Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 118 (2023) 590–595

www.elsevier.com/locate/procedia

16th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '22, Italy

Quality Assurance of Composite Grinding

Osman Bodur[a,]*, Eva M. Walcher[a], Jens Brier[a], Stephan Krall[a], Friedrich Bleicher[a], Alexandru Sterca[b], Johann Sauprigl[a], Harald Peherstorfer[a]

[a]*TU Wien, Institute of Production Engineering and Photonic Technologies, Wien 1030, Austria*
[b]*Technical University of Cluj-Napoca, Faculty of Industrial Engineering, Robotics and Production Management, Cluj-Napoca, Romania*

* Corresponding author. Tel.: +43-676-576-0023 ; *E-mail address:* osman.bodur@tuwien.ac.at

Abstract

In the forthcoming, composites are progressively preferred as raw materials instead of non-reinforced materials in industrial applications due to their high stiffness, strength, young's modulus, and low density. One machining operation in the overall value-added chain is the grinding of these composite material qualities, which turns out to be an inevitable step in the subtractive machining area. The reinforced structure, constituents, and non-uniforms cause challenges in achieving the requested quality concerning accuracy and surface integrity. Hence, the essential purpose of this paper is to provide a strategy for the quality inspection of composites, including profile and surface roughness. Depending on the grinding processes parameters, the aim is to assess effective machining for reasonable quality characteristics demonstrated on selected reinforced matrix composites.

Keywords: Composite; Grinding; Quality assurance; Precision engineering; High precision metrology

1. Introduction

One unavoidable operation in the field of manufacturing and precision engineering of composite materials is the grinding process. This type of material presents some difficulties for subtractive manufacturing technologies due to their reinforced structure, constituents, and non-uniformities, which influence the mechanical characteristics and surface integrity of composites.

Composite materials have an inversely-proportional relationship between tensile strength and compressive strength. However, compared to traditional materials, the prominent specifications of composites present better stiffness and strength over a broad temperature range, better young's modulus, better corrosion resistance, lower density, lighter weight, better thermal and electrical conductivity, and better wear resistance [1]. A critical characteristic of any functional component is the surface quality, which, for composite materials in comparison to bulk materials, tends to be lower due to their orthotropic and fibrous nature.

Nomenclature

MMC	Metal Matrix Composites
CMC	Ceramic Matrix Composites
PMC	Polymer Matrix Composites
UV-A	Ultrasonic Vibration Assisted Grinding
ZAG	Zero Amplitude Grinding (Without UVA)
S_a	Arithmetical mean height of the surface
S_z	Maximum height of the surface

Studies [2] on machining composite materials show that maintaining surface integrity is challenging. Grinding is the manufacturing operation employed for obtaining a high surface quality, and it is known to be dependent on grinding versus fiber direction [3,4]. Studies also indicate a relationship between the main process parameters and surface quality [5], where peripheral tool speed, feed rate, and grinding direction have a high impact. Fiber percentage rates also affect the delamination and thus surface quality of composite materials [6]. Due to difficulties obtaining a high surface quality in composite materials, new grinding methods like UV-A

2212-8271 © 2023 The Authors. Published by Elsevier B.V.

10.1016/j.procir.2023.06.101

Grinding are developed and employed in the manufacturing process chain [7,8,9,10]. Ultrasonic vibration velocity and fiber direction have a significant impact on the surface quality of composite materials manufactured using these methods [11].

One crucial part of manufacturing composite material components is quality assessment and assurance. For this purpose, studies are being performed [12, 13, 14, 15] on using non-destructive measurement techniques for determining the surface quality and topology, the effects of delamination, material defects, and fiber tearing modes. Studies on the grind ability of composite materials [16, 17] indicate that excellent results might be obtained with the proper selection of grinding method, parameters, and grinding versus fiber direction.

This paper proposes using high precision, non-destructive measurement techniques and statistical analysis for the quality assurance of composite material components by determining the correlation between different grinding methods, parameters, directions, and materials and informing decisions on the best compromise for obtaining the quality imposed by the application. The quality assurance process is presented in Fig. 1 and starts with the computer-aided design of the part, followed by computer-aided process planning and computer-aided manufacturing. Quality assurance of the process is done by subjecting the resulting components to measurements by high precision metrology, the results of which are subjected to statistical analysis. The design of the experiment for statistical analysis takes as input factors the main parameters of the grinding process and correlates them with the measurement results in the form of mean and maximum surface roughness.

