Influence of different cooling strategies on the process temperatures and chip transport quality in one-shot drilling CFRP/ Al-stacks

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 101 (2021) 310–313

www.elsevier.com/locate/procedia

9th CIRP Conference on High Performance Cutting (HPC 2020)

Influence of different cooling strategies on the process temperatures and chip transport quality in one-shot drilling CFRP/Al-stacks

Lukas Seeholzer[a,1,*] , Martina Spahni[a,1], Konrad Wegener[a]

[a]*Institute of Machine Tools and Manufacturing (IWF) ETH, Leonhardstrasse 21, 8092 Zürich, Switzerland*
[1]*These authors contributed equally*

* Corresponding author. Tel.: +41-44-632-5309 ; fax: +41-44-632-1125. *E-mail address:* seeholzer@iwf.mavt.ethz.ch

Abstract

This study focusses on the influence of different cooling strategies on process temperatures and chip transport quality in one-shot drilling CFRP/Al-stacks. In addition to the maximum temperatures in both individual stack components, temperature changes in the CFRP material due to hot aluminium chip interactions are analysed. The following cooling strategies are compared: compressed air through the drilling tool, cryogenic CO_2 cooling at the aluminium bore exit as well as the combination of both. It is shown that process temperatures and chip transport quality significantly differ for the tested cooling strategies. Whereas CO_2-cooling of the Al-plate results in overall smaller chips, the use of compressed air mainly improves chip evacuation. The combination of both cooling strategies shows high potential to prevent clogging in the chip flute as well as its negative impacts on workpiece quality.

Keywords: Fiber reinforced plastic; Aluminium; Drilling; Cooling; Cryogenic machining

1. Introduction

Modern aircraft structures show a high percentage of carbon fibre reinforced polymers (CFRPs), which are characterised by high specific strength and stiffness properties and thus show high potential for lightweight constructions. Therefore, the increasing substitution of metallic components by CFRP elements aims to enable considerable weight savings to improve the aircraft's fuel-efficiency [1]. According to Rivero et al. [2], the assembly process in commercial aircraft constructions is dominated by rivet joint connections, where prior drilling operations are necessary. To ensure proper hole alignment in the subsequent fastening procedure, CFRP and metallic components are usually drilled in stacks [1]. Drilling these multilayer stacks is often handled by one-shot drilling operations [3]. However, the machinability of CFRP and metals and thus the corresponding drilling tool requirements are fundamentally different, which means that one-shot stack drilling tools are always a trade-off between tool geometries optimised for the respective stack component [4].

In order to support chip transport and heat dissipation during drilling, the use of cutting fluids is generally recommended. However, for most stack machining operations settled in aerospace applications, liquid cutting fluids are prohibited due to quality and automation requirements. Although alternative, non-liquid cooling strategies exist, these CFRP/Al-stacks are usually drilled under dry conditions. On the one hand, dry machining comes with ecological and economic advantages as well as improvements in handling and recyclability [2]. On the other hand, the lack of cooling in dry machining usually causes high process temperatures and therefore is often related to thermal workpiece damages. Combined with the absence of effective flushing, these high temperatures cause an increased risk for metallic chip accumulations in the chip flute [5].

10.1016/j.procir.2020.12.005

Accumulations of compressed chips interact thermally and mechanically with the CFRP bore channel, resulting in a degraded surface finish and adhered aluminium (Al) chips [6].

In this work, compressed air through the tool and an external CO_2 supply are used as non-liquid and residue-free cooling strategies to avoid the disadvantages of dry machining without making additional cleaning and drying steps necessary as for liquid cutting fluids. Whereas compressed air through the tool is a common method to support chip evacuation, expanded CO_2 provides very low ambient temperatures, which affects both, chip formation and chip transport [7].

2. Experimental Setup

The following cooling strategies are analysed with respect to the process temperatures in the respective stack component and the chip transport quality in drilling CFRP/Al-stacks.

