Drilling of CFRP/Ti Stacks in Wet and Cryogenic Condition

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Abstract: This paper studies the effects of cryogenic liquid nitrogen compared with conventional wet coolant in drilling of CFRP/Ti using diamond-like carbon coated solid carbide tools. The experimental investigation was carried out taking into account the influence of main process parameters and adopting different strategies in the two different materials. The influence of the two different cooling conditions on tool wear was investigated through the comparison of the thrust force and torque; the effect on the hole quality was analysed through the measurements of burr height and diameters. The use of a cryogenic coolant results in both lower thrust force and torque but in a slightly poorer quality of the holes.

Keywords: Cryogenic cooling, Liquid nitrogen, Ti drilling, Thrust force, Torque.

INTRODUCTION

In the aeronautic, the need to reduce weight and, consequently, fuel consumption and operating costs is becoming more and more urgent. Carbon Fiber Reinforced Plastics (CFRP) are widely used to this aim. Their use in aircraft construction is due to their substantial benefits in terms of high specific strength, stiffness and excellent corrosion resistance. Nevertheless, metals are still used in those parts of the aero-structure that are heavily stressed by concentrated loads: the metals most commonly used are titanium alloys. These metals, stacked with CFRP parts, are used to realize mainly the skin segments, fuselage and wing segments. This stack is chosen for its high strength - to - weight ratio, high yield strength, low density and excellent corrosion resistance and similitude of thermal properties. Arise, as a consequence, the need to join in an effective and reliable way CFRP and metals. The aircrafts of last generation, for example the Boeing 787 (well known as "Dreamliner"), consist of 50% of CFRP and 15% of titanium alloys and several other materials in different percentages [1]. To join all the different parts of the structure, several thousands of fasteners are used. It is fundamental to use specific tools capable to drill the CFRP/titanium stacks with a high process stability and short process times with low costs. In order to reduce the manufacturing time and to ensure the correct alignment of the holes of the two parts, the materials are stacked and then drilled simultaneously. This is possible if the appropriate set of process parameters and drilling conditions has been previously correctly defined and, as a consequence, the number of holes in tolerance that can be made has been accurately stated. In this way, it is possible to put the fastener avoiding to perform any kind of further control, saving time and money. Most of research works focused on conventional drilling of single materials (CFRP or titanium). Rawat and Attia [2] examined the wear mechanisms of solid carbide tools during dry drilling of woven carbon fibre composites and they determine that both the thrust force and cutting force increase with the increase of flank wear and, as consequence, the hole quality gets worse. Thrust force was found to be higher than the cutting force in the primary and the secondary wear regions. However, in the tertiary wear region, the cutting force overcomes the thrust force. This is likely due to the high temperature built up on the tool with continuous drilling at such high speeds [2]. Fernandes and Cook [3] focused their studies on drilling of CFRP of various layers and they found that the increase of the thickness of the workpiece and the feed results in increase of the thrust force due to the wear of the tool. The investigation reported by Sushinder *et al*. [4] on drilling of Ti6Al4V using tungsten carbide (WC) tools at various cutting speeds resulted in thrust force and torque higher at low cutting speed due to higher resistance to plastic deformation. Consequently, thrust force and torque decrease when higher cutting speeds are adopted due to the thermal softening occurring in this condition, enhanced by the very low value of thermal conductivity of titanium alloys. At the beginning the research focussed on drilling of stacks were focused on drilling of titanium/CFRP/Aluminium stacks [5-6] where the aluminium was used in order to reduce the delamination of CFRP hole. Successively the studies were focused on drilling of CFRP/titanium stacks without the support of the other metals [7-10]. From literature, it is well known that the wear mechanisms of uncoated and coated WC tools and the