The study presented in this paper also looks at the interaction between different process factors and their effect on surface quality while at the same time using detailed scans obtained by electron microscopy and focus variation microscopy to explain the mechanism by which defects are produced, informing decisions for strategies to mitigate the adverse effects. The quality of surfaces processed by surface flat grinding and deep grinding with and without UV-A are compared and could be used to inform decisions on the choice of grinding technologies and process parameters necessary to obtain the best surface quality for a given material and application.

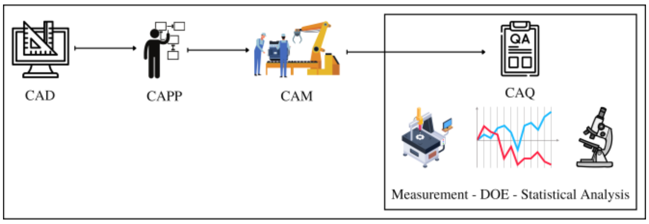


Fig. 1. CAD / CAPP / CAM / CAQ flow chart of production process.

2. Methods and Theoretical Parts

2.1. Manufacturing Process

A total of nine samples are prepared, three for each material tested, CMC, MMC and PMC and are subjected to flat grinding and deep grinding. The two grinding methods are implemented on opposing faces of the sample in order to ensure consistent process conditions. The proposed grinding surfaces, direction and methods are presented in Fig. 2 and Table 1.

Table 1. Grinding surfaces, methods, and directions of composites.

Process Nr.	Surface	Grinding Methods	Grinding Direction
1	Top	Flat Grinding	Vertical
2	Top	Flat Grinding	45° Diagonal
3	Top	Flat Grinding	Horizontal
1	Bottom	Deep Grinding - ZAG	Vertical
2	Bottom	Deep Grinding - UVA	Vertical
3	Bottom	Deep Grinding - ZAG	Horizontal
4	Bottom	Deep Grinding - UVA	Horizontal
5	Bottom	Deep Grinding - ZAG	45° Diagonal
6	Bottom	Deep Grinding - UVA	45° Diagonal
7	Bottom	Deep Grinding - ZAG	135° Diagonal
8	Bottom	Deep Grinding - UVA	135° Diagonal

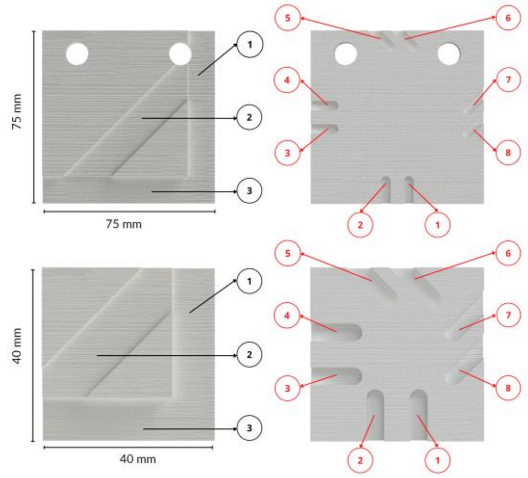


Fig. 2. Top and bottom surface of CAD models of composite and their grinding directions.

The speed parameters used for flat grinding and deep grinding are presented in Table 2 for each material processed.

Table 2. Operation machining flat and deep grinding speeds.

Usage Material	Flat Grinding Feed Rate Speeds (m/min)	Deep Grinding Feed Rate Speeds (mm/s)
CMC	50 / 100 / 150	3750 / 4285 / 5000
MMC	50 / 100 / 150	3750 / 4285 / 5000
PMC	50 / 100 / 150	3750 / 4285 / 5000

The frequency and amplitude for UV-A deep grinding in the case of MMC and PMC materials are 40Khz and 2μm, while the frequency and amplitude are 20Khz and 1μm for CMC.

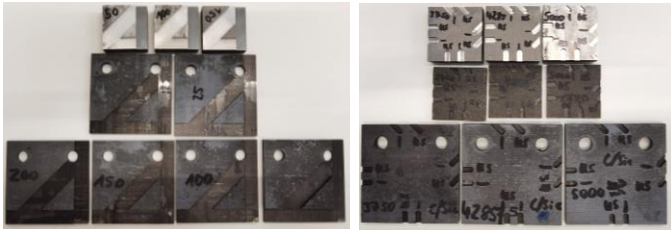

(a) (b)

Fig. 3. (a) Top surface - flat ground composites; (b) Bottom surface - deep ground composites.