- **CS0:** Uncooled (reference)
- **CS1:** Compressed air cooling through the tool
- **CS2:** Cryogenic CO_2 cooling from the Al side
- **CS3:** Combination of CS1 and CS2

For CS1, compressed air is guided through the drilling tool with an inlet pressure of 6 bar. By air injection close to the cutting edges, the air flow reduces the process temperatures in the immediate cutting zone and supports heat transport through the chip flutes including chip evacuation. For CS2, the cooling effect of expanded liquid carbon dioxide is used to cool down the stack materials, in particular the Al -plate. Therefore, an expansion nozzle is fixed vertically under the bore exit of the Al-plate with a distance of 10 mm as shown in Figure 1. At the nozzle exit, the aggregate state of the carbon dioxide changes from liquid to solid and gaseous due to the pressure drop from 57 to 1 bar. The resulting CO_2 jet is characterised by a temperature of nearly -80°C. The mass flow rate of the CO_2 supply is 25 kg/h.

Drilling experiments are conducted on a *Mikron VC1000* three-axis machining centre. CFRP and Al-plates are prepared in the dimensions 50 x 300 x 10 mm and 50 x 300 x 6 mm respectively. Both plates are clenched together by screws and fixed on the machine table. No bonding agent is used between the plates hence its effect on the results is not considered in this work. The epoxy-based, woven CFRP material is produced by Resin Transfer Moulding (RTM) with *HexFlow RTM6* matrix material and high strength carbon fibres type *HTA G0926*. The aluminium alloy is *AL7175*. For drilling experiments diamond-coated cemented carbide spiral drills with a tool diameter of

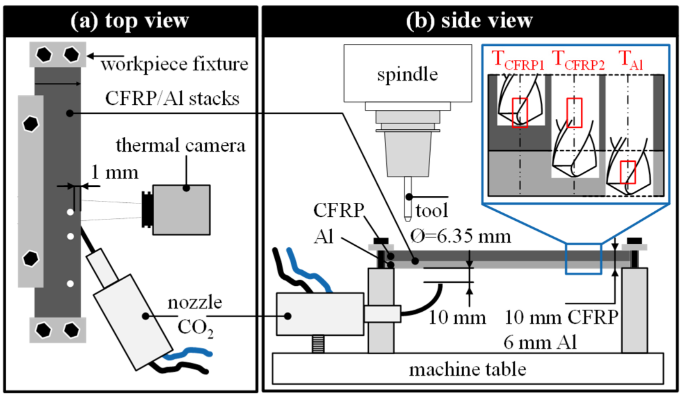

Figure 1: Schematic illustration of the test rig, (a) top view and side view (b)

Ø=6.35 mm, a helix angle of ψ=40° and a tip angle of σ=130° are used. The cutting velocity of v_c=90 m/min and the feed rate of f=0.1 mm/rev are kept constant. During the experiments, the drilling tool does not show considerable wear effects. The drill enters on the CFRP side and exits on the Al-side. An IR camera type *PI 640* from *Optris* with a frame rate of 125 Hz and a temperature range of 0-250 °C is used to analyse the influence of the different cooling strategies on workpiece temperature and chip transport quality. Therefore, the side face of the stack is prepared with a thin layer of high temperature resistant black coating with an approximated emissivity factor of 1. According to Figure 1, the bores are then placed with a remaining wall thickness of 1 mm at the material edge. The orientation of the IR camera perpendicular to the black coated side face enables comparative temperature measurements.

Three representative temperatures are evaluated for a differentiated analysis of process temperatures with respect to the relative axial tool position. The value T_{CFRP1} represents the maximum temperature measured in the 2 mm x 4 mm field indicated in Figure 1 during drilling of CFRP. Similarly, T_{Al} represents the maximum temperature which is measured in a 2 mm x 3 mm field in the Al-plate during drilling aluminium. The temperature values T_{CFRP1} and T_{Al} allow an evaluation of the cutting process and the chip formation within the respective stack components. However, during drilling aluminium, hot metallic chips are transported through the chip flute and get in contact with the CFRP bore channel. The value T_{CFRP2} describes the maximum temperature value in CFRP during drilling of the Al-plate and therefore provides information about the influence of hot Al-chip evacuation on the temperature level in the CFRP plate and thus represents a measure for chip transport quality. The temperature rise from T_{CFRP1} to T_{CFRP2} is strongly influenced by the chip type and the chip interaction with the bore channel. Whereas small chips show the lowest potential for heat transfer, an accumulation of compressed chips causes continuous physical contact and thus heat transport between the chips and the bore channel.

By comparing the thermal measurements of CS0 with those of CS1, CS2 and CS3, the influence of the individual cooling strategy can be analysed separately for the cutting process in the respective materials and the chip transport quality. For each cooling strategy, six repetitions are conducted. By averaging these six measurements, representative mean temperatures are obtained for each cooling strategy. Representative Al-chips for each cooling strategy are analysed by microscopy.

