An Experimental Study on Hole Quality and Different Delamination Approaches in the Drilling of CARALL, a New FML Composite

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In this study, the hole quality was investigated in the drilling of CARALL composite. In addition, the delamination factor calculation approaches of Chen, Davim, and Machado were compared in terms of the delamination damage at the hole entrance surface. Chen's approach is based on the conventional delamination factor (F_d) and Davim's on the adjusted delamination factor (F_{da}). Finally, Machado's approach is based on the minimum delamination factor (F_{min}). The values closest to the nominal hole diameter value were obtained with the uncoated (T1), followed by the TiN-TiAlN-coated (T2) and TiAl/TiAlSiMoCr-coated (T3) carbide drills, respectively. The average circularity error values for the hole top and bottom surfaces were 6.184 µm, 7.647 µm, and 8.959 µm for T1, T2, and T3 tools, respectively. Delamination factor values varied between 1.174 and 1.804. The F_{da} values were found to be the highest, followed by F_d values, with F_{dmin} values determined as the lowest.

Keywords: *Carbon reinforced aluminum laminate (CARALL), fiber metal laminate (FML), dimensional accuracy, circularity error, delamination factor*

1. INTRODUCTION

While research on traditional carbon and glass fiber reinforced polymer (CFRP and GFRP) composites [1-5] and sandwich composite materials [6-10] is still ongoing, fiber metal laminates (FMLs) have been introduced as a new composite family in recent years in order to meet the different mechanical property demands of engineers. Fiber metal laminates are composite materials consisting of alternating layers of metal and composite bonded together using epoxy adhesive [11]. Aramid reinforced aluminum laminate (ARALL) and glass fiber aluminum reinforced epoxy (GLARE), as the best known and most widely used fiber metal laminates, have been commercialized. However, studies on carbon fiber reinforced aluminum laminate (CARALL) are ongoing.

During the assembly of the composite/metal components, tens of thousands of holes must be drilled to meet the demand for mechanical bolting or riveting. Their assembly accuracy is critical to the flight performance of aircraft and is highly dependent on the quality of the machined holes [12]. The characteristics of hole quality include hole size, circularity or circularity error, burr formation, and surface roughness. In the final assembly of aircraft components, high rejection rates (up to 60%) are due to poor hole quality. Hard work is always required to overcome these poor hole quality problems [13-16]. Precise dimensional and geometric tolerances have been applied in the machining of polymeric composite materials. However, due to the nature of these materials, the targeted results have not been achieved [17, 18].

On the other hand, the drilling of composite/metal composite structures is an extremely challenging task due to their different machinability properties [19]. The difference in modulus of elasticity between composite and metal causes different machining deformations. Therefore, the diameters of different layers in the same hole are inconsistent and the diameter deviation is often large [20]. This causes an error in dimensional tolerance, which complicates the assembly process [21].

On the other hand, damage due to delamination during drilling is the main limiting factor for drilling performance and is the most serious problem with drilled holes that are rejected in aerospace applications. Although there are many approaches for the analysis of delamination damage, starting with Chen, whose method has been improved and developed by many researchers, there are no clear guidelines on which method to use or which hole to accept or reject depending on the amount of damage determined. In addition, there is no linear relationship between the methods used to determine delamination damage and the drilling process variables (tool geometry and properties, drilling parameters, drilling method and conditions, etc.). Therefore, it is very important to use different delamination damage measurement approaches in evaluating the relationships between the delamination factor and process variables. Several studies have examined the effect of tool geometry, size, and coating properties on hole quality and delamination damage in the drilling of FMLs. In the drilling of GLARE, Pawar et al. obtained holes with values smaller than the

Received: June 2021, Accepted: September 2021
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doi:10.5937/fme2104950E

nominal diameter of the drill in all four different geometries due to the elastic stresses caused by the different elastic modulus and thermal expansion coefficients of the drill and workpiece materials [22]. Giasin et al. investigated the effect of machining parameters and cutting tool coating on hole quality in the dry drilling of FMLs. In terms of average roughness (Ra) and mean Rz roughness values as well as burr formation, the TiN-coated tool showed the best performance, followed by the AlTiN/TiAlN- and TiAlN-coated tools, respectively. They also concluded that using lower feed rates and spindle speeds produced better hole roughness regardless of tool coating properties [23].

