DESTRUCTION OF FIBROUS STRUCTURES DURING MACHINING OF CARBON FIBER COMPOSITES

[1]Tomáš KNÁPEK, [1]Dora KROISOVÁ, [1]Štěpánka DVOŘÁČKOVÁ, [1]Artur KNAP

[1]Technical University of Liberec, Liberec, Czech Republic, EU, tomas.knapek@tul.cz, dora.kroisova@tul.cz, stepanka.dvorackova@tul.cz, artur.knap@tul.cz

https://doi.org/10.37904/nanocon.2022.4612

Abstract

A large part of composite components undergoes a finishing machining process before assembly. Composite systems – carbon fiber/epoxy resin behave differently than metals during machining. The released polymer particles, particularly the carbon fiber segments, can affect human health. The presented study deals with the release of fibers from the composite materials - the formation of chips and their destruction or breaking into shorter segments related to the machining process. Composite samples with recycled carbon fibers and carbon roving were subjected to selected machining processes. The scanning electron microscope was used to characterize the carbon fibers used in both types, especially to study the destruction of fibrous structures formed during machining processes. Based on the study, it was found that at the ends of the carbon fibers, there is a cleavage of microscopic fragments whose dimensions range from 2 to 3 µm, which is the WHO limit size for particles that can be inhaled. Dimensions of separate surface layers are micrometers in terms of length/width and the sub-micrometer level in terms of their thickness. Layers separated from the surface of the carbon fiber were found both in the case of the use of new carbon fibers and recycled carbon fibers.

Keywords: Machining, composite systems, carbon fibers, epoxy resin

1. INTRODUCTION

Composite material components have become commonly used technical elements in recent decades. Advanced composites with carbon fiber reinforcement in roving or fabrics find application from the aerospace and automotive industries to objects of everyday use. The significant expansion of these systems is due to their physical and mechanical parameters, which are responsible for the carbon fibers used, which provide the products with high strength, stiffness, resistance to dynamic stress, low density, corrosion resistance, and maximum dimensional stability [1]. No matter where these products are finally used, it is impossible to do without some of the finishing machining operations associated with the growing production of composite parts. However, unlike metal parts, composite systems behave differently during machining due to their material composition. Chips and dust are formed based on short carbon fibers, most often stored in epoxy or polyester resins [2,3]. The machining method, the type of tool, and the process conditions affect the nature of the resulting chip or the length of the broken carbon fibers, the fiber fracture surface, and whether they remain connected to the matrix or are released as individual fibers or composite segments. The destruction or splitting of the fibers along their axis is related to the type of fibers, their production method, and used material. The potential toxicological hazard is conditioned by the internal structure of carbon fibers, the nature of the fiber structures formed during machining processes, and the number of particles generated in a given volume over a given period selected by the technology [4]. The issue of machining composite systems is currently well described. However, new studies are still emerging that deal with the issue of tool wear, optimization of machining conditions, fiber pulling, and the nature of the machined surface [5-10]. Less work deals exclusively with the issue of chip formation and dust particles released from composite materials based on carbon fiber/polymer matrix, which is formed in connection with the machining process, or other related operations and their conditions and arrangement of fiber reinforcement. Already the work of 1978 states that a small number of particles can be inhaled, of which only less than 1% are fibrous particles [11]. The particles that can be inhaled have a diameter ranging from 1 to 2.5 μm and a length of up to 15 μm. Further work shows that the mechanical chopping of new fibers produces a significant number of particles or fiber segments with sharp edges, which have the character of particles and the dimensions of inhaled particles [12]. Particles or fragments with a diameter of fewer than 3 micrometers can be inhaled as expressed by WHO [13]. Other published works also addressed the environmental impact and impact on human health in terms of the size of released segments during machining and the possibility of splitting carbon fibers along the axis, which can be very undesirable [14,15,16]. It is necessary to seriously address the toxicological and environmental impacts of working with carbon fibers and recycled carbon fibers and the waste generated by them, especially in terms of the potential risks they may cause in the short and long time.

