

Studying the Performance of Cutting Carbon Fibre-Reinforced Plastic Using an Abrasive Water Jet Technique

Ahmed A. Hussien^{1,*} – Isam Qasem¹ – Pramodkumar S. Kataraki² – Wael Al-Kouz³ – Ayub Ahmed Janvekar⁴

¹ Al-Balqa Applied University, Al-Huson University College, Department of Mechanical Engineering, Jordan

² REVA University, School of Mechanical Engineering, India

³ German Jordanian University, Department of Mechanical and Maintenance Engineering, Jordan

⁴ VIT University, School of Mechanical Engineering, India

In recent years, composite materials such as carbon-fibre-reinforced plastic (CFRP) have been widely used in medical devices, industries, marine and aerospace applications due to their high resistance-to-weight ratio toughness, corrosion resistance, and other novel properties. The machining of these composite materials using conventional machines results in poor precision and surface finishing due to excess heat generation at the tool-material contact zone. The drawbacks of the conventional machining process can be overcome with the adoption of a novel cutting technique using pressurized water, which can dissipate the heat generated by the impact of abrasive particles against the material in order to eliminate the poor precision and surface finishing caused by overheating. In this experimental study, the performance of surface quality (roughness and kerf angle) of CFRP machining using an abrasive water jet technique has been studied for a wide range of cutting parameters, such as water pressure and cutting speed.

Keywords: composite materials, CFRP, abrasive water jet, surface quality, roughness, kerf angle

Highlights

- An abrasive water jet (AWJ) technique can be used for machining composite materials such as carbon-fibre-reinforced plastic (CFRP).
- The roles of some cutting parameters, such as water pressure and cutting speed on surface quality have been studied.
- The enhancement of cutting surface quality depends on increasing water jet pressure and decreasing the cutting rate.

0 INTRODUCTION

In recent years, carbon-fibre-reinforced plastic (CFRP) composite material has been utilized in various engineering and medical applications, such as the aerospace industry, renewable energy, medical devices, and the automotive industry [1]. The maximum utilization of CFRP has been due to their high strength with low weight, anti-corrosion and negligible effect on thermal expansion [2] and [3].

CFRPs are carbon/graphite fibres reinforced polymers. The polymers used in this composite can be epoxy, vinyl ester, polyester, or nylon. CFRPs are usually used in aerospace and automotive industries due to the superior properties, such as high specific strength and modulus, chemical stability, high corrosion and fatigue resistance, etc. [4].

Many researchers have been concerned about the difficulties of machining CFRP, especially thermal damage and low surface quality during manufacturing process [5] and [6]. The complexity of machining different materials' thermal and mechanical properties and the inhomogeneity and anisotropy of CFRPs influences the selection of the machining process and of the tools used. For example, cutting high strength and heat resistance of carbon fibres required a more

hazardous environment and thermal-associated wear processes, which caused unexpected matrix crack and delamination [4]. Therefore, for enhancing the functional performance after machining CFRP, post-finishing processes include super-finishing, contour milling, honing, mass finishing, lapping, polishing, and drilling have been used. These processes required significant efforts and cost [7] and [8].

Therefore, advanced machining techniques using abrasive high-pressure water jet machining process are widely utilized to cut the high strength materials without thermal damage; this advanced machining technique is called abrasive water jet (AWJ). The main advantages of using AWJ in the manufacturing process are fewer recast layers, high cutting precision, and low cutting forces, and the lack of excess heat generated [9]. This machining technique has been adopted in production to process high-strength materials, such as stone, composite material, glass, etc. [10] to [12].

Manufacturing of the composite materials using conventional machining process faced many difficulties such as workpiece damage, crack formation in workpieces, and low surface finish quality. Thus, it has led to the utilization of abrasive water jet method to machine the composite materials [13] and [14].

*Corr. Author's Address: Al-Huson University College, Al-Balqa Applied University, Irbid, 21110, Jordan, ahmed.hussien@bau.edu.jo

To meet the expectations of best surface finish quality during manufacturing process using the AWJ technique, various parameters related to the quality of surface finish has been discussed. Bañon et al. [15] discussed in their comprehensive review the different defects generated on CFRP with AWJ machining. Damage caused by delamination, fibre fraying, degradation, or micro-cracks effects on the machining surface quality, which depends on the thickness of the material. In addition, macro-geometric deviations caused variations of kerf widths at three zones on the cutting surface, which produced taper angles. Therefore, many researchers have utilized experimental approaches to optimize these parameters for the best-expected surface finish quality results [16].

