Method for evaluating cooling strategies in terms of chip formation/transport in drilling CFRP/Al-stacks

Conference Paper

Author(s):
Kneubühler, Fabian; Seeholzer, Lukas ; Spahni, Martina; Di Pierno, Luca; Wegener, Konrad

Publication date:
2021-09-30

Permanent link:
https://doi.org/10.3929/ethz-b-000515235

METHOD FOR EVALUATING COOLING STRATEGIES IN TERMS OF CHIP FORMATION/TRANSPORT IN DRILLING CFRP/AL-STACKS

Fabian Kneubühler[a,*,1], Lukas Seeholzer[a, 1], Martina Spahni[a], Luca Di Pierno[a], Konrad Wegener[a]
[a] Institute of Machine Tools and Manufacturing (IWF), ETH Zürich, Leonhardstrasse 21, 8092 Zurich, Switzerland
[*] Corresponding author / [1]These authors contributed equally

ABSTRACT

In modern aircrafts, CFRP and aluminium are often drilled in stacks via one-shot operations under dry conditions, which makes that process highly prone to clogging due to insufficient chip evacuation. In this study, the borehole in the CFRP layer is replaced by a transparent PMMA tube. With this method, the aluminium chip formation/transport through the chip flute in dependence of compressed air and liquid CO_2 cooling are investigated based on high speed recordings and online force measurements. It is shown that the combination of low temperatures and high pressures can be used to realise a secondary material separation during chip formation/transport resulting in small chips.

1. INTRODUCTION

Carbon fibre reinforced polymers (CFRP) are used with increasing amount in aerospace applications due to their high potential for lightweight construction that can be used to reduce the airplane's fuel consumption considerably. In the context of mechanical joining metallic and non-metallic components via riveting, CFRP often has to be drilled in combination with aluminium alloys. This is usually done via one-shot drilling operations because otherwise the required positioning accuracy for the subsequent assembly process cannot be achieved.

Since CFRP and metals show very different material properties, the ideal tool geometry for drilling these materials differs as well. This means that a trade-off solution needs to be made for the tool geometry in one-shot drilling of CFRP/metal-stacks. Drilling operations, where CFRP material is involved, are often performed under dry conditions due to quality standards and automation requirements [1]. When drilling stacks with the bore entry in the CFRP, hot metallic chips have to be transported through the chip flute and get in contact with the previously machined borehole in the CFRP plate. According to Hong et al. [2], this process is associated with a high risk of thermal and mechanical related workpiece damages in the bore channel of the CFRP material. As experimentally shown by different researchers [5, 8], small and separated chips can be evacuated better through the chip flute than larger chips and hence show a smaller risk for chip clogging.

In literature, different methods are presented for generating small chips during drilling CFRP/metal-stacks. These methods can be separated into process- and geometry-based approaches. Popular representatives for process-based approaches are peck-drilling and vibration-assisted drilling, where either the machine control or a specialised tool adapter are used to generate an interrupted cut and therefore separated chips. Geometry based approaches follow another strategy; small chips are enabled via a secondary material separation during the chip formation at the tool tip. For this purpose, the tool geometry and the process parameters have to be adjusted and attuned to each other. This is done by introducing a specific stress state in the material, which initiates a crack in the produced metallic chip during its guidance into

the chip flute. Instead of adapting the tool geometry, several authors highlight the possibility of using cryogenic cooling for producing small chips. The high potential of cryogenic cooling is attributed to a low temperature level in the cutting region. This can be used to achieve a more brittle fracture behaviour of the workpiece material, which supports early chip fracture and hence smaller chips [6]. Furthermore, cryogenic cooling decreases the tendency to adhere workpiece material avoiding build-up edge formation at the cutting edge [1, 3].
In drilling CFRP/metal-stacks, chip clogging is usually investigated by analysing the process forces, the temperatures of the stack components and the produced metallic chips. Furthermore, high-speed recordings are used to observe the chip evacuation from the bore entry. However, these analysis approaches are only indirect methods and do not allow to directly inspect the chip formation in the bore hole, the chip transport through the chip flute and the potential clogging process due to a lack of visibility caused by the CFRP bore channel.
In this work, a method is presented which enables the investigation and the correlation of the chip formation process, the chip transport and the thrust force with respect to different cooling strategies in stack drilling. As a result, an enhanced process analysis of the CFRP/metal-stack drilling process is possible that can be used for tool optimisation in terms of clogging prevention.

