as some conditions within the confined area are invisible and as a result unmeasurable. Currently, no publications have reported pertinent results specifically toward drilling operation, which should be an interesting and challenging topic for future investigations.

This issue was also discussed by Outeiro et al. [63] in their cryogenic drilling simulation, where a function proposed by Astakhov [115] was adopted toward characterizing heat transfer in general metal cutting processes as shown in Eq. (2):

$$h_f = \frac{0.20}{b^{0.35}\times g^{0.33}}\cdot\frac{v_f^{0.65}\times k_f^{0.67}\times c_{p-f}^{0.33}\times \gamma_f^{0.33}}{\upsilon_f^{0.32}} \quad (2)$$

where b is the equivalent length, and remaining parameters are all related to properties of the fluid, including v_f the velocity, k_f the thermal conductivity, γ_f the specific weight, υ_f the dynamic viscosity, and c_p the specific heat. This function is more of a general estimation of heat convection coefficient other than a specific development toward drilling operation, which neglects some specific issues involved in this process. It also neglects the consideration of multiphase flows as well as phase change heat transfer, which should be improved in the future work.

Thus, concerning all the literature listed earlier, due to the complexity of the heat transfer problem and difficulties in modeling toward drilling, simplified conditions are always adopted when referring to implementation of heat transfer induced by cryogenic coolants into numerical models of drilling. Generally, the simplification is carried out through two approaches: (1) the coefficient is determined as a spraying condition between cryogenic flows and work material without consideration of machining operations; (2) the coefficient is determined through simplified machining operations like orthogonal cutting or turning. Lubricating effects are also determined through this approach as the friction coefficient. It significantly decreases the difficulties in terms of modeling the physics involved in cryogenic drilling, which is efficient toward modeling the deformation of materials; however, it also loses some reality as a result. In this case, several general expressions of heat transfer coefficients available for implementation into cryogenic drilling simulations are recommended.

The first one was raised by Courbon et al. [62,116,117], and they investigated the evolution of heat transfer partition and frictional behaviors at the tool–work interface with respect to cutting speeds and cooling conditions, which is presented as shown in Fig. 11, and also functions to characterize the parameters were deducted as Eqs. (3) and (4):

$$\mu = a \cdot V_s^b \tag{3}$$

$$\alpha = c \cdot V_s^d \tag{4}$$

where μ is the frictional coefficient, α is the heat partition coefficient, V_s is the cutting speed, and a, b, c, and d are fitted against the experimental data. This function is an empirical expression, which is concluded from experimental results and only eligible for specific contact pairs of coolants and tool/work, such as carbide/Ti6Al4V and carbide/Inconel 718 pairs with the supply of gas/liquid nitrogen. As a result, it cannot explain the fundamentals from physical perspectives; however, the data are still valuable and beneficial especially toward implementation in numerical models with higher efficiency.

Another method concerning a more detailed description with respect to effects of delivery parameters was proposed by Lequien et al. [118] under a spraying condition. They assumed a Gaussian function for its distribution during the interaction with work material in terms of nozzle diameter, projection pressure, projection distance, and projection angle, which can be written as Eq. (5):

$$\begin{cases} h(x) = a_0 \cdot \exp\left(\dfrac{-x^2}{2\sigma^2}\right) \\ a = A \cdot \left(\dfrac{\phi}{\phi_{ref}}\right)^{\varepsilon} \cdot \left(\dfrac{P}{P_{ref}}\right)^{\beta} \cdot \left(\dfrac{D}{D_{ref}}\right)^{\gamma} \cdot \left(\dfrac{\alpha}{\alpha_{ref}}\right)^{\delta} \\ \sigma = S \cdot \left(\dfrac{\phi}{\phi_{ref}}\right)^{i} \cdot \left(\dfrac{P}{P_{ref}}\right)^{j} \cdot \left(\dfrac{D}{D_{ref}}\right)^{k} \cdot \left(\dfrac{\alpha}{\alpha_{ref}}\right)^{l} \end{cases} \tag{5}$$

where ϕ, P, D, and α are nozzle diameter, projection pressure, projection distance, and projection angle, respectively, where the variables with subscript "ref" are reference values, and other variables are all fitted parameters. This model presents a good agreement with the results from CFD simulation, as shown in Fig. 12. It can be used to optimize the delivery system of cryogenic coolants as it merges more process conditions into the function, which is more practical toward industrial applications.

To summarize, direct characterization of heat transfer involved drilling is still difficult at the current stage. Cryogenic flows through fixed channel inside cutting tool can be modeled through analytical method under the assumption of tube cooling. However, cooling of coolants/work within a confined area is still assumed to be the same as in open area from the perspective of modeling. It is mainly due to the difficulties of direct measurement of heat transfer coefficients within confined areas. CFD simulation may be a good solution toward this purpose, while the supports from experimental data are still difficult. Moreover, the coefficient is influenced by multiple factors including material properties, delivery systems [119], projection parameters, etc. As a result, depending on different targets, different modeling approaches are recommended: (1) if the physics of interactions between cryogenic flows and work materials or cutting tool are major concerns, CFD simulations with multiphase flows should be a good solution, although it is a challenging work and is still in lack; (2) if material deformation involved in cryogenic drilling is a major concern, simplified cooling conditions can be used to improve the calculation efficiency.

3.1.2 *Material Properties.*

To model cryogenic drilling processes precisely, to characterize material properties at cryogenic range is also essential, including temperature-dependent material constants and behaviors. Although multiple papers have reported that high temperatures are still produced in deformed areas like chips, it is still nonnegligible when referring to material responses of the entire material domain, especially for the machined surfaces. Normally, a rapid cooling is always obtained due to the extremely low temperature of cryogenic coolants and high heat convection coefficient induced by forced convection heat

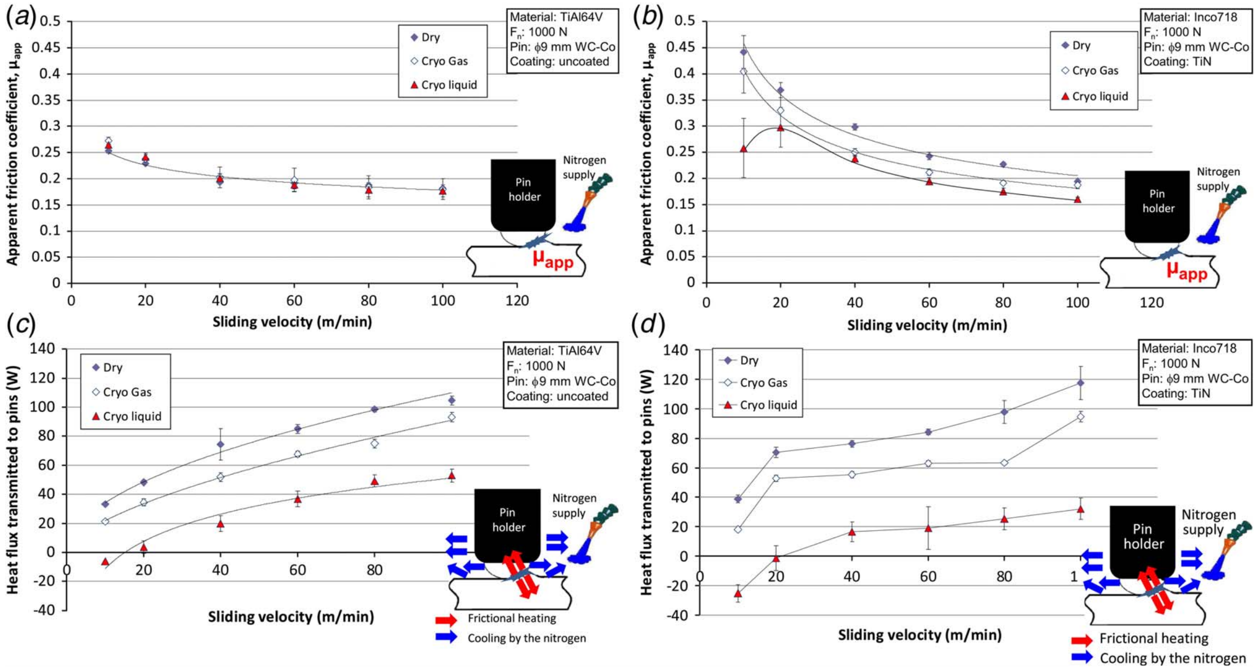


Fig. 11 Characterization of friction coefficient and heat partition coefficient evolutions with respect to cutting speeds for Ti6Al4V and Inconel 718 under different cooling conditions [62]: (*a*) friction coefficients in machining of Ti6Al4V, (*b*) friction coefficients in machining of Inconel 718, (*c*) heat partition coefficients in machining of Ti6Al4V, and (*d*) heat partition coefficient in machining of Inconel 718 (Reprinted with permission from Elsevier © 2013)

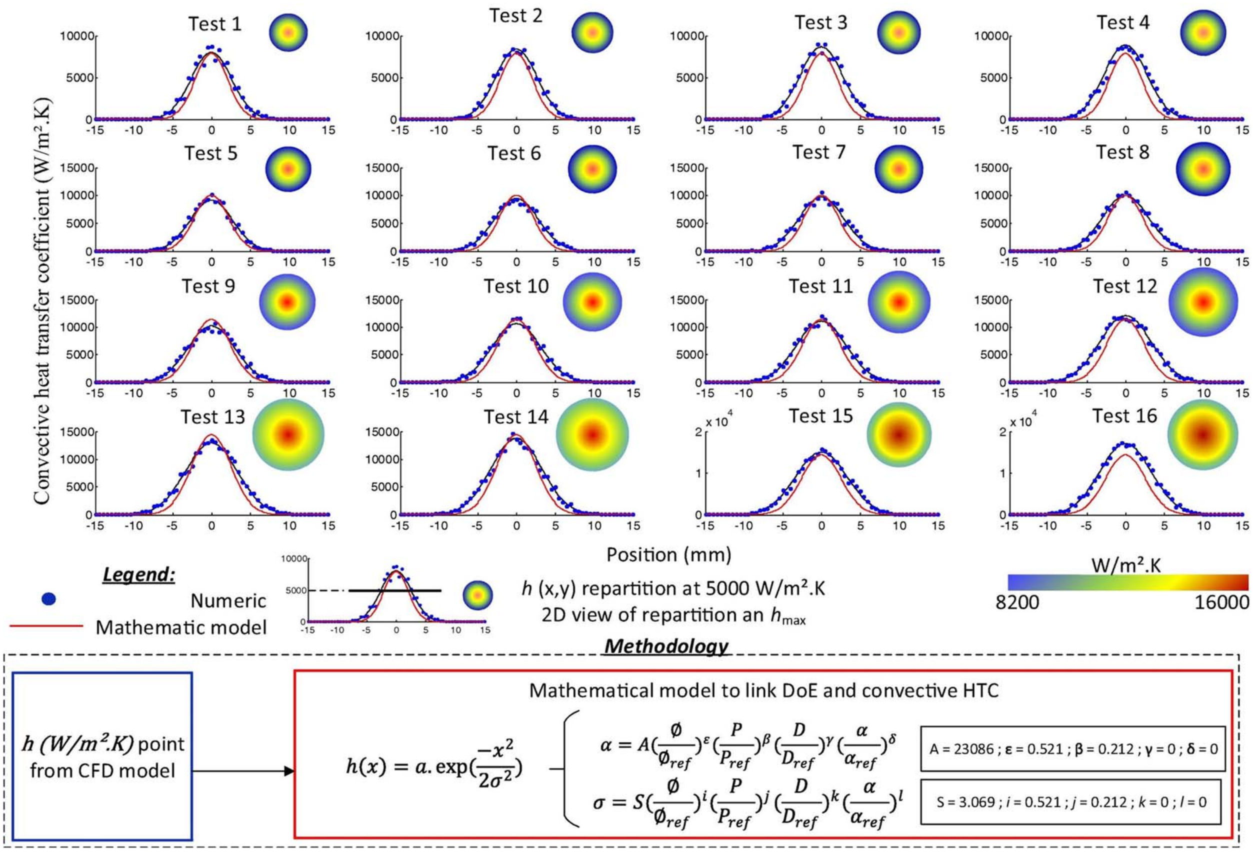


Fig. 12 Comparison of heat convection coefficient predicted by the analytical model and CFD simulation [118] (Reprinted with permission from Elsevier © 2018)

transfer, where an iced layer is always formed on machined surfaces [25].

In this case, both constitutive behaviors and heat conduction properties of the work material are changed, so that cutting performance shows a significant difference compared to normal conditions, such as material side flow during chip formation [120] and distribution of residual stresses in machined surfaces [32,121]. These behaviors are directly influenced by temperature-dependent mechanical properties. As a result, to present a more precise prediction, a new model or database covering material behaviors with a larger temperature range including low temperatures should be developed.

For metals, they are crystallographic materials with specific crystal structures, and their plastic deformation is realized through mobility and evolution of dislocations, which is always thermally activated as presented by Follansbee and Gray [122]. As a result, higher strength and stiffness are always obtained at lower temperatures. In common machining simulations, the most widely used constitutive model is the Johnson-Cook (JC) model [123] with the form as shown in Eq. (6):

$$\sigma = (A + B \cdot \varepsilon^n) \cdot \left(1 + C \cdot \ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \cdot \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right] \qquad (6)$$

In this function, material behaviors are described in terms of strain hardening, strain rate hardening, and thermal softening, which performs well in normal cutting conditions. Meanwhile, the modified JC model is also a common option for researchers when they focus on microstructure evolution in terms of softening behaviors induced by dynamic recrystallization (DRX), which is also implemented in some cases of cryogenic machining [124–127] and is expressed as Eq. (7):

$$\sigma = \left[\left(a + \frac{k}{\sqrt{t}}\right) + B \cdot \varepsilon^n\right]\left(1 + C \cdot \ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right] \times \left[D + (1 - D)\left(\tanh\left(\frac{1}{(\varepsilon + P)^r}\right)\right)^S\right] \qquad (7)$$

where the additional term is used to describe the strain softening behavior induced by DRX or related microstructure evolution, and the initial yielding stress is expressed by lamella thickness.

However, under the cryogenic condition, temperature easily goes below the reference value, which is always used as the room temperature. As a result, the thermal softening term will become invalid with the value of m less than 1 and no hardening effects induced by low temperature can be characterized. Thus, when transferring JC-based functions to cryogenic machining, the common method applied by researchers [63,124,126–128] is to simply set the room temperature T_0 as the boiling temperature of cryogenic coolants, like −196 °C for LN_2. This is a numerical treatment while is not strict enough in terms of physics, as it cannot present a precise description of material behaviors at cryogenic temperatures and is lack of parameters fitted against cryogenic data.

Moreover, when referring to orthogonal cutting cases at a small material domain, this approach is more acceptable as a rapid decrease of temperatures is limited due to its increase induced by tool–work interaction in adjacent areas. However, for simulations of larger material domains like drilling, this method is not suitable as the temperature in machined surface can rapidly decrease to cryogenic region within 1 mm distance away from the machined surfaces, as reported by Merzouki [129]. As cutting conditions always reach a thermomechanical steady state after several seconds, within this period, the temperature can be cooled down

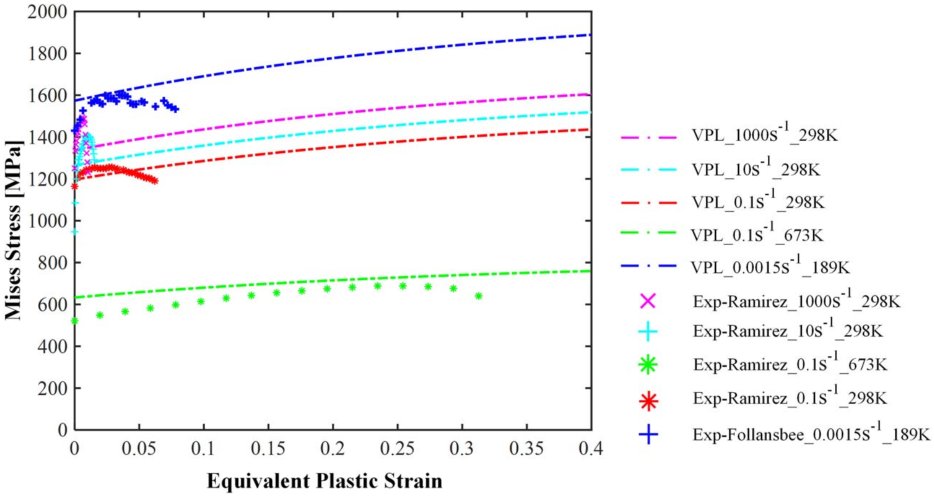


Fig. 13 Constitutive behaviors of Ti6Al4V with respect to a larger range of temperatures and strain rates [130]

to a very low value and results in different responses of materials at adjacent areas of surfaces [130].