2. MATERIALS AND METHODS

The two-component low molecular weight epoxy resin ChS-EPOXY 520 (Districhem a. s., Czech Republic) was selected as a matrix for the production of composite samples. Hardener T0492, added in a weight ratio of 100:26 (Districhem a. S., Czech Republic), was used to cure the resin. Carbon fibers were used in two forms as short, recycled fibers Carbiso TM MF (Easy Composites Ltd., Great Britain) with diameters of 7-8 μm and an average length of 100 μm (**Figure 1a**) and carbon roving 3700 tex 50K (HAVEL COMPOSITES CZ, s.r.o.) with fiber diameters 8 μm (**Figure 1b**).

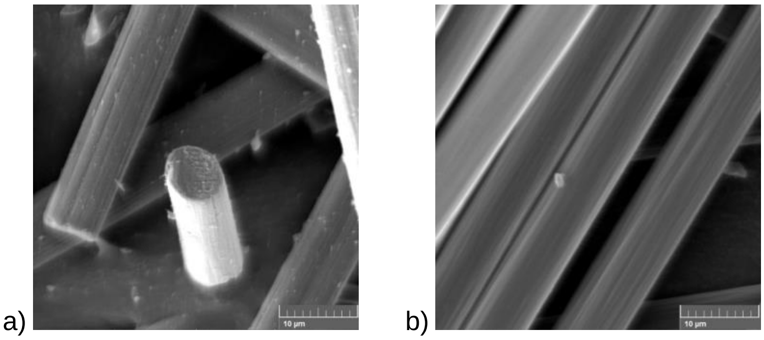


Figure 1 (**a**) Recycled carbon fibers, detailed image of the fiber surface and selected fracture area. (**b**) Carbon fibers roving, detailed image of fibers surface.

Both types of composite samples with recycled carbon fibers and carbon roving were identically subjected to selected machining processes, namely milling and grinding. In the case of models with parallel arranged carbon roving, milling and grinding in the direction parallel to the fibers and the direction perpendicular to the fibers were used.

Milling was performed as a face milling machine on a universal cantilever milling machine FNG 32 (TOS Olomouc, Czech Republic). A cylindrical end mill Ø 25 mm with replaceable inserts TNGX 100404SR-F, Grade M6330 (Pramet Šumperk, Czech Republic) was used for milling the samples. The cutting conditions for the selected milling were as follows: speed n = 1000 [min^{-1}], depth of cut a_p = 1 [mm], feed rate v_f = 75 [mm. min^{-1}]. Milling was performed in the absence of process fluid.

Grinding was performed on a BPH 320 A surface grinder (Junker, Germany). A corundum grinding wheel (Tyrolit, Austria) T1 250x32x76 98A 60 K 9 V 40 was used for grinding. Cutting conditions of the selected grinding were as follows: cutting speed v_c = 35 [$m.s^{-1}$], depth of cut a_p = 0.05 [mm], feed rate v_f = 10 [$m.min^{-1}$], grinding was performed in the absence of process fluid.

The TESCAN MIRA3 scanning electron microscope was used to characterize the carbon fibers used in both types, especially to study the destruction of fibrous structures formed during machining processes. The fiber diameter and length, the fiber surface morphology, the fiber surface character, and the fibers' adhesion to the matrix used were evaluated. Samples surfaces were sputtered with a Pt-Pd layer (Quorum Q150R ES) with a 2-4 nm thickness.

3. RESULTS

When milling a recycled carbon fibers sample, fibers are shortened. The average length of fibers is 100 µm but fibers size of 20 to 40 µm were identified. In the images (**Figure 2**), fibers with perpendicular fracture and angles of 40° to 60° fracture were identified. Perpendicular fracture fibers can be released from the polymer matrix in the milling process without destroying fibers. Fracture at an angle of 40° to 60° (**Figure 2b**) is typical for the machining process [10]. **Figure 2b** observed that a thin layer of sub-micrometer size was broken from the fiber surface. **Figure 2c** shows a fiber end jagged break. This type of break was not a unique case, so it may occur in recycled fibers and composite materials. It is evident (**Figure 2c**) that uneven fiber destruction resulting fragments released from the fiber surface. These layers reach dimensions at the sub-micrometer level.

