

4th CIRP Conference on Composite Material Parts Manufacturing (CIRP CCMPM 2026)

Fibre-pattern-aware machining (FPAM) of carbon fibre-reinforced polymer (CFRP) composites

Norbert Geier^{a,*}, Levente Bukor^a

^a*Department of Manufacturing Science and Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary*

* Corresponding author. Tel.: +36-1-463-2641. E-mail address: geier.norbert@gpk.bme.hu

Abstract

Fibre orientation has a significant impact on surface generation during the machining of carbon fibre-reinforced polymers (CFRPs), yet it is rarely explicitly incorporated into machining planning. Instead, process optimisation typically treats the laminate as a layered structure and relies on tooling and cutting strategies that mitigate, but do not eliminate, orientation-dependent damage. This paper demonstrates that the explicit detection and exploitation of local fibre-pattern information can significantly improve the quality of machined features. We present a numerical study in which fibre pattern maps of CFRP plates are used to guide a systematic optimisation of hole and groove machining. Results indicate that fibre-pattern-aware planning can improve quality by 10.9–51.5% compared to conventional strategies, with the gain primarily dependent on feature size and local fibre-pattern entropy. The findings highlight a practical route to integrate in-plane fibre information into CAM algorithms, offering a cost-effective strategy to reduce machining-induced damage in high-value CFRP manufacturing.

© 2027 The Authors. Published by ELSEVIER B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)

Peer-review under responsibility of the scientific committee of the 4th CIRP Conference on Composite Material Parts Manufacturing (CIRP CCMPM 2026)

Keywords: CFRP; milling; fibre direction; fibre cutting angle; optimisation; burr; delamination

1. Introduction

Carbon fibre-reinforced polymer (CFRP) composites are increasingly used because of their excellent specific properties, including high specific strength, ease of formability, corrosion resistance, and dimensional stability [1–3]. Although machining is often required to cost-effectively produce difficult-to-mould features such as pockets, grooves and holes [2,4], it remains challenging due to the anisotropic and heterogeneous structure of CFRP and the abrasive nature of carbon-containing chips. In unidirectional CFRP composites, the influence of anisotropy is commonly described by the fibre

cutting angle (θ), defined as the angle between the cutting speed vector (v_c) and the fibre direction.

The effect of θ on chip formation mechanisms of unidirectional CFRP has been discussed in detail by Sheikh-Ahmad [1] and An et al. [5]. In orthogonal cutting with a cutting tool having positive rake angle, four characteristic cutting modes can be distinguished: (i) at $\theta \approx 0^\circ$ (or 180°), chip formation is governed by pressure-induced mode-I (opening-mode) failure; (ii) at $\theta \approx 45^\circ (\pm \Delta)$, pressure-induced shearing of the fibres and the fibre-matrix interface predominates; (iii) at $\theta \approx 90^\circ$, fibre cutting occurs under predominantly compressive loading from the radial direction; and (iv) at $\theta \approx 135^\circ (\pm \Delta)$, chip separation is dominated by macrofracture and out-of-plane

2212-8271 © 2027 The Authors. Published by ELSEVIER B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)

Peer-review under responsibility of the scientific committee of the 4th CIRP Conference on Composite Material Parts Manufacturing (CIRP CCMPM 2026)

fibre bending. Cutting force is typically highest at $\theta \approx 90^\circ$ [6–8], surface quality is poorest at $\theta \approx 135^\circ$ [6,9,10], whereas the probability of burr formation is maximal at $\theta \approx 45^\circ$ [11–13].

The influence of fibre cutting angle on surface and subsurface damage during CFRP machining has been demonstrated in several studies. Wang et al. [9] reported that, during edge milling of CFRP, more pronounced subsurface damage and cavity formation occur primarily in the cutting-against-the-fibre regime ($\theta \approx 135^\circ$). In contrast, both surface roughness and damage severity are lower in the other angular regimes. These findings were further supported by Wang et al. [6], who showed that within the 120° – 170° fibre cutting angle range, especially under severe tool wear, the fibre fracture location shifts below the machined surface, and blockwise fibre bundles lead to pull-outs and poor surface integrity. Similarly, Meng et al. [14] found that both surface roughness and subsurface damage depth reach their maximum in the 135° – 140° range.

Hintze et al. [12] pointed out that delamination and burr formation depend primarily on the fibre cutting angle defined at the top (and bottom) ply of the composite. According to their observations, the range $90^\circ \leq \theta < 180^\circ$ can be considered favourable, since neither significant delamination nor burr formation develops even under substantial tool wear, whereas the range $0^\circ < \theta < 90^\circ$ is critical in terms of such macroscopic damage formation. This conclusion was corroborated by Kwon et al. [13] and Du et al. [15], who reported that burr formation during CFRP drilling is most pronounced in the 0° – 90° range. Park et al. [11] further narrowed this critical interval and identified the most intense burr formation between 45° and 80° . Likewise, the analytical model of Su et al. [16] confirmed the importance of angular dependence and identified the interval $29.8^\circ \leq \theta \leq 90^\circ$ as critical for burr formation.