Popan and Popan [17] used the AWJ technique to manufacture a composite material containing many layers of CFRP. They studied and analysed the surface roughness surface quality and dimensional accuracy using a highly accurate microscope. Their experimental results after cutting the complex part reveals that using AWJ process in manufacturing composite materials is the best solution to avoid, tool wear, material mass delamination and abrasive inclusions.

Selvam et al. [18] investigated the performance in manufacturing the hybrid composite materials using AWJ technique. The hybrid composite materials containing 54 % e- glass fibres and carbon fibres manufactured with a hand lay-up method were used in experimental investigation. The study mainly focused on significant cutting parameters: water pressure, traverse speed, and abrasive mass flow rate on kerf taper angle and average surface roughness. The results showed that the traverse speed was a most important factor in obtaining high surface quality. This was due to the number of colliding and impact of abrasive particles with the side of the working material.

Xiao et al. [19] experimentally investigated the cutting quality of CFRP using a multi-pass of the AWJ technique. The composite material used in their experiment contained 60 % carbon-fibre with cross-ply at different angles. They evaluated the surface roughness, kerf taper angle and material mass delamination by changing the values of traverse speed, water pressure, and impact angle on multi-pass cutting using AWJ. They selected the values of traverse speed and water pressure at 1100 mm/min to 2300 mm/min and 180 MPa to 230 MPa, respectively. They concluded that the appropriate values of traverse speed and water pressure could improve the efficiency of surface quality. In addition, the modified AWJ

machining can be applied to other materials, such as ceramic and metal.

The surface quality of the machining surface of hybrid structure that contains CFRP/Steel using AWJ have been examined by Bañon et al. [20]. Their results showed that the lowest roughness and profile height of cutting surface accrues when hydraulic pressure of 420 MPa and a travel speed of 50 mm/min.

Unde et al. [21] asserted that the reinforcement orientations have a notable effect on surface quality in the manufacturing of CFRP composite materials using AWJ. They investigated the effect of surface methodology on surface quality during the machining process on composite materials. The results revealed that the lowest values of surface roughness occurred to the laminate with a fibre orientation of 90° compared to 60° and 45°, which was due to lower shear plane resistance.

The literature mainly concentrated on studies to find the advantages of machining fibre-carbon-reinforced plastics using AWJ. However, the challenges of material delamination and surface quality still are based on different cutting parameters, including traverse speed, water flow rate, and water pressure in addition to the orientations and thickness of composite materials. Hence, greater research is necessary to find the optimum ranges of these parameters to meet the requirements of surface quality.

In this study, a hand lay-up of fabricated carbon-fibre-reinforced plastics at different orientation angles was subjected to abrasive water-jet machining in order to evaluate the surface roughness and kerf taper with a wide range of cutting parameters, including traverse speed and water pressure.

1 MATERIAL PREPARATION AND EXPERIMENTAL PROCEDURE

The work composite material is a carbon-fibre-reinforced plastic with a size of 300 mm × 300 mm × 7 mm. All the tested samples were manufactured using a hand lay-up based on a compression moulding method [22]. This method is very simple and gives an effective production of complex arrangement in short time.

The weight fraction of carbon fibres was 60 %, and the fibre orientations were 0°/90°/0°/90° for the all tested samples. Table 1 illustrates the materials of the tested samples.

Preparation was carried out in two stages; first, the mould was allowed to intake well-prepared resin mixture. Next, the fibre was placed over them carefully. This process was repeated continuously

in suitable interval of time gap. Once the required thickness was achieved, the stacking sequence was completed. The next stage was curing, in this CFRP laminates was exposed to pressure which is under compression mode. Dead weight was placed over the mould to bring necessary pressure.