In another study, Giasin et al. investigated the effect of drilling parameters, cooling technology, and fiber orientation on hole perpendicularity error in FMLs using minimum quantity lubrication (MQL) and cryogenic liquid nitrogen coolants (LN_2). The LN_2 increased thrust forces, whereas using both MQL and LN_2 coolants improved surface roughness by up to 44% compared to dry conditions. The use of liquid nitrogen as the coolant increased the post-drilling hardness of the upper and lower aluminum workpiece plates by 6.5 and 9.5% [24]. Park et al. stated that, in general, the interaction between tool hardness and feed rate was the most important determinant of the level of damage in the drilling of GLARE. Hard sintered carbide cutting tools provided better surface roughness and a lower degree of delamination than HSS-Co cutting tools [25]. Under MQL conditions, large-diameter holes were always produced at the hole top location and small-diameter holes at the hole bottom location. Hole circularity was higher in the upper position compared to the lower position and feed rate was the main factor on hole circularity. The MQL and dry conditions produced holes close to the nominal diameter of the drill in both positions of the hole (hole entry and hole exit). Under cryogenic conditions, the hole size and circularity at the hole top location were larger than at the hole bottom location, and the hole circularity decreased with increased feed rate. As a result, hole circularity was reduced by more than 70% under cryogenic conditions compared to MQL and dry conditions [26]. Ekici et al. investigated the effects of drilling parameters and coating properties of cutting tools on thrust force, surface roughness, and hole output delamination factor in drilling CARALL composite via the hybrid gray relational analysis-principal components analysis (GRA-PCA) approach. In their research, the most effective control factors for thrust force, surface roughness, and the delamination factor were the feed rate, with a contribution rate of 93.87%, the interaction of coating state-cutting speed with a contribution rate of 66.504%, and the cutting tool coating properties with a contribution rate of 29.137%, respectively. After GRA-PCA analysis, the optimum machining parameters were determined as 110 m/min cutting speed, 0.1 mm/rev feed rate, and the uncoated cutting tool [27]. Boughdiri et al. investigated the effects of machining parameters and tool coating on cutting forces, hole quality, and formation of harmful dust particles during the drilling of a hybrid aerospace material (GLARE). When the feed rate was increased from 0.02 to 0.3 mm/rev, the thrust and torque increased by 80% and 85%, respectively. Although the increasing feed rate did not affect the circularity of the drilled holes, the circularity error of the holes increased with increasing spindle speed. Noxious particles in the air were reduced by 50% when drilling at a lower spindle speed compared to drilling at a higher spindle speed [28]. Ekici et al. investigated the effects of drilling parameters and tool geometry on thrust force (Ft) during the drilling of CARALL. After the experiments were carried out in accordance with the Taguchi L_{27} (33) orthogonal array, the effects of drilling parameters and tool geometry were evaluated by analysis of variance (ANOVA), and the most effective parameter for thrust force was found to be the tool geometry (84.3%) [29]. Giasin et al. used TiAlN-, TiN-, and AlTiN/TiAlN-coated carbide drills in their study investigating the effect of cutting tool coating on hole form and dimensional errors in the drilling of GLARE. The researchers determined that the TiAlN-coated drills produced the highest thrust force values, whereas the TiN-coated drills produced the lowest number of deviations between the hole diameters measured at the hole entrance and hole exit. The worst hole cylindricality was found when AlTiN/TiAlN- and TiN-coated drills were used, and the perpendicularity of all holes deteriorated with increasing feed rate [30]. Thirukumaran et al. conducted extensive analyses of the effect of different drill bit geometries (drill bit margins) with various characterization techniques to minimize delamination during the drilling of differentially stacked GFRP-aluminum FMLs (3/2 GLARE). For machining laminates, the results of the research supported the use of marginless drill bits that allow precise cylindrical holes to be obtained with high surface quality and less delamination [31].

In their previous studies, the authors evaluated the effects of drilling parameters and cutting tool coating properties on thrust force, surface roughness, and the hole output delamination factor in the drilling of CARALL via the multi-objective optimization method [27].

In the current study, we focused on the hole quality (hole diameter, circularity error) and hole entrance delamination damage. The originality of this study lies in its determination of the drilling behavior of CARALL composite, a new member of the FML group, and at the same time, contrary to the damage analysis evaluations frequently seen in the literature, in the examination of hole entry damage. Moreover, a comparative evaluation was carried out with the adjusted delamination factor (F_{da}) and the minimum delamination factor (F_{dmin}) along with the conventional delamination factor (F_d). In addition to drilling parameters, cutting tool coating properties were also considered. In this respect, the findings obtained in this study will contribute to the scientific understanding of the relationship between drilling parameters and coating properties, hole dimensional stability, and hole damage conditions in the drilling of CARALL composites. It is hoped that this study will serve as a guide for further research that leads to increased usage of CARALL in aviation industry applications.

2. EXPERIMENTAL PROCEDURE

This study started with the production process of the CARALL composite, as a newly developed member of the FML family. Afterwards, a suitable experimental study was carried out following the process sequence specified in the flow diagram presented in Figure 1, including drilling experiments, three-dimensional coordinate measurements, and delamination measurements. Thus, after the drilling process, hole quality and hole entry surface damage of the FML composites were comprehensively addressed in this study as important elements in the rejection or acceptance of parts required for assembly.

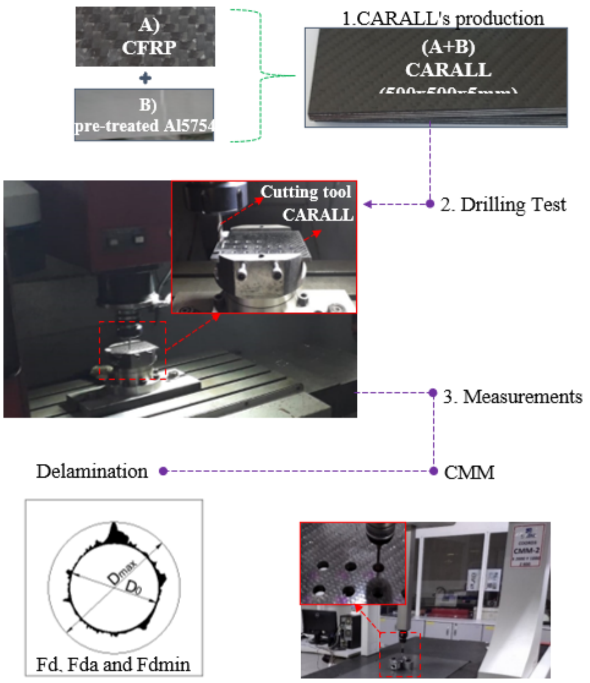


Figure 1. Flow chart of experimental setup and measu–rements

2.1 Material and methods

The CARALL material was composed of stacked metal (Al5754 alloy) and carbon-fiber-reinforced polymer (CFRP) composite layers, respectively. Each CFRP plate consisted of three layers of 245 g/m^2 woven carbon fiber.

In order to improve the interfacial properties of the carbon fiber and Al alloy, first, mechanical abrasion was applied to the Al5754 alloy with 400-mesh sandpaper, and the surfaces were then rinsed with pure water. Before the anodizing process, the samples were etched in 100 g/L NaOH electrolyte at 60 °C for 6 min and rinsed with pure water. After this process, the samples were kept in 200 mL/HNO_3 at room temperature for 4 min and rinsed with distilled water. Anodizing was carried out in 180 g/L sulfuric acid electrolyte for 15 min. After this application, the Al plates were placed in vacuum bags and the production of CARALL was completed in a short time (less than 60 min). As seen in Figure 2, CARALL samples were prepared in the dimensions of 500 × 500 × 5 mm, and consisted of seven layers in total, including four carbon fiber layers and three Al alloy layers, which were cured for 1 h at 125 °C under a 15-ton press.