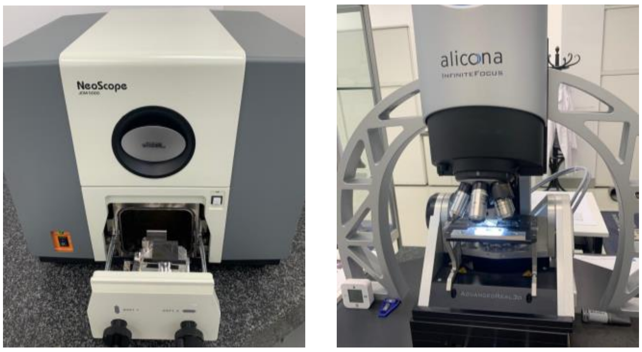
Deep grinding is performed for all materials with both ultrasonic vibration assistance and without to determine how UV-A influences the surface quality of the processed samples. A picture of flat grinding on the samples is available in Fig. 3a. Processing by deep grinding on the samples is seen in Fig. 3b. Grinding for all materials is also performed at zero amplitude to determine the effects of UV-A grinding on surface quality. Flat grinding is performed on a Schütte 325 Linear [18] seen in Fig. 4a. Deep grinding is performed using an Ultrasonic 30 Linear machine [19] seen in Fig. 4b.

(a) (b)

Fig. 4. (a) Flat grinding machine; (b) Deep grinding machine.

2.2. Measurement Process

Surface topology and microstructure measurements are performed using a JCM-5000 electron microscope [20] seen in Fig. 5a. Surface roughness and topology measurements are performed on the samples using focus variation microscopy [21], employing an Alicona Infinite focus microscope [22], presented in Fig. 5b. Alicona is a focus variation microscope, and the reasonable standards for surface topography are described in the parts of ISO 25178. With this unique measurement process, the surface is imaged sharply by moving the optics vertically along the optical axis. The result is a 3D measurement with actual color or pseudo color information, where the height values are used to calculate the roughness values.



(a) (b)

Fig. 5. (a) Raster electron microscope; (b) Infinite focus microscope.

2.3. Quality Assurance

The 3D roughness parameters and measurement methods are described and defined in the ISO 25178 [23] series of standards. These standards are, therefore, the basis for 3D roughness measurement technology. Principles of geometric product specification for filtering and the master plan for the filter standards are summarized in the 16610-1:2015 [24] standard. Further, the basics of linear surface filters are found in ISO 16610-60:2015 [25]. The results are in the form of mean roughness (S_a) and maximum roughness (S_z). Data analysis is performed using the Taguchi method [26], for which the factors are material, grinding method, grinding direction, speed and the responses are S_a and S_z. Three separate Taguchi analyses are performed for different grinding methods and parameter combinations. The design of the experiment for each of the analyses is presented in Table 3.

Table 3. Design of experiment – Taguchi analysis.

Evaluation Nr.	Taguchi Design	Factors	Equation
1	L27	Material, Flat Grinding Speed, Direction	(3^2) ∗ (2^1)
2	L36	Material, Deep Grinding Speed, Grinding Methods, Direction	(3^2) ∗ (2^2)
3	L54	Material, Deep Grinding Speed, Grinding Methods, Direction	(3^3) ∗ (2^1)

3. Results

Electron microscopy scans are performed under a high vacuum at 10 kV with a magnification of 1000x on the 20 µm range area, and the results are presented in Fig. 6. where surface topology and microstructure are inspected.