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borehole quality are due to the cutting parameters like cutting speed and feed, different work piece materials, cooling strategy and their combination [8]. The cutting temperatures and the morphology of chip can also be influenced by the use of particular drilling strategy as fixed position or adaptive pecking [9]. The former is characterized by the repetition of the pecking movements with a constant step. In the latter method, the tool switches to Z-axis extraction when the difference between the cutting torque at the hole entrance and the cutting torque during cutting exceeds the allowable difference [10]. A lot of researchers took the interest on the effect of the process parameters on force and torque [7] establishing a relation between the tool wear and the forces and torque. Wang *et al*. [8] focused their interest on the influence of the workpiece material. They conducted wet drilling experiments on CFRP, on titanium and on the CFRP/Ti stack in order to compare the wear mechanisms due to drill of single materials and the stack and the different hole quality achieved. They demonstrated the important benefits of process interactions when drilling the CFRP/Ti stack on tool life. The tool life attainable in drilling of the CFRP/Ti stack was about three times longer compared to that achievable in drilling of Ti only. They found that the drilling of the top CFRP the cutting edges were smoothed and rounded, which reduces the subsequent edge chipping when drilling the bottom titanium sheet. The cutting temperature is one of the most limiting factor for the process parameters for cutting titanium. The occurrence of an excessive tool wear causes bad surface qualities and alterations of the metallic structure. A lot of methods were applied to reduce the temperatures during drilling as the use of the Low Frequency Vibration Assisted Drilling (LFVAD) [9] that enhances chip extraction of titanium. The heat in the cutting zone is mainly dispatched by the hot metallic chips causing the damages at exit hole of CFRP. So, an improved extraction of the small chip segments involves a decrease of cutting temperatures reducing the damages of the borehole of CFRP and the burr height of titanium. Another method to reduce the cutting temperature is the use of cryogenic cooling [12] that was determined as one of the most favourable method for material cutting: due to the related reduction of the tool wear, it results in a noticeable improvement in tool life and surface finish. The main interest towards the use of cryogenic over conventional coolant during drilling and other machining is due to its various advantages like longer tool life, better chip breaking and chip handling, higher productivity, lower cost, better surface finish, environmentally safer and healthier for the worker [12].Several research works focused their attention towards the drilling of single materials, CFRP [13] and titanium [14-16] investigating the performance of the operation in terms of torque, force, tool wear, hole quality and morphology of chip. The researches on CFRP drilling found that the forces and the torque acquired during cryogenic drilling are higher than the same in dry condition explaining this behaviour through the mechanical characteristics of CFRP: its Young's modulus and tensile strength increase as the temperature decrease [13]. Dix at al [14] took the interest at drilling of grey cast iron studying the temperature distribution using two applications of cryogenic coolant: pre-cooling, through spray model, and cooling during drilling, through the coolant channels of tool. In addition, they found that the tool geometry and particularly the position of the coolant channel outlets are crucial for the temperature distribution during the process. Finally, in the literature, most of the researchers interested on the cryogenic drilling studied the effect of cutting temperatures on thrust force and torque. Dilip Jerold and Pradeep Kumar [15], confirmed by Ahmed and Kumar [16] discovered that the cutting temperatures in cryogenic machining of Ti6Al4V using liquid CO2 is reduced up to 50% over the dry machining; the same reduction, in case of wet machining, range from 15% up to 47% depending on the feed rate adopted. The reduction in cutting temperatures resulted in the reduction of cutting forces [15-16]. When the cryogenic coolant is applied the temperature in cutting zone is reduced considerably, thereby reducing the stickiness of the metal chip with the tool rake (build up edge phenomenon). In this paper, the attention has been focused on the drilling of stacks of CFRP and Ti6Al4V at various cutting parameters and cooling conditions using DLC coated tungsten carbide tools in order to understand the tool wear and to maintain the desired hole quality. Based on the above-mentioned results available in literature, in this paper thrust force and torque have been acquired even to take into account their effects on tool wear on the quality of the holes. These effects were analysed at different feeds and coolant conditions. The hole quality parameters investigated in this study include the diameter size in entry and exit hole for both material, CFRP and Ti6Al4V, and the burr height in exit titanium hole.