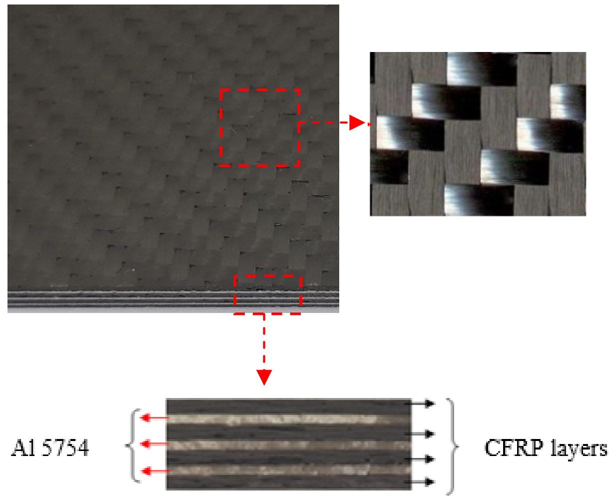


Figure 2. Top and cross-section view of a CARALL specimen.

2.2 Machinability tests

After the CARALL plates were produced, for the dril–ling experiments, they were cut in 110 × 80 mm dimen–sions using a water jet machine. Drilling experiments were carried out under dry conditions using a Johnford VMC 850 CNC vertical machining center. In the expe–riments, uncoated carbide drills (T1) and Signum (T2) and and Nanofire (T3) coated carbide drills were used. The tools had a 118° tip angle, 30° helix angle, total length of 66 mm, 6-mm diameter, and 0.4-0.6 friction coefficient. The T2 and T3 coating specifications are given in Table 1. The experiments were carried out at 65, 85, and 110 m/min cutting speeds and 0.10, 0.14, and 0.20 mm/rev feed rates.

Table 1. Coating specifications of coated carbide cutting tools

Properties	*Nanofire coated* (T2)	*Signum coated* (T3)
Coating process	Physical Vapor Deposition	Physical Vapor Deposition
Color	Black violet	Bronze Copper
Layer structure	Graded multilayer	Multilayered nano composite
Coating thickness [μm]	2.0 - 4.0	3.0 - 5.0
Nanohardness [HV 0.05]	3300	5500
Coating	TiN-TiAlN	TiAl/TiAlSiMoCr
Friction coefficient	0.6	0.5
Thermal stability [°C]	800	800

The dimensional accuracy of the diameters of the drilled holes (Da) and the circularity error of the holes (Re) are very important in terms of determining hole quality. In this study, deviation from dimensional accu–racy (Da) was considered as the determination of values smaller or larger than the nominal diameter value (∅6.0 mm) for drilled holes.

The circularity error was considered as the deter–mination of the waviness on the hole surface by taking the differences between the largest and smallest radius values measured by touching the surface of the hole diameter from 10 points at equal angles.

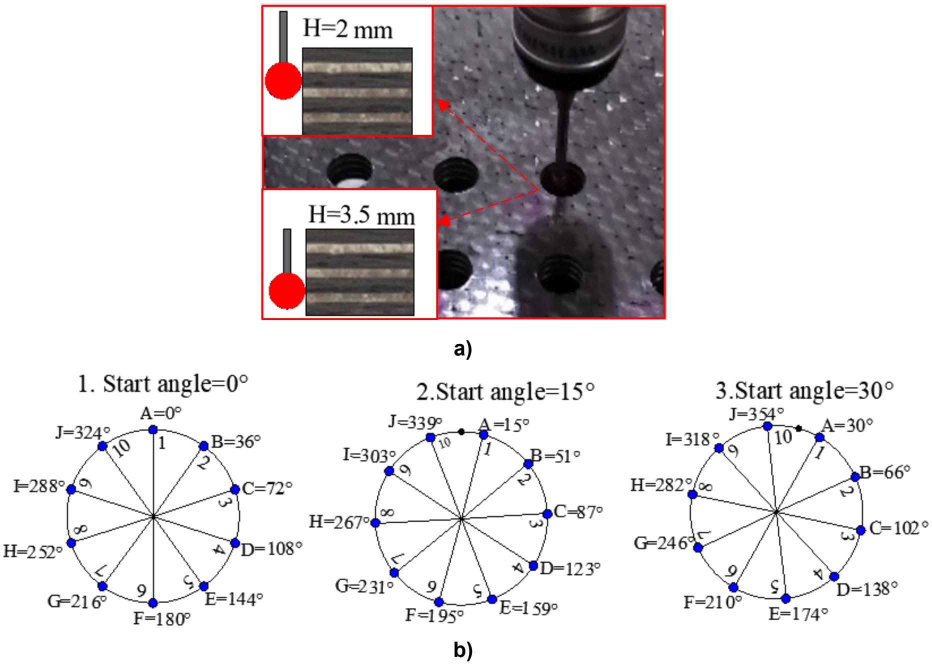


Figure 3. Measurements of Da and Re at two different depths with the probe: a) measurement points for the top and bottom surface of the hole, b) measurement positions depending on the starting angle (A = 0°, 15°, and 30°)

The Da and Re measurements were performed on a COORD3 three-dimensional coordinate measuring machine (CMM) (Fig. 3). In order to precisely deter–mine the quality of the drilled holes, Da and Re mea–surements were made 2 mm below the top surface of the workpiece (the surface where the drill enters the hole, HT) and 3.5 mm above the bottom surface of the hole (the surface where the drill exits the hole, HB) (Fig. 3a).

For the 1st hole, the probe was first put in contact with a point on the hole surface at the starting angle A:0°, 2 mm below the top surface of the workpiece, and Da and the Re measurements were then completed by touching 10 points in total at 36° intervals. Next, for the same hole, the probe was touched to a point on the hole surface at the initial angles of A:15° and A:30°, respectively, and Da and Re measurements were taken by touching a total of 10 points at 36° intervals (Fig. 3b).

2.3 Delamination factor

In this study, the hole entry delamination factor was evaluated in the drilling of CARALL with coated and uncoated carbide drills. Delamination is defined as the separation of adjacent composite layers formed by the development of interlaminar cracks in the material [17]. Due to crack propagation, this damage to the composite is known to cause a great decrease in mechanical performance [13].