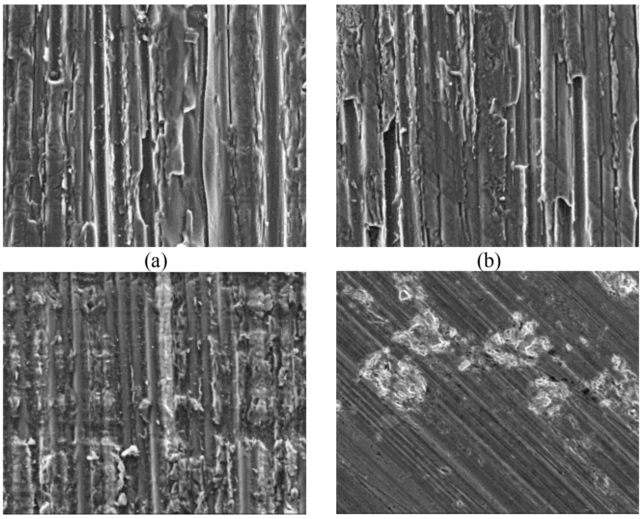
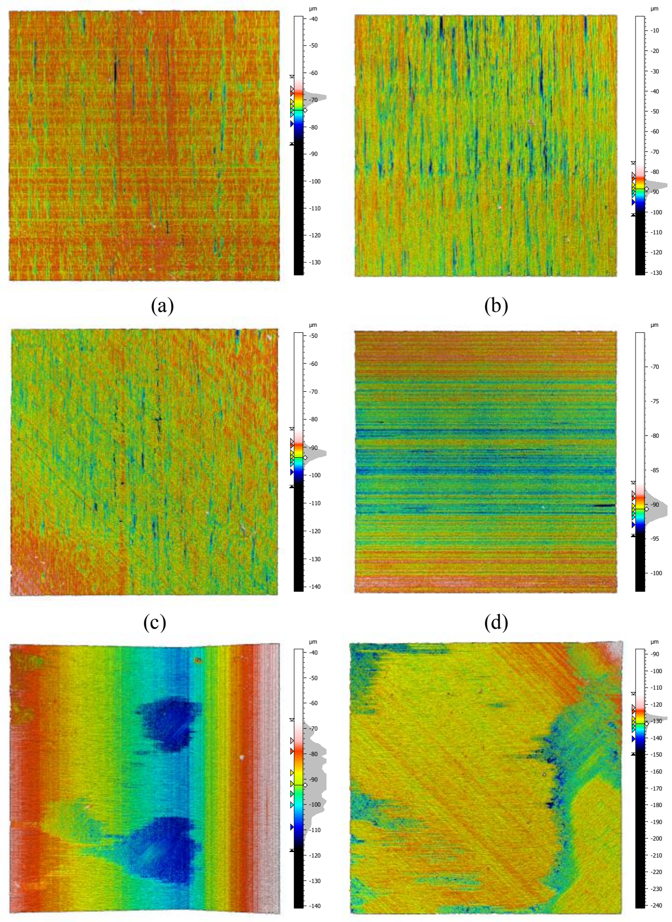

(a) (b) (c) (d)

Fig. 6. (a) CMC – grinding along with the fiber orientation; (b) CMC – diagonal grinding 45 degrees to the fiber orientation; (c) PMC – horizontal grinding perpendicular to the fiber orientation; (d) MMC – diagonal grinding 45 degrees to the fiber orientation.

The results from electron microscopy corroborate the focus variation results. Delamination on the grinding surface is detected in detail in Fig. 6a, while fiber tearing is visible in Fig. 6c. The results indicate less delamination and fiber tearing due to the direction of grinding being diagonal to the fiber orientation in Fig. 6b. The effects of cratering by abrasive particles are presented in Fig 6d. Cratering can lead to further fiber tearing and delamination while the processed component is in use as a functional part and is subjected to various stress factors.

Surface measurement results from focus variation microscopy in 3D areal scans are presented using specific software in Fig. 7. The images show the expected abrasion lines resulting from the grinding process and the direction of grinding versus fiber orientation. Effects of fiber tearing are evident in the case of grinding direction perpendicular to fiber orientation, as seen in Fig 7a. For the grinding direction parallel to fiber orientation, deep longitudinal grooves are formed due to delamination, as detailed in Fig. 7b. In the following case of the grinding direction diagonal to fiber orientation seen in Fig. 7c, the effects of fiber tearing and delamination are reduced. Besides, the effect of tool runout is denoted, manifested in the form of waviness on the processed surface in Fig. 7d. The effects produced by the stick-and-slip phenomenon caused by the accumulation of resin on the tool are highlighted in Fig. 7e. while extreme fiber tearing due to the stick and slip phenomenon is evident in Fig. 7f.