Other than adjusting the value of T_0 for JC models, Shi et al. [131] proposed to use a Voce Power Law for describing material behaviors at cryogenic temperatures as Eq. (8):

$$\sigma = [a - b \cdot \exp(c \cdot \varepsilon)] \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^n \left(\frac{T}{T_0} \right)^\upsilon \tag{8}$$

This function also integrates different terms of strain hardening, strain rate hardening, and thermal softening. Here, the thermal term is expressed through the ratio between actual temperature and room temperature; therefore, when the unit is used as Kelvin, effects of low temperature can be still performed even if it is lower than reference value, so that this model can be more reasonable when considering material behaviors at cryogenic temperature from numerical perspectives. The fitted material behaviors are characterized as shown in Fig. 13 [130], which is appropriate for a larger temperature range including cryogenic conditions.

The application of this constitutive law is more reasonable compared to JC models parametrically. However, the fundamentals of this model are still out of the purpose for describing material behaviors at the cryogenic temperature. As a result, it is still required to raise more appropriate models to supplement this drawback. A potential approach to model material behaviors at both high and cryogenic temperature ranges is to use physics-based laws, as they rely on basics of material behaviors at microscale, regardless of the temperature. As reported by Meyers et al. [132], compared to dislocation slip at ambient temperature, twinning becomes the dominant mechanism of deformation within the low-temperature range, while it requires the high strain rate to be activated at mediate temperature and will disappear at high temperature, as shown in Fig. 14 for titanium. However, these models are still in lack, especially in terms of applications in machining, and may prominently increase the calculation time.

Besides constitutive laws, other material properties are also strongly dependent on temperatures. Material parameters with respect to a large temperature range for Ti6Al4V were concluded from previous literature and reports [133–136], as listed in Table 3. A huge variation between material properties at room temperatures and cryogenic temperatures is notified in this case, which is nonnegligible for numerical modeling. These properties can significantly influence the material responses toward plastic deformation and damage and therefore surface integrity.

For composites like CFRP, the 3D numerical simulation of the drilling process is currently carried out in terms of purely mechanical responses [97–99,137,138], and as for normal cutting conditions without coolants, the temperature rise is not huge, which is normally lower than 150 °C as presented by Xu et al. [76] and Fu et al. [77]. Within this temperature range, alterations of material behaviors are negligible. Moreover, the main concern in constitutive modeling of CFRP materials is attributed to damage evolution, which is composed of fiber tension, fiber compression, matrix tension, and matrix compression. It is not sensitive to thermal effects under normal cutting conditions as well. These damage models are generally referred to brittle fracture, where inelastic energy dissipation is not taken into consideration; therefore, no temperature rise is induced by material deformation.

However, cryogenic temperatures do have a significant impact on mechanical behaviors of composites, as summarized by Sápi and Butler [139]. In some cases at −196 °C, the increase of Young's modulus can be more than 100% with the increase of tensile strength about 50% for GFRP, while for CFRP, the increase of Young's modulus can also be more than 50% with the increase of tensile strength more than 50%. When considering the average value with respect to different compositions of fibers and resins, the increase can still be about 20–30% for Young's modulus and 20% for tensile strength and Poisson's ratio, which can also enhance the heterogeneity of the material. As a result, to precisely predict mechanical responses of composite materials at cryogenic temperature, material should be further developed to merge more data and behaviors related to cryogenic temperature.

To model machining composites at cryogenic temperature, the authors recommend two solutions. The first is to develop fully coupled thermomechanical models, where the major difficulty is to calculate temperature-dependent behaviors and inelastic energy dissipation. It reflects the most realistic condition as actual machining operations; however, it significantly increases the computational costs. Moreover, inelastic heat dissipation should be considered in terms of modeling material behaviors. Another issue lies within the heat transfer of the interface layer, which is always modeled through cohesive elements and they do not support the degree-of-freedom for temperature in most of the current machining simulations. The second is to develop sequentially coupled models, where the working temperature of composites involved in cryogenic drilling should be measured experimentally. Then mechanical tests at pertinent temperature should be carried out to obtain accurate mechanical behaviors under the working condition. This is a hybrid approach with both experimentally determined inputs and numerical simulation. It is practical and effective in terms of understanding the fundamentals involved in cryogenic drilling, while less realistic compared to the previous method.

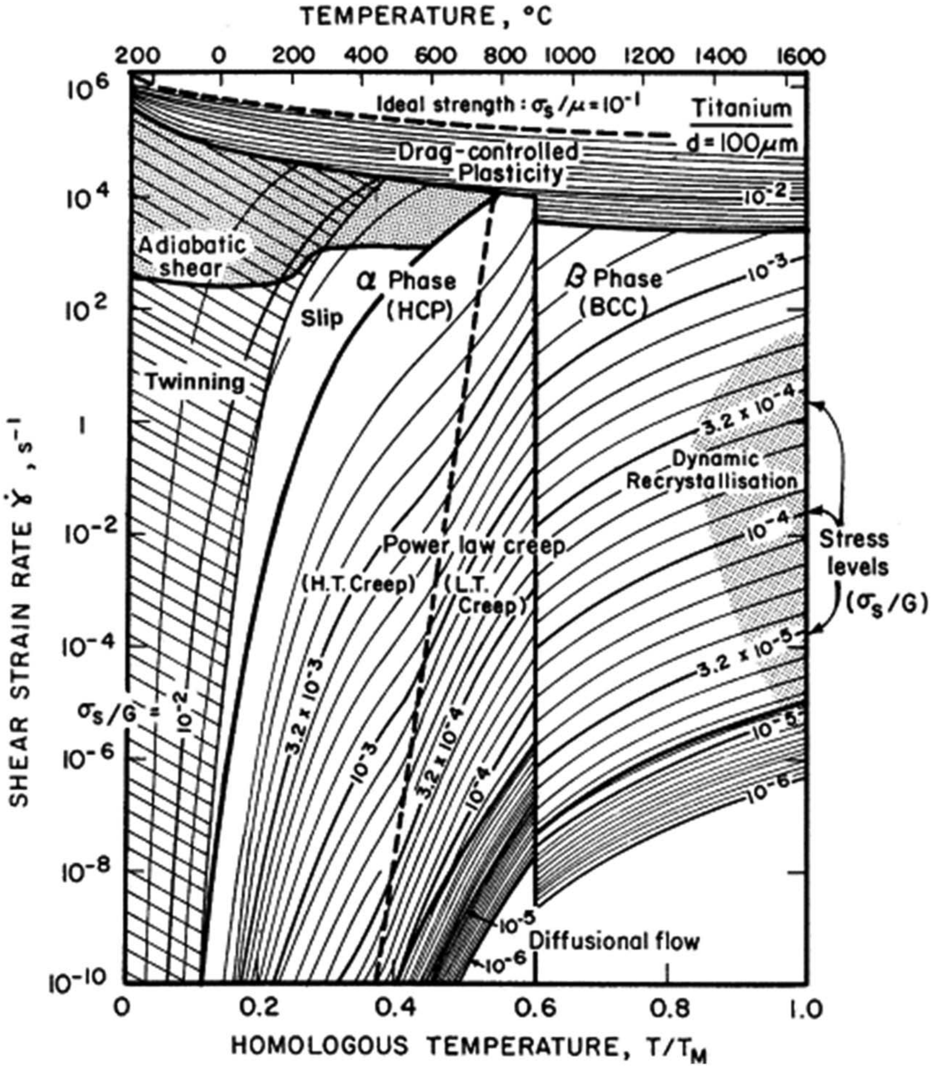


Fig. 14 Alteration of deformation mechanisms and constitutive behaviors with respect to temperature and strain rate for titanium [132] (Reprinted with permission from Elsevier © 2001)

3.1.3 Numerical Approaches. The finite element method (FEM) is the most commonly used approach in terms of numerical simulation of machining processes. It has a wide range of application and thorough consideration of both mechanical and thermal phenomena. Concerning machining simulations, dry conditions are always applied to simplify the problem. While for cryogenic machining, cooling is a key and nonnegligible procedure. Preliminary models of cryogenic machining are normally developed toward orthogonal cutting processes due to their simplicity, and general methods on numerical modeling of cryogenic machining processes can be concluded as follows.

The first approach is to model through sequential coupling method with FEM and CFD. It simulates the dry cutting condition through FEM and then applies the simulation results as initial conditions of the CFD model to launch a cooling simulation [140,141]. This method presents a good description of cooling performance of cryogenic flows on the cutting procedure, which is beneficial in terms of optimizing cooling parameters. However, mechanical interactions between coolants and work material cannot be characterized, as thermomechanical conditions involved in cutting processes are treated as initial conditions for cooling, while no feedback of cooling effects is returned for the responses in thermomechanical loading.

The second one, which is also the most popular one, is to set up a heat exchange window within a specific area involved in cutting, so

Table 3 Material properties of Ti6Al4V with respect to a wide temperature range [130,133–136]

Temperature (°C)	Specific heat (J/kg·K)	Thermal conductivity (W/m·K)	Thermal expansion ($\times 10^{-6}$ m/m·K)
−253	8.21	0.8426	−86.8
−248	16.04	1.5763	−69.44
−223	99.52	2.4107	−34.16
−193	228.85	3.5308	−20.1375
−173	301.03	3.8045	−15.16
−123	415.5	4.6215	−7.94
−73	478.13	5.7498	−3.93
−23	513.72	6.5931	−1.415
2	530.05	6.9826	−0.524
22	538.84	7.4145	8.5
100	562	7.45	8.78
200	584	8.75	9.14
300	606	10.15	9.49
400	629	11.35	9.85
500	651	12.6	10.21
600	673	14.2	10.57
700	694	15.5	10.93
800	714	17.8	11.28
900	734	20.2	11.64
1000	754	22.7	12

that a fully coupled thermomechanical simulation can be launched with heat transfer to cryogenic coolants. In this case, the heat convection coefficients are simplified to a constant value. Normally, the simplified values should be validated against CFD simulation as proposed by Shi et al. [131]. However, in most cases, to reduce high computational costs and reach fast thermal balance, the authors used an assumed high value as conductive coefficients instead of identifying it through more reliable approaches [126,142–144], which lose some reality.

The heat exchange window is embedded into areas of either cutting tool or work material, depending on cooling conditions performed through internal or external methods. Liu et al. [145] decomposed the machining procedure into chip formation and ploughing, and the effects of coolants were implemented as a heat convection coefficient for the two separate procedures, respectively. Generally, this method is more effective and easily configured compared to the previous one. It simplifies the description of cryogenic flows, while presents a better work on thermomechanical interactions when cryogenic cooling is involved. However, the physics of cryogenic flows are significantly simplified, as well as the interaction between cryogenic coolants and work materials. It mainly focuses on the mechanisms of material deformation under the assumption that the deforming temperature is not prominently influenced by cryogenic coolants. As a result, it can be applied when chip formation is the major concern, while for other conditions with more focuses on flow behaviors and surface integrity, it is not recommended.

Generally, although these methods are developed based on different purposes, mechanical responses of work material to cryogenic coolants are always neglected. To overcome this issue, the approach of fluid–structure interaction (FSI) is highly recommended, which was proposed by Ayed et al. [146] for the application in water-jet-assisted machining, where a coupled Eulerian-Lagrangian (CEL) approach was applied with the boundary conditions shown in Fig. 15(*a*). This method provides a close-loop consideration of interactions between fluids and solids, while the major drawback lies in the heat transfer during the interaction. As discussed by Ayed et al. [146], heat transfer was realized through developing an individual script, as it is not a built-in function involved in the commercial software ABAQUS/EXPLICIT. This issue increases the difficulties of its application, as well as the computational costs, especially when considering multiphase flow behaviors of cryogenic coolants.

Another FSI approach was proposed by Oezkaya et al. [147] toward the application in drilling, as shown in Fig. 15(*b*). While it is a sequentially coupled approach based on FEM and CFD, instead of fully coupled thermomechanical interactions of fluids and solids as CEL. They simulated the chip formation and then developed a substitute model to represent chip geometry with verified thermomechanical conditions, where the CFD simulation of cutting fluids was performed with the substitute model. Although this method presents a good idea in terms of simplifying the complicated boundary conditions in drilling, it neglects the feedback of influences of fluids on mechanical behaviors.

However, both methods are not applied in cryogenic machining despite a high potential to be used in the future. The major challenge to use this method is attributed to the following aspects: (1) heat transfer between liquids and solids and (2) multiphase flow characteristics of cryogenic coolants and pertinent phase change heat transfer.

Concerning 3D numerical simulations of cryogenic drilling, theoretically, approaches illustrated earlier are all eligible. However, due to the difficulties of simulating the behaviors of multiphase flows, rare reports are performed toward cryogenic drilling through sequential coupling method with FEM and CFD. A CFD simulation of cryogenic drilling with LN_2 was reported by Outeiro et al. [63], where they modeled the fluid characteristics with consideration of tool rotation realized through a moving reference frame model. However, the influence of chip formation was neglected in their model, and the characteristics of multiphase flows were not clearly addressed.

To address the influences of chip formation on fluid behaviors, Oezkaya et al. [147] proposed a simplified CAD model with formed chips when launching the CFD simulation for conventional cooling cases. It introduces the effects of chip geometry on streamlines of fluids, which characterizes more realities involved in real drilling operation. However, for multiphase flows involved in drilling, no good CFD models have been developed, which may be due to the difficulties of convergence of complex boundary conditions and fluid characteristics.

As a result, configuration of heat exchange windows is the most commonly adopted method in terms of cryogenic drilling simulations, and the values of heat transfer coefficients are most likely to be identified through analytical models as discussed in Sec. 3.1.1. However, compared to 2D orthogonal cutting and 3D turning, the time domain required for accessing thermal steady state is much longer in drilling. As the drill passes a same location multiple times following the continuous revolutions, thus, thermal accumulation is a major concern that can directly influence processes including chip evacuation, surface integrity, etc., which cannot be easily neglected. This makes simulation of drilling extremely time consuming.

Moreover, due to the complex boundary conditions and easily occurred issues of elements distortions in drilling simulations, the

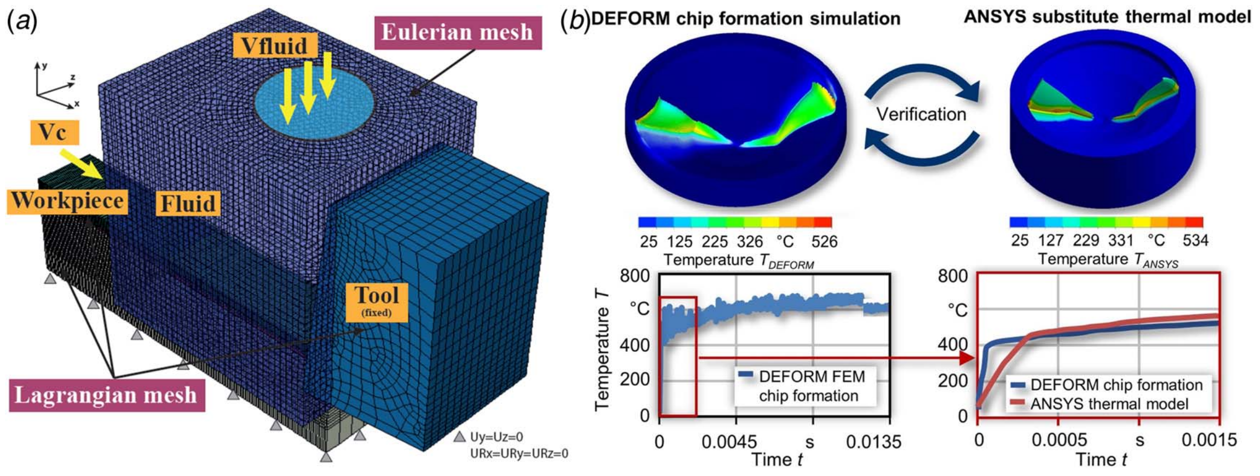


Fig. 15 Schematic of the FSI method during machining: (*a*) orthogonal cutting with CEL approach [146] (Reprinted with permission from Elsevier © 2016) and (*b*) drilling with sequential coupled FEM and CFD [147] (Reprinted with permission from Elsevier © 2019)

Table 4 Summary of current modeling approaches for cryogenic drilling

Researchers	Approach	Platform	Description
Kheireddine et al. [148,149]	FEM simulation with internal cooling of cutting tool	Deform 3D	A 3D FEM model for drilling was set with remeshing technique, and effects of cryogenic coolants are implemented through assignment of constant heat convection coefficient inside the internal lubrication holes of the drill.
Dix et al. [114]	FEM simulation with internal cooling of cutting tool and spray cooling on surface of workpiece	Deform 3D	3D FEM simulation was performed with implementation of heat transfer induced by cryogenic coolants, and the coefficient was calculated according to thermal models and assigned to different areas. This model is more realistic while the computational costs are very high, and more than 1 week is required for a simulation of merely 2.5 revolutions.
Outeiro et al. [63]	CFD model for flow condition of coolants and FEM model with implementation of heat convection at tool–work interface	Deform 3D	CFD model and FEM model were used for calculation of coolants flowing and cryogenic drilling, respectively. In FEM simulation of cryogenic drilling, heat convection was configured at tool–workpiece interface with a constant value.
Attanasio et al. [128]	FEM simulation with implementation of heat convection at tool–work interface	Deform 3D	FEM model was developed with implementation of heat convection coefficient applied at the tool–work interface with a value calculated theoretically, and a novel progressive model of tool wear was developed.
Liu et al. [130]	A hybrid modeling approach based on FEM	ABAQUS/ STANDARD	A hybrid model based on FEM method was proposed to investigate deformation of surfaces during drilling under different cooling conditions. Material models with properties at low temperature are used, chip formation is equivalent as thermomechanical loadings applied on the machined surface, and nonuniform distributed heat convection is also applied following the actual drill trajectory.

platform Deform 3D turns to be the most popular option due to their updated Lagrangian algorithm with remeshing techniques and optimization toward machining. To realize FSI with models developed by this platform, a communication with other CFD software is always required, which also enhances the difficulties of modeling. This also explains the reason why heat transfer window is always used in terms of modeling cryogenic drilling. Table 4 summarizes the major contributions concerning 3D numerical simulations of cryogenic drilling.