The approach to the delamination factor (F_d) presented by Chen [32], which is the most widely used in the literature, is based on the maximum damage diameter concentrically surrounding the circumference of the drilled hole (Fig. 4a). The delamination factor (F_d) is defined as the ratio of the maximum damage diameter (D_{max}) to the nominal diameter (D_{nom}) as presented in (1).

$$F_d = \frac{D_{\max}}{D_{nom}} \tag{1}$$

Because the conventional delamination factor (Chen's approach) does not take into account the damaged area alone, it may not always be sufficient in defining the delamination factor. Davim [33] stated that crack size was not an appropriate representation of damage size since delamination occurs in an irregular form, with breaks and cracks at the hole entrance and exit. Therefore, he proposed the adjusted delamination factor (F_{da}) to measure the delamination factor (Fig. 4b), as presented in (2).

$$F_{da} = F_d + \frac{A_d}{A_{\max} - A_{nom}}\left(F_d^2 - F_d\right) \tag{2}$$

The adjusted delamination factor (F_{da}) seems to be a better approach for determining the delamination factor since it also considers both the maximum crack length and the damaged area [34]. In (2), F_d is the conventional delamination factor, A_{max} is the area at the maximum diameter (D_{max}) in the delamination region, and A_{nom} is the area of the hole at the nominal diameter value (D_{nom}). The damage area (A_d) is the difference between the maximum damage area (A_{max}) and the nominal hole area (A_{nom}).

Although delamination factors are classified as one-dimensional and two-dimensional in the literature, Machado et al. focused on the preferential aspect of the delamination factor. The researchers reported that the focus of quantification of delamination was to evaluate the smallest area containing all damage from drilling, and also to determine the preferential direction of drilling-induced delamination using the vector between centers. The minimum delamination factor (F_{dmin}), has been proposed as a new approach to measure drilling-induced damage [35]. In this method, which is based on the Chen approach, the minimum diameter (D_{min}) indicating the maximum damage is determined by shifting the maximum damage diameter from the nominal hole diameter center (Fig. 4c). The F_{dmin} can be calculated using Chen's approach, as in (3), by dividing the minimum diameter (D_{min}) by the nominal hole diameter (D_{nom}).

$$F_{d\,\mathrm{min}} = \frac{D_{\mathrm{min}}}{D_{nom}} \tag{3}$$

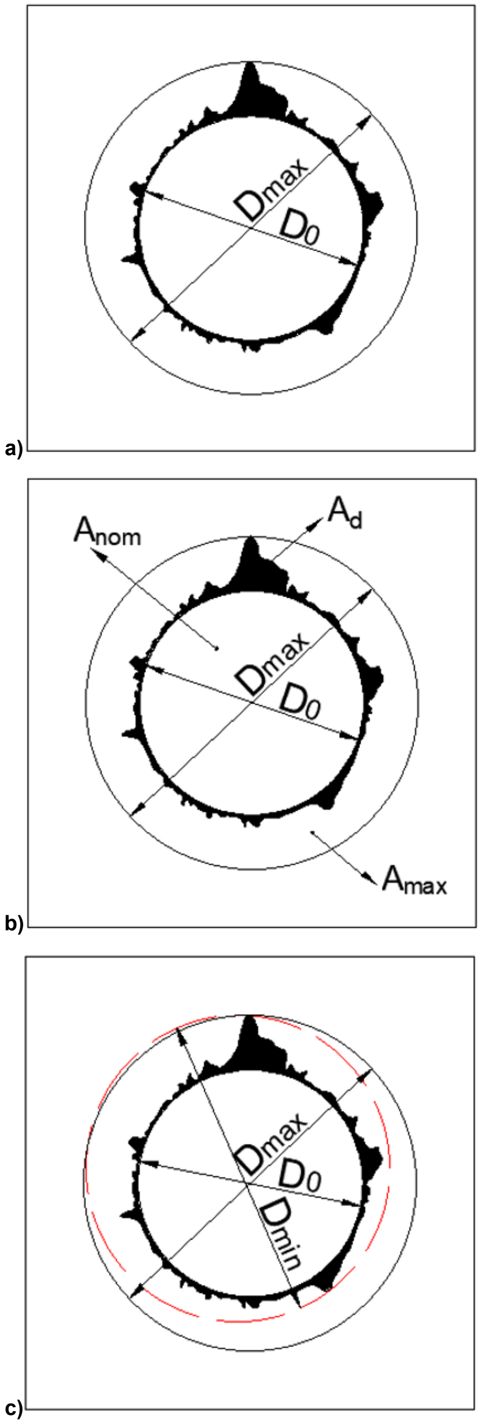


Figure 4. Determination of delamination factors: a) Conventional delamination factor (*F*d), b) Adjusted delamination factor (*F*da), and d) Minimum delamination factor (*F*dmin)

In recent studies, researchers have used various techniques such as light optical microscopy (LOM), ultrasound (US), computerized tomography (CT), and X-ray radiography to determine the damage around the hole. However, the high cost and limited accessibility in practice are disadvantages. Digital image processing (DIP) is a convenient and widely used technique for analyzing geometrical damage in CFRPs. In this study, the steps of DIP were applied in order to determine the delamination factors. First, image color matching (as black and white pixels) was carried out using a gray–scale color histogram and the image was then trimmed to the size of 1280 × 500 pixels. In the second stage, the area of the damage was calculated by entering the codes in MATLAB. As a final step, since the damage caused by drilling was correctly defined, the nominal hole diameter and its area, and the maximum damage diameter and its area were determined, and the F_d, F_{da}, and F_{dmin} values were calculated.

3. RESULTS AND DISCUSSION

Dimensional accuracy (Da) and circularity error (Re) measurements of the holes drilled in the CARALL composite, depending on the drilling parameters with uncoated and coated tools, are presented in column charts in Figures 5 and 6. A comparison of the different approaches for calculating the delamination factor is shown in Figure 7, and damage images are given in Figures 8 and 10. The effects of drilling parameters and cutting tool coating properties on the conventional delamination factor (F_d) are presented as a column chart in Figure 9.