Most of the research done until now had been focused on conventional drilling of a uniform stack. Rawat and Attia [2] had examined the wear mechanisms of solid carbide tools during dry drilling of woven carbon fibre composites and had determined that the thrust and the cutting force increase with the flank wear and consequently the hole quality decreases. Fernandes and Cook [3] focused their studies on drilling of CFRP of various layers and found that the increase of the thickness of the workpiece and of the feed rate causes an increase of the thrust force due to the wear of the tool. The experiments done by Sushinder *et al*. [4], on drilling of Ti6Al4V using WC tool at various cutting speeds, found an inverse relationship between cutting speed and thrust force/torque. This is due to the increased heat generation at high speed, that in union with the relatively low heat conduction of titanium alloys causes thermal softening of the material. The oldest research on metal/composite stack drilling focused on titanium/CFRP/aluminium stacks [5, 6], in which the aluminium was used as backstop to reduce delamination in the composite, while the newer ones study pure CFRP/titanium stacks [7-11]. It is a fact that wear of uncoated and coated WC and the hole quality are related to the cutting parameters, the cooling strategy and the different combination of materials [8]. The cutting temperatures and the morphology of chip is also influenced by the drilling strategy, *e.g*. fixed position or adaptive pecking [9]. The former is characterized by the repetition of the pecking movements with a constant step while the latter adopts a switching strategy based on the difference between the cutting torque at the entrance and the cutting torque at the cutting face [10]. Wang *et al*. [8] studied the influence of the worked material on the tool wear. They conducted wet drilling experiments on CFRP, on titanium and on the CFRP/Ti stack to compare the wear mechanisms and the different hole quality achieved. They found that when drilling CFRP/Ti stacks the cutting edges were smoothed and rounded during the drilling of the CFRP layer, with consequence reduction of edge chipping when drilling the Ti layer.

The cutting temperature is one of the most limiting factor for the selection of the process parameters involved into titanium drilling. A lot of techniques had been proposed to reduce the temperatures during drilling. Low frequency vibration assisted drilling [9] increases the chip evacuation from the hole by the use of low frequency vibration. Because in Ti drilling the chip is the main route of heat extraction any improvement in its extraction decrease the cutting temperature. Another method to reduce the cutting temperature is the use of cryogenic liquids for cooling. Their use was showed to reduce tool wear with a noticeable improvement in tool life and surface finish [12]. The main advantages of cryogenic cooling over their conventional counterpart are a longer tool life, a better evacuation of the chip, and a higher productivity [12]. Several research works had focused their attention on cryogenic drilling of single materials, CFRP [13] and titanium [14-16] investigating the performance in terms of torque, force, tool wear, hole quality and chip morphology.

Dix *et al.* [14] researched the cryogenic drilling of grey cast iron by two different techniques: pre-cooling through spray and cooling during drilling. They found that the tool geometry and in particular the position of the cooling channels are crucial for the temperature distribution during the process. Jerold and Kumar [15] and Ahmed and Kumar [16] proved that the use of liquid CO2 in machining of Ti6Al4V reduces the cutting temperatures up to 50% over dry machining; the same reduction, in case of wet machining, ranges from 15% up to 47% according to the feed rate used. There is a positive relation between cutting temperature and cutting forces [15, 16].

This paper compares the drilling of CFRP/Ti stacks in both cryogenic and wet conditions. Both torque and thrust force are compared and the results examined in the light of current literature on the argument. Some of the results found offer a different perspective on the process.

MATERIALS AND METHODS

The experiments were designed to be as close as feasible to the standard assembling procedures common in aerospace manufacturing. The CFRP and Ti6Al4V used were aerospace-grade and supplied as 100 mm x 100 mm plates. The CFRP was an orthogonal woven carbon fabric in an epoxy matrix, manufactured by resin transfer moulding. The areal density of the fabric was 200 g/m^2. The CFRP plate had a thickness of 18 mm with an average ply thickness of 0.2 mm. The Ti alloy plate had a thickness of 10 mm. The configuration adopted for the experiments was a CRFP-Ti stack, with entry point on the composite side, the most common one found in the case of aircraft final assembly.

