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Influence of drill bit material on the bearing strength of holes in GFRP composite

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The article aims at assessing the influence of the drill bit material on the bearing strength of holes made in glass fabric reinforced epoxy composite. Six twist drills made of widely used drill materials such as high speed steels and carbides in different configurations were selected to drill holes in the composite. In the first stage of the work, optimum drilling parameters were selected and then used for drilling holes in specimens tested in single lap shear experiments. For each tested specimen two different delamination factors, one based on the delamination area and another – on its diameter, were calculated in order to assess the quality of the holes and then compared to the results of the bearing strength experiments. The results of the bearing tests showed that the highest strength was achieved for the high speed steel drill with titanium coating while the lowest for the cemented carbide drill. This finding is in opposition to the majority of results reported in literature.

1. Introduction

Fibre reinforced composites find their use in aviation more and more frequently, and have achieved above 50% of the structure mass in the most modern transport aircrafts B787 and A350 [1, 2]. The most widely used joining method for composite elements remains bolted joining, originally used for joining metal elements, where it has been successfully used for years. However, bolted joining of composite elements brings about certain problems. Firstly, the joining method requires machining of a hole in the composite element, which cuts the reinforcing fibres disrupting the load distribution around the hole and decreasing the strength of the structure [3].

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The drilling process may also damage the composite material. The damages involve delamination, fibre pull-out, matrix thermal degradation, burrs, splintering and micro cracks [4–8]. The drilling-induced delamination is the most critical damage and a challenging failure mode during drilling of composite laminates, which results in heavy losses in the industry [9]: it has been reported that the drilling-induced delaminations are responsible for 60% of rejections in composite parts during the final assembly [10]. However, although some special non-conventional hole-making methods, such as water-jet, laser and electro-erosion have been industrialized for composite laminates, the conventional mechanical drilling involving use of drilling tools is still a mainstream technique of making holes in composite laminates and draws attention of many scientists [9–14].

For many years, the drilling of composite materials has been developed in order to improve the quality of the drilled holes, suppress drilling-induced damages and decrease the tool wear. For instance, pre-drilled pilot holes [15] or step drills [16] have been used for drilling fibre reinforced composites. In step drills, the first step has a lower diameter than the second one, which has the diameter of the final hole. The use of step drills leads to the drop of the thrust force during drilling [15] and in consequence to lower push-out delamination. Reduction of the push-out delamination was possible thanks to use of variable feed rate [11]. As the feed rate was reduced in the final phase of drilling, the push-out delamination factor was reduced by 26% for GFRP and by 37% in the case of in CFRP. In some works, oscillations have been used in order to improve the drilling process. Ultrasonic oscillation of the drill made it possible to achieve a 36% lower thrust force and a 35% lower tool wear [17]. Mounting GFRP composite on oscillating background allowed for decreasing the tool wear [18]. A method developed to decrease trust force and in consequence delamination is vibration-assisted drilling. In this method the drill bit vibrates along its axial direction, so there is no continuous contact of it with the workpiece, which results in a lower value of induced thrust force than in conventional drilling [19]. Another method widely used in the industry to reduce drilling induced delamination consists in positioning a support plate under the composite laminate [6, 20]. The backup force helps suppressing the delamination as the drill approaches the last ply, hence a higher drilling thrust is needed to trigger the propagation of the delamination [6]. Tsao et al. developed an active backup support [6]. A tubular solenoid electromagnet was mounted to the composite subjected to drilling in order to provide adjustable suppressing load. The applied backup force suppressed the growth of the push-out delamination in carbon-epoxy laminate by 60–80% [6]. Recently, also cryogenic conditions were applied for drilling carbon fibre-reinforced composite [21]. The composite was dipped into liquid nitrogen during drilling. This approach allowed reducing the tool wear by 30% and improve surface quality by 31%. However, it also increased the thrust force during drilling. All of these method make some improvements in drilling of fibre reinforced composites; however, they also bring about complications of the process.

The simplest way to improve the hole quality is the use of an appropriate drill. It has been widely reported that the drill geometry and material have a significant impact on the hole quality, so numerous studies have been performed to compare the influence of different drill bit types on the quality and strength of holes drilled in fibre reinforced composite materials. These papers generally indicate that the special drills designed for drilling fibre reinforced composites outperform traditional twist drills. Xu et al. compared drills including diamond-coated carbide brad-spur drill, carbide twist drill and carbide dagger drill in cutting performance during drilling of T800/X850 CFRP [22]. The damage analysis made by an ultrasonic C-scan confirmed that the brad-spur drill yielded the lowest drilling-induced delamination, while the use of twist drill and one shot drill resulted in a worse cutting performance. Kumar et al. used three drills with different geometries and made of different materials for drilling glass fibre reinforced plastics (GFRP), namely, a helical flute made of high speed steel (HSS) drill, a carbon tipped straight shank made of K20 stainless steel drill and a solid carbide eight-facet drill [23]. The best hole quality was achieved for the solid carbide eight-facet drill and the worst for the HSS helical flute drill. Durão et al. compared delaminations and bearing strengths of holes drilled in glass/carbon-epoxy laminate with the use of 5 types of drills: a HSS twist drill, a carbide twist drill, a carbide brad drill, a carbide dagger drill and a carbide step drill [24]. The worst results in terms of both delamination and strength were achieved by drilling with use of the HSS twist drill. The smallest delamination was achieved with use of the carbide twist drill. However, slightly higher bearing strength than for the carbide twist drill was achieved for the holes drilled by the carbide step drill [24]. Tsao and Hocheng recognized the effect of drill bit geometry on delamination of carbon fibre reinforced plastic (CFRP) laminates by Taguchi analysis [25]. The results showed that the saw drill and the candle stick drill led to a smaller delamination factor compared with that caused by the twist drill. All the drills were made of HSS. In their other study, the authors compared the influence of five different HSS drill bit geometries, including twist drill, saw drill, candle stick drill, core drill and step drill, on both thrust force and delamination [26]. They reported that the core drill allows the highest feed rate without delamination, whereas the twist drill required the lowest feed rate to avoid delamination. Qiu et al. reported a lower value of delamination factor in CFRP composites drilled by a carbide step drill in comparison to a carbide twist drill [16, 27]. Rubio et al. also compared the influence of carbide drill geometry on delamination at hole entry during drilling GFRP and found that the brad-spur drill gave better performance than twist drill [28]. Gemi et al. used three types of drill bits, namely a conventional twist drill, a brad-spur drill and a brad centre drill, to manufacture holes in a GFRP pipe [29]. The brad-spur drill, and the brad centre drill were designed for fibre composites machining. All the drills were made of solid carbide, but the twist drill and the brad centre drill had a titanium coating, whereas the brad and spur drills had no coating. Cutting forces, which are responsible for delaminations, were reduced by 8% and 13% for the brad-spur drill and the brad centre drill compared to the results of the twist drill. The brad centre drill generates little delamination compared to the other two drills. The twist drill is responsible for the worst hole quality. However, there are also papers, though admittedly fewer, which indicate that twist drills can sometimes outperform special drills. For instance, Durão et al. studied experimentally the influence of different geometries of tungsten carbide drills including twist drills with point angles of 120° and 85°, step drill, brad-spur drill and dagger drill on delamination of CFRP laminates [30]. They found that the twist drill with 120° point angle can obtain the minimum delamination, whereas the brad-spur drill resulted in the largest delamination factor. Marques et al. observed that the conventional twist drill outperformed other types of drills in terms of delamination during CFRP drilling [31]. Four carbide drills: a twist drill, a brad drill, a dagger drill and a special step drill were used to drill CFRP laminate. The highest bearing strength was achieved for the special step drill and the lowest delamination factor – for the twist drill. The worst results, both in terms of strength and delamination, were obtained for the dagger drill [31].