3.1 Evaluation of dimensional accuracy

The deviation of the hole from its nominal size, i.e. the deviation in the hole diameter value and the circularity error of the hole diameter, are important for evaluating the performance of a machined part [36]. Various factors such as the mechanical properties, hardness, thermal expansion coefficient, and conductivity of materials are effective in obtaining narrow tolerance holes [37].

Drilling in FML structures is a complex process since it takes place simultaneously in two structures with different properties (a combination of different elastic, tribological, cutting, and friction properties). The different coefficients of thermal expansion between the combined composite and metal alloy laminate make it more difficult to produce a consistent hole size. In addition, the diameters at the hole entrance and exit differ due to the forces, bending deformation, friction, and heat to which the cutting tool is exposed during the drilling process at the hole entrance and hole exit. For this reason, hole diameter and circularity error measurements were performed from the hole top surface

(HT) and hole bottom surface (HB), as explained in detail in Section 2.2.

A comparison of the hole diameter values measured on the top surfaces and bottom surfaces of the holes machined under different cutting speeds and feed rates is presented in Figure 5.

In the experiments, the hole diameter values obtained using a helical drill were in the range of 5.99024-6.02027 mm (Fig. 5), which are within the tolerance limit (±0.025 mm) required for rivet and bolt applications in the aviation industry [38]. Soo et al. stated that, when drilling CFRP/Al stack, holes closer to the nominal diameter value were obtained with increasing feed rate, whereas increasing cutting speed increased the nominal diameter value [39]. In the drilling of GLARE, Park et al. obtained values close to the nominal diameter at low feed rates [25]. In general, the results of our study for all tools and hole top and bottom surfaces were in parallel with the findings of Soo et al., but differed from those of Park et al.

Diameter values with the T1 uncoated carbide tool were similar for the top and bottom surfaces of the hole, in the range of 6.000-6.015 mm at 65 and 85 m/min cutting speeds, whereas at 110 m/min cutting speed and all feed rates (0.10, 0.14, and 0.20 mm/rev), the diameter values of 5.995-6,000 mm were lower (∅<6 mm) than the nominal diameter value. With the increasing feed rate, the hole diameter values were closer to the nominal diameter values. In terms of hole diameter accuracy for both HT and HB, the uncoated carbide tool (T1) outperformed both coated tools (T2 and T3) at increased cutting speed (110 m/min).

The hole diameter values were closer to the nominal diameter with the T1 uncoated cutting tool compared to the coated tools because T1 had a sharper cutting edge than the other two [40]. Li et al. reported that, in the drilling CFRP, the uncoated tool performed closer to the nominal diameter value compared to multi-layered TiAlN+AlCrN- and TiN-coated tools and that this did not change with the increasing number of holes [41]. Similarly, Kim et al. reported a higher mean diameter value with coated drills compared to uncoated drills [42]. The performance of the uncoated tools was followed by the performances of the T2 and T3 tools, respectively. The second-place ranking of the T2 could be attributed to the fact that the (TiN-TiAlN) coating applied to this tool combined all the advantages of TiN, TiAlN, and TiCN and also to its near-perfect fire resistance, high toughness, and double-performance coating of TiN. The thickness of the coating was also lower. For all tools, lower diameter values were obtained at the hole exit than at the hole entry. The springback that occurs during the drilling of CFRP is known to reduce CFRP hole diameter values [43]. Similarly, Giasin et al. also reported that the bottom hole circularity was worse than at the top, regardless of drill cover or drilling parameters [43].

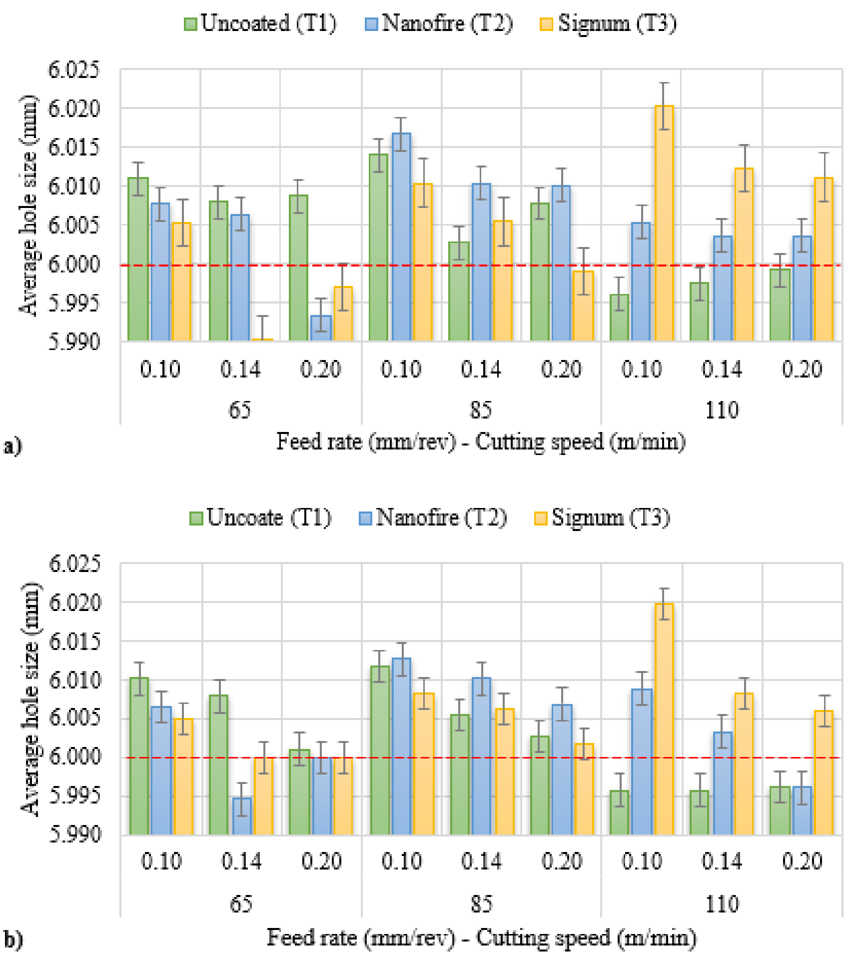


Figure 5. Effect of machining parameters on hole diameter values: a) Hole top surface (HT), b) Hole bottom surface (HB)

