Journal of Cleaner Production 135 (2016) 533–548

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Evaluation of cryogenic cooling and minimum quantity lubrication effects on machining GLARE laminates using design of experiments

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ARTICLE INFO

*Article history:*
Received 29 October 2015
Received in revised form
14 June 2016
Accepted 17 June 2016
Available online 23 June 2016

*Keywords:*
Drilling
GLARE
Surface roughness
Minimum quantity lubrication
Cryogenic cooling
Design of experiments

ABSTRACT

The current study investigates the influence of applying cryogenic liquid nitrogen cooling and minimum quantity lubrication (MQL) during drilling of glass aluminium reinforced epoxy (GLARE) fibre-metal laminates. Cutting forces, surface roughness, cutting tool condition and post-machining microhardness of the surface of the upper and lower aluminium sheets near the edge of drilled holes were investigated. The findings are also compared with results from previous dry drilling trials of a similar GLARE grade. An analysis of variance ANOVA was carried out to evaluate the impact of cutting parameters, and cooling conditions, and their percentage contributions when drilling GLARE. The use of MQL and cryogenic liquid nitrogen coolants increased the cutting forces; however, they both reduced the surface roughness of machined holes, adhesions and built-up edge formation on the cutting tool compared to dry drilling. Inspection of post-machining microhardness of the upper and lower aluminium sheets near the hole edges showed that it increased when using both coolants.



## 1. Introduction

The applications of composite-metal stacks and fibre metal laminates (FMLs) are increasingly being used in aerospace structures due to their enhanced mechanical properties compared to composites or metals alone. Such materials are applied in areas which are susceptible to extreme impact and fatigue loadings (Vlot and Gunnink, 2001). The manufacturing and assembly of those hybrid structures require machining them to desired dimensions using drilling and milling operations. Drilling operations are performed on those structures for the purpose of riveting and assembly operations. However, the dissimilar mechanical and thermal properties of metals and composites in those structures adds an extra challenge when machined. Therefore, there has been an increasing number of research aimed at analysing the impact of cutting parameters on drilling composite-metal stacks (Zitoune et al., 2010, 2012; Park et al., 2011; Park et al., 2014; Shyha et al, 2010, 2011; Neugebauer et al., 2012; Jie, 2013; Poutord et al., 2013; Montoya et al., 2013; Isbilir and Ghassemieh, 2013; Ashrafi et al., 2014; Pecat and Brinksmeier, 2014; Wang et al., 2014a, 2014b; Qi et al., 2014; Kuo et al., 2014; Zhang et al., 2015; Wang et al., 2015; Kolesnyk et al., 2015). Nevertheless, a limited number of researchers looked into the impact of drilling FMLs commercially known as GLARE (Coesel, 1994; Tyczynski et al., 2014; Pawar et al., 2015; Giasin et al., 2016a, 2016b; Giasin et al., 2015). Table 1 summarises some of the most recent work carried out on drilling composite-aluminium stacks and GLARE fibre metal laminates.

Previous studies on drilling composite/aluminium stacks showed that the feed rate and the cutting tool diameter had a significant impact on cutting forces (Krishnaraj et al., 2012a). In addition drilling CFRP/Al stacks and GLARE, laminates showed that the magnitude of thrust force and torque during drilling of composite layers/workpiece is always greater than in aluminium sheets/workpiece (Zitoune et al., 2010; Coesel, 1994; Giasin et al., 2015). Some studies showed that the stacking sequence has a substantial effect on delamination growth, such that placing the metal workpiece beneath or above the composite workpiece could reduce entry and exit delamination (Ashrafi et al., 2014; Zitoune et al., 2016). Some studies looked into the impact of tool geometry and found that two flute and four facet drills outperformed 8 facet and 3 flute drill bits in terms of cutting forces and hole quality

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http://dx.doi.org/10.1016/j.jclepro.2016.06.098
0959-6526/

**Table 1**
Summary of the most recent research on drilling composite metal stacks and fibre metal laminates.

| | Cutting tool info | Stacking sequence | Objectives | Reference |
|---|---|---|---|---|
| Composite-metal stack | 4,6, 6.35 and 8 mm tungsten carbide drills | U.D CFRP/Al2024<br>copper mesh/CFRP/woven ply | C R Z Y | (Zitoune et al., 2010; Zitoune et al., 2012; Zitoune et al., 2013) |
| | 6.35 mm uncoated and diamond coated drills | Ti6Al4V/U.D CFRP/Al7050-T651 | Z Y R B H F | (Shyha et al., 2011; Shyha et al., 2010) |
| | 6.8 mm solid carbide twist drill<br>5–7.93 mm solid carbide stepped drill | CFRP/Al2024 | C A | (Neugebauer et al., 2012) |
| | 6 mm diamond, TiAlCrN, AlTiSiN-G coated carbide drills | CFRP/Al7010-T7451 | C W Z D R | (Montoya et al., 2013) |
| | 6 mm coated and AlTiN coated carbide drills | CFRP/Al2024/CFRP | D Z R C | (Ashrafi et al., 2014) |
| | 6 mm cemented carbide drills | CFRP/Al5052, Al5052/CFRP | C Q | (Qi et al., 2014) |
| | 6.38 mm CVD diamond-coated tungsten carbide drills | Ti6Al4V/U.D-CFRP/Al7050 | C R | (Kuo et al., 2014) |
| | 5 mm CVD diamond-coated tungsten carbide drills | Woven CFRP/Al7075-T7651 | C Z R B | (Zhang et al., 2015) |
| | 9.53 mm diamond-coated cemented carbide drills | U.D CFRP/Al7075-T651 | C T Z | (Wang et al., 2015) |
| Fibre-metal laminates | 5 mm HSS TiN coated drill, HSS with 8% Co drill, carbide tipped HSS drill<br>5 and 5.5 mm solid carbide drill<br>4.8 mm diamond tipped HSS drill | GLARE 3-3/2–0.3<br>GLARE 3-2/1–0.3<br>GLARE3-4/3–0.3 | C Z B | (Coesel, 1994) |
| | 6 mm uncoated carbide drill | GLARE-like made of Al2024 sheets and fibreglass type R | C Z | (Tyczynski et al., 2014) |
| | 6.35 solid carbide drills | GLARE 5 3/2–0.3<br>GLARE 6 3/2–0.3 | C Z F D B Ae | (Pawar et al., 2015) |
| | 6 mm TiAlN coated carbide drill | GLARE 2B 11/10–0.4<br>GLARE 2B 8/7–0.4<br>GLARE 3 8/7–0.4 | C R Q B Z Y O | (Giasin et al., 2016a, 2016b; Giasin et al., 2015) |