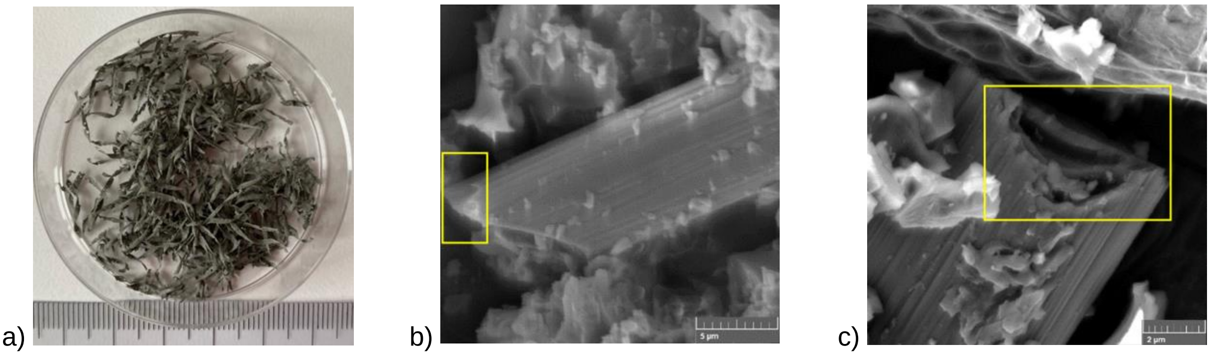


Figure 2 Chip formed after milling a composite sample with recycled carbon fiber. (**a**) Chip overview image.; (**b**) Detailed image of chipped fiber surface layer.; (**c**) Detailed image of the fiber end.

When milling the sample perpendicular to the distribution of carbon fibers in the sample, a coarser chip is formed with a length in units of centimeters and a width in hundreds of micrometers (**Figure 3a**). This chip breaks down into individual segments with dimensions in the tens to hundreds of micrometers (**Figure 3b**), which are made of a heterogeneous material - carbon fibers joined by an epoxy matrix. It is evident (**Figure 3b and Figure 3c**) that the fibers are shortened to tens of micrometers in length, the break at the end of the fibers not being perpendicular but at an angle, similar to the previous case. The surface of the fibers is smooth, without any residual resin. Tiny polymer particles formed during milling adhere to the surface.

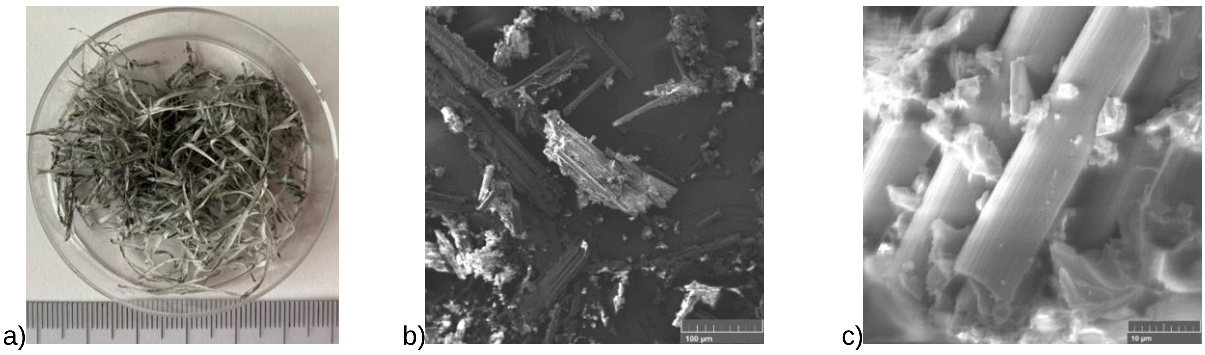


Figure 3 Chip formed after milling a composite sample with carbon fiber in the transversal direction. (**a**) Chip overview image.; (**b**) Chip segments with a noticeable connection of fibers and polymer.; (**c**) Detailed image of the fracture at the end of the carbon fiber.

When milling the sample in the longitudinal direction to distribute the carbon fibers in the sample, both more delicate and coarser chips are formed. The coarser and larger parts contain long carbon fibers that come loose during the milling process (**Figure 4a and Figure 4b**). Residues of the polymer matrix are visible on the carbon fibers (**Figure 4b and Figure 4c**). The refraction of the carbon fibers was both perpendicular and at an angle to the direction of the axis fiber.