All drilling experiments were performed using a commercial 3-axis CNC vertical mill. A WC twist drill made of ultrafine tungsten carbide grains (average size 0.5 μm) with 5% cobalt binder was employed. The drill is characterized by a diameter of 7.94 mm, a point angle of 150°, a helix of 26° and a chisel edge angle of 105°, see Figure **1**. To allow lubrication and cooling of the drill two internal helical channels are built into it. To

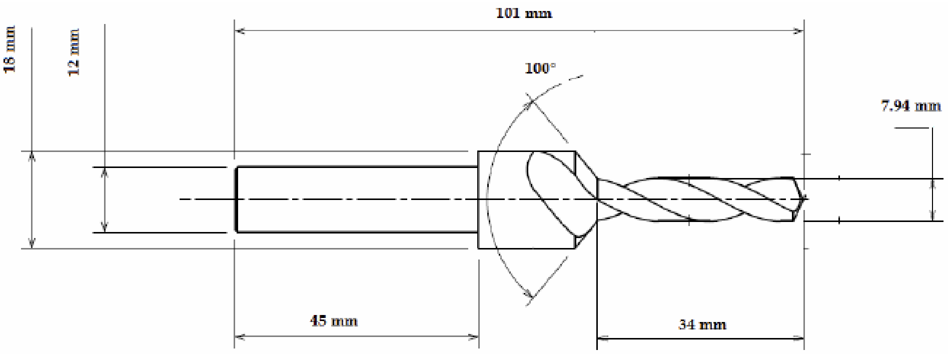

Figure 1: the drill bit used in the experiments.

eliminate the effect of the tool wear upon the study the drill was replaced with a new one every two experiments. As reported by researches on tool wear in drilling of composite/titanium stacks [12, 11] this procedure ensures that the flank wear of the toll is kept below 0.1-0.2 mm. As further check the wear of the discarded tool was measured by an optical microscope with 100 times magnification.

The drilling procedure and parameters were optimized independently for the CFRP and the Ti plates. For the CFRP a standard drilling cycle was adopted, while for the Ti a deep hole drilling cycle was chosen. This cycle contemplates pecks of 1 mm followed by a rapid retracts to a set level outside the hole and a rapid back in to the previous depth less a clearance level of 0.1 mm. A total of 11 pecks (P1-P11) were needed to drill the titanium plate. A breakthrough of 1.5 mm was set in the last peck. The feed rate adopted for the Ti plate was much lower than the one used for the CRFP, to avoid high-speed machining which has been shown to result in severe tool chipping and tool failure for Ti alloys [12, 11, 17]. Two spindle speeds and two feed rate, low and high, were adopted for the study, for a total of four different test conditions. Table **1** reports the drilling parameters used.

To study the effects of different cooling conditions on peck drilling the experiments were carried out for wet and cryogenic conditions. The fluid adopted for the wet cutting was an emulsion of mineral oil and water with a ratio of 1:15, while the fluid adopted for the cryogenic cutting was standard liquid nitrogen (LN2). To achieve a realistic comparison between the two coolant technologies, equal pressures and flow rates were used, namely ~2 bar with a flow rate of ~5 l/min.

A plate piezoelectric dynamometer connected to a data acquisition system was used to measure the cutting forces during the drilling. The thrust force and torque developed during the drilling process were continuously acquired during the entire drilling cycle.

The hole diameters were measured in four locations on the CFRP/Ti stack hole, namely the top and the bottom of the CFRP hole and the top and the bottom of the Ti hole. The exit burr height was also measured for the Ti plates. The values reported were averaged over five measurements.

RESULTS AND DISCUSSION

Figure **1** shows the diagrams of the thrust forces and of the torques measured during the drilling. The CFRP is represented by the first zone while the following zones are the pecks of the Ti drilling. It is clear from the figures that the cryogenic conditions are the best for the drilling of the CFRP. Both average and

Table 1: Cutting Parameters

	Spindle Speed [rpm]	Feed Rate [mm/min]	v_c, Cutting Speed [m/min]	*f*, Feed Rate [mm/rev]
CFRP	3590	630	89.5	0.175
Titanium	700	30	17.5	0.043
	700	70	17.5	0.100
	995	30	24.8	0.030
	995	70	24.8	0.070

maximum of the thrust force and the torque are lower than the ones found in wet drilling. The average thrust force goes from 530 N to 442 N while the maximum decreases from 731 N to 641 N, with a reduction of 17%. Because the torque increases continuously during the drilling in the CFRP the comparison must be done between the maximum values in both cases. In wet drilling the maximum torque is 1.29 Nm while in cryogenic drilling the maximum torque is 1.02 Nm, with a reduction of 21%.