Although Deform 3D shows excellent advantages in terms of setting drilling models, the computational costs are still extremely high. As reported by Dix et al. [114], 2 weeks are required to reach 2.5 revolutions for a 7 mm diameter drill with a heat transfer window to cryogenic coolants, which is unreasonable especially toward engineering purpose, as shown in Fig. 16. It characterizes chip formation in drilling with consideration of the drill cooled by cryogenic liquids inside. Although in their case they used 42CrMo4 steel with a higher thermal conductivity and intended to obtain a quasi-static temperature distribution, 2.5 revolutions are still far from enough to reach a thermal steady state, let alone other difficult-to-cut materials like Ti6Al4V.

To reduce the high computational costs and analyze the invisible material behaviors involved in drilling processes, a hybrid modeling approach was proposed by Liu et al. [130]. It was applied toward understanding hole shrinkage mechanisms during drilling under dry and cryogenic conditions. In this case, cryogenic cooling condition was characterized as a nonuniform distributed coefficient sprayed on the work material following the actual path of the movement of drill margin. Meanwhile, the equivalent thermomechanical loadings are calculated from experimental data under thermal steady state. The schematic of their configuration can be characterized as shown in Fig. 17. For future development, it can also provide results concerning physical features involved in surface integrity with implementation of physics-based laws, such as microstructures, micro-hardness, etc.

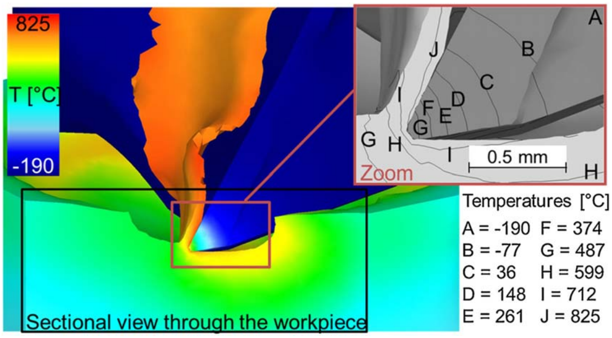


Fig. 16 Numerical simulation of the drilling process with cryogenic cooling [114] (Reprinted with permission from Elsevier © 2014)

The major drawback of this approach is the lack of chip formation, so it is only eligible when surface integrity is the only concern. Moreover, it cannot work as a predictive modeling approach, as all the conditions during chip formation are equivalent as thermomechanical loadings, including heat flux, nominal pressure, tangential pressure, and heat convection coefficient, which should be identified through experiments. As a result, the actual interaction between cutting tool and work material cannot be well characterized, especially when considering tool wear and chip formation/evacuation.

To summarize, high computational cost is the major limitation in terms of drilling simulation. Generally, the numerical approaches involved in cryogenic machining with simplified boundary conditions like orthogonal cutting and turning can be all applied for drilling as well. However, due to the rapid decreasing of computational efficiency, most researchers have chosen to use the most simplified cooling boundaries. Although the hybrid modeling approach accelerates the speed of simulation, it sacrifices the aspects of chip formation. These issues are expected to be overcome through further development of computing techniques and advanced algorithms. While concerning physical aspects involved in cryogenic drilling, FSI is highly recommended due to its realistic description of thermomechanical conditions. The first step is to model the multiphase flow condition and its interactions with work materials during machining, and the high computational cost is still a major obstacle toward its realization. Moreover, numerical models of cryogenic drilling are mainly developed toward metals as reviewed in this section, and no improvements are proceeded toward composites, where a hug gap still exist in this realm and require further attentions.

3.2 Experimentation.

As reviewed in Sec. 3.1, researches on cryogenic drilling are still heavily dependent on experiments due to these obstacles in numerical modeling. Thus, to execute experiments well, a stable system for delivering cryogenic coolants is required. Moreover, reliable approaches and strategies to measure

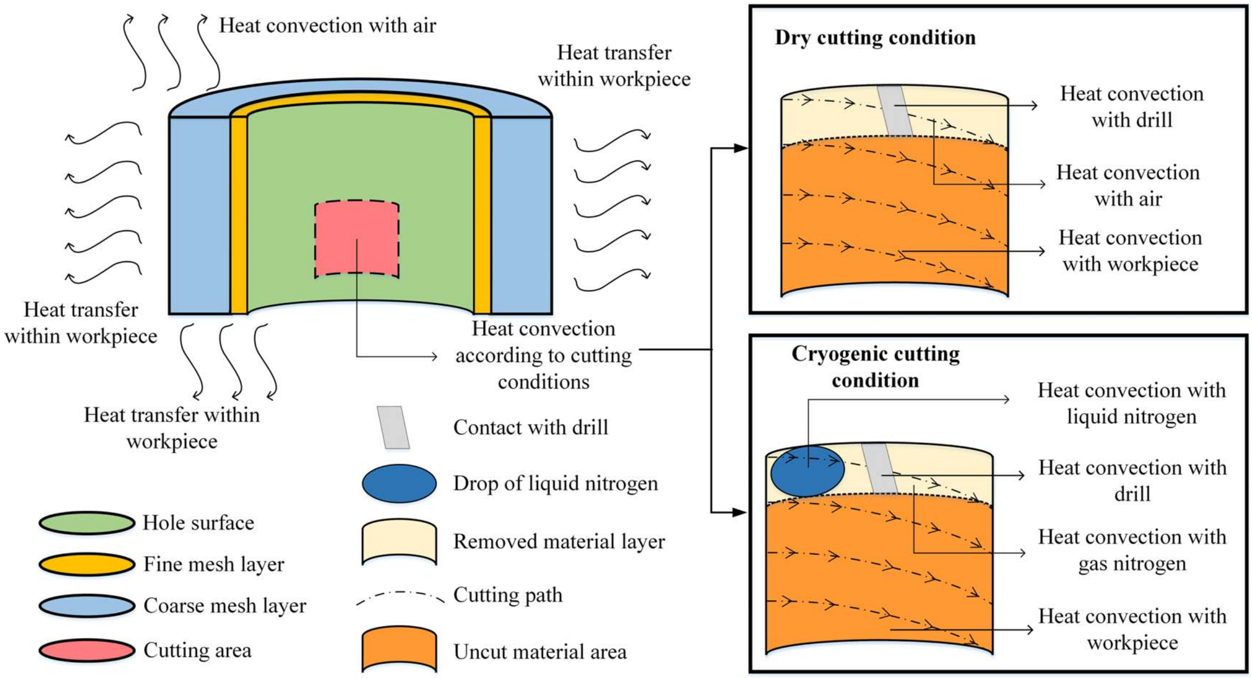


Fig. 17 Boundary conditions of the hybrid modeling approach toward cryogenic drilling [130]

the on-site parameters are essential. This section will present a brief review on experimental setup designed for cryogenic drilling processes from coolants delivery and data acquisition systems.

3.2.1 Delivery Systems of Cryogenic Coolants. For delivering cryogenic coolants into the cutting area during drilling, three methods are always addressed: (1) supply of cryogenic coolants through external devices; (2) supply of cryogenic coolants through internal lubrication holes of the drill; and (3) directly dip the work material into cryogenic liquids, as shown in Fig. 18. For approaches (1) and (2), cryogenic coolants need to be supplied continuously, so it is important to use a phase separator to separate the liquid and gas phases to make sure the coolants worked on the work material are liquids instead of gases. Meanwhile, the flowrate is also an important factor in maintaining the liquid phase as reported by Ayed et al. [48].

The most commonly used method is through external delivery system, and a typical schematic of this setup is presented by Khanna [119] as shown in Fig. 19. The main concern for this device is the storage of cryogenic coolants, and it also requires to make sure that the liquid phase contacts with the cutting tool, so that a phase separator is necessary. Meanwhile, good insulation is also essential toward maintaining a good cooling performance.

One of the major drawbacks of this approach attributes to the chip evacuation, which can interfere the coolant/tool and coolant/work interactions, as shown in Fig. 18(*a*), where the coolants may be blocked outside the cutting area due to the continuous formation of chips. Another disadvantage is that the coolants may be difficult to access the cutting zones with the increase of the drilling depth, even if without the influence of chip formation. This drawback degrades cooling performance at the end of drilling, so that the temperatures in machined surface can be much higher at the exit than that at the entry, as presented by Uçak and Çiçek [67]. Currently, there are still no clear conclusions on the degradation of cooling performances through external device with respect to the depth of drilling. The authors recommend to perform some researches to determine the threshold of the aspect ratio toward delivering cryogenic coolants through external device, and the internal method should be applied instead once the value exceeds the threshold.

Moreover, the requirements for delivering LN_2 are different with LCO_2. When supplying LCO_2, the formation of its solid phase, which is referred as dry ice, also needs to be avoided. As a result, Rodriguez et al. [109] proposed a "plug & play" device to maintain the CO_2 over triple point (see Fig. 20(*a*)), so that the formation of dry ice inside pipes and channels can be avoided before being projected into the cutting zone, as shown in Fig. 20. Shah et al. [152] also reported to store CO_2 in a pressurized cylinder at 60 bars and directed it through a siphon tube toward the cutting zone to prevent the expansion and finally deliver it to the tool tip through a nozzle made of a thermoplastic hose pipe. Moreover, a novel

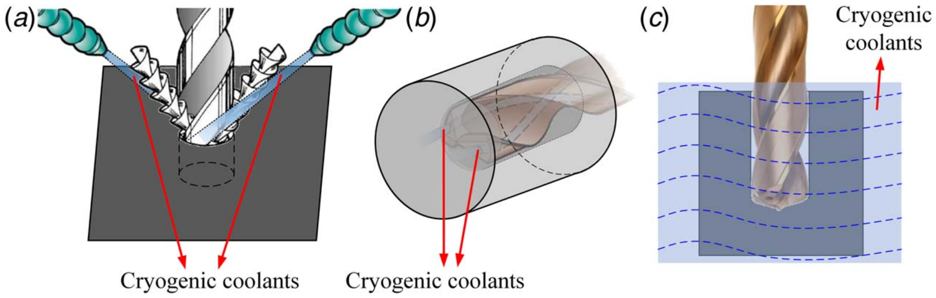


Fig. 18 Delivery methods of cryogenic coolants during drilling operation: (*a*) through external device, (*b*) through internal channels, and (c) dipping into cryogenic liquids. Images adopted from Refs [150,151].

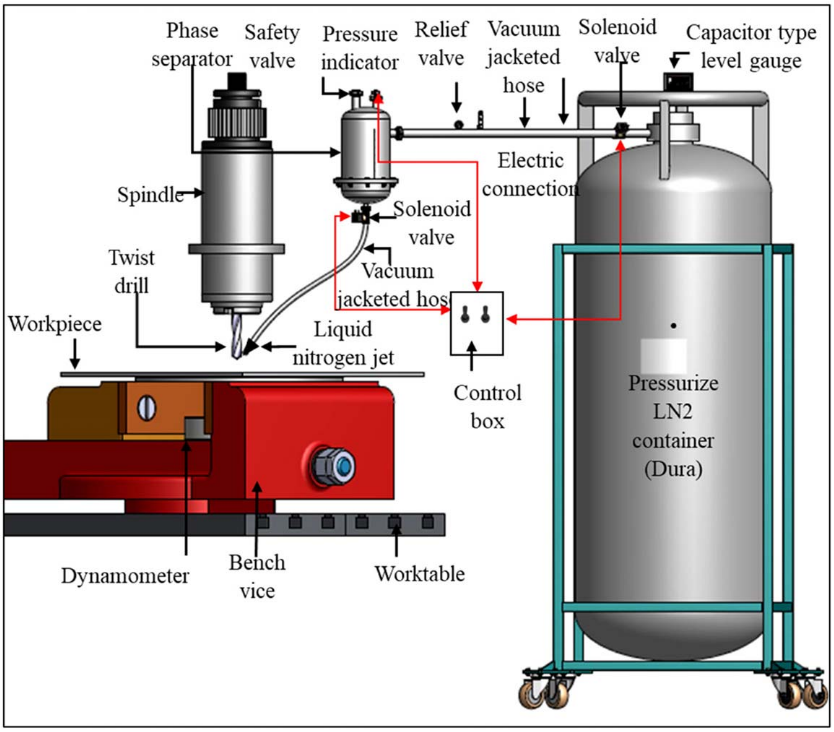


Fig. 19 Schematic of the external delivery system for cryogenic drilling [119] (Reprinted with permission from Elsevier © 2021)

usage of supercritical CO_2 is being attractive for researchers, which also has a high potential to be applied in industries.

As cooling performance of cryogenic coolants is limited due to the drilling depth when using external delivery systems, another method to supply cryogenic coolants through the internal holes of the tool is developed, and the experimental setup is shown in Fig. 21, as presented by Merzouki et al. [69]. This method can deliver the cryogenic coolants directly into the cutting area following the tool path regardless of the hole depth, which can obtain the best cooling performance. As a result, it is regarded as the best way for delivering cryogenic coolants during a drilling operation, especially in terms of deep hole drilling.

However, the configuration of this device is more complex as some modifications are required to be made directly on the machine tool, especially for the spindle system. The cryogenic coolants will pass through the spindle to access the cutting area through the internal holes. Therefore, a good insulation or a specific design should be applied to the spindle to suppress thermal errors induced by cryogenic temperature, and these effects need to be taken into account during the drilling operation. Generally, a precooling procedure is required to obtain a thermal steady state for the whole device before executing the experiments. In this case, Dix et al. [114] analyzed the performance of the through-tool cooling system, which shows that both the chuck and tool are cooled down to an extremely low temperature, and the mechanisms for the cooling procedures are different with respect to different areas, as discussed in Sec. 3.1.1. For LCO_2, the configuration may be more complex in terms of avoiding the formation of dry ice.

Moreover, for delivering cryogenic coolants, it is important to monitor the delivery conditions at real time to maintain a good cooling performance, as performances of liquid and gas phases are very different as reported by Courbon et al. [62]. The flowrate is a variable that can directly present this condition, which is easily measured as well. Ayed et al. [48] reported that the liquid phase can be well presented with a high flowrate, and they proposed to use a force sensor to monitor the continuous change of the weight of the container to characterize evolution of flowrates, as shown in Fig. 22.