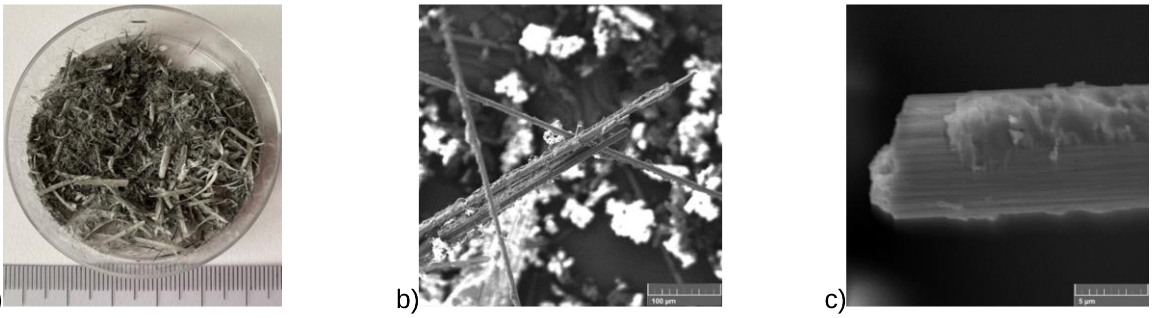


Figure 4 Chip formed after milling a composite sample with carbon fiber in the longitudinal direction. (**a**) Chip overview image.; (**b**) Carbon fibers are released during the milling process in the longitudinal direction to the fiber-bearing axis.; (**c**) Detailed image of carbon fiber with epoxy resin residues on its surface and the refractive character of the fiber.

A fine chip with a dust character is formed when grinding a sample with recycled carbon fibers (**Figure 5a**). This dust is created by loose carbon fibers connected to the polymer matrix or fibers alone. The average length of used recycled fibers is 100 µm. Fibers with a size of about 20 micrometers were identified in the samples of the collected chips. **Figure 5b** shows a chipped segment at the lower end of the fiber. **Figure 5c** shows the chipping of the surface layer at the left edge of the fiber, the chipped fragment of micrometer dimensions can be seen at the right edge. According to the WHO, carbon fiber fragments are approaching dimensions that are considered potentially dangerous, according to the WHO [13].

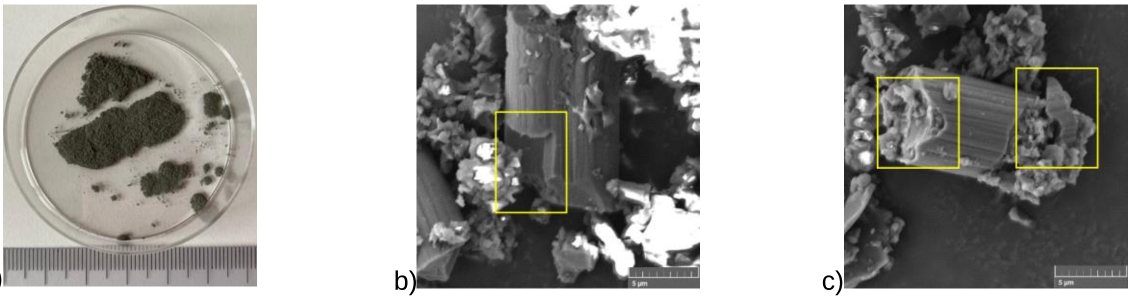


Figure 5 Chip formed during grinding a composite sample with recycled carbon fiber. (**a**) Chip overview image.; (**b**) Snapshot of the fiber with the broken end.; (**c**) Image of a fiber fragment with a chipped surface layer and a fragment.