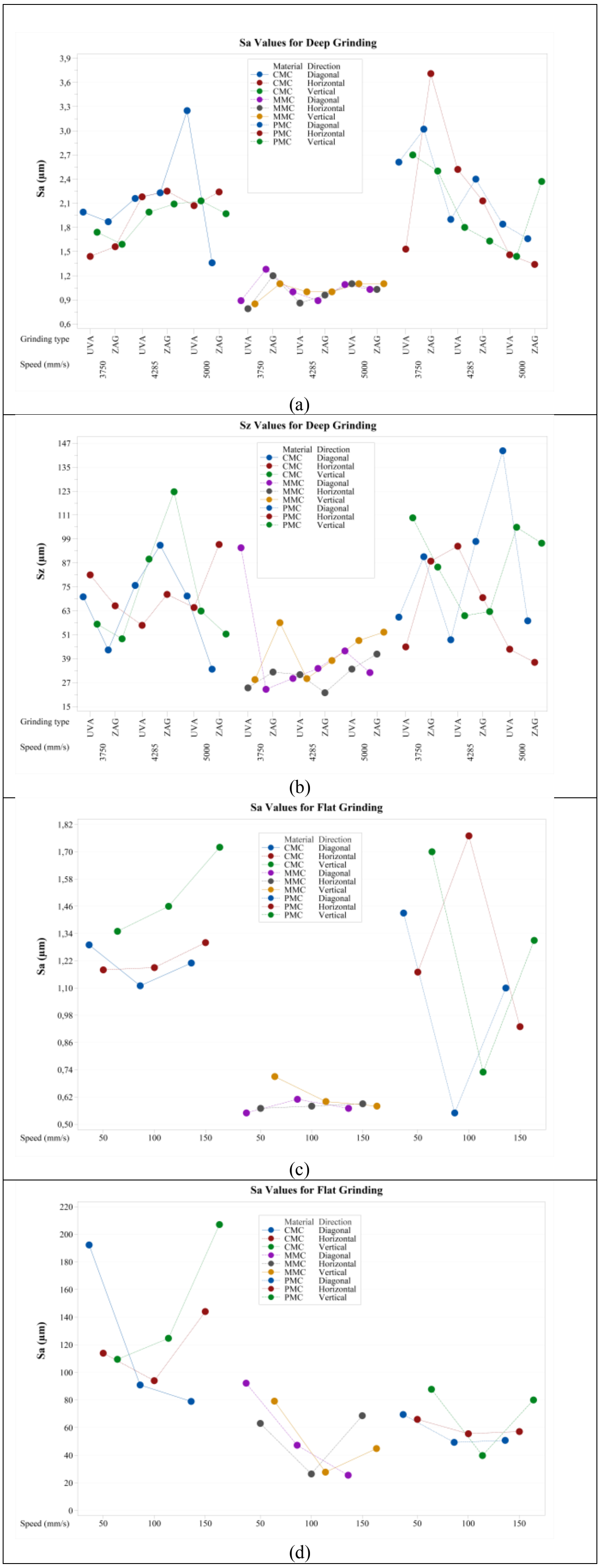
(a) (b)

(c) (d)

(e) (f)

Fig. 7. Surface Topology of Flat Ground Materials (a) CMC – Horizontal, (b) CMC – Vertical, (c) CMC – Diagonal, (d) MMC – Horizontal, (e) PMC – Vertical, (f) PMC – Diagonal.

The results for S_a and S_z roughness values are illustrated according to each material, grinding method, and parameter combination in Fig. 8. The cut-off filter for surface roughness measurements is ʎc=0,8mm and is chosen according to the16610-1:2015. The values are grouped by material, grinding method, and speed on the X-axis, while the Y-axis represents the measured values for S_a and S_z, respectively.



(a)

(b)

(c)

(d)

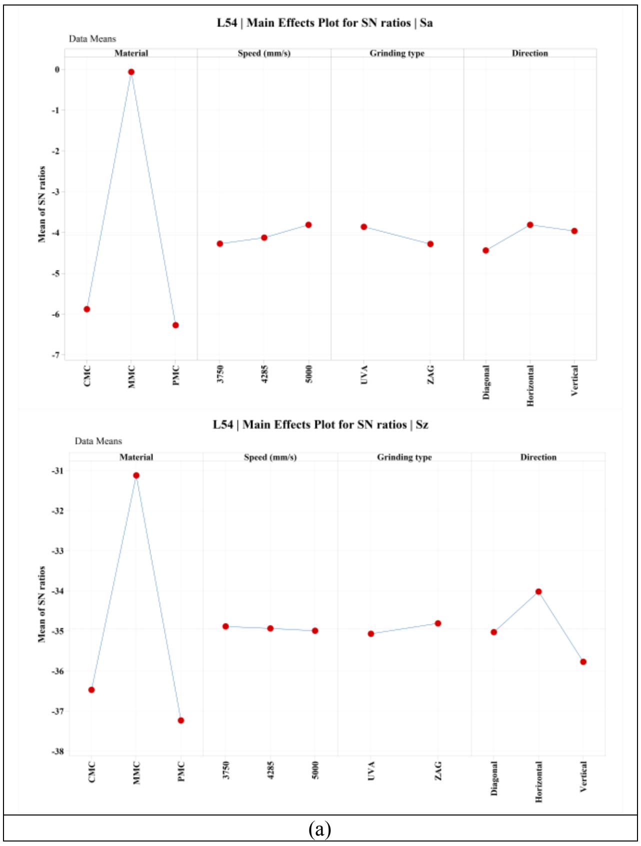
Fig. 8. Measurement results (a) S_a values for deep grinding; (b) S_z values for deep grinding; (c) S_a values for flat grinding; (d) S_z values for flat grinding.