The behaviour of the thrust and of the torque during the Ti drilling are more complex and require a detailed analysis. In both drilling conditions the tool is not fully engaged in the first two pecks and for this reason the values for the thrust force and the torque are lower than the ones measured during the following pecks. Because of this the values measured for them are discarded and the following analysis covers only the drilling from the third to the eleventh peck. The eleventh peck is the one in which the tool exit the plate and for this reason the thrust force decays to zero. Because of this a cut off is used to exclude the values of the thrust force measured after complete penetration had been achieved.

Under a close scrutiny is evident that the thrust force measured during the drilling decreases with the increase of the depth of penetration. This decrease is much more dramatic for cryogenic drilling and it is proportional to the increase in feed rate [mm/rev], for a given cutting speed. There is a substantial difference in behaviour during the single peck between wet drilling and cryogenic drilling in regard to this. While in wet drilling the thrust force oscillates around the average value in cryogenic drilling there is an initial spike at the beginning of each peck, as shown in Figure **3**. This spike increases with the increase in the feed rate used and must be considered when choosing the tool to avoid any damage or breakage of the same.

Unlike the case of the thrust force the behaviour of the torque is different between the two drilling conditions. For wet drilling the torque increases as function of the drilling depth, and reaches a plateau only at the ninth peck, while for cryogenic drilling the torque reaches a stationary plateau sooner, in particular at the third peck. On the other side, during a single peck it can be seen that the torque increases with the depth for both cases, and that the increase between the beginning and the end of the peck is sharper for cryogenic drilling than for wet drilling.

Due to the complex nature of the experimental data it is necessary to introduce the following parameters to better appreciate the differences between wet and cryogenic drilling: global average thrust force, global average torque, delta thrust force, and delta torque.

The global average thrust force is defined as the average thrust force between the peck 3 and the tool exit. namely the thrust under regime conditions. Figure **4** shows the global average thrust force for the different drilling parameters adopted for both wet and cryogenic

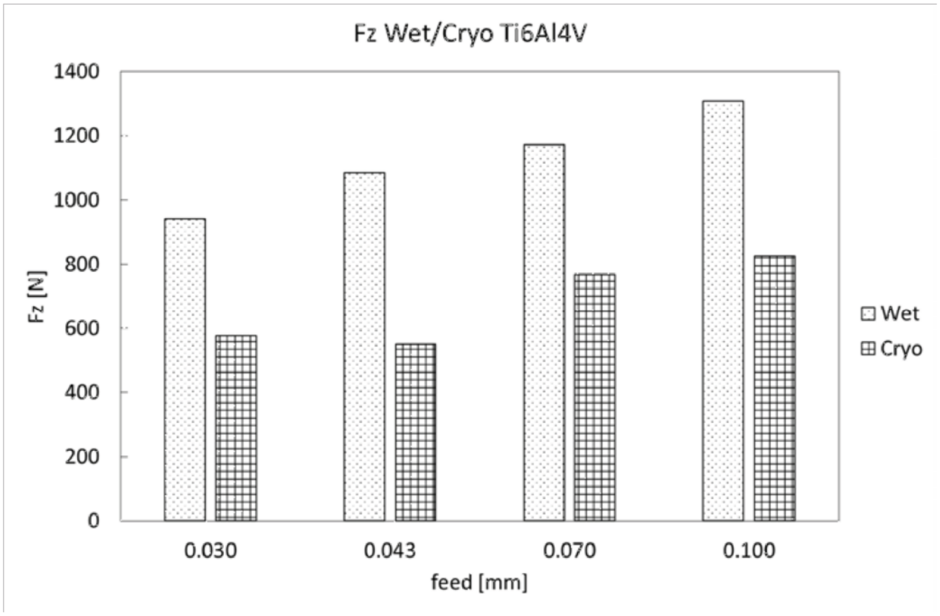

Figure 2: global Average thrust force as function of the feed rate for revolution.

drilling. The upper and lower errors are calculated as the average of respectively maximum and minimum measured values.