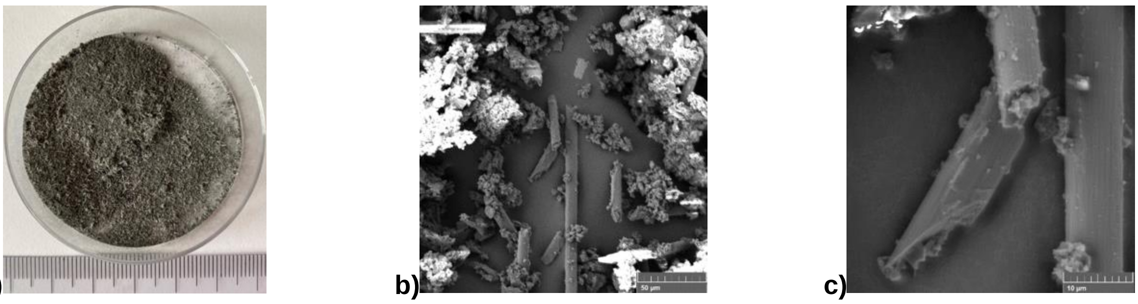


Figure 6 Chip formed during grinding of a composite sample with carbon fiber in the transverse direction. (**a**) Chip overview image.; (**b**) Overview image of chips with different lengths of carbon fibers.; (**c**) Detailed image of the fracture surface of carbon fiber.

When grinding the sample in the direction perpendicular to the distribution of carbon fibers, a delicate chip with millimeter particle dimensions is formed. The ground resin particles agglomerate and adhere to the surface of the fibers. The chip samples contain fibers with lengths of tens to hundreds of micrometers. The fiber fractures are at an angle of about 40**°** to 60**°.**

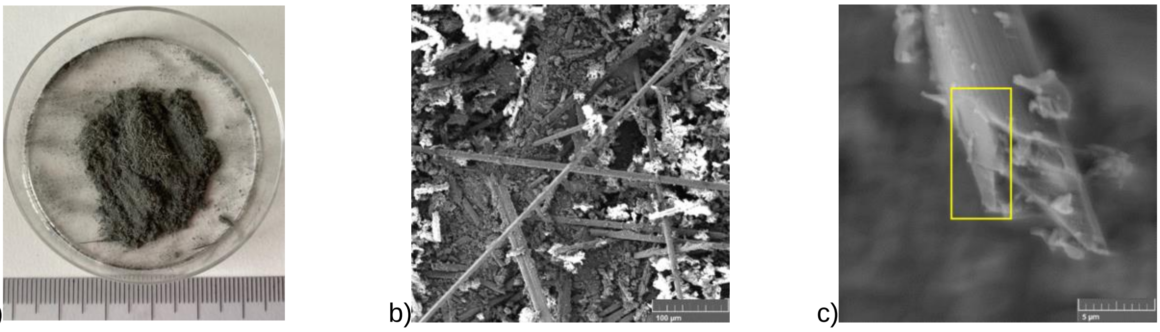
a) b) c)


Figure 7 Chip formed during grinding of a composite sample with carbon fiber in the longitudinal direction. (**a**) Chip overview.; (**b**) Chip overview with loose long carbon fibers.; (**c**) Detailed image of carbon fiber end with a fracture surface and a chipped surface layer.

When grinding the sample in the longitudinal direction to distribute the carbon fibers in the model, a delicate chip is formed (**Figure 7a**). There is a considerable amount of loose carbon fibers with a length of up to several hundred micrometers (**Figure 7b**). The ground resin adheres to the surface of the carbon fibers (**Figure 7c**). The fracture surface is seen at the end of the carbon fiber. **Figure 7c** shows the destruction of the end of the fiber at an angle at which, however, there is no longitudinal splitting of the fiber. On the surface, the separation of the surface layer is visible as in the previous cases.

4. DISCUSSION

Based on the study, it was found that at the ends of the carbon fibers, there is a cleavage of microscopic fragments (**Figure 5b and Figure 5c**), whose dimensions range from 2 to 3 μm, which is the WHO limit size for particles that can be inhaled [13]. In several cases, it has been observed that part of the surface layer of the fiber separates at the ends of the fracture surfaces of the carbon fibers (**Figure 2b, Figure 2c, Figure 5c, Figure 7c**). Dimensions of separate surface layers are in micrometers in terms of length/width and the sub-micrometer level in terms of their thickness. Separated layers from the ends of the carbon fibers are practically impossible to identify in the surrounding material formed during the machining process. However, by comparing the ends of the fibers before and after machining, it is clear that the layers separate. The explanation of the layer separation in the above description lies in the nature of the internal microstructure of the carbon fibers. The internal microstructure depends on the raw material used and the production process. During the process, fibers with a diameter of 7 to 8 μm are formed, but they are also internally structured. The internal structure consists of graphite layers, which are more or less arranged and parallel to the fiber axis, thus providing the fibers with high values of mechanical parameters [18,19].