The results show that MMC presents the best overall surface quality for both S_a and S_z values in every combination of grinding methods and factors.

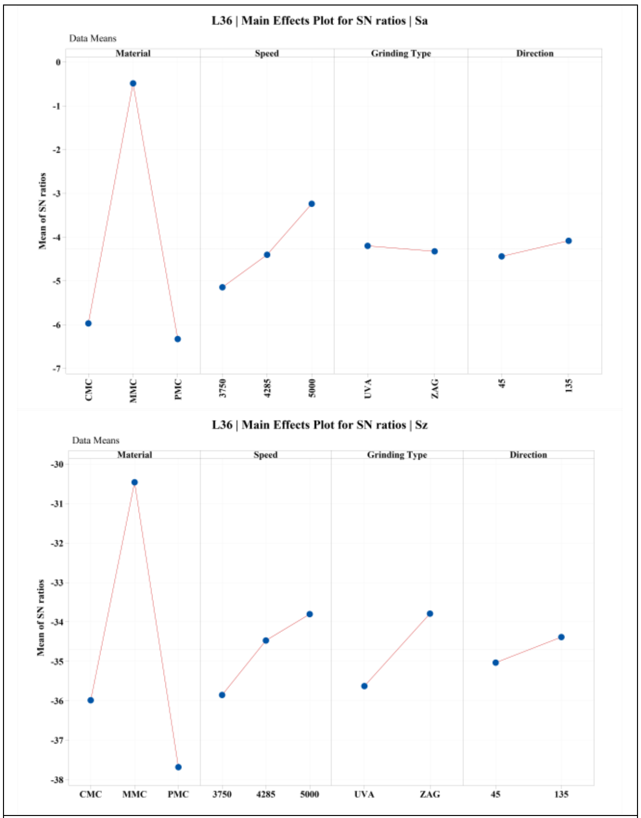
The value plots indicate that the matrix material properties significantly affect the quality of the processed surface. Interactions between the matrix material and the fibers, specifically the bonding among them, affect the behaviour of composite materials during machining, stronger bonds leading to lower delamination, pulling, and tearing effects on the fibers. The bonding strength between the matrix material and the fibers is dependent on the ability of these materials to fuse and the depth of the interface between them. Due to manufacturing constraints imposed by the polymer, for PMC materials, the bonding strength between the matrix and fibers is lower, indicated by the low overall surface quality that is inferred from the measurement results. CMC materials stand somewhere between PMC and MMC, indicating better fusion between matrix and fibers than PMC but lower than MMC.

Statistical analysis is performed on the measurement result using the Taguchi method; the results are presented in Fig. 9. in the form of main effects plots for signal-to-noise ratio, indicating how different factors influence the values of S_a and S_z. The results indicate that the best surface quality is obtained with the MMC material and that the diagonal grinding direction tends to give the best results for all materials and grinding methods analyzed.

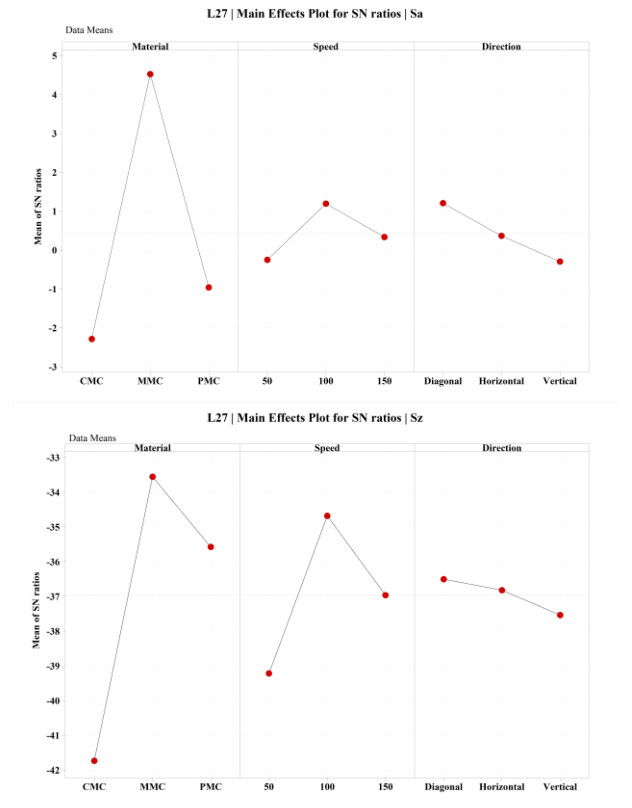
The grinding direction versus fiber orientation also influences delamination and fiber tearing. If the grinding direction is parallel to the orientation of the fibers, delamination is increased, leading to defects in the form of grooves on the surface of the material, which negatively impacts S_z and S_a values.