It is evident that the thrust force for cryogenic drilling is lower than the one for wet drilling under the same parameters, in accordance with what observed by Wstawska *et al*. [18] for Ti drilling. Similar results were obtained by Ahmed *et al*. in [19, 16, 20]. The increase in the global thrust force with the feed rate for revolution is due to the increase of the chip load for both drilling conditions. No conclusion can be inferred about the influence of the cutting speed on the thrust force because the difference between the two averages is lower than the error on each one.

Cryogenic cooling acts in opposite ways upon the two main phenomena which influences the cutting forces. On one side, the reduction in temperature of the work piece increases its shear strength with consequent increase of the cutting force [20]. On the other side, cryogenic cooling reduces the adhesion between the tool rake and chip, due to the hardening of the latter at low temperature, with consequent low friction between them [20]. Lowering the temperature results also in an increase of chip breakability which is very important in cases where the chip has to be evacuated from confined spaces, as in drilling. In the case of deep hole drilling the reduction in friction and the increased breakability of the chip have a higher weight than the increase in shear strength of the material. The consequence of this is the overall reduction of the thrust force. Similar results shall be found for the torque (see below).

Under the case of wet drilling the global average thrust force coincide with the middle point between upper and lower error; but in the case of cryogenic drilling the average thrust force is lower than the middle point. This is caused by the thrust spike at the beginning of each peck, as observed before. These spikes are due to the cooling of the material by the liquid nitrogen that fills the hole between the pecks. This cooling causes an increase in the surface hardness of the material, with consequent increase in the thrust required to machine it at the start of each peck. On proceeding of the peck, however, the resultant heating of the worked material causes the same to soften, with subsequent reduction of the cutting force required. This is compounded by the fact that, for a metal, titanium is a bad heat conductor.

While Figure **2** shows the behaviour of the thrust force during the whole process for each combination of the drilling parameters it offers no information about the behaviour during the single drilling operation for a certain set of parameters. An analysis of Figure **3** shows that the thrust force decreases during the process for both cooling conditions. To better study this phenomenon a new parameter must be introduced, the delta thrust force. This is defined as the difference between the average thrust force for the third peck and the average thrust force for the eleventh peck, expressed as a percentage of the global average thrust force. The choice of the two pecks is due to the fact that they offer the highest and the lowest average values for Ti drilling, so that the delta thrust force offers an idea of the decrease of the thrust force during a single drilling process. The values of the measured delta thrust force are shown in Figure **5**.

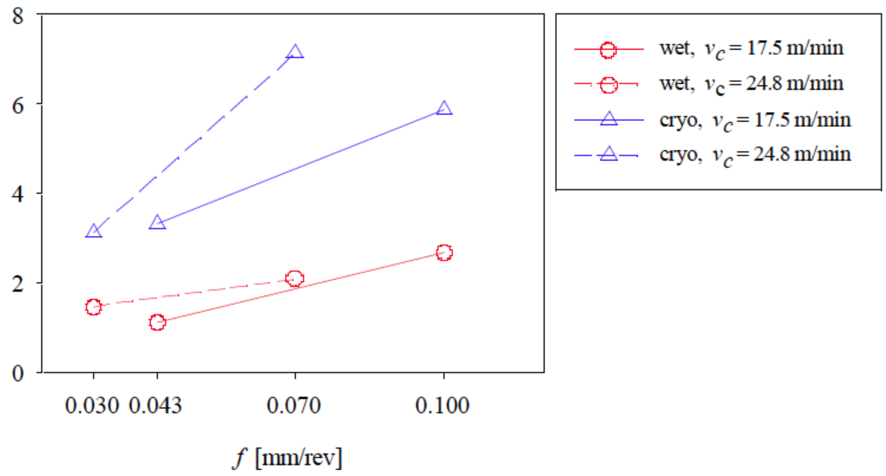

Figure 3: Delta Trust force as function of the feed rate for revolution.