The bonds in the graphite layers are strong, in contrast to the bonds between the graphite layers, which are relatively weak. There may be an explanation of the layer separation/splitting above described under mechanical loading by machining processes. Assuming that the used tool hits directly into the carbon fiber, both its destruction in the fiber axis and the chipping of the surface layer will occur (**Figure 7c**). The similar nature of the fragmentation described in the present study has been discussed in the work of other authors [12,16,20].

Identified microscopic fragments analogous to, for example, (**Figure 5c**) with sizes from 2 to 3 micrometers were observed in half of the analyzed samples. Placed sub-micrometer surface layers from the carbon fiber end as in the images (**Figure 2, Figure 5, Figure 7**) were in one-third of all evaluated samples. Due to the large number of small dimension particles generated during the machining of composite samples, it is clear that the number of particles of these dimensions is considerable and should be adequately monitored.

5. CONCLUSION

The experimental study aimed to monitor the fracture surfaces of the carbon fiber ends, reinforcing a composite system with an epoxy matrix. It was found that there are standard types of carbon fiber fractures with the selected machining methods realized under the given conditions. In these processes, small fiber pieces with dimensions of 2 to 3 μm are split simultaneously at the ends of the fibers. Sub-micrometer surface layers separate on the surface of the fiber ends. Comparing the fiber ends before and after machining makes it clear that the separation of layers and segments occurs during the process.

The reason for this study was to assess the possibility of generating micrometer and sub-micrometer fragments due to machining processes, which are currently implemented in many workplaces where finishing operations are performed on composite components. Small parts of the fragmented carbon surface layers may be similar to graphite layers in which the interlayer bonds are not significant, and they are identical to nanocarbon structures. So, it is necessary to address this issue in more depth and assess the potential hazards of these wastes in further studies and steps to eliminate them.

ACKNOWLEDGEMENTS

This research study was funded by the Student Grant Competition of the Technical University of Liberec under the project number SGS-2022-5043. "Research and development in the field of machining of metal and composite materials using new knowledge for industrial practice"

REFERENCES

[1] MALICK, P.K. *Fiber-Reinforced Composites: Materials, Manufacturing and Design*, 3rd ed.; CRC Press: Boca Raton, Florida, USA, 2007. Available from: https://doi.org/10.1201/9781420005981.

[2] UHLMANN, E.; SAMMLER, F.; RICHARZ, S.; HEITMÜLLER, F.; BILZ, M. Machining of carbon fibre reinforced plastics. *Procedia CIRP.* 2014, vol. 24, pp. 19-24. Available from: https://doi.org/10.1016/j.procir.2014.07.135.

[3] KARATAS, M.; GÖKKAYA, H. A review on machinability of carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composite materials. *Defence Technology.* 2018, vol. 14, pp. 318-326. Available from: https://doi.org/10.1016/j.dt.2018.02.001.

[4] RAMULU, M.; KRAMLICH, J. Machining of fiber reinforced composites: Review of environmental and health effects. *Int. J. Environ. Conscious Des. Manuf.* 2004, vol. 11, pp. 1-19.

[5] KOMANDURI, R.; ZHANG, B.; VISSA, C.; Machining of fiber reinforced composites. *Processing and Manufacturing of Composite Materials* 1991, vol. 112, pp. 817-829. Available from: https://doi.org/10.1016/0890-6955(94)00055-O.

[6] AZMI, A. I. Chip formation studies in machining fiber reinforced polymer composites. *International Journal of Materials and Product Technology.* 2013, vol. 112, pp. 1-36. Available from: https://doi.org/10.1504/IJMPT.2013.052790.

[7] UHLMANN, E.; SAMMLER, F.; RICHARZ, S.; REUCHER, G.; HUFSCHMIED, R.; FRANK, A.; PROTZ, F. Machining of carbon and glass fibre reinforced composites. *Procedia CIRP.* 2016, vol. 46, pp. 63-66. Available from: https://doi.org/10.1016/j.procir.2016.03.197.