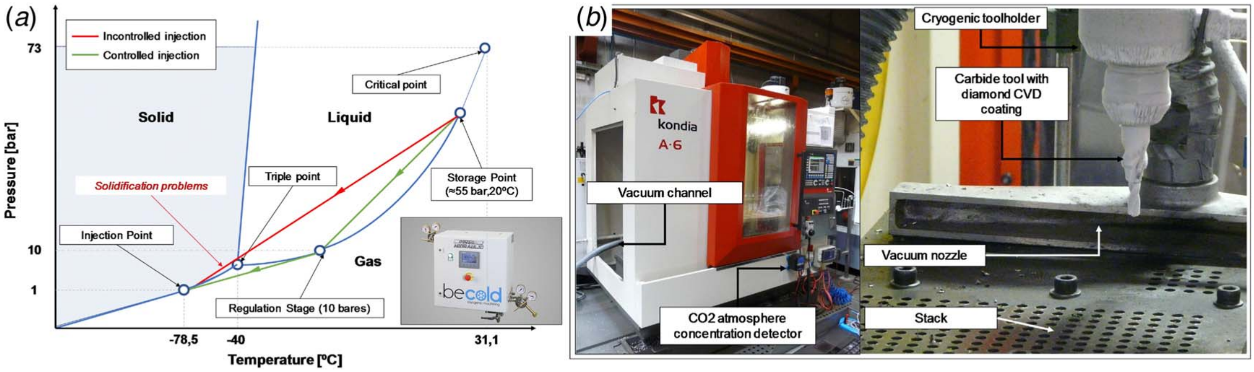


Fig. 20 Schematic of the experimental setup for delivering LCO_2 [109]: (a) diagram phase of CO_2 and (b) the drilling device with delivery of LCO_2 (Reprinted with permission from Elsevier © 2021)

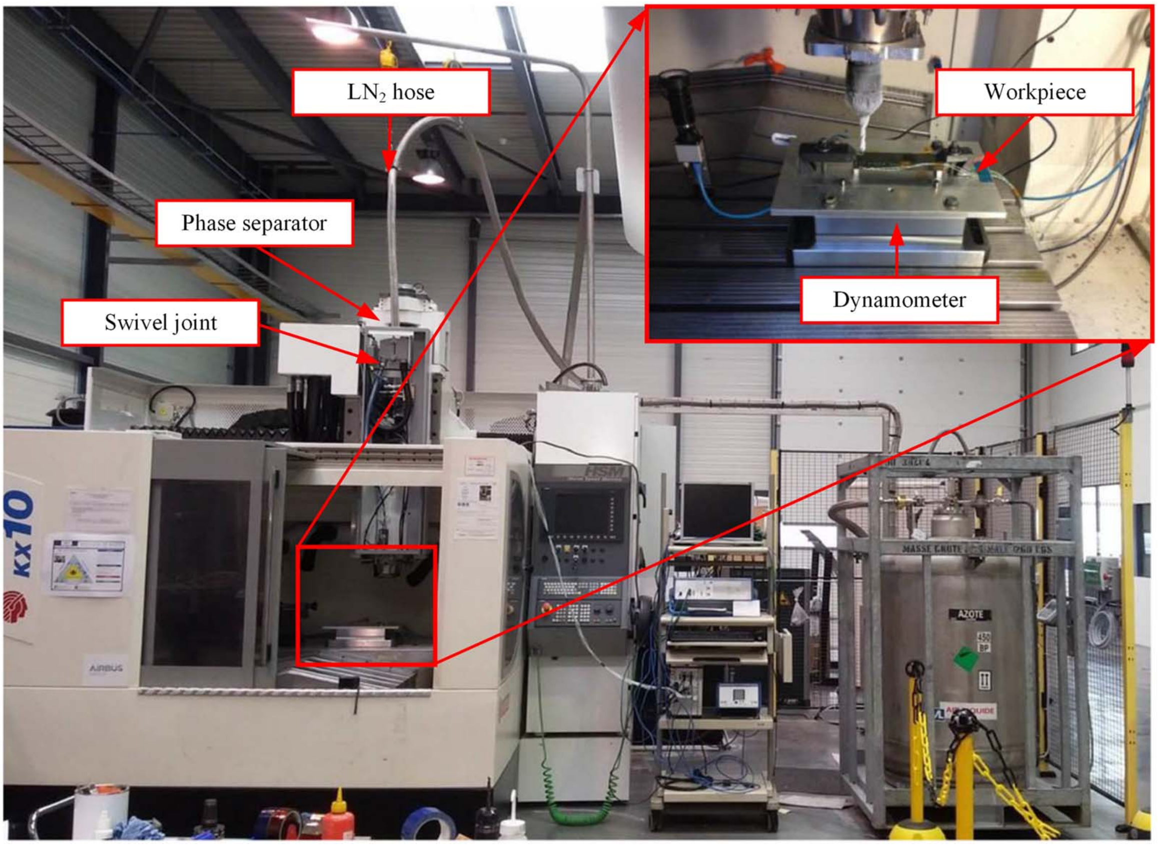


Fig. 21 Experimental setup of supplying cryogenic coolants through internal lubrication holes of the cutting tool [69]

Besides delivering cryogenic coolants, to directly dip work materials into cryogenic liquids is also a solution (see Fig. 18(*c*)), which can significantly simplify the configuration of delivering systems. Koklu and Coban [68] used it for drilling AZ31 magnesium alloy, while it is rarely reported for applications in drilling heat-resistant superalloys and more commonly used in composites. Basmaci et al. [39] and Koklu and Morkavuk [153] presented a setup to hold LN$_2$ within an adjustable fixture made by thermal insulation materials to maintain liquid phases during the drilling process. It was then developed by Morkavuk et al. [154] with better insulation condition to keep LN$_2$ reserved inside the box, as shown in Fig. 23, where polystyrene was filled at the bottom

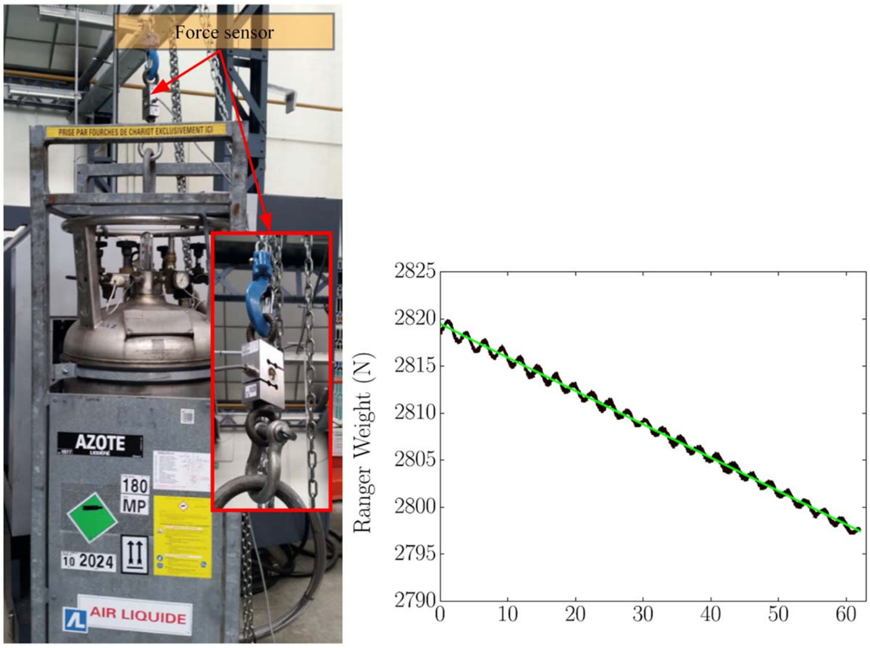


Fig. 22 Flowrate monitoring system for cryogenic coolants [48]

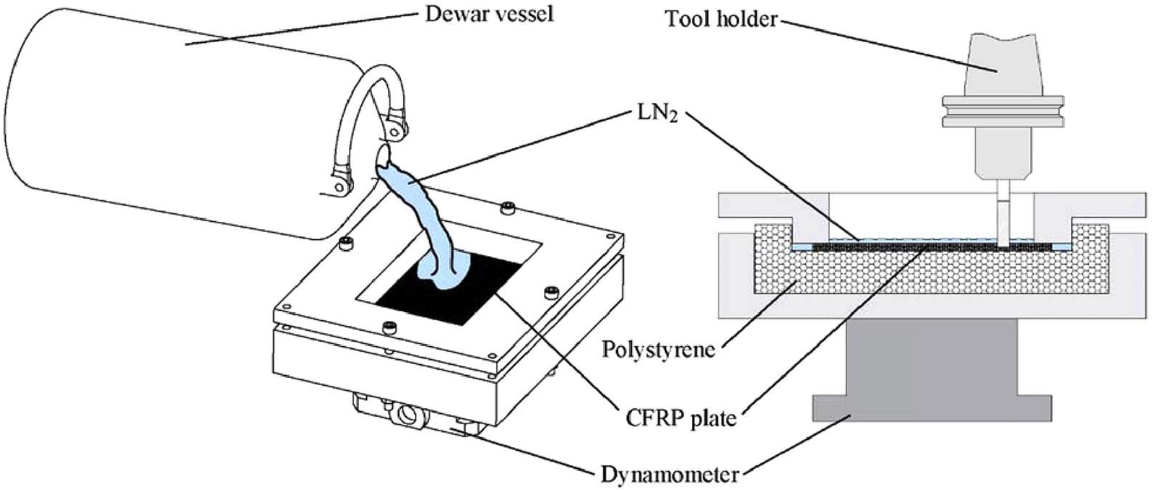


Fig. 23 Schematic of the setup for directly dipping CFRP in cryogenic coolants [154] (Reprinted with permission from Elsevier © 2018)

and around the side of the box. It provides lower heat convection coefficients compared to direct delivery due to the lack of turbulence condition at high pressures, and it is less realistic to industrial applications.

Moreover, for CFRP drilling in the cryogenic environment, Zhang et al. [155] proposed a setup using a temperature-controlling box to fix the work material, and drilling process is operated within this box. This device is integrated with the machine tool, as shown in Fig. 24. The box can maintain a low temperature at −25 °C without the supply of cryogenic coolants, and the environment temperature distribution can be more uniform and stable in this case. However, this method highly relies on the temperature-controlling box, which limits its application in industries. Meanwhile, the controlling environment temperature is not an effective method in improving cooling performance compared to supply of coolants, as the cooling effect is also significantly influenced by the heat convection condition but not merely environment temperature. As a result, this is not a practical method in terms of cryogenic machining.

Generally, these configurations reviewed in this section are all available for obtaining a cryogenic environment during drilling operations. Delivery approaches through both external device and internal holes are practical toward industrial applications. External delivery systems show better flexibility and convenience, while through-tool cooling can provide better cooling efficiency, especially for deep-hole drilling cases. Regarding the third method through directly dipping work materials into cryogenic liquids, it is more of a laboratory approach rather than an industrial technique, which is always developed toward fundamental understandings. For the last one with temperature-controlling box, it only provides low temperature without more effective heat convection conditions, which is not recommended as approaches for cryogenic machining.

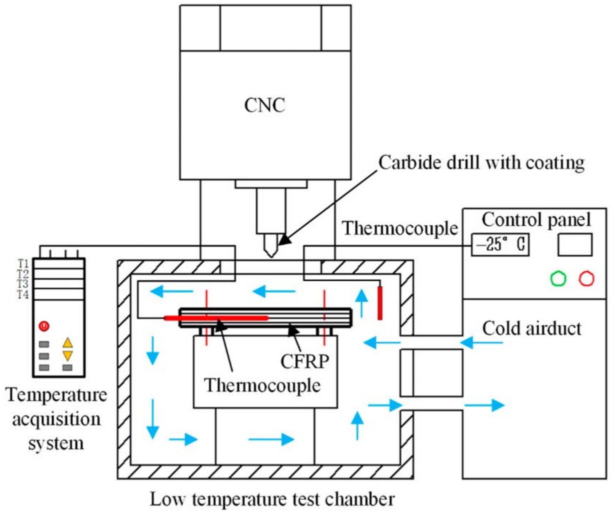


Fig. 24 Cryogenic drilling with the temperature-controlling system [155]

3.2.2 Force and Temperature Measurements. The most commonly used device for measuring cutting forces is the piezoelectric dynamometer, which can provide the most accurate and reliable data. According to different types of dynamometer, the configurations of experimental setups also show some slight differences. The easiest and most commonly used method is to mount the work material directly on a static dynamometer on the worktable [66,68,83,93,156], and normally the dynamometer can provide cutting forces of three directions and torques, a case of this configuration is shown in Fig. 25(*a*). This method is generally eligible for most cases including hybrid drilling operation with cryogenic and ultrasonic assistances, as presented by Thirumalai Kumaran et al. [157].

Moreover, some inverse configurations are recommended for delivering cryogenic coolants through-tool and measuring cutting forces with respect to the drill through a static dynamometer. This configuration can reduce the complex modifications on the spindle and the influences of cryogenic coolants on spindle systems. It is realized through mounting the drill instead of work material on a static dynamometer [85,91,92,149], as shown in Fig. 25(*b*). In general, this is more of a lab operation to fix the drill and rotate and move the work material, and drilling operation is performed through the relative movement between drill and workpiece. The major drawback of this approach is that the inertia is different between the spindle-tool system and spindle-work system, which may induce some errors of forces measurements. As a result, the comparative study depending on this setup may not be practical toward normal configurations due to the differences of dynamics. However, this issue is not discussed in cited references, so some details still remain unknown. Another drawback is that the workpiece should be built as a rotary body, and the hole to be drilled has to pass the central axis of spindle, which means only one hole can be drilled in a single operation.

Besides the static dynamometer, rotary dynamometer is also a good solution [69,128], and the detailed cutting forces in terms of phase angles and drill trajectory can be obtained through calibration in advance, as shown in Fig. 25(*c*). However, rotary dynamometers may not be eligible when cryogenic coolants are supplied

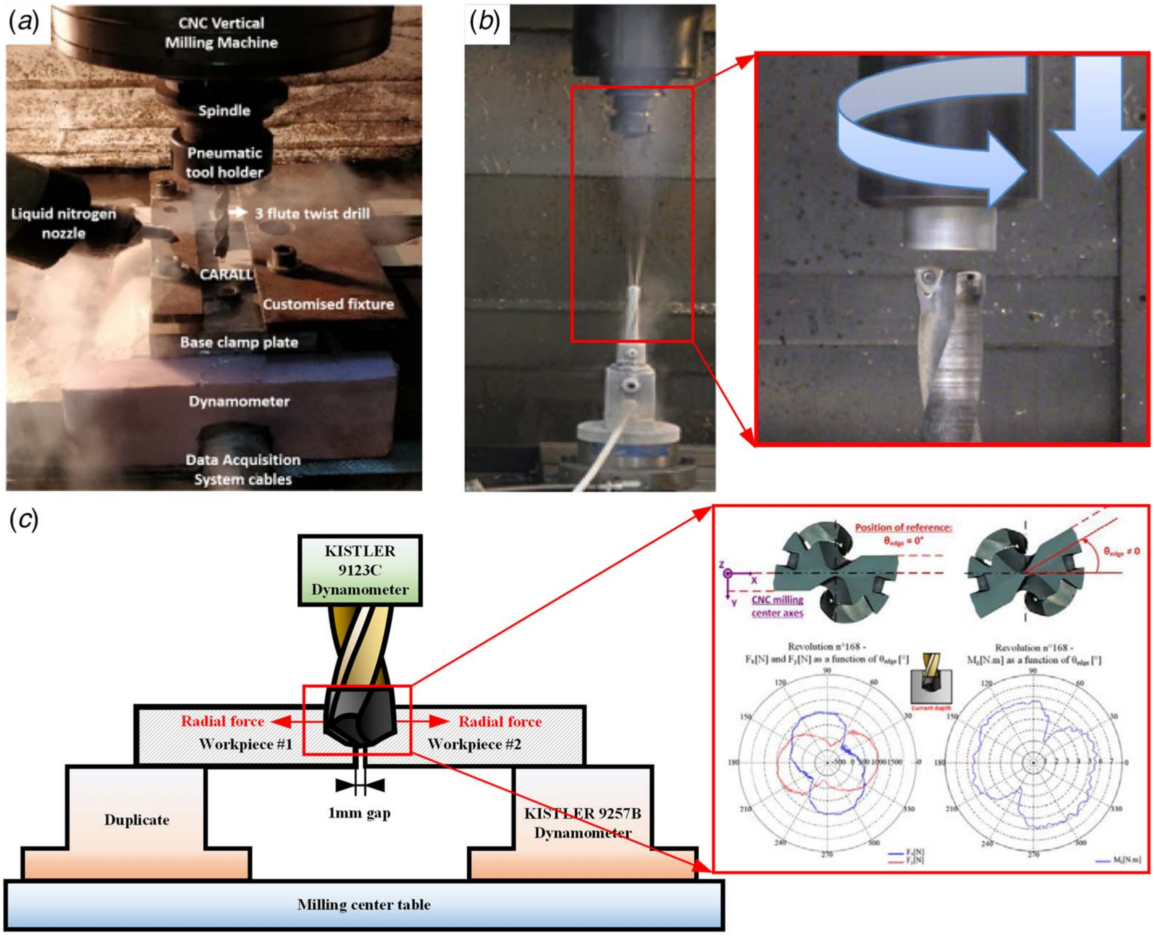


Fig. 25 Different configurations of cutting forces measurement systems with dynamometer: (*a*) workpiece mounted on static dynamometer [93], (*b*) drill mounted on static dynamometer [85,149], and (*c*) cutting forces measurement in terms of phase angle through rotary dynamometer [100,129]

through-tool, as low temperature may have negative impacts on a dynamometer. In this case, good insulation should be provided to maintain a good working temperature, protect the device, and acquire accurate data.

Cutting temperature is another key variable to be measured during the cutting process, and two devices are always proposed in this case, which are infrared camera and thermocouples. With the infrared camera, distribution of the temperature field can be easily obtained; however, it is dependent on the imaging system, which is only eligible for dry conditions, as the existence of cutting fluids significantly reduces the image quality [76,77,103,158,159]. Morkavuk et al. [154] used infrared camera to capture temperature fields during cryogenic machining with the dipping method; however, temperature distribution is only available for static condition as shown in Fig. 26, and limited information can be obtained inside the machining zone.