Table 1. The materials consist of tested samples [23] and [24]

Material	Type	Properties
Carbon fiber	Bidirectional (T300)	Nominal diameter [μm]
		7
		Density [g/cm^3]
		1.76
		Areal weight [g/m^2]
Epoxy resin	Araldite LY-556	200
		Tensile strength [MPa]
		3530
		Tensile modulus [GPa]
		230
Hardener	Aradur HY-951	Clear, Pale yellow liquid
		Density at 25 °C [g/cm^3]
		1.2
		Viscosity at 25 °C [Pa·s]
		12
		Viscosity at 25 °C [mPa·s]
		10–20
		Density at 20 °C [g/cm^3]
		0.95–1.05
		mixed to a ratio of 10:1 by weight

The cutting was performed using an AWJ cutting machine (Jiangsu, China (Mainlan)) with ± 0.1 mm of precision and repeatability (Fig. 1). The maximum values of lateral speed and water pressure in this machine are 15 m/min and 200 MPa, respectively. The values of process parameters were kept constant during the experiment as recommended by the manufacturer. The constant process parameter is shown in Table 2.

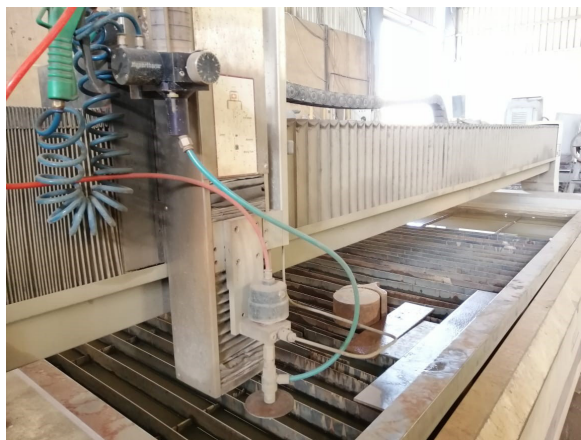


Fig. 1. Abrasive water jet cutting machine

The quality of the cutting surface obtained by AWJ machining process was examined and evaluated at different cutting parameters. The effect of different

values of traverse speed and water pressure on kerf taper angle and surface roughness were investigated. Five different values of these parameters were taken into consideration for each measurement. The water pressure ranged from 100 MPa to 200 MPa while the traverse speeds ranged from 100 mm/min to 200 mm/min.

Table 2. Constant process parameters

Parameter	Value
Thickness, [mm]	7
Abrasive flow rate, [g/min]	300
Impinging angle, [deg]	90
Orifice diameter, [mm]	0.25
Stand off distance, [mm]	3
Abrasive type	Garnet #80
Abrasive grain size	80 mesh
Nozzle diameter, [mm]	0.79

Evaluating the surface quality of the surfaces produced during AWJ manufacturing can be done by measuring surface roughness and kerf taper angle. In this experiment, the surface roughness R_a value was measured using a portable roughness tester RT10 with measure range $\pm 150 \mu\text{m}$ and resolution of 5 nm. According to Hloch and Valíček [25], the cutting surface using AWJ generates three distinguished geometrical zones, namely the initial region, the surface cut (smooth zone), and the bottom (rough cutting region). These zones were related to many parameters includes material properties and cutting parameters. The output results of surface roughness of smooth cutting zone (maximum of 3 mm in the depth direction) were showed at various water jet parameters in a quantitative manner. The recorded value of every measurement was the mean of at least three repeated measurements.

Furthermore, the tapering effects in cutting zone at different values of cutting parameters is measured in this research. It can be characterized by measuring the upper and lower kerf width in the complete geometry of cutting, Eq. (1) [26]:

$$K_t = \tan^{-1} \left(\frac{(w_{top} - w_{bottom}) \times 180}{2\pi t} \right), \quad (1)$$

where K_t is a kerf taper angle [$^\circ$], t is a material thickness [mm], w_{top} and w_{bottom} are top and bottom kerf width [mm], respectively.

Fig. 2 shows CFRP samples after the cutting process. The distance between each cutting line was at least 20 mm. The measurements were obtained at

the middle of the cutting line to avoid the start cutting process on the material.



Fig. 2. Illustrates CFRP material

2 RESULTS AND DISCUSSION

This research aimed to investigate the effect of cutting parameters of AWJ machine on the surface quality of carbon FRPC material experimentally. The influence of cutting factors, namely traverse speed and water pressure on surface roughness and kerf taper, is discussed in this section. Also, R_a and kerf taper angle were measured for every cutting surface at different water pressure and traverse speed values.