[8] CAGGIANO, A. Machining of fiber reinforced plastic composite materials. *Materials* 2018, vol. 11, pp. 442. Available from: https://doi.org/10.3390/ma11030442.

[9] KODAMA, H.; OKAZAKI, S.; JIANG, Y.; YODEN, H.; OHASHI, K. Thermal influence on surface layer of carbon fiber reinforced plastic (CFRP) in grinding. *Precision Engineering.* 2020, vol. 65, pp. 53-63. Available from: https://doi.org/10.1016/j.precisioneng.2020.04.005

[10] TENG, G.; CHANGE, L.; MIN, Y.; YANBIN, Z.; DONGZHOU, J.; WENFENG D.; SUJAN, D.; TIANBIAO Y.; ZAFAR, S.; JUN, W. Mechanics analysis and predictive force models for the single-diamond grain grinding of carbon fiber reinforced polymers using CNT nano lubricant. *Journal of Materials Processing.* 2021, vol. 290. Available from: https://doi.org/10.1016/j.jmatprotec.2020.116976.

[11] HOLT, P. F.; HORNE, M. Dust from carbon fiber. *Environmental Research.* 1978, vol. 17, pp. 276-283. Available from: https://doi.org/10.1016/0013-9351(78)90030-0.

[12] MAZUMDER, M. K.; CHANG, R. J.; BOND, R. L. Aerodynamic and morphological properties of carbon-fiber aerosols. *Aerosol Science and Technology.* 1982, vol. 1, pp. 427-440. Available from: https://doi.org/10.1080/02786828208958606.

[13] The WHO/EURO man-made mineral fiber reference scheme, WHO/EURO Technical Committee for Monitoring and Evaluating MMMF. *Scand J Work Environ Health*. 1985, vol. 11, no. 2, pp. 123-9. Available from: https://doi.org/10.5271/sjweh.2251, PMID: 3890161.

[14] BOATMAN, E. S.; COVERT, D.; KALMAN, D.; LUCHTEL, D.; OMENN, G. S. Physical, morphological, and chemical studies of dust derived from the machining of composite-epoxy materials. *Environmental research.* 1988, vol. 45, pp. 242-255. Available from: https://doi.org/10.1016/S0013-9351(89)80070-2.

[15] WANG, J.; SCHLAGENHAUF, L; SETYAN, A. Transformation of the released asbestos, carbon fibers and carbon nanotubes from composite materials and the changes of their potential health impacts. *Journal of nanobiotechnology.* 2017, vol. 15, pp. 1-16. Available from: https://doi.org/10.1186/s12951-017-0248-7.

[16] KEHREN, D.; SIMONOV, B.; BÄGER, D.; DZIUROWITZ, N.; WENZLAFF, D.; THIM, C.; PLITZKO S. Release of respirable fibrous dust from carbon fibers due to splitting along the fiber axis. *Aerosol and air quality research.* 2019, vol. 19, pp. 2185-2195. Available from: https://doi.org/10.4209/aaqr.2019.03.0149.

[17] DVOŘÁČKOVÁ, Š.; KROISOVÁ, D. Thermal Expansion of Composite System Epoxy Resin/Recycled Carbon Fibers. *Materials Science Forum.* 2020, vol. 994, pp. 162-169.

[18] DIEFENDORF, R. J.; TOKARSKY, E. High-performace carbon fibers. *Polymer Engineering and Science.* 1975, vol. 15, pp. 150-159. Available from: https://doi.org/10.1002/pen.760150306.

[19] DRESSELHAUS, M. S. Fifty years in studying carbon-based materials. *Physica Scripta.* 2012. Available from: https://doi.org/10.1088/0031-8949/2012/T146/014002.

[20] SCHLAGENHAUF, L.; KUO, Y. Y.; MICHEL, S.; TERRASI, G.; WANG, J. Exposure assessment of high-energy tensile test with large carbon fiber reinforced polymer cables. *Journal of occupational and environmental hygiene.* 2015, vol. 12, pp. 178-183. Available from: https://doi.org/10.1080/15459624.2015.1029614.