Some of the cited papers compare holes made in composites by several drill bits with different geometry, but made of the same material, which allows a researcher to draw clear conclusions about the influence of the geometry on the hole quality [22, 24–28, 30–32]. However, most of the papers did not compare holes made with drills of the same geometry, but made of different materials, and thus the influence of the drill material on the hole quality is obscured by the use of different drill geometries. The only exemptions are articles by Erturk et al. and Mudhukrishnan et al. In the former, the holes made by two helical bits with the same geometry made of HSS with titanium coating and HSS with addition of cobalt show similar results in the terms of delamination. The composite material considered in this work was polyester composite reinforced with woven polyester fibres and polytetrafluoroethylene particles [33]. However, this work does not address the question which drill material yields the best results for the composites used most often in aviation: GFRP and CFRP. Mudhukrishnan et al. used helical drills made of different materials: HSS drill, tipped carbide drill and solid carbide drill to drill holes in glass fibre reinforced polypropylene composite [34]. However, the differences in drill geometry did not allow them to draw clear conclusions about the influence of the drill material on the hole quality. Moreover, the influence of the drill material on the hole bearing strength was not investigated in either of these two articles.

Therefore, a comparison of the bearing strength of the holes made in GFRP composite by drills with the same geometry, but made of different materials is made in the present work. The wide use of carbide drills for manufacturing holes in composite materials [22–24, 27–31, 34, 35] suggests that such drills give the best results. On the other hand, the carbide drills are several times more expensive than the drills made of plain HSS or HSS with additions and/or coatings. Therefore, the investigation carried out in the present work should explain whether the carbide drill bits are really better for composite materials than those made of HSS. Six helical drill bits with similar geometry, but made of different materials were chosen for the experiments. In the first stage, the influence of the drilling parameters such as spindle speed and feed, on the hole quality represented by delamination was investigated and optimum drilling parameters were chosen. Then, single lap shear (SLS) composite specimens in which holes were made with each drill were tested and the strength results along with measured delamination factors for each drill were compared.

2. Experimental methods

2.1. Selection of drills

The majority of the articles available suggest that the use of conventional twist drill results in worse hole quality and strength than the use of drills designed to minimise the drilling-induced damages like brad, dagger, step, saw candle stick or even core drills [22, 24–28, 32, 36] made of the same material. However, two articles indicate a different tendency, namely that a carbide twist drill outperforms a brad drill, a dagger drill and a special step drill made of the same material in terms of drilling-induced delamination [30, 31]. Twist drills are also most widely used in general drilling, so that the biggest range of materials is available in their case. Therefore, the twist drills were chosen to perform tests in the present work in order to assess the influence of the drill material on the hole quality and strength. Even though the quality of the holes may not be as good as it might have been if special drills had been used, all the holes will be affected by the geometry of the drills in the same way, so the comparison of the material influence should be fair.

The point angle is one of the key characteristics for a twist drill, so the influence of the point angle on the hole quality in composite material is discussed in several works. Heisel and Pfeifroth conducted drilling experiments in CFRPs and analysed the influence of large point angles (155°, 175°, 185°) on thrust force and delamination [37]. The increase of the point angle is supposed to increase the delamination at the exit of the holes, but also to decrease the delamination at the entry of the holes [37, 38]. Some authors pointed out that the bigger point angle generally yields a better hole quality. Shyha et al. achieved lower delamination at the hole entry with an angle point of 140° rather than 118° [39]. Durão et al. observed that the delamination is lower for the twist drill with the point angle of 120° than for the drill with the point angle of 85° [30]. Iliescu et al. recommended the use of twist drills with a point angle of 125°–130° [40]. On the other hand, some authors recommend the use of smaller point angles. Some authors claim that the increase in point angle leads to an extension of the area of pressure on the uncut layers of the laminates and consequently a higher thrust force, which in turn could increase the push-out delamination damage [9, 41]. Gaitonde et al. found out that delamination factor at the hole exit in CFRP had been reduced to 45% by using a twist drill with a lower point angle (85°) than with point angles 118° and 135° [38]. Kilickap and Rubio et al. observed that exit delamination obtained for the point angle of 118° was smaller than for 135° [42], and for the point angle of 85° it was smaller than for 115° during GFRP drilling by twist drills [28]. Feito et al. analysed the cutting ability of three different twist drills (point angles of 90°, 118° and 140°) and concluded that a low point angle in the range of 90°–108° is recommendable for reducing delamination [43].

Due to the fact that the conclusions of the abovementioned works are nonunanimous, the moderate point angle of 118° was chosen for the twist drills tested in the present work. All the drills used also had a 20° helix angle, two cutting edges, a chisel edge angle in the range of 120°–130° and the diameter of 4 mm. The photographs of the drills are presented in Fig. 1.

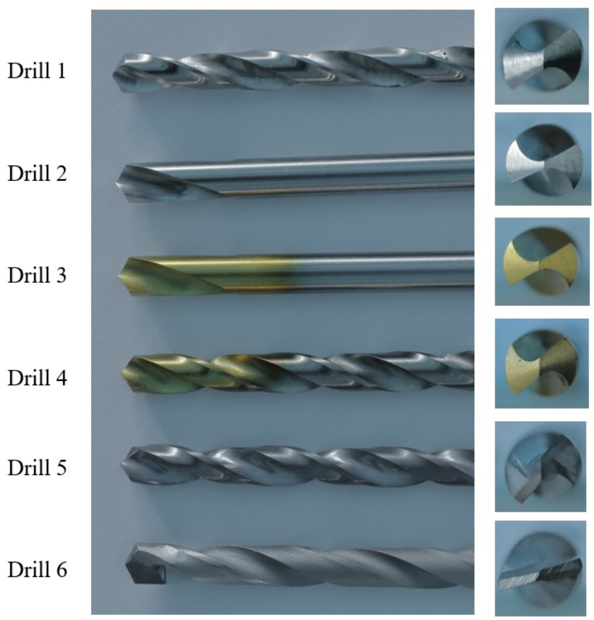


Fig. 1. Drills used for drilling GFRP

The geometric parameters which differentiate the drills are the chisel edge length and the lip relief angle. For drills 1, 2 and 5 the chisel edge length is in the range of 0.9–1.0 mm, for drills 3 and 4 it is equal to 0.45 mm and for drill 6 it equals 0.2 mm. The lip relief angle for drills 1, 4 and 6 is in the range of 7°–9° for drill 5 it is equal to 4.5° and for drills 2 and 3 is close to 0^o. However, these differences should not affect the results, because the most important geometry parameters affecting hole quality are the point angle, the helix angle and the cutting edge radius [44]. For instance, Xu et al. take into account only the point angle and helix angle in their work [22]. Moreover, only these two parameters affect the process-induced delaminations, whereas the cutting edge radius is mainly responsible for burr formation [45]. Burrs usually do not reduce the resultant strength of composites [45]; therefore, they were not considered in the present work and the influence of the cutting edge radius is neglected.