The effect of traverse speed on kerf taper angle at lower and higher values of water pressure are introduced in Fig. 3. The experiment reveals that as traverse speed increased, the kerf ratio decreased for all water pressure values. This is due to the increase in the cutting rate, and this leads to a lesser affected of hitting particles during the cutting process, which caused the width of the kerf taper to decrease [27].

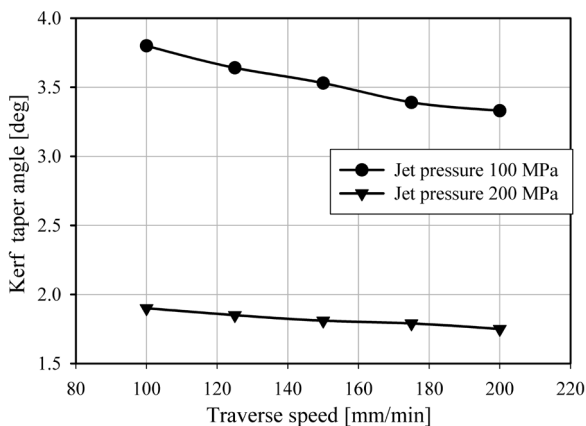


Fig. 3. Kerf taper angle vs traverse speed at different water pressure levels

On the other side, increasing the water pressure caused a decrease of the kerf taper angle, as shown in Fig. 3. In addition, the curve behaviour of different values of cutting speed is the same but at different

magnitudes. Increasing the pressure of impinged particles leads to increased kinetic energy; this could be caused by reducing the kerf taper ratio [26]. Therefore, localized machining could be occurring at high velocity, and energy abrasive particles crash into the surface of CFRP composite materials. That caused a lower kerf width. Gnanavelbabu [28] observed lower kerf taper at high water pressure when machining aluminium metal matrix composites. The enhancement of kerf taper could be reached up to 50 % when the water pressure changed from 100 MPa to 200 MPa, as shown in Fig. 4. Minimizing the value of kerf taper angle is necessary to produce high quality cutting surface. Therefore, increasing both water pressure and cutting rate can be meet the required of manufacturing CFRP laminates at extraordinary quality. These results have been confirmed in previous research done by Vigneshwaran et al. [29]. They studied the effect of jet pressure on kerf taper angle during machining of red mud-filled sisal polyester hybrid composite using AWJ. They revealed that kerf taper reduced at higher pressure. From the Figs. 3 and 4, it is evident that the effect of changing water pressure on kerf taper is more significant of changing cutting rate.

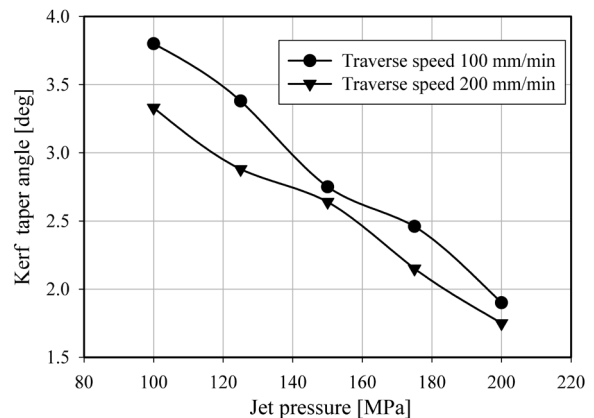


Fig. 4. Kerf taper angle vs. water pressure at different traverse speed

Fig. 5 illustrates the effect of surface roughness at different values of traverse speed at lowest and highest water pressure. It can be noted that increasing cutting rate caused increasing surface roughness. During the cutting process, the particles of hardener materials become unstable, especially at a high cutting rate. This leads to observe irregular holes and cavities on the cutting surfaces [30]. Thus, increasing the speed of machining CFRP laminates causes high surface roughness. Pahuja and Ramulu [31] showed that increasing cutting rate caused high surface roughness

regardless of the stacking configuration. This is due to the loss of kinetic energy. However, the surface roughness can be enhanced by increasing the water pressure as shown in Fig. 6. The results reveal that, at high water pressure, collisions between high-energy water particles and composite materials caused high erosions with fewer cavitation and waviness patterns on the cutting surfaces [28].