2. MATERIALS AND METHODS

In this chapter, the process and the process parameters are introduced first. Afterwards, the samples that allow to observe the chip formation, chip transport and the used tool are detailed. This is followed by the explanation of the experimental setup and the different cooling strategies considered in this work. Finally, the applicable process analysis in the given framework is explained.

2.1 Process and process parameters

The drilling experiments are conducted on a *Schaublin 42L* CNC-lathe. The workpiece samples perform the rotational movement, i.e. cutting velocity, and are clamped in the spindle using a collet clamping system. The drilling tool is mounted to the turret and executes only a linear motion between the tool and the workpiece sample, i.e. feed velocity, which takes place in direction of the Z-axis. The tool/workpiece configuration is shown in Fig. 3 (b). For the drilling experiments, a cutting speed of v_c=120 m/min and a feed rate of f=0.2 mm/rev are used and kept constant during the machining operation.

2.2 Samples

In this work, the stack drilling process with the bore entry in CFRP and the bore exit in aluminium is taken into account. In this context, a material thickness of 5 mm for both materials is used. The schematic illustration of the stack drilling process is shown in Fig. 1 (a). Drilling CFRP mainly produces powder like chips that do not show a high risk for clogging. The manufacturing issue arises if hot Al-chips from the underlying Al-plate have to be transported through the chip flute. In this context, potential clogging of Al-chips results in mechanical and thermal damages in the bore channel of the previously drilled CRRP material. In order to observe the chip formation and evacuation processes, the bore channel is required to be visually accessible. Therefore, the CFRP bore channel is simulated by replacing it with a tube made out of the transparent thermoplastic material polymethyl methacrylate (PMMA) as shown in Fig. 1 (b). The tube is connected to the aluminium cylinder via press fit and has an inner diameter of 7 mm, which leads to a distance of 0.5 mm between the cutting edge corner and the inner surface of the tube. The additional space helps to ensure the observation of the process, since the chips in the chip flute have less contact with the PMMA and thus cause fewer scratches. The diameter of the inner aluminium cylinder, as seen in Fig. 1 (b), consists of 6 mm, which is the same diameter as the one of the drilling tool. Therefore, effects of the tool margins are neglected.

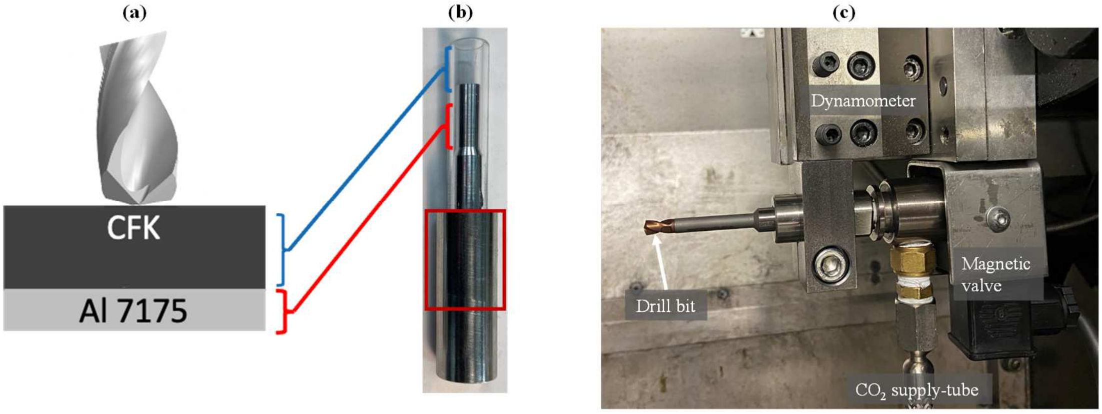

Fig. 1: (a) CFRP/Al-stack drilling illustration; (b) Sample to approximate an arbitrary stack-drilling process (CFRP entry, Al exit) made out of aluminium with PMMA tube highlighting workpiece side cooling area with red rectangle; (c) Test rig configuration for tool-side cryogenic CO_2 cooling with drill bit (C3)