The selected drills were made of the most widely used drill materials, HSS and carbides, in different configurations: plain HSS (drill 1), HSS with 5% addition of cobalt (drill 2), HSS with 5% addition of cobalt with titanium coating (drill 3), HSS with titanium coating (drill 4), cemented carbide (drill 5) and HSS tipped with tungsten carbide (drill 6). Detailed information about the drill materials was not revealed by the manufacturers. Therefore, the hardness of the drills, which seems to be one of the properties differentiating the drills and which may affect the resulting hole quality, was measured. The HV hardness of all the drill materials was tested with the use of Digital Micro Hardness Tester MHVD-1000IS. The results are presented in Table 1.

Table 1. HV hardness of drills

Drill material	HV hardness	Standard deviation
HSS (drill 1)	712	2.3%
HSS with 5% addition of cobalt (drill 2)	951	2.9%
HSS with 5% addition of cobalt with titanium coating (drill 3)	888	3.1%
HSS with titanium coating (drill 4)	961	1.7%
cemented carbide (drill 5)	1512	4.3%
tungsten carbide (drill 6)	1601	5.5%

3. Composite material

The composite plates used in the experiments had a stacking sequence $[0^{\circ}_{4}]$ of plies made of twill 2/2 glass fabric with a weight of 280 g/m^2 and epoxy resin EPIDIAN 53 with Z1 hardener. The plates were manufactured using hand lay-up and then cured in a vacuum bag under pressure of 0.7 bar in room temperature. Then, the plates were post-cured in the temperature of 60°C for 8 h. The average thickness of the composite plates was 0.88 mm, the Young modulus was 23.46 GPa (standard deviation 1.54%) and the strength 386.10 MPa (standard deviation 6.00%).

3.1. Drilling parameters

Delamination is the most severe and wide-spread damage caused by composite machining. As it is known to affect the hole fatigue strength, it diminishes the performance of a part and shortens its life [9]. There are two main drilling parameters which have a significant influence on the delamination in FRP drilling, namely feed f_m [mm/min] and spindle speed ω [rev/min]. If the feed is divided by the spindle speed, the feed rate f_r [mm/rev] is defined. The linear cutting speed v [m/s] is obtained by multiplication of the spindle speed by the hole perimeter. Proper selection of these parameters is beneficial for delamination reduction during FRP drilling [9]. In recent years, many papers have been dedicated to the effects of cutting parameters on drilling induced delamination. It was reported that for drilling of CFRP [11, 32, 46–48] and GFRP [11, 49] composites the increase in the feed rate increases the push-out delamination [11, 44, 47, 50]. The influence of the spindle speed is less clear and weaker than the influence of the feed rate [44]. The researchers suggest that the effect of this parameter is small when the feed is low, but when the feed is higher, the increase in the spindle speed increases the delamination [11, 46, 47]. Some of them suggest also that the speed should be kept as low as possible to reduce temperature during drilling [48, 51]. There are also some articles which do not indicate any clear tendency of the delamination factor with increasing the spindle speed [38, 47, 49].

Those results suggest that the optimum drilling parameters should be selected for each case separately. Therefore, experiments aiming at selection of the optimum spindle speed and feed for the glass/epoxy composite were carried out in the present research. The drilling process was carried out with the use of a drilling machine with a programmable spindle speed (ω) and feed speed (f_m). A wide range of drilling parameters, namely four spindle speeds: 450 rev/min, 1000 rev/min, 2000 rev/min and 3000 rev/min and four feeds: 20 mm/min, 50 mm/min, 100 mm/min and 140 mm/min were investigated. For every combination of these parameters, the holes were drilled in a composite plate. The resulting feed rate for each combination of parameters is presented in Fig. 2.

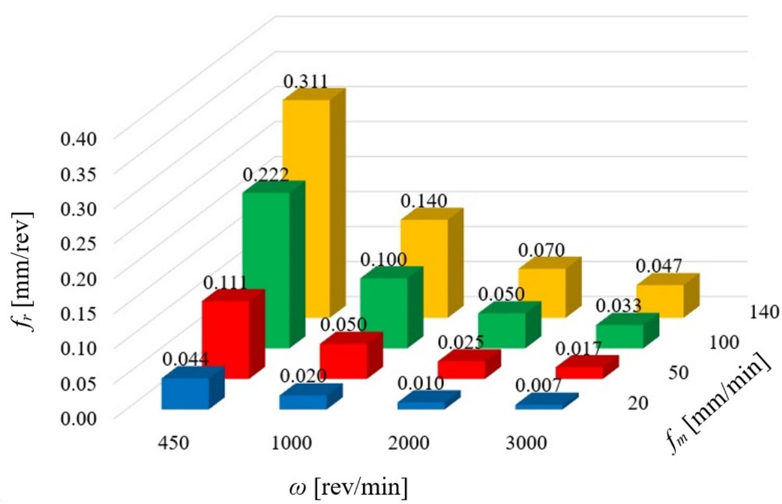


Fig. 2. Graph of f_r feed for all sets of drilling parameters

All the holes were manufactured using a support and were pressed from above to minimize delaminations. It seems that the choice of material of the supports does not affect the delaminations significantly [52]. Therefore, the tool designed to provide pressure during drilling was made of wood (Fig. 3). The plates were 20 mm thick in order to eliminate their potential deflection under the thrust of the drill.

Fig. 3. Drilling set-up

3.2. Delamination measurements

The entry delamination, also called peel-up delamination, occurs when the drill cutting edge makes contact with the composite and the peeling force causes the separation of the composite plies through the slope of the drill bit flutes. The exit delamination, also called push-out delamination, appears when the drill bit approaches the hole exit side and the uncut plies beneath the drill become more susceptive to the deformation due to the decrease of the thickness [53]. Eventually, push-out delamination appears at the drilled holes exit if the thrust force applied to the uncut plies exceeds the inter-ply bonding strength [6, 53]. Then, an interlaminar crack occurs when the interlaminar bonding strength can no longer withstand the bending deformation [6]. Peel-up and push-out delamination mechanisms are presented in Fig. 4. As the delaminations are good indicators of the hole quality, the holes subjected to bearing tests should have the lowest possible delaminations. Too large delaminations may cause dispersion of the results and thus decrease their credibility.