As a result, for cryogenic conditions, thermocouple is a better choice toward obtaining accurate curves of temperature evolution, especially in terms of temperature distribution inside work material and cutting tools. To access temperature data within the cutting zone, two approaches can be used. The first one is to embed thermocouples into the workpiece, which is the most commonly used method, as shown in Fig. 27. It requires multiple thermocouples along the depth direction of the plate to obtain temperature evolution with respect to the feed position. The distance between the bottom of thermocouple boreholes and the hole surface to be drilled is a key factor influencing the data accuracy. Thermal grease or glues should be used to fill the boreholes increase thermal conductivity between thermocouples and work materials. However, filling the holes with grease may increase the distance between thermal conjunction and machined surface, which should be noticed during actual operation.

The second method is to embed the thermocouples into cutting tools. This application is commonly used in turning cases as the cutting tool is fixed and static [31]. For drilling operation, it is difficult due to the rotation of the drill. To overcome this issue and obtain cutting temperatures from the perspectives of cutting edges, Lazoglu et al. [160] developed a new device named as

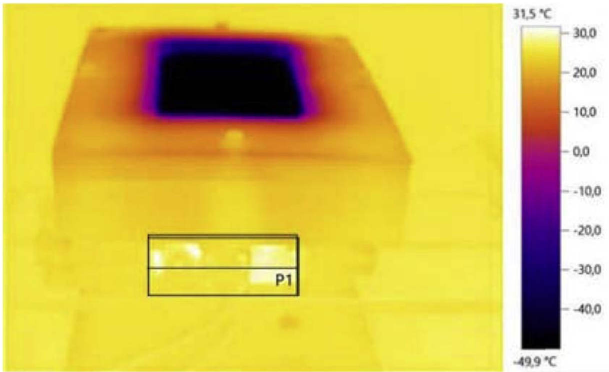


Fig. 26 Temperature measurement through infrared camera for the cryogenic condition when dipping workpiece directly into the coolants [154] (Reprinted with permission from Elsevier © 2018)

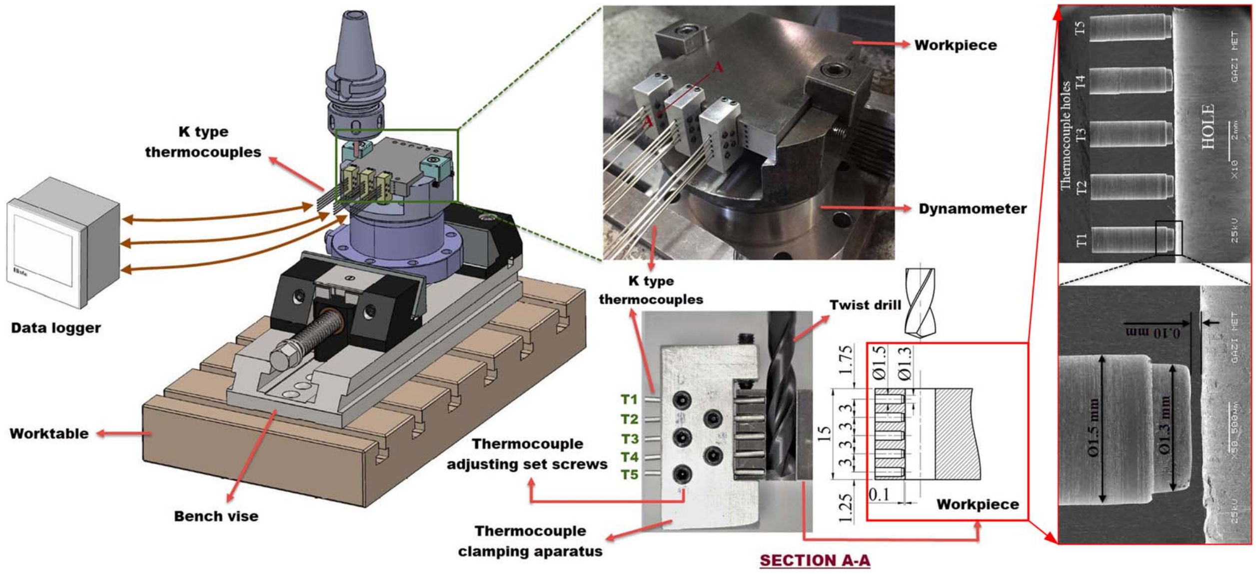


Fig. 27 Schematic of embedding thermocouples into workpiece to measuring cutting temperatures during cryogenic drilling [67] (Reprinted with permission from Elsevier © 2018)

rotary tool temperature (RTT) device. This device is mainly composed of three parts: (1) thermocouples; (2) controlling and data acquisition module; and (3) memory. For embedding thermocouples into the drill, two small holes with a diameter of 0.5 mm should be drilled in the drill bit through electrical discharge machining, and the wires of thermocouples are inserted into them through the internal lubrication holes. Metal glues are used to connect thermocouples and the drill. A calibrated clock is implemented into the device to record data with respect to timeline. The data are recorded into an individual memory to be downloaded after each measurement. The schematic of this device is presented as shown in Fig. 28. In this case, the RTT device is integrated with a rotary dynamometer, and due to the application of the calibrated clock, a real-time evolution of both cutting forces and temperatures can be simultaneously obtained and analyzed.

The accuracy of temperature measurement is also dependent on the distance between thermocouples and cutting edges. Lazoglu et al. [160] positioned thermocouples in both drill lips and corners with a same distance of 0.4 mm for a comprehensive description of temperature evolution within different areas of the cutting tool. While in the cases of Xu et al. [76,103] and Dang et al. [161], a similar device as RTT was used without drilling additional holes for embedding thermocouples, which leaves a distance of about 1.5 mm between the thermocouples and cutting edges, and this may lead to a large difference between measured data and actual temperature in the cutting zone. Furthermore, this approach requires

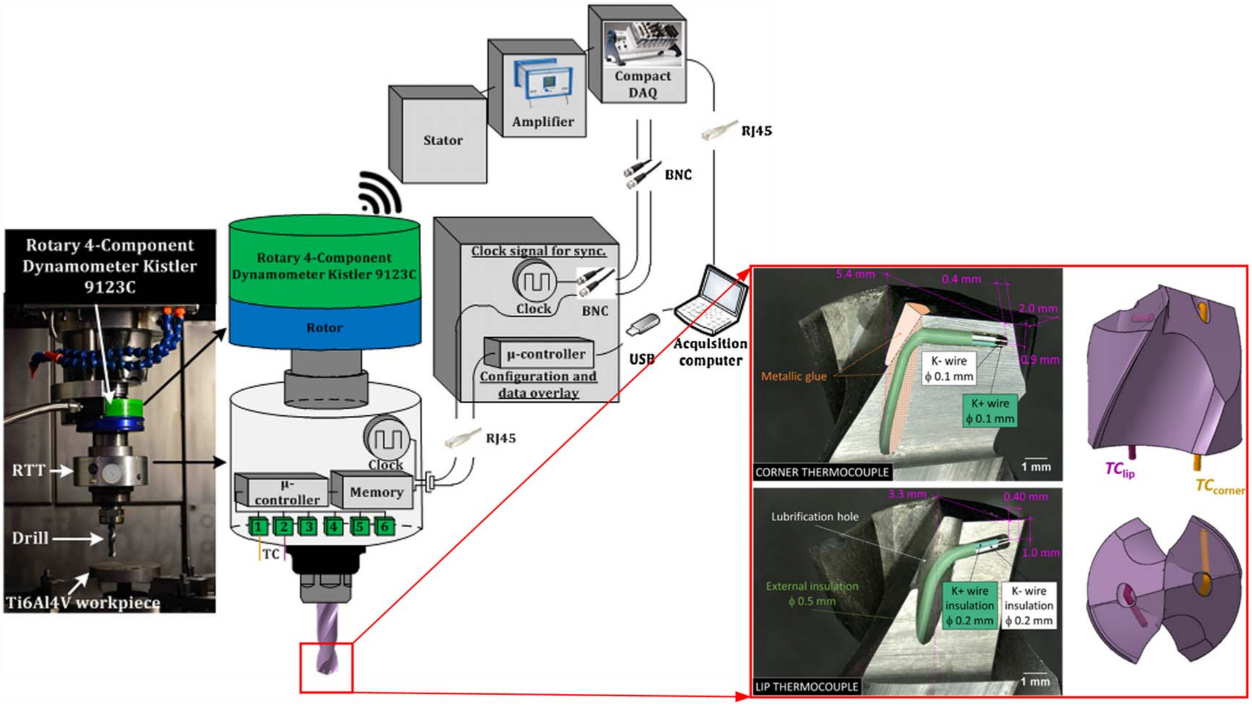


Fig. 28 Schematic of the RTT device [160] (Reprinted with permission from Elsevier © 2017)

internal lubrication holes for embedding thermocouples, which is conflict when the coolants are supplied through-tool. As a result, it is recommended for most conditions exempting supply of cryogenic coolants through-tool.

To summarize, data acquisition is very important in terms of evaluating cutting performance quantitatively. In cryogenic drilling processes, more technical issues may appear other than the rest cutting conditions due to the excellent cooling performances and physical properties of cryogenic coolants. As a result, different devices and approaches are developed toward different applications, which should be carefully addressed and adjusted according to the entire experimental setup to obtain the most reliable and accurate data. Moreover, for measuring cutting forces and temperatures in cryogenic drilling directly and simultaneously, rotary dynamometer integrated with RTT device is highly recommended, as it can provide robust data of both forces and temperatures from a unique perspective, even if some drawbacks and limitations exist, and the treatments of cutting tools are difficult.

4 Impacts of Cryogenic Coolants on Cutting Performances

Cutting performance can be evaluated from following parts: (1) thermomechanical conditions, including cutting forces, temperatures, chip evacuation, etc.; (2) surface integrity, such as roughness, hardness, etc.; (3) tool wear and sustainability. This section summarizes the performance of cryogenic drilling on these aspects.

4.1 Thermomechanical Loadings. Forces and temperatures are the most important process parameters directly acquired towards evaluating on-site conditions of cutting. Cutting forces and torques can be measured through both static and rotary dynamometers as reviewed in Sec. 3.2.2. Generally, cryogenic assistance induces the rise of cutting forces as higher stiffness always appears at low temperature, and the percentage of cutting forces increase can be suppressed with the increase of cutting speeds, as shown in Fig. 29(*a*) from the study by Merzouki et al. [69]. Meanwhile, for heat-resistant superalloys including both Ti6Al4V and Inconel 718, although thrust forces increase when cryogenic coolants are supplied, torques decrease, as shown in Figs. 29(*a*) and 29(*b*), which is also reported for drilling CFRP/Ti stacks compared to the flood condition [107]. However, for drilling individual CFRP, both thrust forces and torques increase under the cryogenic condition, as shown in Fig. 29(*c*).

The phenomenon of the decrease of torques with the supply of cryogenic coolants in drilling Ti6Al4V is explained by Merzouki et al. [69], where they decomposed the torques with respect to their sources and analyzed their contributions individually, as shown in Fig. 30. The results showed that contributions from main cutting edges and chips are similar regardless of cooling conditions, while the contribution from margin is significantly decreased when cryogenic coolants are used, as hole shrinkage can be prominently restrained under the cryogenic condition. As a result, the additional interaction between cutting tool and machined surface can be well prevented.

Fundamentals of phenomenon are further explained by Liu et al. [130] through incorporating a hybrid numerical model, which shows that the spring-back of work materials is significantly reduced once cryogenic coolants are applied. This explanation is also beneficial for similar phenomena in other heat-resistant superalloys with a high sensitivity of temperature-dependent properties; however, for CFRP, this approach may not be practical as its thermal reactions are not so sensitive as for superalloys. Meanwhile, other factors like delamination will also influence pertinent behaviors, which will be discussed in the following section.

To access temperature evolution in cutting zones during cryogenic drilling, thermocouples are more reliable while their positions require to be strictly controlled. Islam and Boswell [162] presented some experimental data of temperature evolution during cryogenic drilling of AISI4340 steels, which shows a similar value between cryogenic and flood conditions; however, detailed information of the positions for thermocouples were not provided, so that some in-depth analysis of this phenomenon cannot be well addressed.

Uçak and Çiçek [67] embedded five thermocouples into the positions with a distance of 0.1 mm to hole surface along the feed direction, as presented in Fig. 27, which can be used to present a good description of temperature evolution during the whole drilling process in terms of different drilling depths, as shown in Fig. 31. According to their results, cryogenic coolants provide an excellent cooling performance for work material, where the temperature decreases rapidly to negative at the entry and increase slowly with respect to the feed depth. Meanwhile, when an appropriate coating is applied on the drill, cutting temperature can be better controlled even at the exit. In their case, external device was used to deliver cryogenic coolants, so cooling effects start to degrade following the increase of the depth of drilling. With through-tool cooling strategy, a different curve of temperature evolution with better cooling performance may be obtained.

Generally, with respect to all the materials categories, low cutting forces and low temperatures are always contradictory, and cryogenic coolants can significantly reduce cutting temperatures, while forces are increased. One interesting thing to be highlighted is, with the increase of cutting forces in cryogenic drilling superalloys, torques decrease. It is due to their sensitivities in responses to thermal effects. While for composites like CFRP, this phenomenon disappears. The variations of cutting forces, torques, and temperatures are also important factors for explanations and evaluations of some effects induced by cryogenic coolants on surface integrity and tool wear, as discussed in the following section.

4.2 Surface Integrity. Surface integrity is a comprehensive evaluation of components from the perspectives of surface characteristics and functional performances [163,164], including geometrical features like surface roughness, waviness, and physical–mechanical features like hardness, corrosion resistance, and fatigue life. Drilling operation is normally a semi-finishing procedure toward assembling the components, which is always performed immediately before assembling and requires good surface integrity to maintain the precision in assembling and performances in services, especially under cyclic loadings. With the supply of cryogenic coolants, a prominent alteration is introduced into the material properties, and the reactions are different with normal conditions as well.

4.2.1 Geometrical Characteristics. For cryogenic drilling of superalloys like Ti6Al4V, the most profound improvements are the decrease of surface roughness and burr formation and the increase of geometrical accuracies like circularity and cylindricity. Biermann and Hartmann [45] reported a reduction of burr formation in drilling tempered steel 34CrNiMo6 and aluminum alloy AlMgSil with cryogenic assistance of CO_2 snow, which shows an impact on material ductility and reduces the burr height as a result. Shah et al. [29,71] and Ahmed and Kumar [38] tested the effects of cryogenic coolants on hole quality in drilling Ti6Al4V, where a prominent improvement toward surface roughness, circularity, and cylindricity was reported compared to the flood cutting condition. Moreover, Shah et al. [29] also tested and compared the performances of LN_2 and LCO_2, where a better performance was found with the supply of LCO_2, especially when large amounts of holes were drilled, as shown in Fig. 32.