In the scope of this paper, the chip formation process and the chip transport mechanisms are analysed for four different cooling methods. As a reference, dry cutting (C0) is compared with the effects of the cooling media compressed air at 8 bar and liquid CO_2 at 60 bar. Cooling with compressed air through the cooling channels of the tool is referred to as C1. Liquid CO_2 is used either from the workpiece side applied via cooling stream on the circumference of the aluminium cylinder (C2) or from the tool side through the cooling channels (C3). For the workpiece side cooling, a CO_2 jet is oriented perpendicular to the cylindrical surface of the sample. The area that enables the heat transfer via forced convection is marked by a red rectangle in Fig. 1 (b). The aluminium alloy AW-7075 (AlZn5,5MgCu) is used for the samples, which is an optimised alloy for aerospace applications. The good thermal conductivity of the material makes it interesting to compare cooling at different locations, i.e. on the workpiece and the tool.

2.3 Tool

ArCr-based coated cemented carbide drill bits from *Heule Werkzeug AG* are used for the experiments. The tools have two internal coolant channels that are used for supplying the cooling media for C1 and C3 via the clearance face, shown in Fig. 2 (a), to the cutting zone. The diameter of the drill is 6 mm with a working length of 12 mm and a pointing angle of $\sigma=144°$. The drill bit is mounted via a screw connection on a drill rod, which allows rapid changes of different drill bits.

The cooling mechanism of CO_2 is based on a volumetric expansion, which leads to a temperature drop of the room temperature stored liquefied pressurised CO_2 to a minimum temperature of -78.5 °C [2]. The volumetric expansion in the coolant supply needs to take place right before the cutting zone in order to use the available cooling capacity in the most efficient way. The cooling media flow is supplied through a 0.5 mm diameter entry hole of the drill rod and is divided inside the drill bit into the two inner coolant channels. A tube with an inner diameter of 1 mm conducts the liquid CO_2 from the smallest orifice through the entire drill rod directly to the drill bit. This reduces interfaces to a minimum and avoids sudden pressure changes that could lead to blockages, when some percentage of the liquid CO_2 transforms into dry ice. The assembled drilling tool inside an adapter for mounting different valves and the connecting copper tube is shown in Fig. 2 (b).

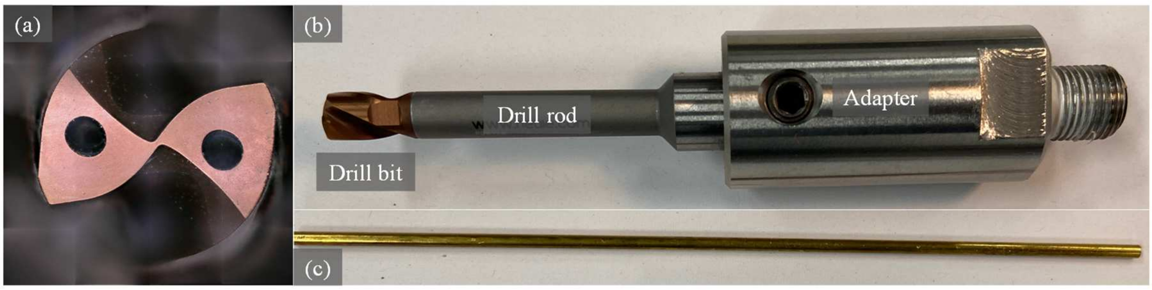

Fig. 2: (a) Top view of drill bit showing cooling channels; (b) Drilling tool configuration with adapter; (c) Connecting tube