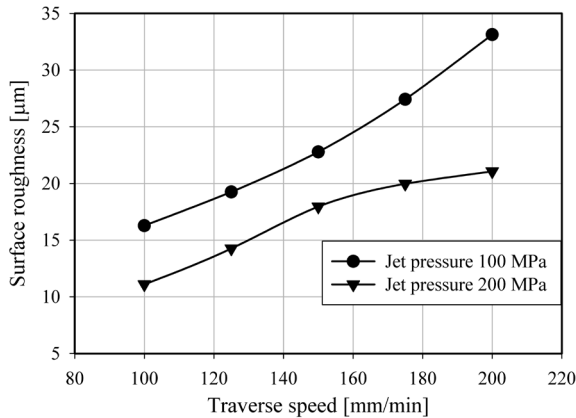


Fig. 5. Surface roughness vs. traverse speed at different water pressure

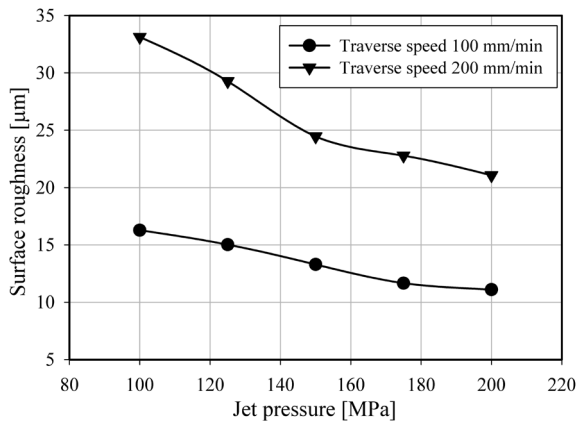


Fig. 6. Surface roughness vs. water pressure at different traverse speed

Finally, correlations were produced based in experimental results to predict the surface roughness and kerf taper angle by changing the values of water pressure and cutting rate. The curve-fitting toolbox of MATLAB was utilized to find the relationship between independent input process parameters and the experimental responses. A second-order polynomial curve-fitting model was selected based on previous research done by [5] and [32]. The regression models have acceptable ranges of the sum of square regression, the sum of square error, and root mean square error.

The predicted correlations of surface roughness and kerf taper angle, with the goodness-of-fit variables were shown in Eqs. (2) and (3), respectively:

$$R_a = 8.895 + 0.2039T_s - 0.1254W_p + 6.876 \times 10^{-5}T_s^2 - 6.45 \times 10^{-4}T_sW_p + 5.015 \times 10^{-5}W_p^2. \quad (2)$$

The sum of squared errors, $SSE = 10.22$, R -square = 0.9835, adjusted R -square = 0.9753, and root mean square error, $RMSE = 1.011$.

$$K_t = 6.643 - 0.01214T_s - 0.02053W_p + 1.319 \times 10^{-5}T_s^2 + 3.45 \times 10^{-5}T_sW_p - 5.634 \times 10^{-6}W_p^2. \quad (3)$$

$SSE = 0.03247$, R -square = 0.9961, Adjusted R -square = 0.9942, and $RMSE = 0.05698$, where R_a , K_t , T_s and W_p are surface roughness, kerf taper angle, traverse speed, and water pressure, respectively.

The realistic correlations in Models 2 and 3 can adequately predict the surface roughness and kerf taper angle, respectively. The considering experimental values of water pressure and traverse speed and predicted values for Eqs. (2) and (3) are shown in Figs. 7 and 8, respectively.

It can be noted from Fig. 7 that the minimum value of R_a occurred at the highest water pressure (200 MPa) and the lowest traverse speed (100 mm/min). This is due to the rise of kinetic energy, which caused concentrated breakage forces for carbon fibre as well as polymer matrix in a relatively long time of cutting [18].