3.2 Evaluation of circularity error

A comparison of the mean circularity error results for the hole top and bottom surfaces is presented as a column chart in Figure 6. The circularity error for all tools was generally in the range of 2.41-12.31 µm for HT and 4.25-17.33 µm for HB. Although the circularity error was found to increase to 33 µm in the drilling of CFRP/Al/CFRP stacks [40], these results were not considered excessive in terms of industrial requirements [44]. The circularity error generally increases with increasing cutting speed. The higher vibration resulting from increased cutting speed causes cutting tool instability that increases circularity error. The increased friction exerted by the cutting tool on the hole wall at high cutting speeds causes the circularity of the hole to deteriorate [45]. With increasing feed rate, the circularity error always increased when the coated tools (T2 and T3) were used and generally increased with the uncoated tool (T1). With the increase in feed rate, faster penetration of the tool into the workpiece increases the uncut chip thickness [46], thus increasing vibrations and causing higher hole diameter circularity error [47]. The maximum circularity error (17.33 µm) was obtained in HB with T2 at medium feed rate and high cutting speed. Ameur et al. reported that the cylindrical error of the holes could be reduced by applying a low cutting speed and high feed rate [48]. The mean circularity error for HT and HB was 6.184, 7.647, and 8.959 µm for T1, T2, and T3, whereas the maximum circularity error was 11.186, 13.822, and 17.333 µm, respectively. The lowest circularity error value for the HT was obtained with the T2 tool at the lowest feed rate and cutting speed, and for the HB, with the T1 tool under these same drilling conditions.

3.3 Evaluation of delamination factor

During the drilling of CFRP components, delamination (called "peel-up") occurs when the drill enters the composite hole. "Push-out" delamination occurs at the hole exit and is considered an irreparable type of damage [49]. In their previous study, the authors investigated exit delamination caused by the effect of thrust force [27]. However, in order to improve the service performance of the material, it is also necessary to evaluate and minimize the entrance delamination. Peel-up delamination in FML is similar to the delamination mechanism seen in single-fiber-reinforced polymer laminates (FRPs) [50].

The peel-up delamination, which occurs as a result of the thrust force, pulls the material into the helix cavity/spiral of the drill, causing the upper layers to be pulled out and, as a result, the bonds between the layers are broken [51]. Peel-up delamination, which starts when the drill first comes in contact with the workpiece, is related to flute shape, helical angle, and drilling torque. The CARALL composite material has a layered structure with an upper CFRP layer that continues with a 0.5-mm Al layer underneath.

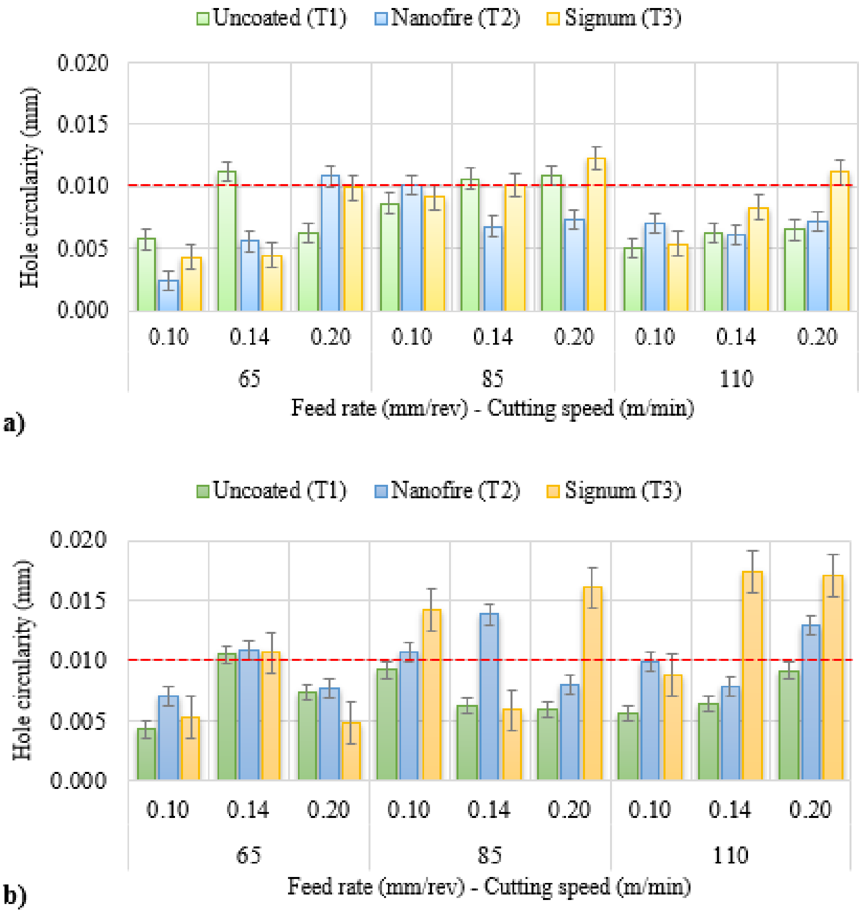


Figure 6. Effect of machining parameters on circularity error: a) Hole top surface (HT), b) Hole bottom surface (HB)