2.4 Experimental setup

In order to analyse different cooling strategies on chip formation and transport mechanism, a test rig is developed, which allows to apply compressed air and liquefied CO_2 as cooling media. The compressed air is supplied to the tool adapter via a safety coupling whereas the cryogenic media requires a magnetic valve that can withstand high-pressure differences and low temperatures. The tool in the before described configuration is fixed to a dynamometer force plate type *Kistler 9121A5* on the turret of the CNC-lathe, which is used to measure the thrust forces during the drilling operations. For the force measurements, a sampling rate of 1.1 kHz and a low pass filter of 3 kHz are used. The fully assembled test rig with the configuration for cryogenic cooling (magnetic valve) is shown in Fig. 2 (c).
For cooling the workpiece from the outside (C2), a curved tube is used to supply a aligned coolant jet to the aluminium surface of the sample. This tube is connected to an adapter, which is mounted on the turret of the CNC-lathe so that the horizontal distance in Z direction between the drill bit and the coolant flow remains constant during the drilling operation. Fig. 3(a) shows the technical realisation of the cooling procedure from the workpiece side with focus on the adapter, whereas in Fig. 3 (b), the tool and the workpiece are highlighted.

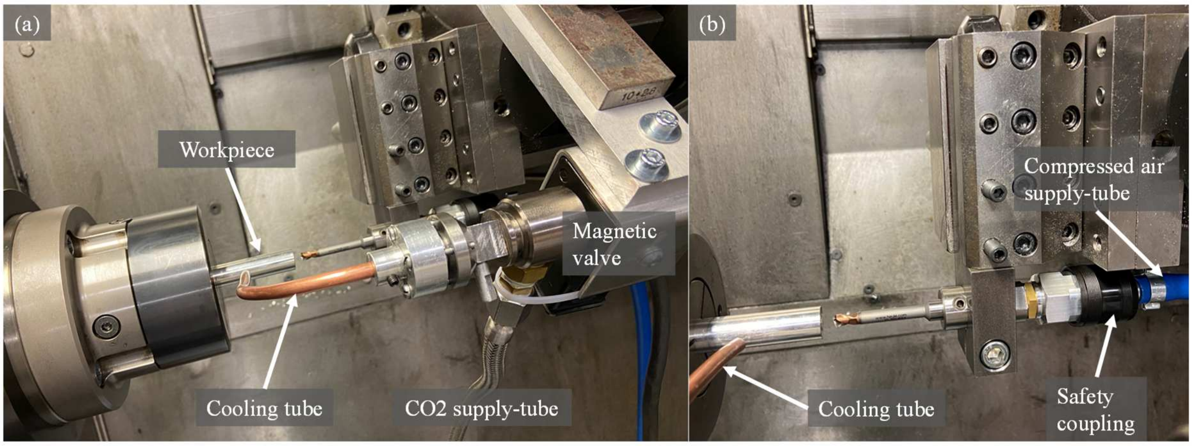

Fig. 3: (a) C2 cooling configuration showing the cooling from the CO_2 supply-tube to the magnetic valve through the cooling tube to the workpiece surface; (b) Combination of workpiece side cooling via cooling tube (C2) and tool-side cooling via compressed air supply tube (C1)

2.5 Process analysis

For the process analysis, the high-speed recordings of the chip formation and transport process through the PMMA tubes and the measured thrust forces are considered. Each force measurement is repeated three times and the mean value is calculated. The measurement evaluation for the arithmetic mean value takes place over the area where the oblique cutting edge is fully engaged and an approximated constant load situation is reached. For the high speed analysis, a high-speed camera type *Vision Research Phantom v12* is used, which is oriented perpendicular to the drilling axis focusing on the cutting zone. With a sample rate of 10’000 fps and an exposure time of 110 µs, a comprehensive angular resolution of 2.8° per image is achieved.