(a)



(b)



(c)

Fig. 9. Main effects plot for SN ratios of S_a and S_z, (a) L54 Taguchi Design; (b) L36 Taguchi Design; (c) L27 Taguchi Design.

In the case of grinding direction perpendicular to the fiber orientation an increased fiber tearing effect is present, leading to an increased S_a value. A grinding direction that is diagonal to the orientation of the fibers reduces these effects, the angle of the grinding direction and fiber orientation being the determining factor for which effect is more predominant between delamination and fiber tearing. The main effect plots for the speed and grinding method show different S_a and S_z values results. UV-A grinding shows a positive effect in terms of S_a values and a negative effect in terms of S_z value for all materials, speeds, and directions analyzed. The effect of grinding speed on surface quality is more significant in the case of surface flat grinding, while UV-A grinding shows less sensitivity to speed. Complex interactions between the factors of the grinding process are detected by the Taguchi analysis. These interactions affect the surface quality and need to be accounted for when choosing parameters. The significance of the factor's effects on the resultant S_a and S_z and the parameters for the factors are chosen to provide the best compromise between the S_a and S_z values.

4. Conclusions and Discussion

Results indicate a correlation between Grinding methods, process parameters, materials, and surface quality. The type of material plays a significant part in the resulting surface quality, specifically the matrix material used. That could be a consequence of the bonding strength between the matrix material and the fibers. The grinding type and method are selected for a specific application depending on which surface quality parameter is critical. UV-A grinding has a beneficial effect on the value for S_a and a detrimental effect on S_z and is less sensitive to grinding speed. Complex interactions between process parameters are manifested, which affect surface quality. By using a more extensive dataset, a predictive mathematical model can be developed and used to inform decisions on selection process parameters and grinding methods for specific applications.

Future studies performed to analyze the bonding strength between the matrix material and fibers can inform developments in the field to reduce delamination and fiber tearing.

References

[1] Arvind Kumar Chauhan, Amarjeet Singh, Deepak Kumar, and Kuldeep Mishra, Properties of Composite Materials, Composite Materials, Taylor Francis Group, (2021): 61-78.

[2] Gavalda Diaz, Oriol; Garcia Luna, Gonzalo; Liao, Zhirong; Axinte, Dragos (2019): The new challenges of machining Ceramic Matrix Composites (CMCs): Review of surface integrity. In: International Journal of Machine Tools and Manufacture 139, S. 24–36. DOI: 10.1016/j.ijmachtools.2019.01.003.

[3] Chen, Yan; Liang, Yuhong; Xu, Jiuhua; Hu, Andong (2018): Ultrasonic vibration assisted grinding of CFRP composites: Effect of fiber orientation and vibration velocity on grinding forces and surface quality. In International Journal of Lightweight Materials and Manufacture 1 (3), pp. 189–196. DOI: 10.1016/j.ijlmm.2018.08.003.

[4] Zhang, Lifeng; Ren, Chengzu; Ji, Chunhui; Wang, Zhiqiang; Chen, Guang (2016): Effect of fiber orientations on surface grinding process of unidirectional C/SiC composites. In: Applied Surface Science 366, S. 424–431. DOI: 10.1016/j.apsusc.2016.01.142.

[5] Kang, Bo; Ma, Hongru; Li, Jun; Xu, Buqin (2020): Effect of grinding parameters on surface quality, microstructure and rolling contact fatigue behaviors of gear steel for vacuum pump. In Vacuum 180, p. 109637. DOI: 10.1016/j.vacuum.2020.109637.

[6] Cavusoglu, Ignur; Walcher, Eva Maria; Ugur Tuncer, Gamze; Durakbasa, Numan (Eds.): Effects of the Fiber Percentage Rate of the Gfrp Composites (15).

[7] Brier, Jens; Bleicher, Friedrich (2021): Design of a contactless powered and piezoelectric-actuated tool for non-resonant low-frequency vibration-assisted machining of brittle-hard materials. In Int J Adv Manuf Technol. DOI: 10.1007/s00170-021-07436-1.