Four holes were drilled for each combination of the drilling parameters (Fig. 2). The specimens with holes were placed on the illuminated background and the photographs were taken with use of a laboratory microscope. An example of such a photograph of a hole is presented in Fig. 5a. The pictures were submitted to processing in ImageJ software [54] to determine the delamination area clearly (Fig. 5b).

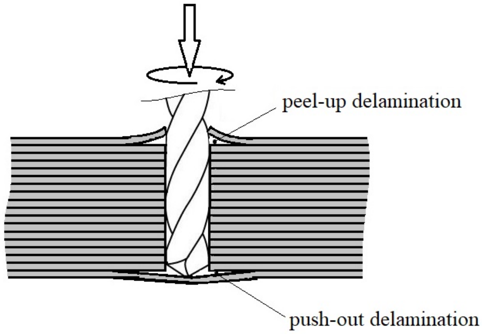
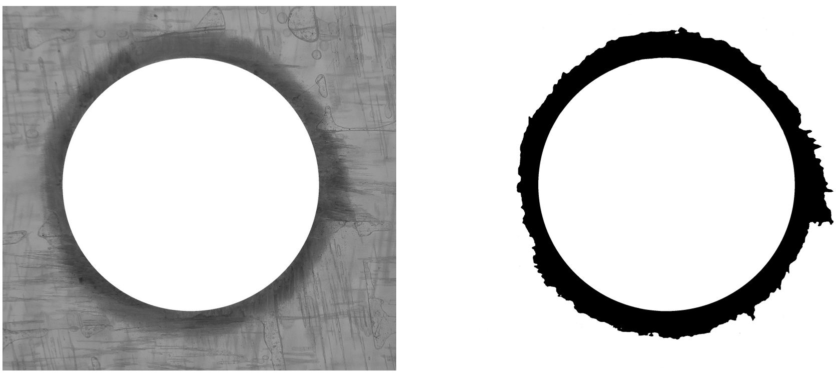


Fig. 4. Peel-up and push-out delamination



(a) (b)

Fig. 5. (a) Exemplary raw picture of a hole; (b) The picture after processing

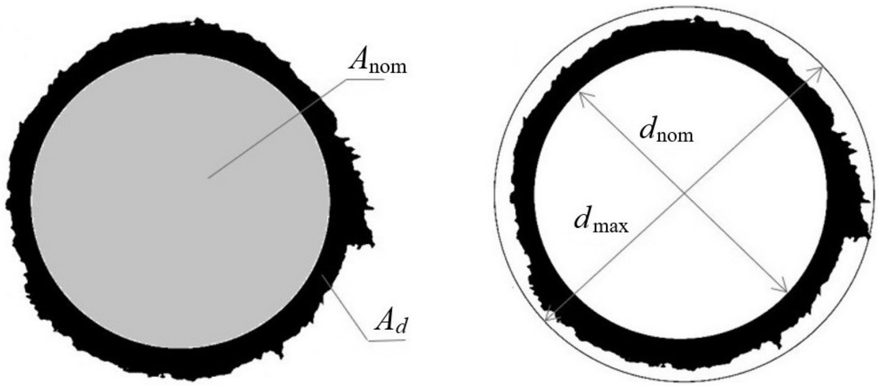
There are two basic factors allowing assessment of the severity of the delamination around a hole [9, 55]. The first one F_a is expressed by formula (1):

$$F_a = \frac{A_d}{A_{\mathrm{nom}}}, \tag{1}$$

where A_{nom} is the nominal area of the hole and A_d is the measured area of the delamination (Fig. 6a). The second factor F_d is expressed by formula (2):

$$F_d = \frac{d_{\max}}{d_{\mathrm{nom}}}, \tag{2}$$

where $d_{\max}$ is the maximum diameter of the circle covering the delamination area and d_{nom} is the diameter of the nominal hole when the two circles are concentric (Fig. 6b). Each of the two factors takes into account different geometric features of the delaminations and, therefore, both are used in the present work to assess the quality of the holes.



(a) (b)

Fig. 6. Definition of delamination factors (a) F_a and (b) F_d

Recently, also a 3D delamination factor, which takes into account the average of all inter-ply delaminations embedded through the thickness of the laminate, has been formulated [22]. It is more comprehensive than the 2D factors and it should be an obvious choice in the case of carbon and thick glass reinforced laminates. However, in the present work, the glass reinforced laminate is so thin that after illuminating it from the bottom side, the sum of all delaminations is visible. Therefore, the delamination shape used in the 2D factors (1) and (2) consists of all the delaminations embedded through the thickness of the specimen and in this case these factors are substitutes of the 3D factor.

The results of factors F_a and F_d for the holes made by each drill 1–6 with all the combinations of the drilling parameters are presented in Figs. 7 and 8. In Fig. 7g and 8g the delamination factors averaged for all drills are also presented. In the case of F_a factor for almost all the drills and for the averaged values of the factor saddle-shaped graphs were obtained with higher values of factors near the corners where the low spindle speed is coupled with the high feed rate and the low feed is coupled with the high spindle speed. This suggests that either a low feed should be coupled with a low spindle speed, which is recommended by some authors [35, 48], or a high feed with a high spindle speed. If the results are to be related to the feed rate f_r (Fig. 2), the lowest values are grouped near the diagonal of the graph where the values of f_r are approximately 0.05 mm/rev. The graphs of F_d factor show a different tendency. In the case of the majority of the drills and for the averaged values of the factor, the highest factors were obtained for the low spindle speed and the high feed and they tend to decrease as the spindle speed increases and the feed decreases. These results correspond well with the graph of f_r drilling parameter (Fig. 2) – it seems that the lower the feed rate, the lower the delamination factor F_d. These results are in opposition to the suggestion that a low feed coupled with a low spindle speed yields the best results [35, 48]. The results for both factors F_a and F_d are also in opposition to the results suggesting that when the feed is higher, the