Although the fibre cutting angle is not the only factor influencing the quality of machined CFRP composites, and it may interact strongly with cutting edge radius (CER), cutting strategy (up-milling vs down-milling), and other process parameters, it is often not considered during machining process planning. Fibre cutting angle is therefore frequently treated as a parameter that cannot be controlled, rather than as an actively adjustable variable that can be optimised to improve part quality. To address this limitation, Geier [17] developed a fibre-orientation-driven defect-probability mapping method based on the digitalisation of fibre clusters using digital image processing, and brute-force optimisation of hole position to minimise cases with critical fibre cutting angle along the hole contour, thereby reducing delamination and burr formation. Although the algorithm significantly improved hole quality, its computational cost was high and only linear translation was considered. To further develop the fibre-pattern-aware machining (FPAM) concept, the present work aims to: (i) evaluate the method for hole patterns and grooves; (ii) extend the search space by allowing rotation of geometric features; and (iii) substantially reduce the computational effort of the algorithm using stochastic approaches such as Monte Carlo simulation and genetic algorithms. Numerical simulations were conducted to demonstrate the relevance of FPAM and to motivate extended factorial experimental investigations.

2. Numerical experimental setup

Synthetic images were generated using the algorithm shown in Fig. 1a to establish a large database for the verification and evaluation of the developed FPAM planning algorithms. In total, 250 synthetic images were created, each comprising multiple fibre clusters represented by black rectangles. The fibre-cluster length and width were randomly assigned within the ranges of 6–14 mm and 6–10 mm, respectively, using a step size of 1 mm, while the orientation angle was varied between 0° and 165° with increments of 15° . Each image contained a target total of 84 fibre clusters. The image resolution was set to 1000×1000 pixels, with one pixel corresponding to 0.1 mm. To ensure robustness, the algorithm incorporates safeguards against both infinite looping and overlap between fibre clusters. The nominal fibre content ranged from 55 to 61 wt%. Figure 1b shows a representative synthetic image. The generated images exhibit good correspondence with the fibre clusters observed on the top surface of a chopped carbon-fibre-reinforced polymer composite (Fig. 1c). Accordingly, this synthetic image set provides a suitable basis for numerical testing on a database substantially larger than could be obtained through high-cost digital image acquisition.

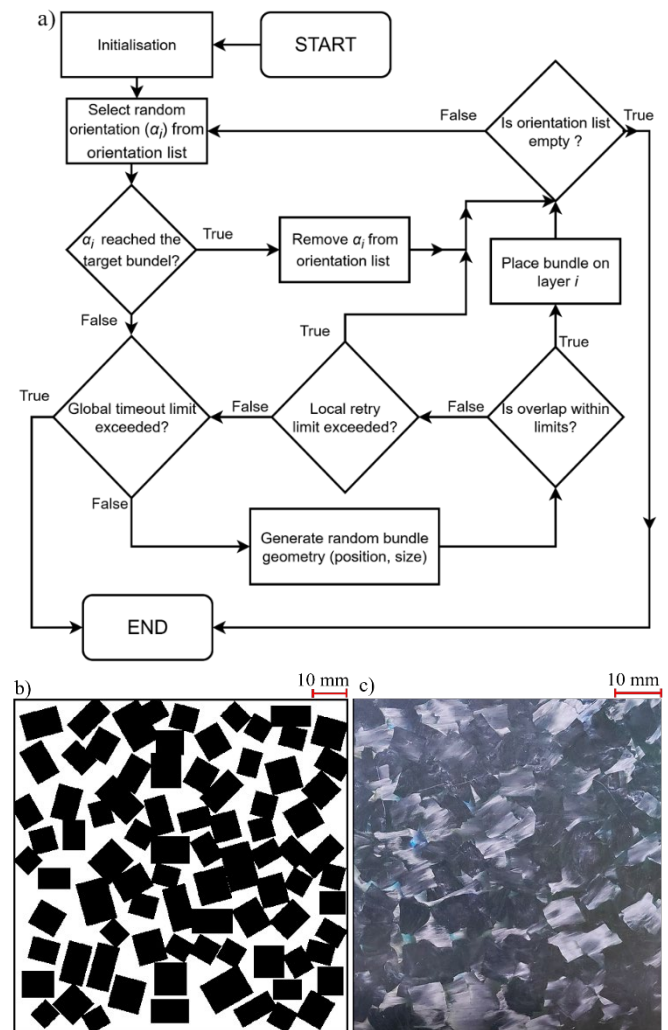


Fig. 1. (a) synthetic image generation algorithm; (b) representative output image; (c) top surface of a polymer composite plate reinforced by chopped carbon fibre clusters.