Furthermore, due to the high elasticity and low thermal conductivity of Ti6Al4V, spring-back is easy to be activated to induce additional interactions between cutting tool and work material in drilling operations, which is referred as hole shrinkage [69,130]. This phenomenon always occurs at the interface of drill margin and machined surface, which brings negative impacts on hole geometry, and the unique shape of holes cannot be well maintained as a result, especially when large amounts of holes are drilled and

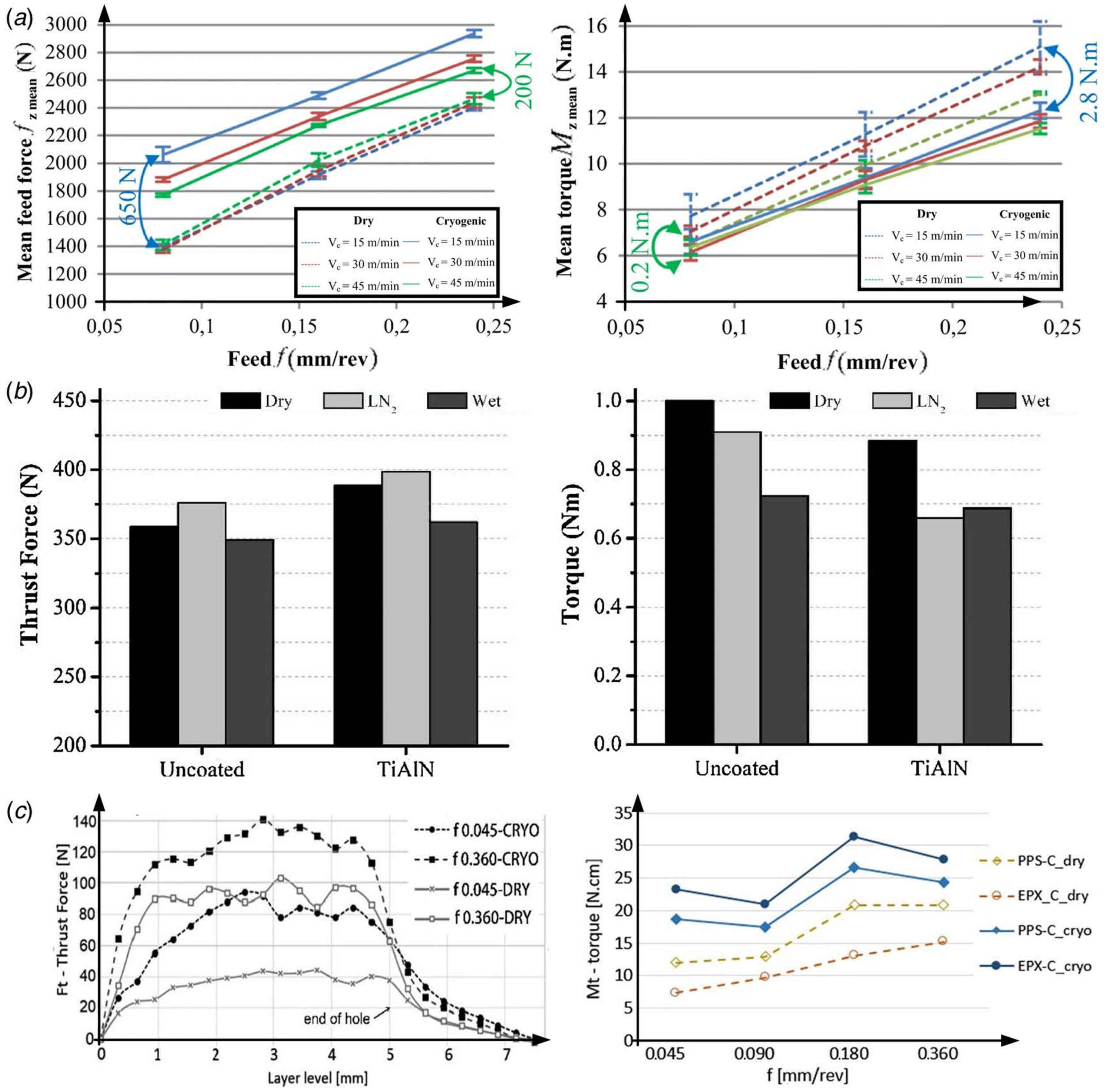


Fig. 29 Comparisons of thrust forces and torques under different cooling conditions for different work materials: (*a*) Ti6Al4V [69], (*b*) Inconel 718 [67] (Reprinted with permission from Elsevier © 2018), and (*c*) CFRP [92]

tool wear appears. This impact can be well controlled through supply of cryogenic coolants, as most of heats are removed by coolants instead of being transferred into cutting tool and workpiece, and thermal expansion of Ti6Al4V at low temperatures shows a different behavior compared to that at high temperatures [130]. Meanwhile, the height of contact between margin and hole surface can be significantly decreased [69]. As a result, better accuracy of hole geometries is obtained under cryogenic conditions, even after drilling a considerable number of holes, as shown in Fig. 33.

However, the characteristics are highly dependent on material properties. When drilling operation is performed for Inconel 718, although better surface can still be obtained compared to the dry condition, as reported by Khanna et al. [70] and Musfirah et al. [165], the improvements are limited or some performances are even worse compared to the flood cutting condition, as reported by Uçak and Çiçek [67] and shown in Fig. 34.

Here, the circularity and cylindricity still show better performances when using cryogenic coolants; however, the improvements are not significant. Meanwhile, surface roughness is higher than the flood condition due to the existence of some major scratches, and the authors attributed this phenomenon to chipping of cutting edges, which is a tool failure model appearing more frequently under cryogenic conditions due to material embrittlement at low temperatures.

For composites, a prominent improvement of geometrical characteristics using cryogenic coolants has been reported for both FRPs [82,83,92,166] and FMLs [88,167]. This phenomenon could be explained through the shrinkage of resin phase at cryogenic temperatures, which provides a tighter connection with respect to the fiber phase, and as a result, debonding can be well prevented and surface quality can be improved. However, another major concern in drilling composites is delamination between different plies, which significantly degrades the performance of components during service. Delamination is mainly induced by high thrust forces, as composites always show a low stiffness along feed direction, and cryogenic temperature will induce hardening behaviors of work materials and therefore thrust forces will be increased.

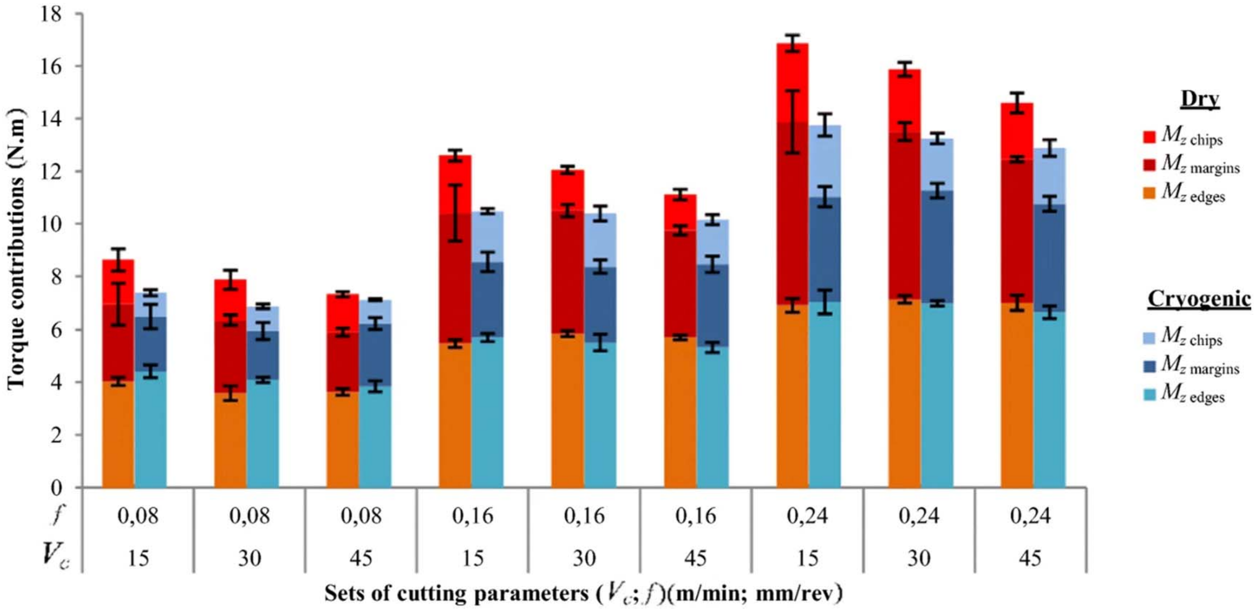


Fig. 30 Contributions to cutting torques as a function of cutting speeds and feeds from main cutting edges, margins, and chips under dry and cryogenic conditions in drilling Ti6Al4V [69]

As a result, the strength along feed direction is easily exceeded under the cryogenic condition, which provides a higher delamination factor compared to the dry condition. However, according to Joshi et al. [81], this condition can be controlled and improved through adjusting cutting parameters, as shown in Fig. 35. With higher cutting speeds and higher feeds, the average performance in terms of delamination factor is better with cryogenic assistance through multiple evaluation criteria. As a result, cryogenic assistance is still an attractive technique and shows high potential toward drilling composites like CFRP due to its excellent performance in surface quality, especially in terms of geometrical accuracy and controllable delamination via cutting parameters.

4.2.2 Physical and Mechanical Characteristics. Physical and mechanical characteristics of surface integrity are mainly determined through hardness, microstructures, and residual stresses. Hardness, especially micro-hardness, is always raised together with microstructures, as the average grain sizes and dislocation densities are key factors in terms of determining this property. In drilling of AZ31B Mg, it was found that the thickness of plastic deformation layer in machined surface is higher under cryogenic condition [149], and the average grain sizes within this layer induced by DRX are generally smaller; as a result, micro-hardness is higher, as shown in Fig. 36.

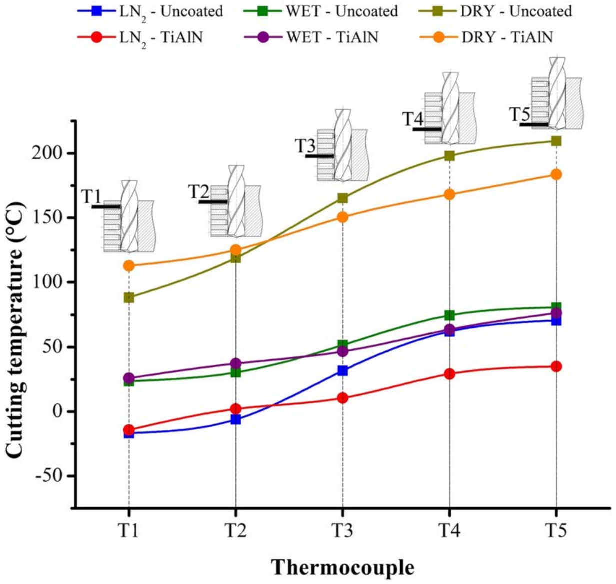


Fig. 31 Temperature evolution of drilling Inconel 718 under different cooling strategies [67] (Reprinted with permission from Elsevier © 2018)

Similar to geometrical characteristics reviewed in Sec. 4.2.1, the performance regarding to physical and mechanical properties is also dependent on material properties. For Ti6Al4V, similar phenomenon were also reported with a higher hardness in machined surface induced by cryogenic temperature [29,66], while the influenced layer with plastic deformation characterizes a thinner thickness than the dry condition. Meanwhile, for Inconel 718, the thickness of plastic deformation layer shows a lowest value under cryogenic condition, a medium value under flood condition, and a highest value under dry condition, as shown in Fig. 37. As a result, compared to AZ31B Mg, for heat-resistant superalloys including both Ti6Al4V and Inconel 718, the thickness of plastic deformation layer generally decreases with the increase of cooling capabilities. Moreover, cooling performance is not the only reason for the increase of micro-hardness in machined surface, as apparent higher hardness values can be obtained under dry conditions with a lower depth under the machined surface when uncoated tools are used, as presented in Fig. 37(*a*).

In terms of residual stresses, not a lot of data were reported with respect to drilled holes, especially for in-depth profiles. Sastry et al. [168–170] proposed surface residual stresses of drilled holes for AA7075, gunmetal, and duplex steel 2507 under different cooling conditions. The results showed that the cryogenic condition always provides more compressive stresses regardless of materials, while its improvement toward flood condition is tiny.

Compared to geometrical characteristics, fewer concerns are focused on physical and mechanical conditions of hole surfaces, currently, as holes are normally used toward assembling, where geometrical accuracy is the most important factor. Moreover, geometrical defect is also a major concern in terms of fatigue life. However, these assembled parts always undergo cyclic loadings during service, and these physical–mechanical properties are important to their behaviors, although some difficulties exist in terms of

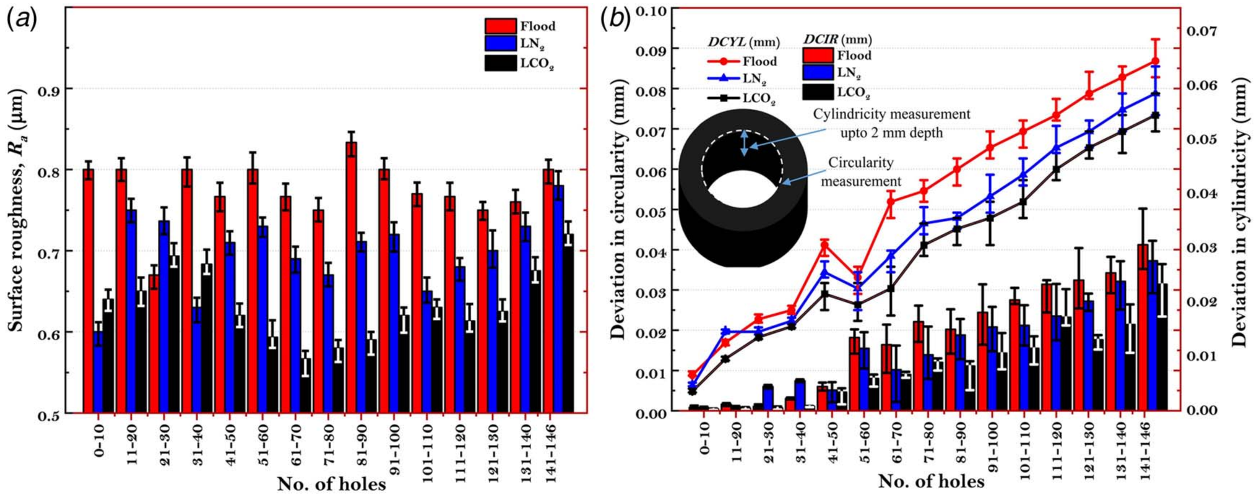


Fig. 32 Improvements of hole qualities by cryogenic coolants from different aspects [29]: (*a*) surface roughness and (*b*) geometry accuracy

their accurate characterization and to link with functional performances. As a result, it is interesting to see if functional performances of these components can also be improved through the application of cryogenic coolants in the future work to show the capabilities of cryogenic coolants in terms of providing both geometrical and physical–mechanical advancements simultaneously.

4.3 Tool Wear. Tool wear is another important concern in industries, as the origins of cryogenic machining are aimed at decreasing tool wear and elongating tool lives by solving the severe thermal issues encountered in machining heat-resistant superalloys, especially for Ti6Al4V, as proposed by Hong et al. [24–27]. With the fast development of this technique, its improvements toward surface integrity also become an attractive matter for researchers, and its application is then expanded from heat-resistant superalloys to other catalogs of materials. As dominant tool wear mechanisms are different with respect to different materials, the irritations induced by application of cryogenic coolants on the change of wear modes are also different. This section provides a brief review regarding to the main features of tool wear in terms of different materials in cryogenic drilling operations.

For heat-resistant superalloys like Ti6Al4V and Inconel 718, adhesion and diffusion wear are major concerns, especially under high pressure and high temperatures. It is consistent with cutting condition, as cutting temperature can reach as high as 1000 °C for both materials [56], where a high pressure at the tool–chip interface will appear simultaneously. In this case, work materials are easy to adhere on the cutting edge and induce the formation of BUEs, which can decrease the sharpness of the cutter, increase cutting forces, and finally cause tool breakage.

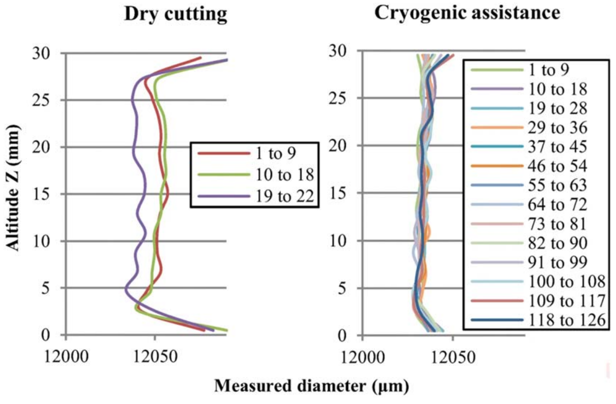


Fig. 33 Hole geometries under dry and cryogenic conditions in terms of drilled number [69]

Although the adhesion of titanium on cutting tool is difficult to be avoided totally due to its chemical properties, formation of BUEs and diffusion wear can be well restrained through the supply of cryogenic coolants, as proposed by Liu et al. [51] in machining of Ti6Al4V. Moreover, with respect to different cooling conditions, cryogenic coolants show the best performance compared to the flood condition and MQL, which brings a 20% increase of tool life as reported by Shokrani et al. [52]. Ahmed and Kumar [38] also presented a cleaner face of cutting tool under cryogenic condition compared to the flood condition, as shown in Fig. 38.

Moreover, due to the low temperature induced by cryogenic coolants, micro-chippings were reported to be more commonly appeared [29,38,52,171]. Nevertheless, limited degradations of hole qualities and tool lives are introduced with respect to drilling Ti6Al4V, compared to flood [29,38] and MQL [52] conditions. Moreover, in terms of different cryogenic coolants, Shah et al. [29] reported that the performance of LCO$_2$ is better than LN$_2$. A moderate low temperature can be provided by LCO$_2$ instead of an extremely low temperature provided by LN$_2$; in this case, an enough cooling capability is supplied and too high stiffness is avoided.

However, for drilling Inconel 718, although the general performance of cryogenic coolants is still better than dry condition [70], marginal improvements toward flood condition are reported [67], where both BUEs formation and chipping increase with apparent decrease of tool life. This phenomenon finally leads to the increase of surface roughness due to the existence of major scratches. Meanwhile, with respect to drilling Inconel 718, the increasing rate of flank wear (VB value) is also higher under the cryogenic condition than that under flood condition with the supply of emulsion or other MWF, which has been validated through both experimental and numerical approaches by Outeiro et al. [63] and Attanasio et al. [128], as shown in Fig. 39.