3. Results and Discussion

Figure 2 shows an overview of the three representative temperature values T_{CFRP1}, T_{CFRP2} and T_{Al} in drilling CFRP/Al-stacks for each tested cooling strategy. In addition to the mean temperature values, the respective standard deviations with respect to the six repetitions are provided. Once the drilling tool has reached the Al-plate, hot Al-chips are transported through the chip flute. According to Figure 2, the interaction of hot Al-chips with the CFRP bore channel always causes a temperature rise in the CFRP material (T_{CFRP2} >T_{CFRP1}). Figure 3 shows a representative selection of resulting Al-chips collected during the drilling operations. In general, two different chip types can be distinguished. Up to a bore depth of approximately 13 mm, rather small chips are produced as representatively shown in the first row of Figure 3. However, with increasing drilling depth, the overall cutting temperature and the chip transport length through the chip flute increase, which in turn means a higher risk for accumulations of compressed chips. In this context, the second row of Figure 3 shows a representative chip accumulation made of compressed single chips as it is sporadically generated during the one-shot drilling operation. Although their dimensions and the probability of occurrence vary regarding the cooling strategy, they are found after each bore operation in this study.

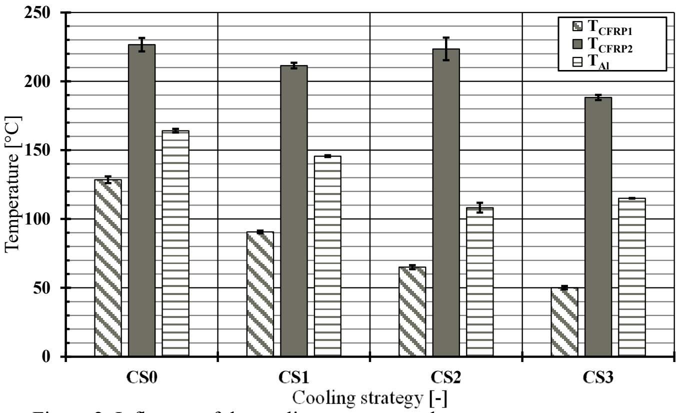

Figure 2: Influence of the cooling strategy on the process temperatures

3.1. CS1 – Compressed Air Cooling

According to Figure 2, using compressed air through the drilling tool results in a reduction of all representative temperature values. In comparison to CS0, T_{CFRP1} is reduced by 38°C (-29%), T_{CFRP2} by 15.2°C (-6.7%) and T_{Al} by 18.5°C (-11.3%). Chip formation in machining CFRP is characterised by consecutive brittle fibre fractures in front of the cutting edge resulting in powder-like chips. This type of chip can easily be transported through the chip flute without risk for chip accumulations. Consequently, the reduction of T_{CFRP1} is not due to an improved chip transport but due to the cooling effect of the airflow within the bore channel by dissipating heat. In comparison to CS0, the use of compressed air results in a reduction of T_{Al}, which is explained by two different effects. On the one hand, the airflow supports the heat transport through the chip flute and thus improves heat removal from the drill tip area. On the other hand, the air injection at the drill tip comes with a temperature drop at the cutting edges, which combined with the flushing effect of the air jet obviously affects chip formation as shown in the first row of Figure 3. Starting from the cutting edge, the produced Al-chip is slipped over the rake face while it is axially twisted due to the tool rotation. Whereas the chip twisting of CS0 persists over multiple tool rotations without chip separation, the twisted chips of CS1 tend to break earlier, which results in generally smaller chips. Although these smaller chips can be transported more easily through the chip flute, chip accumulations as shown in the second row of Figure 3 are produced in the second half of the bore operation. Compared to CS0, they are less in number, however, still occur sporadically for CS1. Consequently, the airflow is not capable to continuously keep the chip flute of the drilling tool free. In case a chip accumulation is generated in the chip flute, the compressed chips interacts thermally and mechanically with the CFRP bore channel causing a temperature rise in the CFRP plate ($T_{CFRP2} > T_{CFRP1}$). Since the risk of chip accumulations is reduced but not eliminated, the cooling effect of CS1 in terms of T_{CFRP2} is rather small.