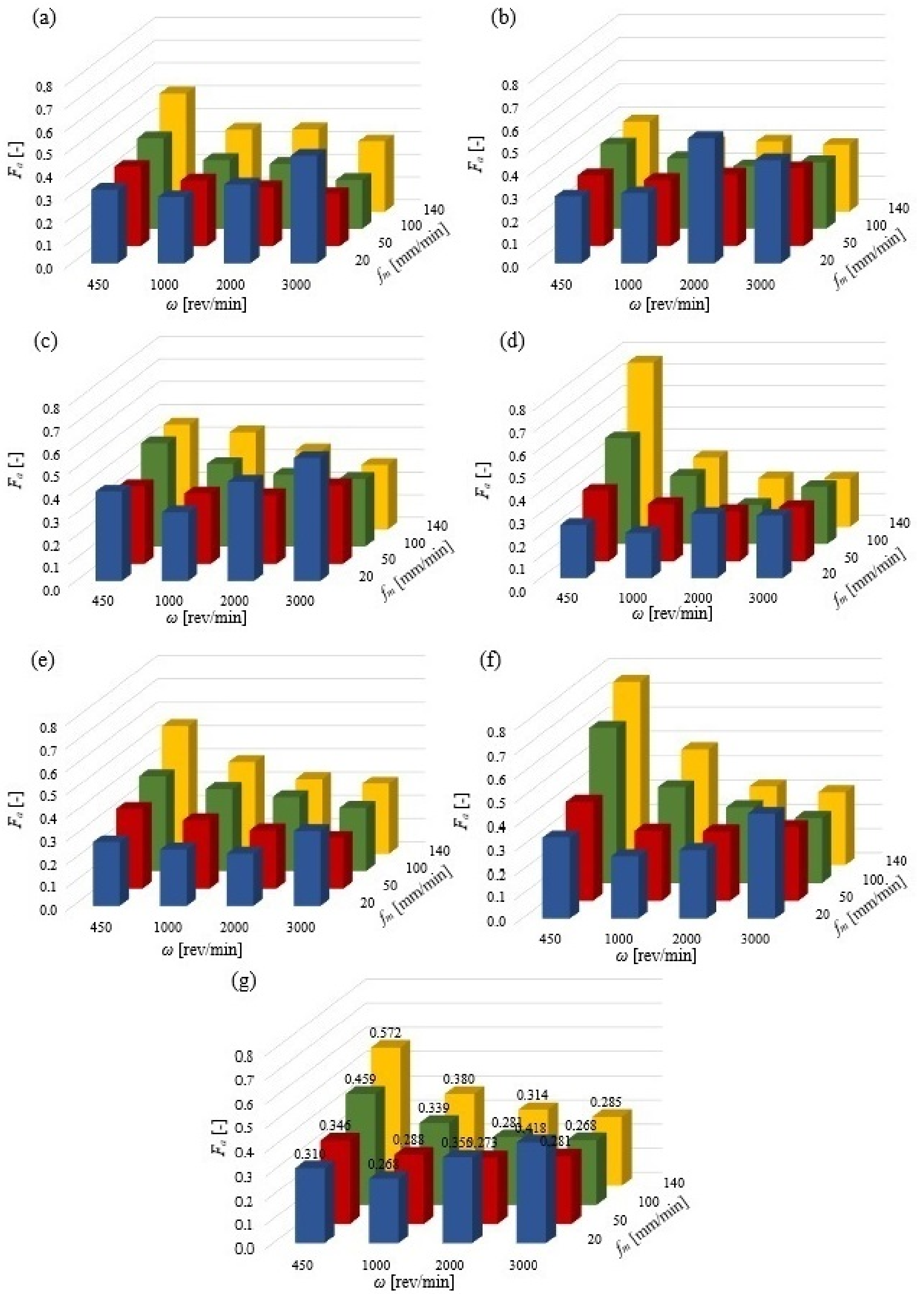


Fig. 7. Delamination factor F_a for holes made by different drills: (a) plain HSS (drill 1), (b) HSS with 5% addition of cobalt (drill 2), (c) HSS with 5% addition of cobalt with titanium coating (drill 3), (d) HSS with titanium coating (drill 4), (e) cemented carbide (drill 5), (f) HSS tipped with tungsten carbide (drill 6) and (g) factor averaged for all drills

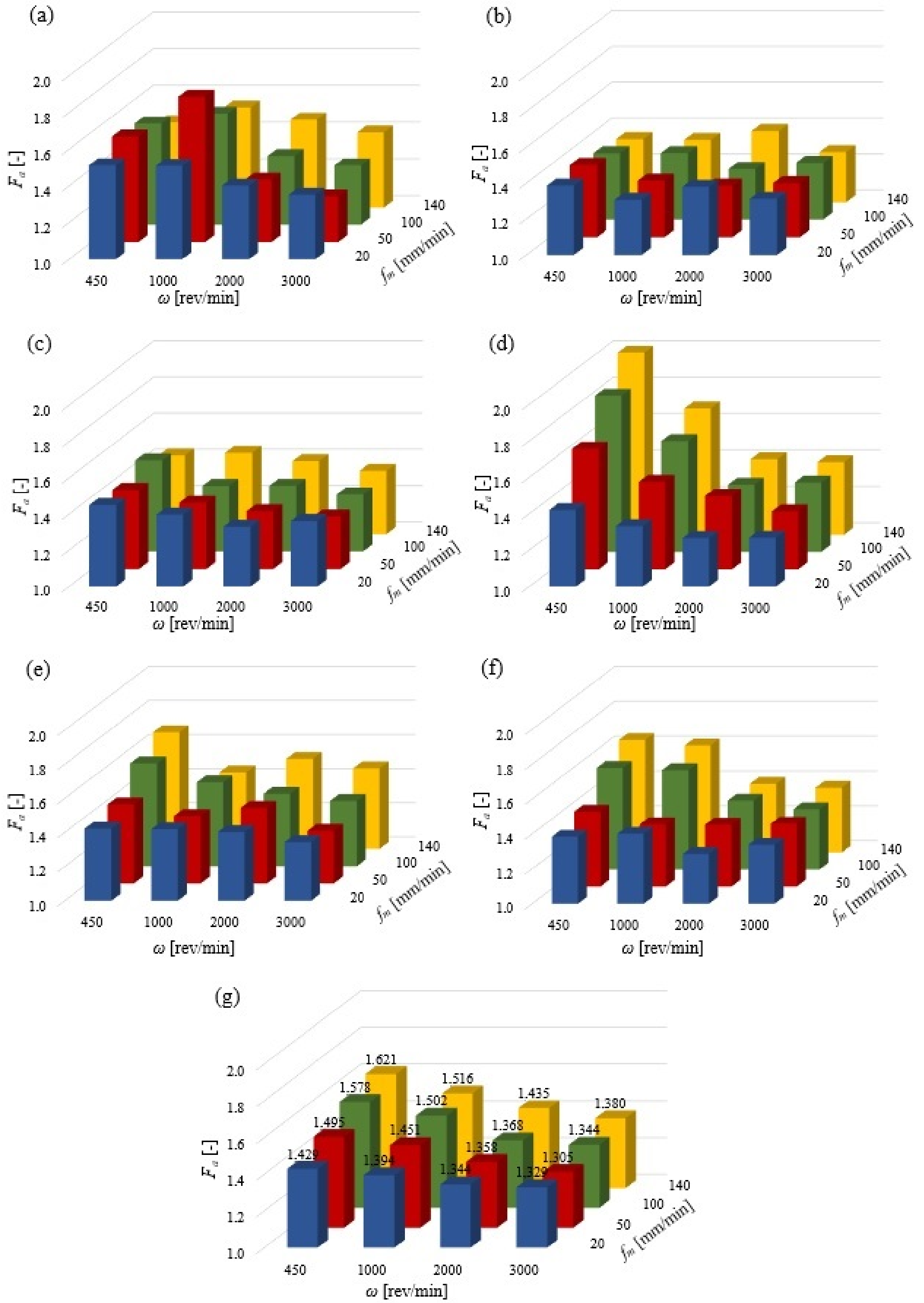


Fig. 8. Delamination factor Fd for holes made by different drills: (a) plain HSS (drill 1), (b) HSS with 5% addition of cobalt (drill 2), (c) HSS with 5% addition of cobalt with titanium coating (drill 3), (d) HSS with titanium coating (drill 4), (e) cemented carbide (drill 5), (f) HSS tipped with tungsten carbide (drill 6) and (g) factor averaged for all drills

increase in the cutting speed increases the delamination [11, 46, 47]. This indicates that the optimisation of drilling parameters obtained for one laminate may not be true for another and thus it is recommended to perform such an optimisation every time.