3. RESULTS AND DISCUSSION

This section contains the results of the prior explained method for evaluating cooling strategies focusing on the chip formation, the chip transport and the thrust forces for drilling aluminium with a simulated CFRP bore channel.

In Fig. 4 (a), (b) and (c), representative time steps of the chip formation process and the chip transportation process in opposite feed direction are shown in dependence of the cooling strategies C0, C1, C2 and C3. The first time step shown in Fig. 4 (a) represents the moment of the chip crack initiation in the Al-chip. In Fig. 4 (b), the subsequent crack propagation is displayed. Finally, Fig. 4 (c) shows the previously described chip at the moment shortly before the next crack is initiated. The situation shown in Fig. 4 (c) represents the key point in terms of the secondary material separation, which describes the chip fracture during the chip’s transport in the chip flute resulting in small single chips. In contrast to C0, C1 and C2, the formation of dry ice at the tool tip found for C3 prevents the analysis of the high-speed recordings. Therefore, only the chips that are ejected from the bore entry are visible and considered in this study. Representative Al-chips produced during the drilling operation are shown in Fig. 4 (d).

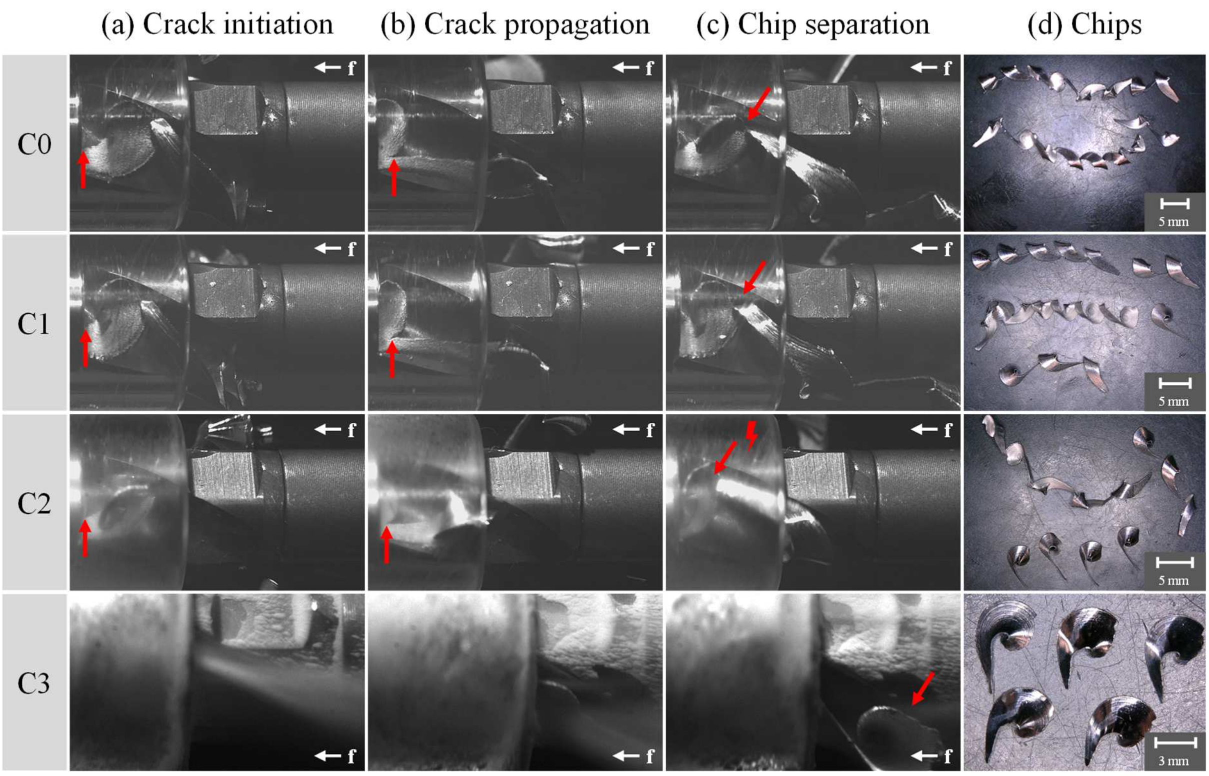

Fig. 4: Representative time steps of the chip formation and transport processes for C0, C1, C2 and C3: (a) Crack initiation, (b) crack propagation, (c) chip separation shortly before new crack initiation; (d) illustrations of representative Al-chips