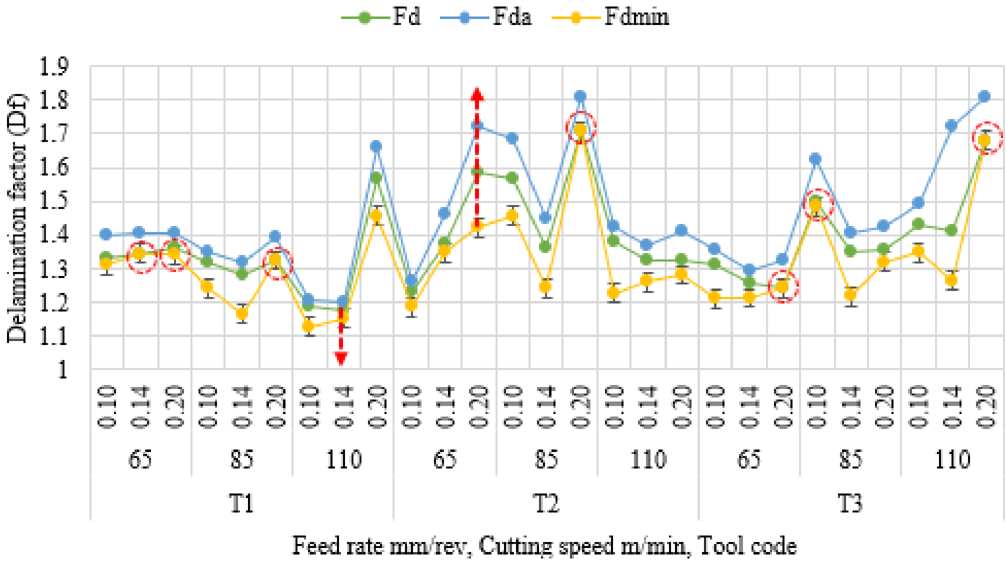


Figure 7. Conventional, adjusted, and minimum delamination factor values based on drilling parameters and coating properties

Delamination occurs in the top CFRP layer that the drill first comes in contact with at the beginning of the drilling process. Figure 7 presents the results of the delamination factor (Df), calculated using different approaches, that occurred on the hole entrance surface after drilling CARALL using uncoated and coated tools. The Df values ranged from 1.174 to 1.804 when drilling CARALL composites with coated and uncoated tools under different machining conditions (Fig. 7).

Among all the delamination factor approaches, the adjusted delamination factor (F_{da}) values were the hig–hest, followed by the conventional delamination factor (F_d), with the minimum delamination factor (F_{dmin}) as the lowest. All three Df values are close to each other for the T1 coded tools.

The difference between all three Df values for the Nanofire coated tool (T2) widened, whereas the Df values increased significantly for all three delamination appro-aches depending on the drilling parameters (Fig. 7). The T3 (Signum) coated tool compared to the T2 (Nanofire) co-ated tool provided a decrease in Df values with all three methods. The F_d and F_{dmin} values were very close under the drilling conditions indicated by the circle in Figure 7.

The delamination damage was generally symmet–rical around the hole under all experimental conditions in this study. The closest results for all three approaches used in the determination of Df in this study (repre–sented by the downward red arrow) were obtained with the T1 uncoated carbide cutting tool, at a cutting speed of 110 m/min and feed rate of 0.14 mm/rev, as shown in the damage image presented in Figure 8a.

The results with the highest difference among all three methods for Df (represented by the upward red arrow) were obtained with the T2 (Nanofire) coated tool at a cut–ting speed of 65 m/min and a feed rate of 0.2 mm/rev, as seen in the damage image in Figure 8b. In cases where the damage was symmetrical and close to the hole axis, close results were obtained for F_{da} and F_{dmin} values, whereas the difference between F_d and F_{da} values increased where the damage was irregular with respect to the hole axis.

The graph based on the conventional Df calculation was used to examine the effects of drilling parameters and coating properties in detail (Fig. 9). The effects of drilling parameters were similar for all three methods used in the evaluation of Df.

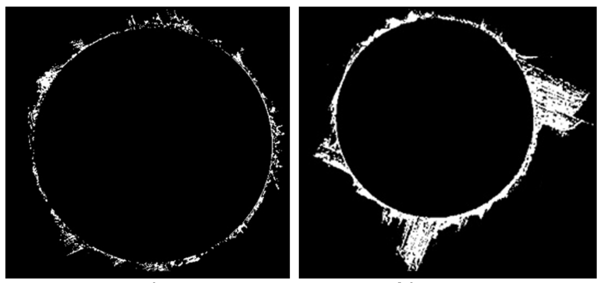


Figure 8. Damage images with minimum difference and maximum difference in Df for all three methods: a) Minimum (T1 tool, V = 110 m/min, f = 0.14 mm/rev), b) Maximum (T2 tool, V = 65 m/min, f = 0.2 mm/rev)

Park et al. stated that increasing the feed rate increased the thrust force because of higher friction on the hole surface [25]. In the literature, increasing feed rate has been shown as the main cause of delamination [22, 52-54] and of increases in the volume of chip removed per unit time. As with the studies in the literature, the increased feed rate in the drilling of CARALL resulted in higher delamination damage [30, 36, 52, 55–57]. In addition, it has been reported that delamination damage is not only related to thrust force, but also to workpiece hardness [52]. No linear effect of cutting speed on Df was observed. As the cutting speed increased, the cutting zone and tool temperature increased in parallel. However, the increase in cutting tool temperature had no significant effect on the formation of delamination damage [58]. It has been confirmed in the literature that the cutting speed is less effective than the feed rate [59, 60]. The Signum coated (T3) cutting tool produced the lowest Df values at low and medium cutting speeds and all feed rate conditions. In general, compared to the T2 and T3 tools, the T1 tool performed better for Df at increasing cutting speeds (excluding values for the highest feed rate and cutting speed).