In the present work, the results for different drills ought to be compared for the same feeds and spindle speeds and, therefore, the selection of these parameters should be carried out. The drilling parameters should ensure the best possible quality of the holes for the bearing tests, so the three sets of drilling parameters characterized by the lowest factor were selected for F_a and F_d. The sets of parameters for F_a factor are as follows:

- ω = 3000 rev/min, v = 100 mm/min – $F_a = 0.278$ (standard deviation = 12.1%),
- ω = 1000 rev/min, v = 20 mm/min – $F_a = 0.281$ (standard deviation = 8.3%),
- ω = 2000 rev/min, v = 50 mm/min – $F_a = 0.283$ (standard deviation = 7.6%).

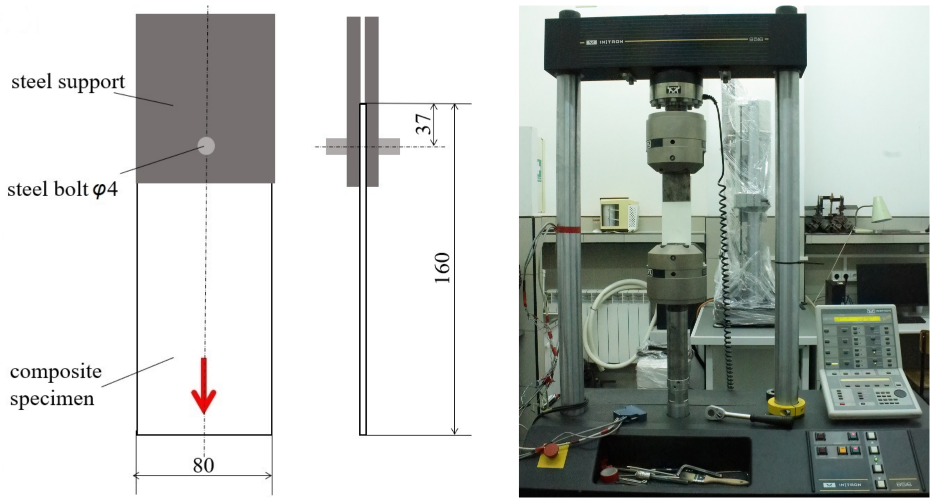
Standard deviations for all these cases are quite low compared to the other sets of parameters (the average standard deviation for all the drilling parameter is 13.0%). Three sets of drilling parameters which give the lowest average value were chosen also for the factor F_d:

- ω = 3000 rev/min, v = 50 mm/min – $F_d = 1.305$ (standard deviation = 2.6%),
- ω = 3000 rev/min, v = 20 mm/min – $F_d = 1.329$ (standard deviation = 2.3%),
- ω = 3000 rev/min, v = 100 mm/min – $F_d = 1.344$ (standard deviation = 2.1%).

The standard deviations for all these cases are also low (the average standard deviation for all the drilling parameters is 5.7%). As the set of drilling parameters ω = 3000 rev/min and v = 100 mm/min gives one of the best results in the case of both factors, these parameters were chosen for manufacturing holes in the specimens used for bearing strength experiments.

3.3. Bearing strength testing

Single lap shear specimens were cut from the same composite GFRP plates in which the holes used to determine drilling parameters had been made. The dimensions of the specimens were 80 × 160 mm. The holes were drilled in each specimen in distance of 37 mm from the free edge and leaving 40 mm margins on both sides (Fig. 9a). Such large margins assured the bearing mode of failure in all the specimens. This mode is a better indicator of the hole quality in terms of delamination than the other modes of failure, since the failure is caused by the direct stress on the delamination.



(a) (b)

Fig. 9. SLS specimen scheme (a) and experimental set-up (b)

The holes were drilled in the SLS specimens with the same drills which were used to drill holes to determine optimum drilling parameters on the basis of delamination factors. 6 specimens were made for each drill. The total distance drilled by each drill was equal to approximately 62 mm. The research into the influence of the drill wear on the delamination intensity was focused mainly on CFRP composites. The majority of work indicates that the drilling distance of 62 mm in CFRP laminate should not cause the drill wear that can cause a significant increase in the delamination compared with the new tool [4, 56, 57]. Therefore, it was assumed that drilling this distance in GFRP laminate has an even smaller impact on the tool wear, as glass fibres are known to be less abrasive than carbon fibres.

The specimens were tested on the hydraulic machine Instron 8516, which had a force capacity 100 kN and displacement capacity 150 mm, with test speed 0.5 mm/min (Fig. 9b). The maximum force obtained in each test was adopted as the indicator of bearing strength.

4. Results and discussion

The average results of the bearing strength for the holes made with each drill along with standard deviations are presented in Fig. 10.

Before testing, both delamination factors F_a and F_d were determined for each specimen. The average results of the factors for the holes made by each drill along with standard deviation are presented in Fig. 11.

The bearing strength averaged for the specimens with the holes made with the use of each drill is the highest for drill 4 – steel with titanium coating (0.544 kN).

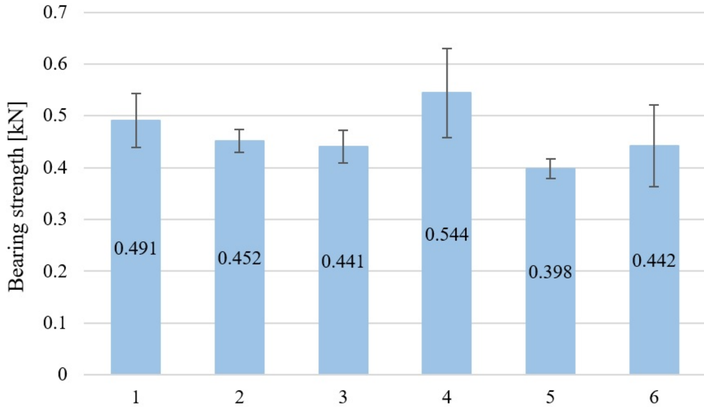


Fig. 10. Bearing strength results for holes made by different drills: plain HSS (drill 1), HSS with 5% addition of cobalt, (drill 2), HSS with 5% addition of cobalt with titanium coating (drill 3), HSS with titanium coating (drill 4), cemented carbide (drill 5) and HSS tipped with tungsten carbide (drill 6)

However, this result is coupled with a large standard deviation (15.85%) compared with the results for the other drills. The second result was obtained for drill 1 made of plain HSS (0.491 kN) and the lowest result for drill 5 made of cemented carbides (0.398 kN). The standard deviation for drill 1 was also quite high (10.76%), while the deviation for drill 5 was the lowest (4.91%). The results for drills 2, 3 and 6 were moderate and similar (0.452 kN, 0.441 kN and 0.442 kN with standard deviations 4.94%, 7.13% and 17.87% respectively).