Since the tool geometry and the process parameters remain constant for the drilling operation, the differences in chip formation and chip transport shown in Fig. 4 are only attributed to the applied cooling strategies. In the following, the general chip formation and chip transport behaviour for the reference situation C0 is explained.
During the progressing engagement of the cutting edge, the main cutting edges first form a spiral formed cone. Subsequently, the chip flows into the chip flute while beginning to twist around itself due to the tool rotation. With growing chip length, the produced chip coil is transported via the rake face into the chip flute. Meanwhile, the growing chip becomes less agile and the rotational moment forced by the tool rotation initiates shearing stresses. The induced stress state leads to a crack that starts nearby the core of the drilling tool, which then propagates across the chip width outwards. The crack initiation has two reasons. On the one hand, the difference in cutting speed over the tool diameter leads to shear stresses in the material of the previously produced chip during its transport along the rake face into the chip flute. On the other hand, the shape of the flute means that the chip cannot move at will but is forced into the helical tool geometry. In combination with the tool motion in feed direction, the superposition of these two reasons leads to a propagation of the previously initiated chip crack, which can lead to a secondary material separation as mentioned before. The chip formation process depends on the material properties of the workpiece, the applied cooling strategy, the process parameters and the tool geometry. However, for ductile materials it is often not enough to completely tear the chip apart since the material can be easily deformed. If the chip is not interrupted, the winding of a new cone occurs, which increases in size leading to the same phenomenon described before. The resulting long continuous chips are associated with a higher risk for clogging as explained in Section 1.
Cooling strategies that reduce process temperatures and enhance chip transport via pressurised media influence the process described above. Therefore, the results of the experimental study are evaluated below with respect to crack initiation, crack propagation and potential chip separation. In Fig. 4 (a), the chip crack initiation in the immediate vicinity of the cutting edge is highlighted with a red arrow for C0, C1 and C2. Comparing the three cooling strategies, no significant difference in the position of the crack initiation is determined. Consequently, the pressurised air (C1) and the workpiece side cooling with CO_2 (C2) have no visible impacts on the position of the crack initiation. It is assumed that the tool geometry and the process parameters play a more dominant role with respect to the crack initiation location than the tested cooling methods. As explained before, C3 does not reveal further information but visualises the ejection of the cooling media. After about 4 to 5 ms from the first crack initiation, Fig. 4 (b) shows the subsequent propagated crack. The red arrow in Fig. 4 (b) displays the approximate end of the crack propagation. C0 and C1 show a continuous stretched crack of about the length of the bore channel. Since a visual difference is not distinguishable, 8 bar seems to have a negligible effect on the chip transport. In comparison to C0 and C1, the length of the crack propagation for C2 is clearly shorter. The different crack propagations are associated with a reduction of ductility of the aluminium due to the workpiece side cooling with CO_2 (C2). Looking at C3, the ejection of a chip at the bore entry is indicated. After the propagation of the crack displayed in Fig. 4 (b), a new chip winding is formed that leads to a rotation and a twisting of the prior generated chip, which is shown in Fig. 4 (c). In this context, a red arrow for C0, C1 and C2 highlights the critical point of a secondary material separation. During all conducted experiments, C0 shows rarely chip breaks (approx. 30%) whereas using pressurised air (C1) leads to a more frequent chip interruption (approx. 40%), which is confirmed by the resulting chips displayed in Fig. 4 (d). This difference is explained by the additional pressure, which forces the chip towards the chip flute supporting a full propagation of the crack leading to a higher probability for a secondary material separation. In comparison,