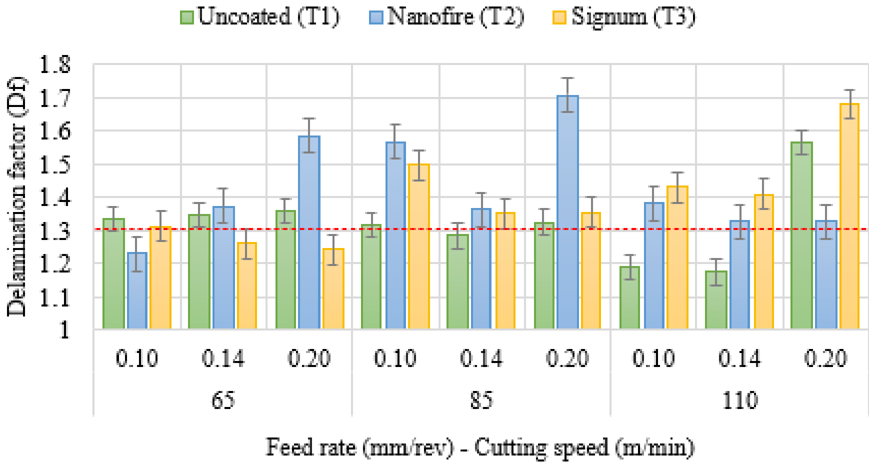
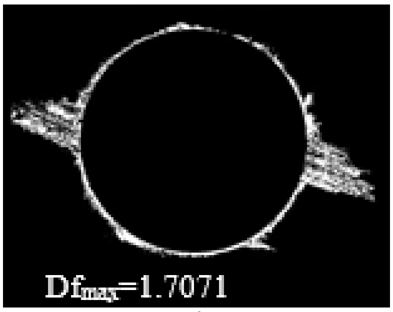
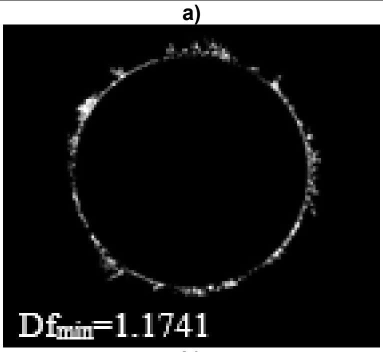


Figure 9. Effect of drilling parameters and coating properties on the delamination factor

When the drilling conditions of high cutting speed and feed rate were ignored, the highest Df value (Df_{max} = 1.707) was obtained with the Nanofire coated (T2) tool, 85 m/min cutting speed, and 0.2 mm/rev feed rate (Fig. 10a); the lowest Df value (Df_{min} = 1.174) was obtained with the uncoated T1 tool at a cutting speed of 110 m/min and a feed rate of 0.14 mm/rev (Fig. 10b).



a)



b)

Figure 10. Drilling conditions for the lowest and highest Df and Df images: a) Maximum Df (T2 tool, V = 85m/min, f = 0.2 mm/rev), b) Minimum Df (T1 tool, V = 110 m/min, f = 0.14 mm/rev)

When evaluated in terms of all approaches, in the experiments performed in triplicate under different drilling conditions where none or very minimal cutting tool wear was observed , the coated tools did not yield a significant effect on Df. It was assumed that Df could be evaluated depending on the number of holes in order to reveal the effect of the cutting tool coating.

4. CONCLUSIONS

The results obtained in terms of the hole quality and entry delamination factor after drilling CARALL composites with coated and uncoated carbide tools are presented below.

- In general, for all cutting tools, with increasing feed rate, values closer to the nominal hole diameter value were obtained for the hole top and bottom surfaces. In both HT and HB, in terms of hole diameter dimensional accuracy, the T1 cutting tool outperformed both coated cutting tools (T2 and T3) at increasing cutting speed (110 m/min).
- The values closest to the nominal hole diameter value were obtained with the uncoated, followed by the TiN-TiAlN-coated and TiAl/TiAlSiMoCr-coated carbide drills, respectively. Lower diameter values were obtained at the hole exit compared to the hole entry in drilling with all tools.
- Although the circularity error values were generally in the range of 2.41-12.31 µm for HT, they were between 4.25 and 17.33 µm for HB.
- The circularity error generally increased with increasing cutting speed. The circularity error always increased with increasing feed rate in the coated carbide tools and generally increased with the uncoated carbide tool.
- When compared in terms of coating properties, the lowest delamination damage was obtained with the uncoated tool.
- The delamination factor was in the range of 1.174-1.804. Among all delamination factor approaches, the adjusted delamination factor (F_{da}) values were the highest, followed by the conventional delamination factor (F_d), with the minimum delamination factor (F_{dmin}) as the lowest.
- When evaluated in terms of all approaches, in the experiments performed in triplicate under different drilling conditions where none or very minimal cutting tool wear was observed, the coated tools did not yield a significant effect on Df.
- In the drilling of CARALL, increased feed rate increased the thrust, resulting in higher delamination damage. No linear effect of cutting speed on the delamination factor was observed.

As a continuation of this study, our future research will investigate the effect of CARALL material structure (fiber orientation) on the machinability properties in detail. We will use image processing method effectively in the evaluation of the delamination factor. Finally, we will also examine CARALL's response to nontraditional machining methods.

ACKNOWLEDGMENT

The authors would like to express their sincere thanks to the Çanakkale Onsekiz Mart University Scientific Research Projects Unit for support of the project (No. FBA-2019-3170).

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ЕКСПЕРИМЕНТАЛНО ПРОУЧАВАЊЕ КВАЛИТЕТА РУПЕ И РАЗЛИЧИТИХ ПРИСТУПА ДЕЛАМИНАЦИЈИ КОД БУШЕЊА НОВОГ CARALL FML КОМПОЗИТА

Е. Екици, АР. Моторџу, Е. Јилдирим

Истражује се квалитет рупе код бушења CARALL композита. Извршено је поређење у израчунавању фактора деламинације тројице аутора, Чена, Давима и Мачада, с аспекта оштећења од деламинације на улазној површини рупе. Ченов приступ се базира на конвенционалном фактору деламинације (F_d), Давимов на подешеном фактору деламинације (F_{da}), а Мачадов на минималном фактору деламинације (F_{min}). Вредности најближе номиналној вредности пречника рупе добијене су коришћењем бушилица од карбида без превлаке (T1), са превлаком TiN-TiAlN-coated (T2) и са превлаком TiAl/TiAlSiMoCr-coated (T3). Вредности просечне грешке кружности су биле 6,184; 7,647 и 8,959 μm за T1 односно T2 односно T3. Вредности фактора деламинације кретале су се у распону од 1,174 до 1,804. Највеће вредности је имао фактор F_{da}, затим F_d а најмање $F_{dmin.}$