These results are surprising, as the best result was achieved for the HSS drill coated by titanium, though admittedly the deviation of the result was quite large and the second best result was obtained for plain HSS drill. Neither HSS with titanium coating nor plain HSS had been described in the available literature as a material for drills used to make high quality holes in fibre reinforced composite materials. On the other hand, the wide use of carbide drills suggests that they allow obtaining a high hole quality and in consequence a high bearing strength. However, in the presented results, the specimens with the holes made with the cemented carbide drill had the lowest strength and the results for the HSS drill tipped with tungsten carbide were also significantly worse than for the HSS drill with titanium coating or the plain HSS drill. The 5% addition of cobalt leads to worse results in the case of uncoated and coated HSS drills, so it can be concluded that the addition of cobalt is undesired in HSS drills used to drill GFRP materials.

As both factors F_a and F_d describe the delamination induced during the drilling process, they should predict the bearing strength of the specimens for which they had been calculated. Therefore, the averaged factors for each specimen group are placed in the same graph as the results of the bearing strength in order to compare their values (Fig. 12). As the absolute values of the factor F_d vary only slightly (Fig. 11b), for the sake of the graph clarity unity was subtracted from

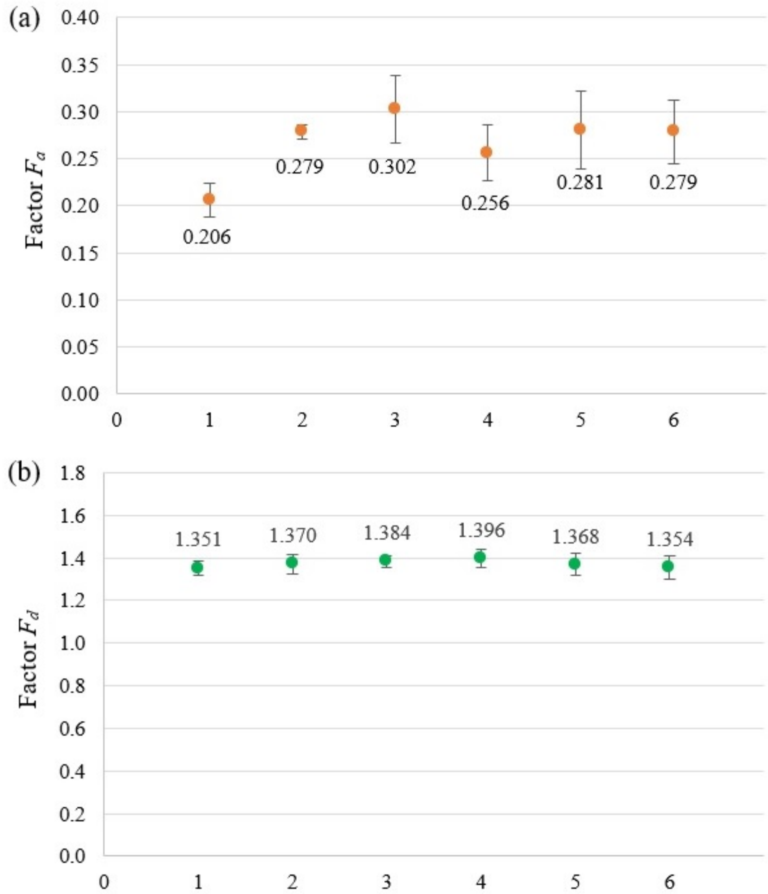


Fig. 11. Delamination factors (a) F_a and (b) F_d for holes made by different drills: plain HSS (drill 1), HSS with 5% addition of cobalt, (drill 2), HSS with 5% addition of cobalt with titanium coating (drill 3), HSS with titanium coating (drill 4), cemented carbide (drill 5) and HSS tipped with tungsten carbide (drill 6)

this factor. Theoretically, the higher the delamination factor, the more harmful the delamination and thus the bearing strength of the specimens in question should be lower. This tendency can be seen in the case of F_a factor. On the other hand, F_d factor results are less consistent with the bearing strength results and have the highest value for the specimens drilled with the HSS drill with titanium coating for which the bearing strength is the highest. However, the results of the F_d factor for the other drills show a similar tendency as the F_a factor and the bearing strength results.

This shows that the results of the bearing strength and factor F_a are consistent and show a real tendency, whereas the factor F_d should be treated more cautiously as a measure of delamination severity. The value of F_d factor for a single hole is

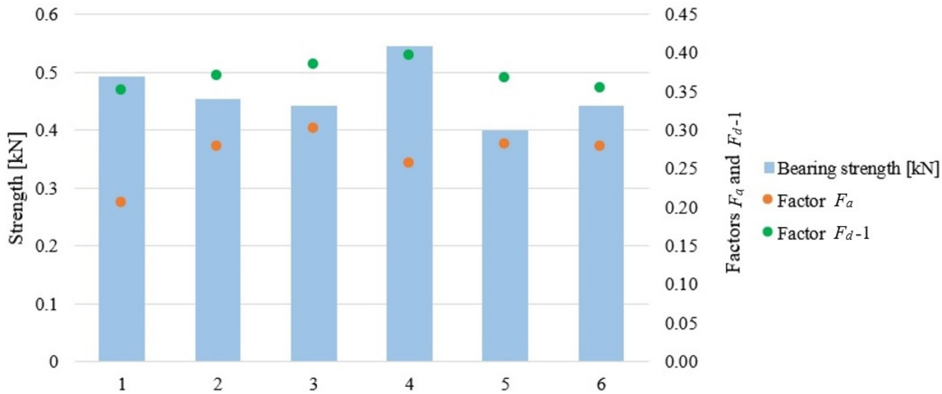


Fig. 12. Comparison of average values of bearing strength and delamination factors F_a and F_d for holes made by different drills: plain HSS (drill 1), HSS with 5% addition of cobalt, (drill 2), HSS with 5% addition of cobalt with titanium coating (drill 3), HSS with titanium coating (drill 4), cemented carbide (drill 5) and HSS tipped with tungsten carbide (drill 6)

often determined by a delamination of a very narrow strip of a composite ply. The above results suggest that such a defect may not have a significant influence on the hole strength. If this assumption is true, it is not the whole area of the delamination, but only the delamination close to the hole edge that is of a major influence on the hole bearing strength.