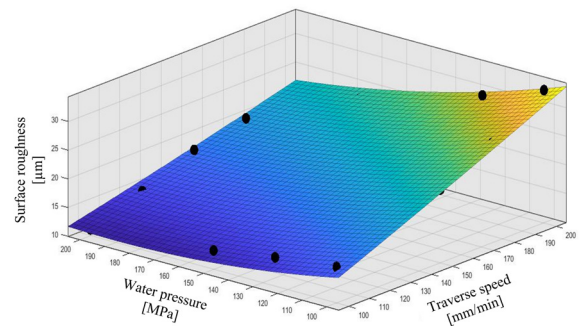


Fig. 7. Surface roughness with traverse speed and water pressure

The 3D graph of kerf taper angle with water pressure and traverse speed is shown in Fig. 8. This figure illustrates that the relations between kerf taper and traverse speed is directly proportional, while the effect of water pressure to kerf taper angle is indirectly proportional, because the increasing cutting rate caused less contact time between the cutting process and CFRP, which means less delamination of the cutting material [26].

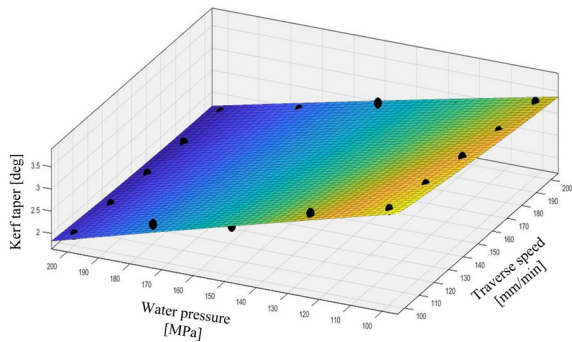


Fig. 8. Kerf taper with traverse speed and water pressure

3 CONCLUSIONS

In this experimental research, hand lay-up of fabricated CFRP at different orientation angles was subjected to AWJ machining. The effects of water jet pressure and traverse speed on surface roughness and kerf taper angle were studied. The results reveal that these cutting parameters have an important role in reaching the desired surface quality. The investigated cutting area was in the middle of the cut surface at different locations (smooth zone). Both the surface roughness and kerf taper could be enhanced with increasing water jet pressure and decreasing the cutting rate. Mainly, this is due to the effect of the kinetic energy observed from impinged particles and the structure of CFRP. Increasing the jet pressure caused increased pressure to increase its kinetic energy while increasing traverse speed caused loss of kinetic energy. Second-order polynomial curve-fitting models were produced using MATLAB regression analysis to predict the surface roughness and kerf taper angle within the range of experimental values of water pressure and cutting rate. Future objectives of the presented work will be focused on larger sets of experimental data and investigation with multiple variables. In addition, relevant information shall be added by enabling various parameters, such as stand-off distance and abrasive grain size.