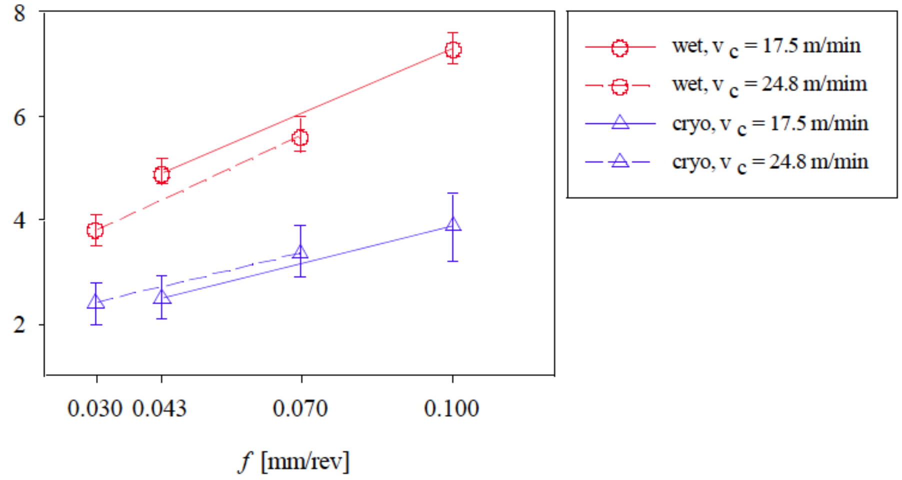

Figure 4: Average torque as function of the feed rate for revolution.

In both cooling conditions the delta thrust force increases with the chip load. A reason behind this is that the increase in the material removal rate causes both an increase in the heat generation, with consequent softening of the material, and an increase of the chip thickness, with consequent increase of the friction on the tool face. In wet drilling this increase is barely perceptible, being about 2% for $f = 0.1$ mm/rev, while it is much more evident in cryogenic drilling, where it reaches 7.3% for $f = 0.1$ mm/rev. This can be justified by the fact that, while the increase in the heat generation due to the removal process is comparable in both cases, the use of cryogenic fluid causes the embrittlement of the chip with consequent breaking of the same. The breaking of the chip helps in the evacuation of the same and this effect is much more pronounced during the later pecks, where the depth of the hole interferes with the easy evacuation of the chip. This phenomenon had been extensively treated by [20].

Figure **4** shows the global average torque for both drilling conditions. Due to the fact that the torque increases with the depth, the global average torque is averaged only on the last three pecks, *i.e*. from the ninth to the eleventh peck, where the torque reaches a plateau. As before the upper and lower errors are the average of the maximum and minimum measured values for the same three pecks. Likewise the thrust force, the torque for cryogenic drilling is much lower than that of wet drilling. As expected the torque increases with the increase in the feed rate, however the increase is lower under cryogenic cooling.

As it was observed before, the torque increases with the drilling depth. Then, to better analyse the behaviour of the torque during a single drilling process, the delta torque is introduced. This is defined as the difference between the average torque for the eleventh peck and the average torque for the third peck, expressed as a percentage of the global average torque. The delta torque gives a measure of the variation of the same during a single drilling process, whereby lower values of the delta torque mean that the torque in the third peck is closer to that in the last peck. This implies then that a sort of steady state is reached as soon as the drill fully engages the Ti plate, *i.e*. from the third peck forward. The values of the measured delta torque are shown in Figure **5**. It is evident that for cryogenic drilling the global average torque is reached sooner than in the case of wet drilling. This is expected due to the fact that the torque is proportional to the chip friction and that the use of cryogenic coolant lowers the latter. On the contrary, in the case of wet drilling the torque continues to increase with the depth due to the increasing difficulty to evacuate the chip. In the worst case the delta torque is 7% for cryogenic drilling, while in the best case the delta torque for wet drilling is 33%, and reaches values up to 48%.