around 50% of chip breaks occur by using CO_2 cooling from the workpiece side (C2), which is exemplarily shown by a red lightening symbol in Fig. 4 (c). In general, shorter interrupted chips are produced as exemplarily shown in Fig. 4 (d). Although the chip formation process and the chip transport cannot be investigated for C3, the subsequent analysis of generated Al-chips shows only small and separated chips, which means that the secondary material separation is continuously achieved resulting in <90% of chip breaks. In this context, Fig. 4 (c) visualises the ejection of the cooling media and a chip that is marked with a red arrow, which is formed evidently due to the cryogenic cooling conditions, i.e. high pressure and low temperature. Furthermore, the high-pressurised cooling media supports the evacuation of Al-chips so that clogging in this study is avoided. However, the effects of pressurised air and CO_2 cooling from the workpiece side are diminishing as further the chip moves along the chip flute. Moreover, as longer the tool is engaged with the workpiece material, as more process heat is generated. These two factors are the reasons why the superposition of high pressure and low temperature in C3 showed clear advantages in terms of small single chips compared to C0, C1 and C2.
Generally, thermal softening is facilitated at higher temperatures by the absence of sufficient cooling so that the material shows less internal resistance to deform. As a consequence, cryogenic cooling leads to a more brittle facture behaviour of the workpiece material resulting in increased process forces. Therefore, this method uses the thrust force measurements in order to obtain a quantitative measure for the chip formation as well as the chip transport behaviour to enhance the optical findings. It is found that the thrust force increases when applying any of the tested cooling strategies compared to the reference situation C0 as shown in Fig. 5. These findings are in good agreement with other research studies [4, 7]. The difference between the mean force values of C0 and C1 is not significant and the air jet resulting in a pressure force is likely to contribute to the increase. A further dominant increase of the thrust force and a reduction of the standard deviation is shown by comparing C0 and C2. Due to the absence of any pressure force from a cooling media introduced through the cooling channels, the increased thrust force is explained only by the increased hardness of the aluminium alloy at lower temperatures, which results in higher forces for generating plastic deformation. When applying liquid CO_2 cooling through the drilling tool (C3), about 20% higher thrust forces are measured. However, this phenomenon cannot be accounted to changing cutting conditions because of lower temperature and the therefore lower deformability of the material only since the injection of pressurised CO_2 of 60 bar adds an unknown force component to the measured signal affecting the mean value and the standard deviation. It is suggested to use the force signal as additional indicator for relative comparisons if high pressure fluids into the cutting zone are involved because of the unknown pressure force component in thrust force direction.