4 REFERENCES

- [1] Geier N., Davim J.P., Szalay T. (2019). Advanced cutting tools and technologies for drilling carbon fibre reinforced polymer (CFRP) composites: A review. *Composites Part A: Applied Science and Manufacturing*, vol. 125, art. ID 105552, DOI:10.1016/j.compositesa.2019.105552.
- [2] Krishnaraj, V., Prabukarthi, A., Ramanathan, A., Elanghovan, N., Kumar, M.S., Zitoun, R., Davim, J. (2012). Optimization of machining parameters at high speed drilling of carbon fiber reinforced plastic (CFRP) laminates, *Composites Part B: Engineering*, vol. 43, no. 4, p. 1791-1799, DOI:10.1016/j.compositesb.2012.01.007.
- [3] Popan, I.A., Bal, N., Popan, A., Carean, A. (2018). Experimental study on reverse engineering in case of composite materials cut by water jet cutting. *MATEC Web of Conferences*, vol. 178, art. ID 03004, DOI:10.1051/mateconf/201817803004.
- [4] Che, D., Saxena, I., Han, P., Guo, P., Ehmann, K.F. (2014). Machining of carbon fiber reinforced plastics/polymers: a literature review. *Journal of Manufacturing Science and Engineering*, vol. 136, no. 3, DOI:10.1115/1.4026526.
- [5] Bañón, F., Sambruno, A., Batista, M., Simonet, B., Salguero, J. (2020). Study of the surface quality of carbon fiber-reinforced thermoplastic matrix composite (CFRTP) machined by abrasive water jet (AWJM). *The International Journal of Advanced Manufacturing Technology*, vol. 107, p. 3299-3313, DOI:10.1007/s00170-020-05215-y.
- [6] Thakur, R., Singh, K.K. (2020). Abrasive water-jet machining of fiber-reinforced composites: A state-of-the-art review. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 42, art. ID 381, DOI:10.1007/s40430-020-02463-7.
- [7] Ruiz-Garcia, R., Mayuet Ares, P.F., Vazquez-Martinez, J.M., Salguero Gómez, J. (2019). Influence of abrasive waterjet parameters on the cutting and drilling of CFRP/UNS A97075 and UNS A97075/CFRP stacks. *Materials*, vol. 12, no. 1, art. ID 107, DOI:10.3390/ma12010107.
- [8] Hashimoto, F., Chaudhari, R.G., Melkote, S.N. (2016). Characteristics and performance of surfaces created by various finishing methods. *Procedia CIRP*, vol. 45, p. 1-6, DOI:10.1016/j.procir.2016.02.052.
- [9] Mayuet Ares, P.F., Girot Mata, F., Batista Ponce, M., Salguero Gómez, J. (2019). Defect analysis and detection of cutting regions in CFRP machining using AWJM. *Materials*, vol. 12, no. 24, art. ID 4055, DOI:10.3390/ma12244055.
- [10] Natarajan, Y., Murugesan, P.K., Mohan, M., Khan, S.A.L.A. (2020). Abrasive water jet machining process: A state of art of review. *Journal of Manufacturing Processes*, vol. 49, p. 271-322, DOI:10.1016/j.jmapro.2019.11.030.
- [11] Kmec, J., Gombár, M., Harničárová, M., Valíček, J., Kušnerová, M., Kříž, J., Kadnár, M., Karková, M., Vagaská, A. (2020). The predictive model of surface texture generated by abrasive water jet for austenitic steels. *Applied Sciences*, vol. 10, no. 9, art. ID 3159, DOI:10.3390/app10093159.
- [12] Naresh Babu, M., Muthukrishnan, N. (2014). Investigation on surface roughness in abrasive water-jet machining by the response surface method. *Materials and Manufacturing Processes*, vol. 29, no. 11-12, p. 1422-1428, DOI:10.1080/10426914.2014.952020.
- [13] Vigneshwaran, S., Uthayakumar, M., Arumugaprabu, V. (2018). Abrasive water jet machining of fiber-reinforced composite materials. *Journal of Reinforced Plastics and Composites*, vol. 37, no. 4, p. 230-237, DOI:10.1177/0731684417740771.
- [14] Dandekar, C.R., Shin, Y.C. (2012). Modeling of machining of composite materials: a review. *International Journal of Machine Tools and Manufacture*, vol. 57, p. 102-121, DOI:10.1016/j.ijmachtools.2012.01.006.
- [15] Bañón, F., Sambruno, A., González-Rovira, L., Vazquez-Martinez, J.M., Salguero, J., (2021). A review on the abrasive