3.2. CS2 – Cryogenic CO_2 Cooling

In comparison to CS0, using the cooling potential of expanded CO_2 results in a reduction of T_{CFRP1} by 64°C (-49.5%), T_{CFRP2} by 3.1°C (-1.5%) and T_{Al} by 56°C (-34%). Accordingly, the CO_2 jet has an influence on all representative temperatures although the drilling tool and the air flow in the chip flute are not directly affected. For CS2, the Al-plate is actively cooled by the CO_2 jet and thus acts as a cooling medium for the overlying CFRP plate. Consequently, the low value of T_{CFRP1} is mainly explained by the continuous heat transfer between the two stack components. The lower temperature of the CFRP could alter the material separation mechanism, leading to less dissipated energy and decreased heating of the CFRP plate. However, this effect is not measurable due to the superposition with the continuous indirect cooling. In the first half of the drilling operation in Al, rather small chips are generated as representatively shown in the first row of Figure 3. Regarding chip size, the chips generated for CS2 are basically comparable to those for CS1, but show an overall lower level of compression. Long chips that are twisted over multiple tool rotations without chip separation as found for CS0, are not found for CS2. In accordance with YILDIZ and NALBANT [7], it is assumed that the overall low temperature level of the Al-plate during drilling results in a more brittle material behaviour. This favours early material fracture and thus small Al-chips. However, similar to the findings for CS0 and CS1, sporadic chip accumulations are detected in the second half of the drilling operations in Al for CS2 as exemplary shown in the second row of Figure 3. In conclusion, the smaller chip size and the overall lower temperature level are not capable to continuously keep the chip flute of the tool free. Based on the chips produced during the six repetitions, overall less compressed chips are found for CS2 than for CS1. Consequently, the flushing effect of compressed

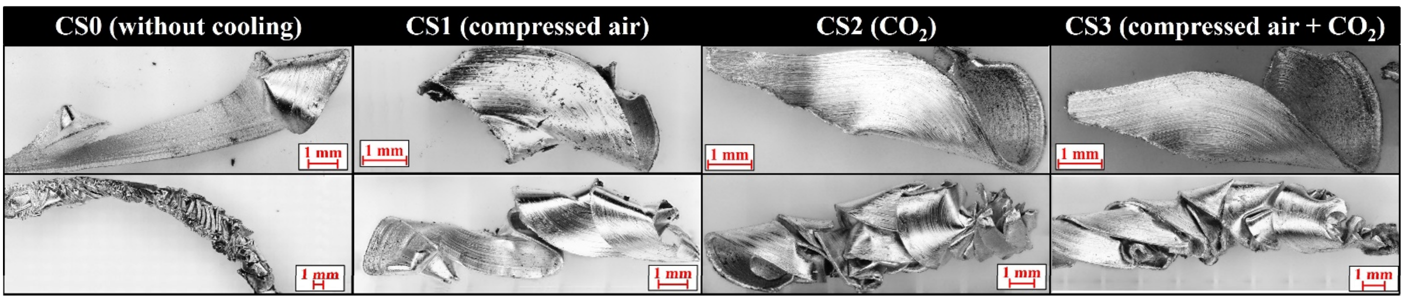

Figure 3: Representative Al-chips in the first (row 1) and second (row 2) half of the stack drilling operation

air (CS1) seems to be more important for clogging prevention than only reducing the ambient temperatures (CS2). According to Figure 2, the value of T_{CFRP2} is liable to strong fluctuations as shown by the corresponding standard deviation. Taking the fluctuations of T_{CFRP2} into account, only a small improvement of CO_2 cooling on chip transport quality is identified.

3.3. CS3 – Compressed Air + Cryogenic CO_2 Cooling

When the cooling potentials of compressed air and CO_2 are combined, T_{CFRP1} is reduced by 78.4°C (-61%), T_{CFRP2} by 38.4°C (-17%) and T_{Al} by 49°C (-30%). According to Figure 2, the combination of CS1 and CS2 leads to a superposition of both individual cooling effects resulting in the overall lowest value for T_{CFRP1}. However, in combination with CO_2 cooling, the additional cooling potential of compressed air is nearly negligible. In contrast, no synergistic cooling effect of CS1 and CS2 is found for T_{Al}. Instead, the mean value of T_{Al} is slightly higher as if CO_2 cooling is used only. It is assumed that the temperature level of the expanded air at the drill tip is higher than the actual material temperature of CO_2-cooled Al-plate. In conclusion, the superposition of CS1 and CS2 results in an overall lower cooling effect in the cutting zone and thus a higher value of T_{Al}. According to the first row of Figure 3, small chips comparable to those found for CS2 are produced during the first half of the drilling operation in Al. In the second half of the drilling operation in Al, sporadic accumulations of compressed chips are detected. Compared to the other cooling strategies, CS3 is characterised by the overall lowest probability of occurrence for compressed chips, which is explained by the combination of a beneficial chip size and the actively supported chip evacuation via air flow. In consequence, the maximum value of T_{CFRP2} as well as its standard deviation are reduced compared to CS0, CS1 and CS2.