It has been found that the average hole diameter is substantially independent from the drilling parameters both for CFRP and Ti. On the other side, there are significant differences in the average hole diameter between wet and cryogenic cooling. For CFRP the average entry diameters are 7.93 mm, for wet drilling, and 7.92 mm, for cryogenic drilling, while the average exit diameters are 7.97 mm and 7.95 mm respectively. The undersizing of the hole diameters under cryogenic cooling is due to the well-known spring-back phenomenon [11]. The burr height is also independent from the cutting parameters but function of the cooling

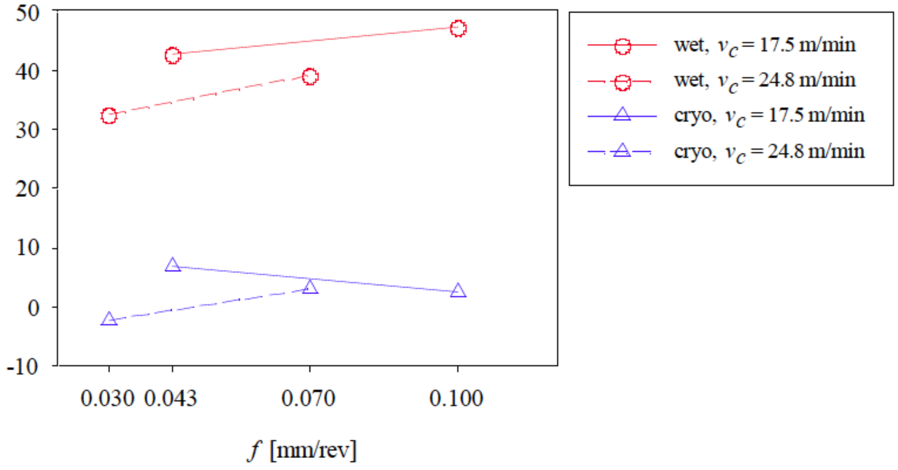

Figure 5: Delta torque as function of the feed rate for revolution.

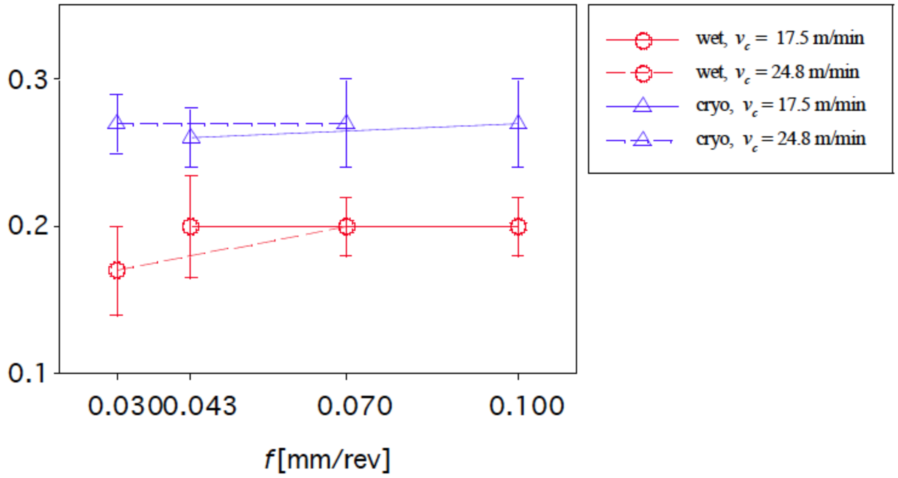

Figure 6: Exit burr height as function of the feed rate for revolution.

conditions, see Figure **6**. It was found that the burr height under cryogenic cooling is higher than the one obtained under wet condition, but the difference is not significant form a technological point of view.

CONCLUSIONS

Cryogenic drilling shows promise of a dramatic improvement upon standard drilling methods for CFRP/Ti stacks. The use of cryogenic coolant reduces the thrust force and the torque, offering to the process engineer the possibility to increase the drilling speed with consequent reduction of the working time. The embrittlement of the chip in cryogenic drilling causes a diminution of the average chip. It is also evident that the cryogenic cooling allows for a steadier cutting than wet drilling. The only parameter that worsens under cryogenic cooling is the burr height, which is higher than in wet condition.

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