As both bearing strength and factors F_a and F_d have significant standard deviations, their average values are not the best representation of the results. Therefore median values were calculated for the strengths and the factors and these are presented in Fig. 13.

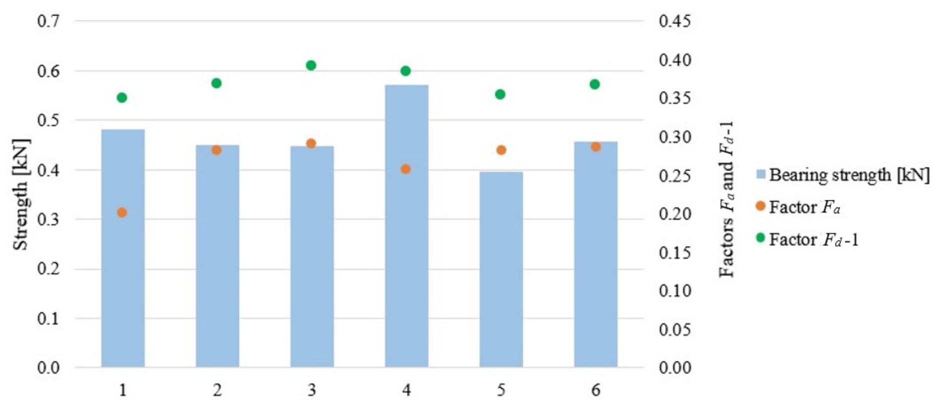


Fig. 13. Comparison of medians of bearing strength and delamination factors F_a and F_d for holes made by different drills: plain HSS (drill 1), HSS with 5% addition of cobalt (drill 2), HSS with 5% addition of cobalt with titanium coating (drill 3), HSS with titanium coating (drill 4), cemented carbide (drill 5) and HSS tipped with tungsten carbide (drill 6)

Even though the values of median differ slightly from the average values, they generally show the same tendency. The highest bearing strength is obtained for the HSS drill with titanium coating and the lowest strength for the cemented carbide drill. Also the tendency of the median results of F_a and F_d factors is similar as in the case of their average values.

A comparison of the average values of bearing strength and HV hardness of the drills is presented in Fig. 14. No clear influence of the drill material hardness on the bearing strength of the holes drilled in GFRP can be seen. The reason for this may be the fact that drills made of hard materials such as carbides or coated drills are used for drilling fibre reinforced composites mainly in order to assure a longer life of the drill, not to improve the quality of the holes [58]. Therefore, the hardness of the drill material or coating is not a key property affecting the quality and the strength of the holes drilled in composites after all. Moreover, the hardness of the GFRP composite is much lower than any hardness of the drills and, therefore, changes of the drill material hardness may have little effect on the quality of the holes.

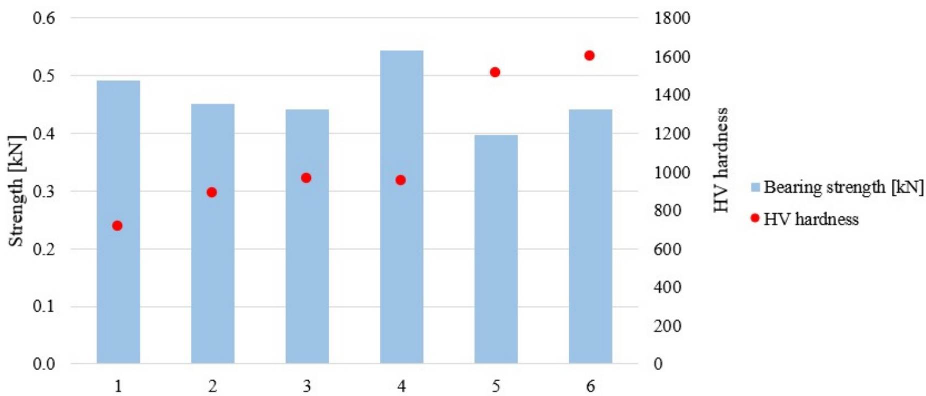


Fig. 14. Comparison of average values of bearing strength and the HV hardness of different drills: plain HSS (drill 1), HSS with 5% addition of cobalt, (drill 2), HSS with 5% addition of cobalt with titanium coating (drill 3), HSS with titanium coating (drill 4), cemented carbide (drill 5) and HSS tipped with tungsten carbide (drill 6)

5. Conclusions

The main goal of the article was to assess the influence of the drill material on the hole quality and the bearing strength of the holes made in GFRP composite. Therefore, the main conclusions are as follows:

- The highest bearing strength was achieved for the drill made of HSS with titanium coating and the plain HSS drill and the lowest for the drill made of cemented carbides. This result is surprising as the carbide drills are often recommended and widely used for drilling composite materials. As

HSS drills with titanium coating and plain HSS drills are manyfold less expensive than carbide drills (respectively, 10 and 15 times in the case of the drills used in this work), the use of such drills instead of carbide is an option worth investigation in commercial use, especially for drilling GFRP composites which are less abrasive than CFRP composites.

- The results of the bearing strength have been confirmed by the delamination factor F_a calculated as a ratio of delamination area to the hole area. The results of another factor F_d calculated as a ratio of maximum delamination diameter to the hole diameter are less consistent with the strength results. This leads to the conclusion that the F_a factor is a better measure of the hole bearing strength than F_d factor and that it is not the whole area of the delamination, but only the delamination close to the hole edge that is of a major influence on the hole bearing strength.
- The addition of 5% cobalt leads to worse results in the case of uncoated and coated HSS drills, so it can be concluded that the addition of cobalt is undesired in HSS drills.
- The hardness of the drill material does not affect the hole strength to a significant extent.

The preliminary experimental investigation necessary to choose the optimum drilling parameters also allowed drawing other conclusions concerning the connection between the drilling parameters and the quality of the holes drilled in the composite:

- F_a factor reaches its highest values corresponding with the worst quality of holes for the highest and the lowest feed rate f_r in the cases of almost all the considered drills. It can be concluded that the f_r should be kept close to 0.05 mm/rev.
- F_d factor decreases with the feed rate; therefore, from the point of view of this factor f_r should be kept as low as possible. However, as F_d factor appeared to have less effect on the bearing strength of the holes and the low values of f_r may extend the time of drilling operation, the value of f_r determined for F_a factor seems to be more advisable.

It is necessary to bear in mind that all the conclusions presented above are drawn on the basis of investigation of holes made in a 4 ply and approximately 0.88 mm thick glass fabric-epoxy laminate. In order to draw more general conclusions on the selection of drill material for manufacturing holes in composite materials, more experimental investigation is needed, including tests with different laminate materials and thicknesses.

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