Compared to heat-resistant superalloys, tool wear mechanisms are very different in CFRP drilling, as thermal issues are not dominating matters as for Ti6Al4V and Inconel 718. However, due to the extreme abrasiveness of carbon fibers, abrasive wear turns to be the major condition when drilling CFRP. Although fundamentals of the roles of cryogenic coolants in restraining tool wear evolution during drilling CFRP are still not clear, an effective decrease of tool wear is found in terms of both the cutting edge rounding and outer corner wear when cryogenic coolants are applied [83,85], and similar phenomenon is also reported for FML composites [167].

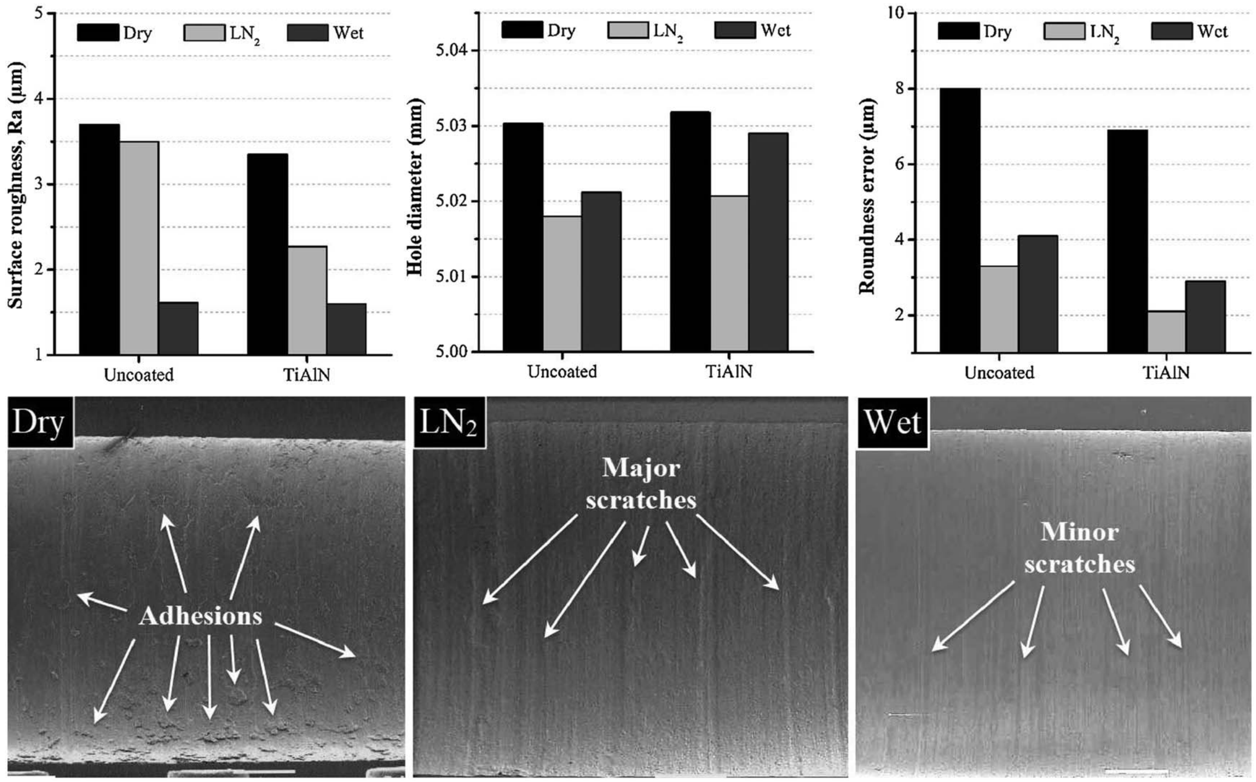


Fig. 34 Geometrical characteristic of hole surface in drilling Inconel 718 with different cooling conditions [67] (Reprinted with permission from Elsevier © 2018)

This evolution can be described as a function with respect to the number of drilled holes and feed, as shown in Fig. 40. Meanwhile, applications of higher feeds do not significantly speed up the tool wear process as for the dry condition. Moreover, as reviewed in Sec. 4.2.1, Joshi et al. [81] presented that higher delamination factors induced by cryogenic coolants can also be controlled through adjusting cutting parameters with higher cutting speeds and higher feeds, which shows a potential to obtain less delamination with longer tool life and higher machining efficiency through cryogenic coolants.

When drilling hybrid stacks like CFRP/Ti6Al4V, issues from both thermal and abrasive aspects appear. High temperature and pressure can induce fast adhesion of titanium on both main cutting edges and margins, and high abrasiveness speeds up the increase of VB and cutting edge rounding. Moreover, another fact that should be referred is that tool wear evolution is also highly dependent on the sequence of drilling stacks. When drilling Ti6Al4V first and then CFRP, BUEs are easily formed during drilling Ti6Al4V, which can easily change drill geometry and influence hole diameter, and its effects on drilling CFRP phase are especially obvious due to the modified edges.

Rodríguez et al. [109] investigated tool wear evolution with the drilling sequence of CFRP/Ti6Al4V under dry and

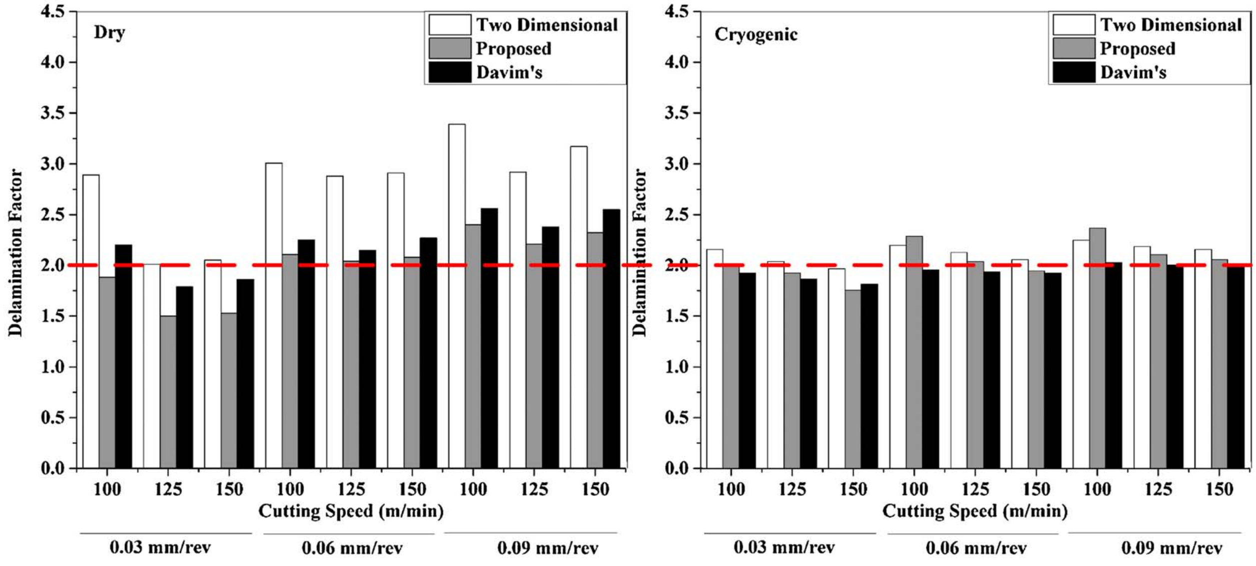


Fig. 35 Comparison of delamination factor under different cooling conditions with respect to cutting parameters [81] (Reprinted with permission from Elsevier © 2018)

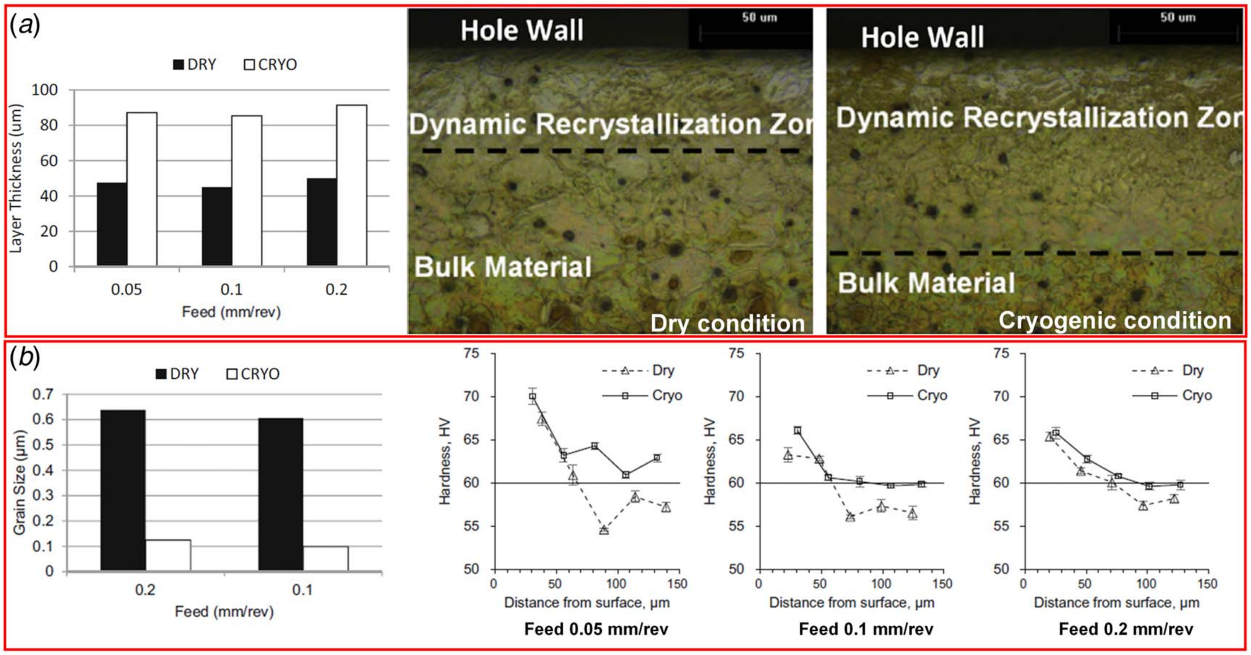


Fig. 36 Microstructure and micro-hardness in drilled surface of AZ31B Mg alloy under dry and cryogenic conditions [149]: (*a*) evolution of the thickness of DRX layer and (*b*) evolution of average grain sizes and micro-hardness

LCO_2-cryogenic conditions, which shows that due to the drastic reduction of temperatures at tool tip, tool wear is well restrained, as shown in Fig. 41. Moreover, machining accuracy of holes in terms of diameter is well maintained, where the error can be controlled within 1% under cryogenic condition with respect to 4.6% under dry condition, especially for the CFRP phase. In this case, a good performance was obtained in terms of a unique drilling sequence of CFRP/Ti6Al4V under the cryogenic condition, while for the inverse sequence of Ti6Al4V/CFRP, more investigations should be performed to analyze its performance and reveal the fundamentals.

To summarize, cryogenic assistance presents a good performance in restraining tool wear, and micro-chipping turns to be a common mechanism in this case due to the high stiffness and material embrittlement induced by cryogenic temperatures. In drilling Ti6Al4V, CFRP, and also Ti6Al4V/CFRP stacks, prominent improvements in terms of tool life and surface quality are still obtained with respect to other cooling strategies, even if chipping occurs. However, during drilling Inconel 718, chipping induces major scratches on machined surface and shorter tool life compared to the flood condition, and this may be attributed to different material behaviors at cryogenic temperatures.

As a result, to determine a good cooling strategy toward drilling operation, material responses with respect to cryogenic temperature require to be thoroughly investigated before actual application. Moreover, this technique shows a high potential toward drilling Ti6Al4V/CFRP stacks in terms of improvements of both surface quality and tool wear. The number of researches pertinent to this topic is increasing rapidly; however, explanations on its fundamentals are still far from sufficient.

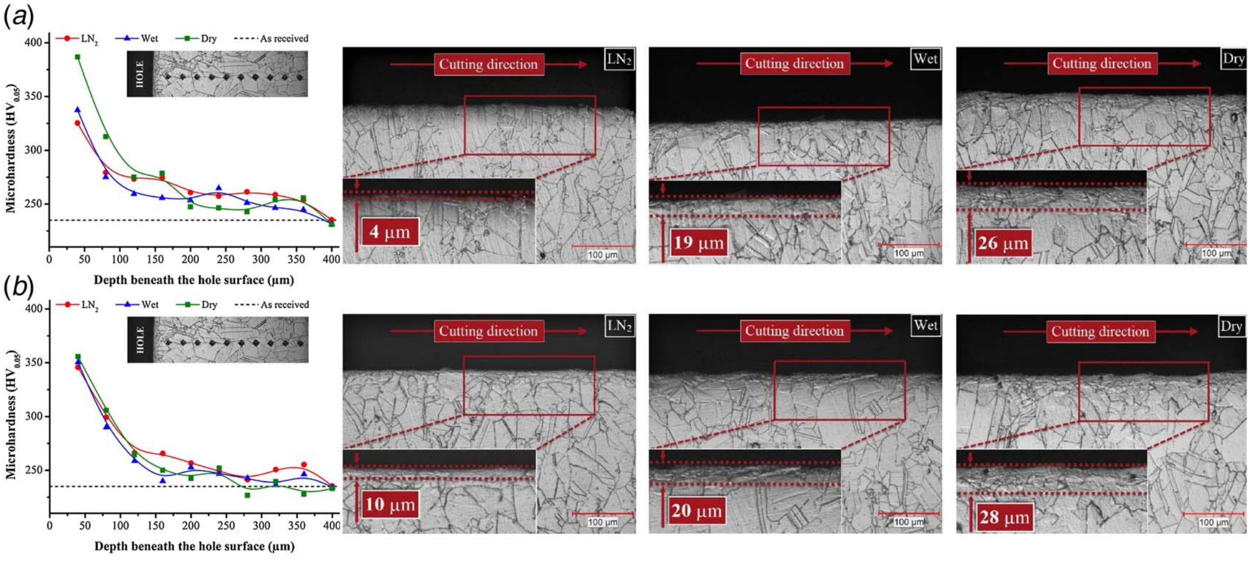
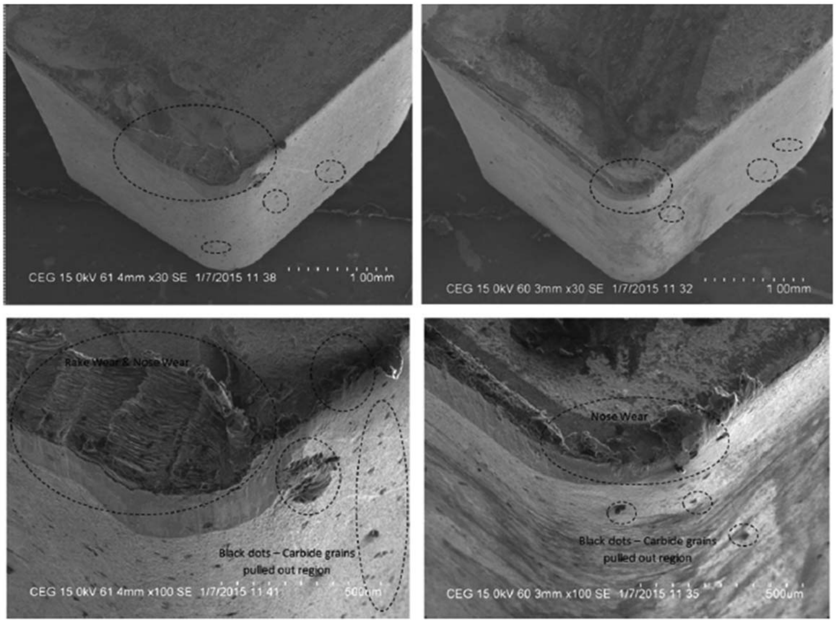


Fig. 37 Microstructures and micro-hardness of machined surface in drilling Inconel 718 under different cooling conditions with different tool coatings [67] (Reprinted with permission from Elsevier © 2018): (*a*) uncoated tool and (*b*) TiAlN-coated tool



Flood condition   Cryogenic condition

Fig. 38 Scanning electron microscopic images of tool wear in drilling Ti6Al4V under flood and cryogenic conditions [38]

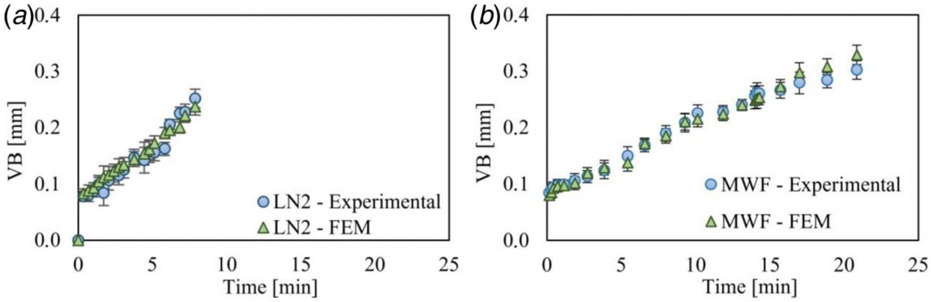


Fig. 39 Evolution of VB value in drilling Inconel 718 under different cooling conditions [128] (Reprinted with permission from Elsevier © 2018): (*a*) cryogenic condition and (*b*) flood condition