- water-jet machining of metal-carbon fiber hybrid materials. *Metals*, vol. 11, no. 1, art. ID 164, DOI:10.3390/met11010164.
- [16] Eneyew, E.D., Ramulu, M. (2014). Experimental study of surface quality and damage when drilling unidirectional CFRP composites. *Journal of Materials Research and Technology*, vol. 3, no. 4, p. 354-362, DOI:10.1016/j.jmrt.2014.10.003.
- [17] Popan, I.A., Popan, A. (2017). Experimental study on manufacturing complex parts from composite materials using water jet cutting. *Acta Technica Napocensis Series: Applied Mathematics, Mechanics, And Engineering*, vol. 60, no. 2, p. 251-254.
- [18] Selvam, R., Karunamoorthy, L., Arunkumar, N. (2017). Investigation on performance of abrasive water jet in machining hybrid composites. *Materials and Manufacturing Processes*, vol. 32, no. 6, p. 700-706, DOI:10.1080/10426914.2016.1198039.
- [19] Xiao, S., Wang, P., Gao, H., Soulat, D. (2019). A study of abrasive water-jet multi-pass cutting on kerf quality of carbon fiber-reinforced plastics. *The International Journal of Advanced Manufacturing Technology*, vol. 105, no. 11, p. 4527-4537, DOI:10.1007/s00170-018-3177-1.
- [20] Bañón, F., Simonet, B., Sambruno, A., Batista, M., Salguero, J. (2020). On the surface quality of CFRTP/Steel hybrid structures machined by AWJM. *Metals*, vol. 10, no. 7, art. ID 983, DOI:10.3390/met10070983.
- [21] Unde, P.D., Gayakwad, M., Patil, N., Pawade, R., Thakur, D., Brahmanekar, P. (2015). Experimental investigations into abrasive water-jet machining of carbon fiber reinforced plastic. *Journal of Composites*, vol. 2015, art. ID 971596, DOI:10.1155/2015/971596.
- [22] Prasad, V., Hunize, C.M., Abhiraj, R., Joseph, M., Sekar, K., Ali, M. (2019). Mechanical properties of flax fiber reinforced composites manufactured using hand lay-up and compression molding—a comparison. *Advances in Industrial and Production Engineering*, p. 781-789, DOI:10.1007/978-981-13-6412-9_72.
- [23] Priya, I.I.M., Vinayagam, B. (2018). Enhancement of bi-axial glass fibre reinforced polymer composite with graphene platelet nanopowder modifies epoxy resin. *Advances in Mechanical Engineering*, vol. 10, no. 8, DOI:10.1177/1687814018793261.
- [24] Muralidhara, B., Babu, S.K., Suresha, B. (2020). The effect of fiber architecture on the mechanical properties of carbon/epoxy composites. *Materials Today: Proceedings*, vol. 22, part. 4, p. 1755-1764, DOI:10.1016/j.matpr.2020.03.008.
- [25] Hloch, S., Valíček, J. (2012). Topographical anomaly on surfaces created by abrasive water-jet. *The International Journal of Advanced Manufacturing Technology*, vol. 59, p. 593-604, DOI:10.1007/s00170-011-3511-3.
- [26] Jagadeesh, B., Dinesh Babu, P., Nalla Mohamed, M., Marimuthu, P. (2018). Experimental investigation and optimization of abrasive water jet cutting parameters for the improvement of cut quality in carbon fiber reinforced plastic laminates. *Journal of Industrial Textiles*, vol. 48, no. 1, p. 178-200, DOI:10.1177/1528083717725911.
- [27] Wang, J., Wong, W. (1999). A study of abrasive water-jet cutting of metallic coated sheet steels. *International Journal of Machine Tools and Manufacture*, vol. 39, no. 6, p. 855-870, DOI:10.1016/S0890-6955(98)00078-9.
- [28] Gnanavelbabu, A., Rajkumar, K., Saravanan, P. (2018). Investigation on the cutting quality characteristics of abrasive water jet machining of AA6061-B4C-hBN hybrid metal matrix composites. *Materials and Manufacturing Processes*, vol. 33, no. 12, p. 1313-1323, DOI:10.1080/10426914.2018.1453146.
- [29] Vigneshwaran, S., Uthayakumar, M., Arumugaprabu, V. (2020). Prediction and analysis of abrasive water jet machining performance on hybrid composite. *Journal of Testing and Evaluation*, vol. 48, no. 2, p. 1505-1519, DOI:10.1520/JTE20180593.
- [30] Karabulut, Ş., Karakoç, H., Çitak, R. (2016). Influence of B4C particle reinforcement on mechanical and machining properties of Al6061/B4C composites. *Composites Part B: Engineering*, vol. 101, p. 87-98, DOI:10.1016/j.compositesb.2016.07.006.
- [31] Pahuja, R., Ramulu, M., (2019). Surface quality monitoring in abrasive water jet machining of Ti6Al4V-CFRP stacks through wavelet packet analysis of acoustic emission signals. *The International Journal of Advanced Manufacturing Technology*, vol. 104, no. 9, p. 4091-4104, DOI:10.1007/s00170-019-04177-0.
- [32] Wong, I.M.M., Azmi, A., Lee, C.C., Mansor, A.F. (2018). Kerf taper and delamination damage minimization of FRP hybrid composites under abrasive water-jet machining. *The International Journal of Advanced Manufacturing Technology*, vol. 94, p. 1727-1744, DOI:10.1007/s00170-016-9669-y.