4. Conclusion and Outlook

In this study, the influence of three cooling strategies on process temperature and chip transport quality are analysed and compared to dry machining in one-shot drilling CFRP/Al-stacks. The analysed strategies are compressed air (CS1), cryogenic CO_2 cooling from the Al-side (CS2) and the combination of both (CS3).

- CS1 focusses on supporting chip evacuation. The increased forced convection results in better heat exchange and a slight reduction of the three temperatures. Although comparatively small chips are produced in the beginning, many chip accumulations occur with increasing drilling depth.
- CS2 focusses on cooling the Al-plate. The low-temperature in machining of aluminium alters the chip formation resulting in small chips. This chip size shows lower risk for accumulations in the chip flute. However, T_{CFPR2} is higher than for CS1 and hardly reduced compared to the uncooled process. Whereas CS1 directly supports chip transport, CS2 alters the chip size and reduces the temperature level but does not actively support chip evacuation.
- CS3 is the combination of CS1 and CS2. This cooling strategy combines the advantages of supported chip evacuation and reduced chip size. Although the risk for chip accumulations is significantly reduced compared to the other strategies, CS3 is still not able to fully prevent them.

Chip accumulations are the result of insufficient chip transport, where single chips get stuck in the chip flute and then are compressed under high temperatures. Subsequently, the therefore missing heat evacuation cause even higher temperatures and thus results in a high risk for thermal damages in the CFRP bore channel. The experiments conducted with different cooling strategies reveal that a reduction of workpiece temperature and support of chip evacuation with compressed air are beneficial for reducing the risk of chip accumulations. However, the formation of chip accumulations is not avoided completely since the cooling/flushing potential is still too low. Further improvements should therefore focus on intensifying these approaches. In this context, the application of using CO_2 through the cooling channels of the tool seems interesting. Furthermore, chip size and chip transport capability are strongly influenced by the tool geometry. Consequently, parallel to improved process cooling, tool geometry has to be optimised. These geometric modification should focus on producing small chips and support their transport through the chip flute.

Acknowledgements

The authors thank the Commission for Technology and Innovation (18309.2 and 18581.1), the companies Dixi Polytool SA, Heule Werkzeuge AG, Oerlikon Surface Solutions AG, Airbus Helicopters and Rollomatic for the support.

References

[1] Wang B, Yin W, Wang M, Zheng Y, Li X, Ma Z (2017) Edge chipping mechanism and failure time prediction on carbide cemented tool during drilling of CFRP/Ti stack. *The International Journal of Advanced Manufacturing Technology*, 91(9-12): p. 3015-3024.

[2] Rivero A, Aramendi G, Herranz S, de Lacalle LL (2006) An experimental investigation of the effect of coatings and cutting parameters on the dry drilling performance of aluminium alloys. *The International Journal of Advanced Manufacturing Technology*, 28(1-2): p. 1-11.

[3] Cirillo P, Marino A, Natale C, Di Marino E, Chiacchio P, De Maria G (2017) A low-cost and flexible solution for one-shot cooperative robotic drilling of aeronautic stack materials. *IFAC-PapersOnLine*, 50(1): p. 4602-4609.

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

[5] Wang C-Y, Chen Y-H, An Q-L, Cai X-J, Ming W-W, Chen M (2015) Drilling temperature and hole quality in drilling of CFRP/aluminum stacks using diamond coated drill. *International Journal of Precision Engineering and Manufacturing*, 16(8): p. 1689-1697.

[6] Shyha IS, Soo SL, Aspinwall DK, Bradley S, Perry R, Harden P, Dawson S (2011) Hole quality assessment following drilling of metallic-composite stacks. *International Journal of Machine Tools and Manufacture*, 51(7–8): p. 569-578.

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