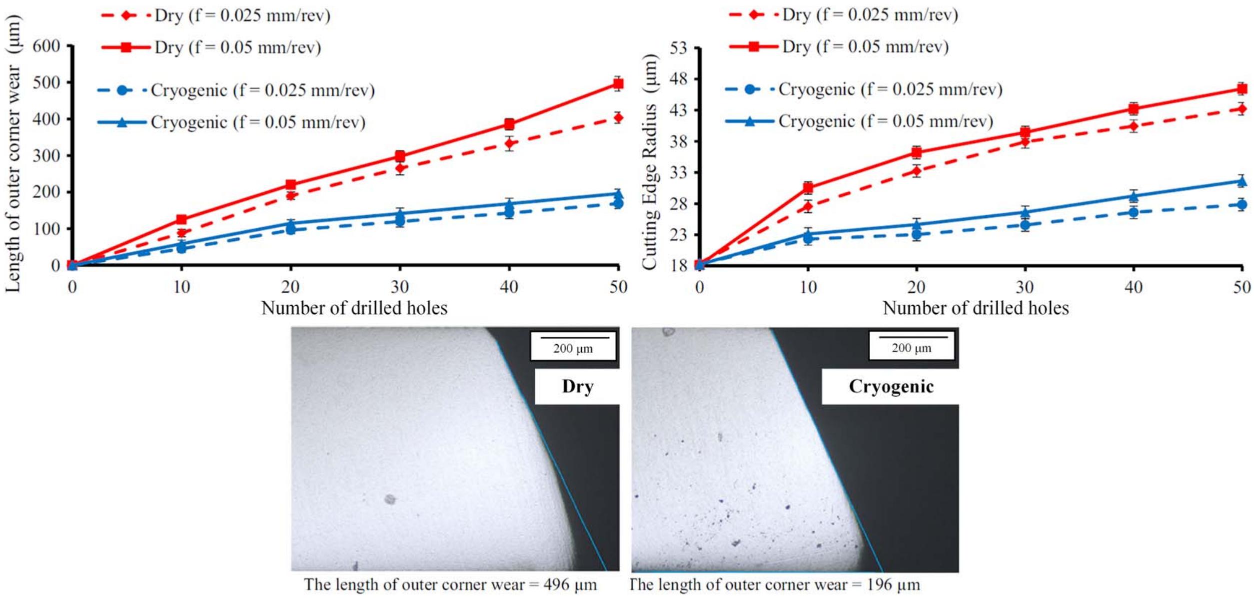


Fig. 40 Evolution of tool wear in terms of cutting edge rounding and outer corner wear in drilling CFRP under dry and cryogenic conditions [85]

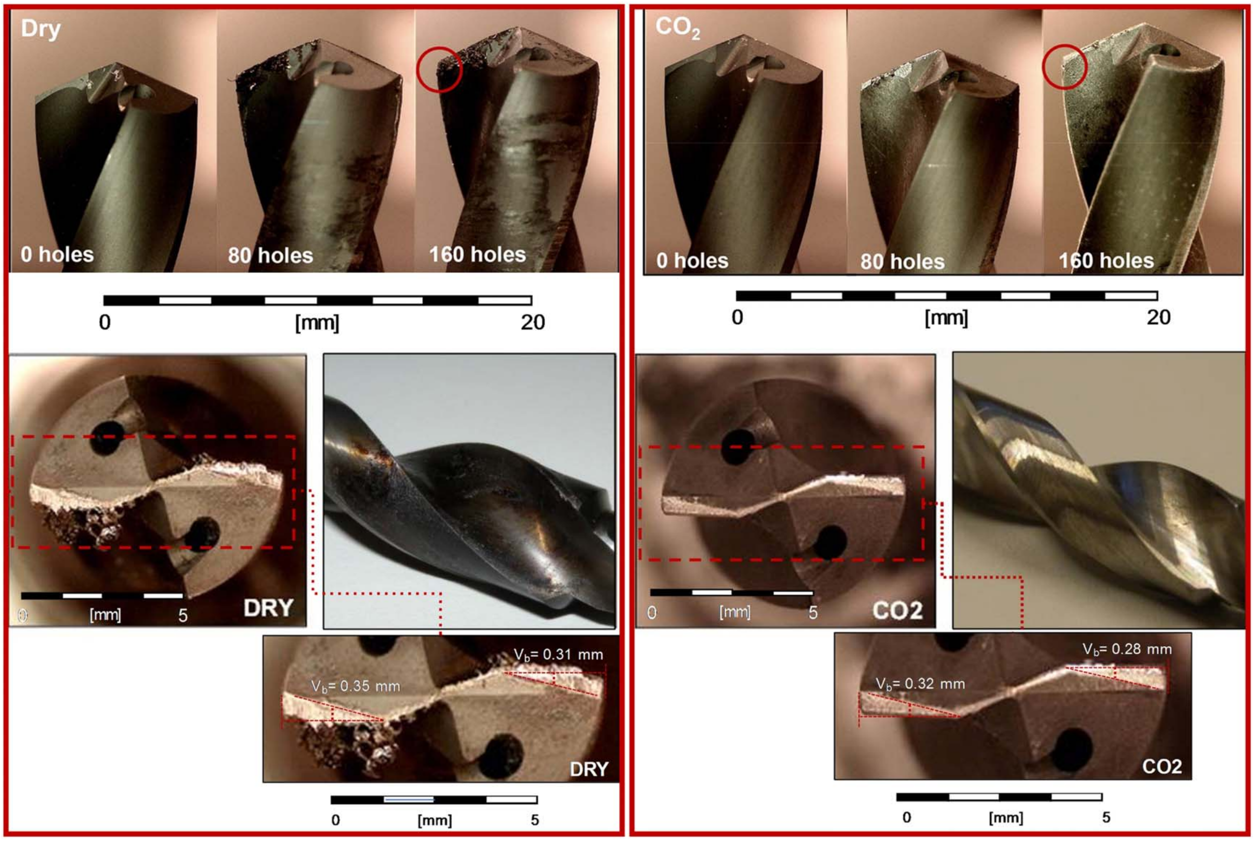


Fig. 41 Tool wear evolution in terms of main cutting edge and margin when drilling CFRP/Ti6Al4V stacks with dry and cryogenic conditions [109] (Reprinted with permission from Elsevier © 2021)

4.4 Sustainability. Sustainability is becoming a more and more important factor in evaluating a technique in modern industries, as it can easily bring environmental burdens, which is a societal and global issue, and driving techniques are developing towards an eco-friendly and energy-saving orientation. This is a general concern in terms of cryogenic machining instead of mere operation of drilling. In this case, cryogenic machining is generally considered as sustainable due to its low energy consumption, low carbon emission, high machining efficiency, high eco-friendliness, and healthy concerns [19–21,71,172], and following reviews present a brief summary from these aspects.

With respect to power consumption, it can be measured through energy and power quality analyzer [152] and evaluated through specific cutting energy [33], where a reduction of more than 20% compared to flood condition is reported [33,71,152] when cryogenic coolants are used. Moreover, the low energy consumption and high machining efficiency with the application of cryogenic assistance are also dependent on its excellent performance in improving surface quality and elongating tool life. Here, the performances of LCO_2 and LN_2 are different for different materials, where LN_2 performs slightly better for Ti6Al4V [71] and LCO_2 is better for Inconel 718 [152]. Meanwhile, Lu and Jawahir [19] pointed out that the hybrid approach to supply cryogenic coolants with similar methods like MQL can further reduce the energy consumption, which only uses a tiny quantity to obtain a near-dry cutting condition.

For concerns on carbon emission, it is always estimated in terms of three major categories, including electricity consumption, coolants/lubricants, and the processing of work material and cutting tool, as illustrated in Fig. 42. Similar as reduction of energy consumption, with the help of cryogenic coolants, tool life can be elongated due to less heat generation, especially for heat-resistant

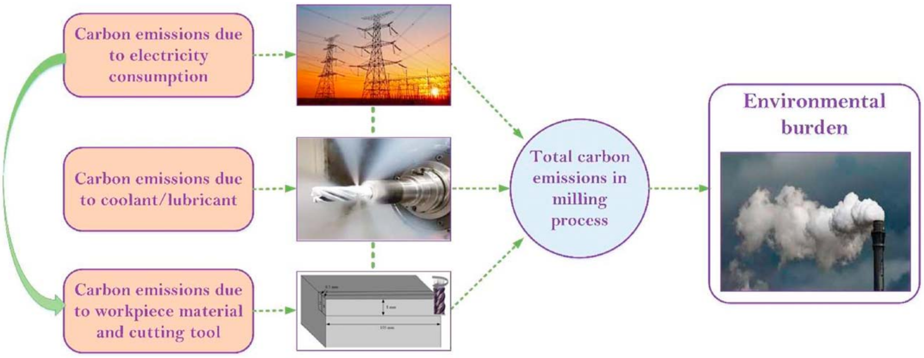


Fig. 42 Sources of carbon emission during machining process [37] (Reprinted with permission from Elsevier © 2021)

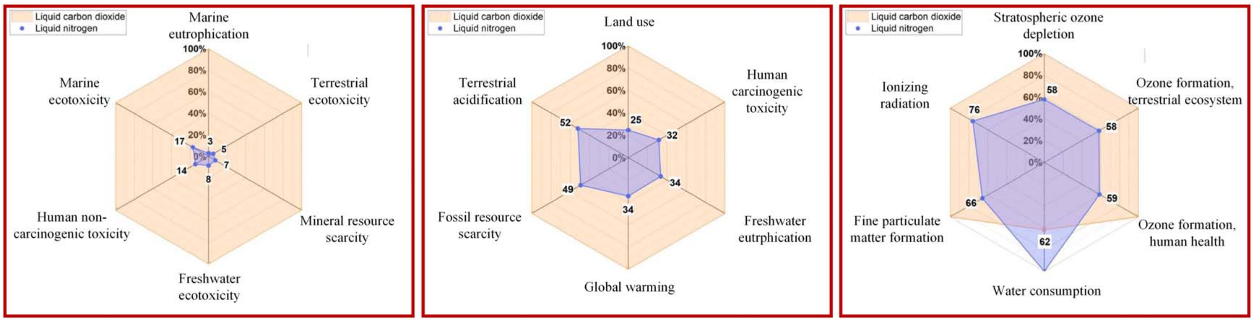


Fig. 43 Evaluation of environmental and healthy impact for LN_2 and LCO_2 [152]

superalloys, which extends tool changing intervals by the operator and reduces carbon emission by using machine tools more efficiently. Moreover, LN_2 provides no emission of greenhouse gases, and for LCO_2, the liquids can be produced from recycling of waste gases, which is also beneficial for reducing greenhouse gases. As a result, industries can proceed in a more sustainable way by using cryogenic coolants.

Moreover, although both LN_2 and LCO_2 perform well in the realms of energy consumption and carbon emission, LN_2 is superior against LCO_2 when referring to environmental and health concerns. Shah et al. [152] evaluated their performances with respect to 18 impact factors, where LN_2 performs better in 17 categories, as shown in Fig. 43, as the gas N_2 brings no burden to the environment and is totally harmless to human beings.

To summarize, cryogenic assistance shows a good performance when referring to sustainability, and some of these performances are also evaluated depending on on-site conditions like cutting forces, torques, and temperatures, as well as the ability to provide better surfaces and longer tool life. These characteristics provide cryogenic machining a high potential to be widely applied in green industries in the future.

5 Conclusions and Outlook

This article presents a review on recent advances of drilling operations with cryogenic assistance, which is mainly discussed from three major aspects, including the main work materials, the main methodologies of both modeling and experimentation, and its major impacts on performances during drilling process. Detailed discussions are followed in each section, where the primary concerns pertinent to advantages and disadvantages of each aspect are presented, to analyze the current developments and direct future orientations. The general conclusions can be summarized as followings:

- Cryogenic machining is a superior technique especially in drilling heat-resistant superalloys. However, the performance is different toward different work materials. For Ti6Al4V, cryogenic assistance performs the best compared to other cooling strategies, where both surface quality and tool life can be prominently improved. While for Inconel 718, although a better geometry is obtained, surface roughness is increased and tool life is decreased compared to the flood condition.
- The interests of using cryogenic assistance in drilling composites are increasing rapidly, as hole quality is generally improved due to the shrinkage of resin phase at low temperature, which reduces its debonding with the fiber phase. However, the knowledge of cryogenic properties with respect to composites is still insufficient, as well as the process data during drilling process, which makes the fundamentals of cryogenic drilling composites still unclear. Moreover, although cryogenic assistance provides better surface quality and machining accuracy through suppressing debonding between resin and fiber, delamination factor between laminates is always found to be larger, while it is reported to be controllable through adjusting cutting speeds and feeds.
- Due to the good performances in both heat-resistant superalloys and composites, cryogenic assistance shows a high potential to be used in drilling hybrid stacks, especially for Ti6Al4V/CFRP stack. It makes the contradictory requirements of each individual material with respect to cooling strategies solvable. Currently, investigations pertinent to this topic are still limited; as a result, a huge vacancy still exists in this area toward analyzing the performances and possibilities its industrial applications, as well as to understand the fundamentals of the mechanisms. Moreover, as the major issues are different in terms of different drilling sequences, another interesting topic can be raised from this perspective, with respect to evolutions of tool wear and surface integrity.
- Fundamentals regarding to deformation during deformation are highly dependent on numerical simulation in the drilling process, as these data are normally unmeasurable. However, due to the limitations of computational capability, simplified models are always used, especially for fully coupled thermo-mechanical conditions with respect to effects of cryogenic coolants on machining process. As a result, a hug gap still exists between reality and numerical simulation. Another major concern is the high computational cost, especially for drilling. Thus, realization of this concern currently relies on the development of high-performance computing technologies or better algorithms.
- Experimental approaches still require further development, especially in terms of temperature measurement during the drilling process. RTT device integrated with rotary dynamometer is a good solution with respect to most drilling cases, which can provide comprehensive data of both thermal and mechanical loadings. However, the treatment of cutting tool is difficult, as small holes are required to be drilled on the drill to embed thermocouples, and it also has some limitations in terms of cooling strategies. As a result, experimental methods still require to be further improved toward acquiring thermomechanical data reliably and conveniently.
- Drilling with cryogenic assistance is also a technique toward future with excellent performances in sustainability, which fits well with the goals of green production with low energy consumption, low carbon emission, and high environmental friendliness toward future industries.

Drilling with cryogenic assistance is becoming more attractive as a future technology following Industry 4.0 due to the excellent cutting performances and sustainability. However, fundamental studies are still required to obtain in-depth understandings toward further development and optimization in terms of technical perspectives. As a result, besides previous discussions and conclusions, several development toward future academic research and industrial applications should be highlighted as follows:

- Fundamental investigations concerning cryogenic flows in drilling operation should be carried out through analytical/

experimental work or CFD simulations, especially toward the heat transfer in the confined drilling area, which is still in huge lack compared to orthogonal cutting and turning. Multiphase flows of cryogenic cooling should be characterized through numerical modeling to present a more comprehensive understanding on its interaction to cutting tool and work material, which is beneficial toward further optimization of the drilling process.

- FSI models should be developed toward applications in cryogenic machining, to characterize the complex procedure of thermomechanical behaviors induced by the interaction between cryogenic coolants and work materials. It is a further improvement based on the characterization of multiphase cryogenic flows. In this case, better algorithms should be developed to save computational time and make it reasonable toward implementation into drilling simulations.
- New designs of cutting tools should be developed toward cryogenic drilling from following aspects. (1) optimization of drill geometry, especially the path of internal channels. Better designs should be raised toward a better supply of cryogenic coolants through-tool. (2) New coatings should be developed to provide a better performance in heat-resistant superalloys toward cryogenic environments and elongate tool life as a result. (3) Bi-material drills could be developed with polycrystalline diamond (PCD) or other materials embedded on the tip, to provide better strength and prevent micro-chipping at cryogenic temperature.
- Through-tool cooling is the most effective method to supply cryogenic coolants, where cryogenic coolants pass spindle to access cutting zones through drill internal channels. As a result, machine tool should also be optimized to provide a good insulation between spindle system and cryogenic coolants, to maintain a healthy operating status during the machining process.
- More comprehensive assessments of life cycle should be proceeded toward cryogenic machining, and better evaluating strategies should be developed to provide an in-depth analysis, especially in terms of its impacts on environments.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

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