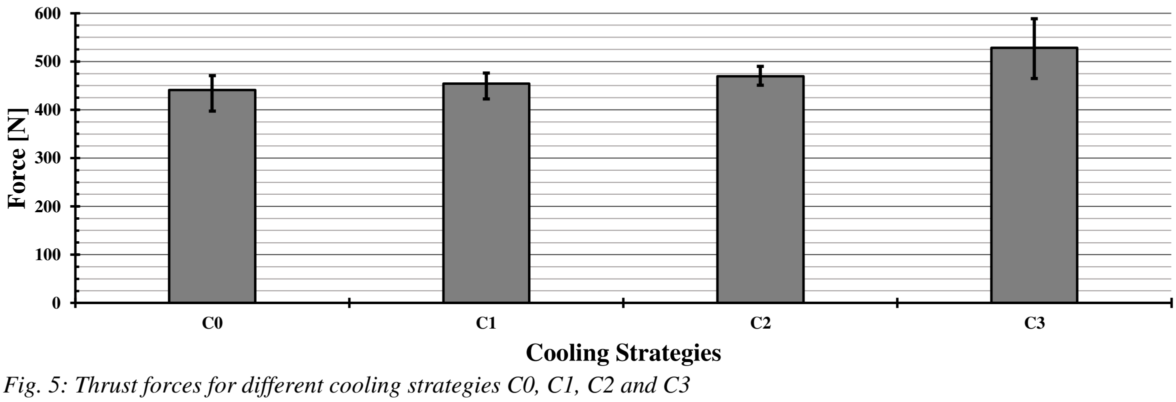

Fig. 5: Thrust forces for different cooling strategies C0, C1, C2 and C3

4. CONCLUSION

In this work, a new method for the efficient evaluation of different cooling strategies in drilling CFRP/Al-stacks is presented and validated. The CFRP bore channel is replaced by a tube made out of PMMA, which allows to reveal insights how the chip formation and the chip transport are affected by cooling strategies. In addition, the change in chip formation/transport is measured by means of the thrust force. It is found that pressurised air and liquid CO_2 through the cooling channels of the tool and a workpiece side applied cooling stream of CO_2 facilitates chip transport through the chip flute and therefore helps to avoid chip clogging. The cooling effect of CO_2 is explained by changing the material properties and therefore influencing the chip formation process of the aluminium alloy whereas the use of pressurised media through the cooling channels supports the evacuation of chips. Smaller chips are achieved at lower temperatures due to a secondary material separation. Even though the chip formation of CO_2 cooling through the tool cannot be observed because of the formation of dry ice, the chip evacuation is also a valuable information, which can be combined in future works with other measures, e.g. relative time between chip ejections. The thrust force increases by applying any of the tested cooling strategies and is most dominant when applying liquid CO_2 cooling through the internal cooling channels. This is because of cooling in the immediate vicinity of the chip formation process and the pressure force of 60 bar. Despite the highest thrust forces, small single chips are obtained exclusively using the combination of high pressure and liquid CO_2 at the tool tip, which minimises the risk for chip clogging. For future investigations, the tool’s geometry can be optimised in combination with a cooling strategy for initiating a different chip break behaviour.

5. ACKNOWLEDGEMETN

The authors thank the Swiss Innovation Agency (Innosuisse-Project 53668.1 IP-ENG) and the company Heule Werkzeug AG for the support.

6. REFERENCES

[1] Dhananchezian, M.,Rajadurai, A., *Experimental investigation of cryogenic cooling by liquid nitrogen in the orthogonal machining process.* International Journal of Recent Trends in Engineering, 2009. 1(5): p. 55.

[2] Hart, A.,Gnanendran, N., *Cryogenic CO2 capture in natural gas.* Energy Procedia, 2009. 1(1): p. 697-706.

[3] Hong, S.Y.,Zhao, Z., *Thermal aspects, material considerations and cooling strategies in cryogenic machining.* Clean Products and Processes, 1999. 1(2): p. 107-116.

[4] Jebaraj, M.,Pradeep Kumar, M., *Effect of cryogenic CO2 and LN2 coolants in milling of aluminum alloy.* Materials and Manufacturing Processes, 2019. 34(5): p. 511-520.

[5] Seeholzer, L., Voss, R., Marchetti, L., Wegener, K., *Experimental study: comparison of conventional and low-frequency vibration-assisted drilling (LF-VAD) of CFRP/aluminium stacks.* The International Journal of Advanced Manufacturing Technology, 2019. 104(1): p. 433-449.

[6] Singla, A.K., Singh, J., Sharma, V.S., *Processing of materials at cryogenic temperature and its implications in manufacturing: A review.* Materials and Manufacturing Processes, 2018. 33(15): p. 1603-1640.

[7] Yildiz, Y.,Nalbant, M., *A review of cryogenic cooling in machining processes.* International Journal of Machine Tools and Manufacture, 2008. 48(9): p. 947-964.

[8] Zitoune, R., Krishnaraj, V., Collombet, F., Le Roux, S., *Experimental and numerical analysis on drilling of carbon fibre reinforced plastic and aluminium stacks.* Composite Structures, 2016. 146: p. 148-158.