Symbols→ C: Cutting forces, D: Delamination, R: surface roughness, B: Burr formation, W: Tool wear, Z: Hole Size, T: Drilling Temperature, Y: Circularity, H: Hardness, F: Chip formation, A: Acoustic emission, Q: Stacking sequence, O: Coolants, Ae: Absolute energy.

(Pawar et al., 2015), while using double cone drills reduced thrust force and surface roughness in composite metal stacks compared to standard twist drills (Zitoune et al., 2016). Other studies reported that using coated cutting tools proved to provide better tool life than uncoated and HSS tools due to the abrasive nature of composites (Vlot and Gunnink, 2001; Coesel, 1994), and improve chip breakability which reduces cutting forces and surface roughness (Zitoune et al., 2012). As it can be seen from Table 1, the size of the cutting tools used is usually between 4 and 6.35 mm, which is the most common hole sizes used for making holes in aerospace structures.

### 1.1. Minimum quantity lubrication machining (MQL)

Near-dry machining, otherwise known as minimum quantity lubrication or simply MQL, is one of the latest technologies for reducing the overall cost of lubricants in machining by delivering precise amounts of cutting fluid to targeted cutting regions. The idea is to use the minimum amount of cutting fluid mixed with air, and typically flow rates of 50–500 ml/h are used in this machining method (Dhar et al., 2010). There have been extensive studies examining the use of MQL for drilling metals in general, and aluminium and its alloys in particular. Nandi and Paulo Davim (2009) reported that increasing MQL flow rate improved surface roughness at low cutting speeds when drilling aluminium AA1050 alloy. However, increasing the flow rate at high cutting speeds had a negative impact on surface roughness. Bhowmick and Alpas (2008) reported that using MQL decreased cutting forces and adhesions on the cutting tool compared to dry conditions when drilling Al–6%Si (319 Al) alloy. They also reported that MQL results are comparable to those obtained when using flood coolants. Davim et al. (2006) reported similar results when drilling AA1050 alloy; their findings suggest that the use of MQL reduced cutting forces and cutting power compared to dry drilling. Additionally, they showed that MQL and flood lubricated conditions had similar surface roughness results.

Kelly and Cotterell (2002) investigated the drilling of ACP 5080 aluminium alloy under dry, mist and flood conditions. Their results showed that mist application was superior to flood applications in reducing the feed force, torque and surface roughness at higher cutting speeds. However, using mist application was not as effective as flood application in preventing the rise of the workpiece and cutting tool temperatures which could be due to the rapid evaporation of the coolant droplets when reaching the cutting zone and therefore, preventing it from cooling down the cutting tool. Additionally, the average hole size was outside the tolerance range when drilling at higher cutting speeds using mist application due to the increase in thermal expansion of the drill bit and frictional heating resulting in lesser stiffness of the cut material and higher diameter (Krishnaraj et al., 2012b). Cadorin and Zitoune (2015), Cadorin et al., (2014) compared the impact of internal and external lubrication when drilling 3D woven composites. They found that supplying the coolant internally reduced internal damage and surface roughness due to a decrease in friction between the clearance face and the machined surface, but it had no impact on tool wear. However, using internal lubrication increased cutting forces compared to external cooling due to high coolant pressure (17 bars).

Fox-Rabinovich et al. (2011) reported that using MQL with appropriate tool coatings could improve tool life and give similar surface finish results to those achieved under wet conditions when drilling B319 aluminium silicon alloy. Murthy and Rajendran (2012) found that using MQL can reduce the dimensional deviation of the hole drilled between 50 and 60% when drilling Al 6063-T6 aluminium alloy, and can reduce burr formation between 22 and 33% compared to both dry and wet conditions. They also found that chip thickness and power consumption decreased considerably while the maximum tool wear was reduced up to 41%. Sreejith (2008) reported that MQL did not reduce tool wear when drilling 6061 aluminium alloy, even with increasing flow rate supply due to the large nose radius of the cutting tool when turning 6061 aluminium alloy but showed promising effects on reducing surface roughness and cutting forces compared to dry and flood coolant conditions. The contradiction in the results of tool wear could be due to the different impact of MQL coolant when used in different machining operations such as drilling and turning. In addition, the