[8] Bleicher, Friedrich; Wiesinger, Gerhard; Kumpf, Christoph; Finkeldei, Daniel; Baumann, Christian; Lechner, Christoph (2018): Vibration assisted drilling of CFRP/metal stacks at low frequencies and high amplitudes. In Prod. Eng. Res. Devel. 12 (2), pp. 289–296. DOI: 10.1007/s11740-018-0818-z.

[9] Feng, Q.; Ren, C. Z.; Pei, Z. J. (2012): Ultrasonic vibration-assisted (UV-A) machining of composites. In : Machining Technology for Composite Materials: Elsevier, pp. 185–201.

[10] El Wakil, S. D. (2012): Grinding processes for polymer matrix composites. In : Machining Technology for Composite Materials: Elsevier, pp. 65–74.

[11] Chen, Yan; Liang, Yuhong; Xu, Jiuhua; Hu, Andong (2018): Ultrasonic vibration assisted grinding of CFRP composites: Effect of fiber orientation and vibration velocity on grinding forces and surface quality. In: International Journal of Lightweight Materials and Manufacture 1 (3), S. 189–196. DOI: 10.1016/j.ijlmm.2018.08.003.

[12] Gholizadeh, S. (2016): A review of non-destructive testing methods of composite materials. In Procedia Structural Integrity 1, pp. 50–57. DOI: 10.1016/j.prostr.2016.02.008.

[13] Goidescu, Cristina; Welemane, Hélène; Garnier, Christian; Fazzini, Marina; Brault, Romain; Péronnet, Elodie; Mistou, Sébastien (2013): Damage investigation in CFRP composites using full-field measurement techniques: Combination of digital image stereo-correlation, infrared thermography and X-ray tomography. In Composites Part B: Engineering 48, pp. 95–105. DOI: 10.1016/j.compositesb.2012.11.016.

[14] Bayraktar, E.; Antolovich, S. D.; Bathias, C. (2008): New developments in non-destructive controls of the composite materials and applications in manufacturing engineering. In Journal of Materials Processing Technology 206 (1-3), pp. 30–44. DOI: 10.1016/j.jmatprotec.2007.12.001.

[15] Wang, Bing; Zhong, Shuncong; Lee, Tung-Lik; Fancey, Kevin S.; Mi, Jiawei (2020): Non-destructive testing and evaluation of composite materials/structures: A state-of-the-art review. In: Advances in Mechanical Engineering 12 (4), 168781402091376. DOI: 10.1177/1687814020913761.

[16] Di Ilio, Antoniomaria; Lambiase, Francesco; Paoletti, Alfonso (2018): Grindability Assessment of Metal Matrix Composites. In Procedia CIRP 67, pp. 313–318. DOI: 10.1016/j.procir.2017.12.219.

[17] Handa, Danish; Sooraj, V. S. (2020): Performance assessment of a hybrid intermittent-progressive grinding strategy for bi-directional carbon fibre reinforced composites. In Materials Today: Proceedings 28, pp. 865–872. DOI: 10.1016/j.matpr.2019.12.314.

[18] Schütte Linear 325. Available online: https://www.schuette.de/produkte-und-leistungen/schleifmaschinen/ (accessed 30.04.2022)

[19] Ultrasonic 30 linear. https://at.dmgmori.com/produkte/maschinen/ultrasonic/ultrasonic-linear (accessed 30.04.2022)

[20] JCM-5000 NeoScope(TM) Tabletop SEM.

[21] Danzl, R., Helmli, F., & Scherer, S. (2011). Focus Variation – a Robust Technology for High Resolution Optical 3D Surface Metrology. Strojniški vestnik - Journal of Mechanical Engineering, 57(3), 245-256.

[22] Alicona Infinite Focus. Available online: https://www.alicona.com/en/products/infinitefocus/ (accessed 30.04.2022)

[23] ISO/DIS 25178-2 (2019). Geometrical product specifications (GPS) – Surface texture: Areal – Part 2: Terms, definitions and surface texture parameters

[24] ISO 16610-1 (2015). Geometrical product specifications (GPS) – Filtration – Part 1: Overview and basic concepts

[25] ISO 16610-60 (2015). Geometrical Product Specification (GPS) – Filtration – Part 60: Linear areal filters – Basic concepts

[26] Osanna P.H., Afjehi-Sadat A., Durakbasa M.N. (2004): Qualitätsmanagement und Prüfungwegen. Abteilung Austauschbau und Messtechnik. Austria. ISBN: 3-901888-18-7