Figure 2 illustrates the two-dimensional geometric features used to evaluate the efficiency and robustness of the FPAM algorithms. The optimal condition (position and orientation) of the 2×2 hole pattern (Fig. 2a) and the groove (Fig. 2b) were determined using three approaches: brute-force (BF), Monte Carlo (MC), and a genetic algorithm (GA). The geometric configuration was considered optimal when the cumulative penalty score, evaluated along the feature contour, was minimal. The penalty score (PS) of each contour point was calculated according to Eq. (1), where θ denotes the fibre cutting angle; $\theta_{c1} = 45^\circ$ and $\theta_{c2} = 135^\circ$ are the mean values of the primary and secondary critical fibre cutting angles, respectively; $A_1 = 100$ and $A_2 = 50$ are the corresponding amplitudes; and $\sigma_1 = \sigma_2 = 8$ are the associated standard deviations. The A_i and σ_i parameters were empirically tuned to ensure robust system performance. The optimisation of these parameters is, however, recognised as a crucial task for subsequent research. The penalty function is illustrated in Fig. 3.

$$f(\theta) = A_1 \cdot \exp\left(-\frac{(\theta - \theta_{c1})^2}{2\sigma_1^2}\right) + A_2 \cdot \exp\left(-\frac{(\theta - \theta_{c2})^2}{2\sigma_2^2}\right) \quad (1)$$

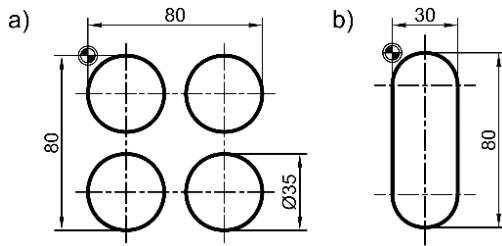


Fig. 2. Dimensions and properties of the applied geometric features: (a) 2×2 hole pattern; (b) groove.

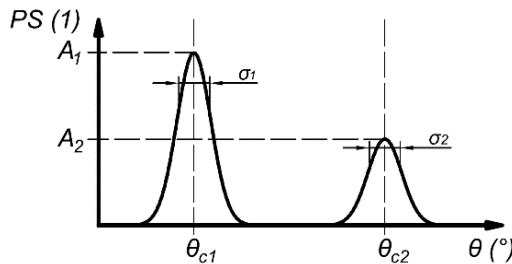


Fig. 3. Illustration of the penalty function (bimodal Gauss distribution).

The parameter space for the optimal configuration was constrained by the intervals listed in Table 1. Within this search space, 40 931 discrete positions were available for locating a single pixel of the geometry contour. Given that the hole pattern comprises 20 328 pixels and the groove comprises 8 290 pixels, a total of 832 045 368 and 173 517 990 independent cases, respectively, had to be evaluated to identify the optimal configuration if all possible cases are considered. The BF algorithm performs an exhaustive search by calculating the penalty score according to Eq. (1). Although this approach guarantees identification of the global optimum by evaluating all possible configurations and requires only limited computational memory, it is computationally expensive and therefore impractical for large datasets and industrial applications. In the present work, the brute-force algorithm

proposed in Ref. [17] was employed, extended to account not only for x - y translation but also for α rotation of the geometrical features.

Table 1. Parameter ranges applied in the optimisation procedure.

Parameter	Range	Step size	Unit
x translation	−30 to 30	1	pixel
y translation	−30 to 30	1	pixel
α rotation	−5 to 5	1	°

The optimal position was also determined using the classical Monte Carlo (MC) method with a maximum of 10,000 iterations (aiming to decrease the operation demand of the BF by 75%). In this stochastic approach, feasible candidate configurations are generated randomly within the defined search space and evaluated according to the penalty function; the configuration with the lowest penalty score is retained as the optimal solution.

The third optimisation strategy was a genetic algorithm (GA), a population-based metaheuristic that approximates the global optimum through selection, crossover, and mutation. The initial population was generated from a fixed starting configuration with random translations and orientations, and the fitness of each individual was defined by the penalty score along the feature contour, which was to be minimised. In each generation, the 60-member population was sorted according to fitness, the elite individuals were transferred unchanged to the next generation, and the remaining positions were filled by offspring produced from parents selected via 1–1 tournament selection and subsequently modified by crossover and controlled mutation. The procedure was repeated until 80 generations were reached, and the best individual was then returned as the solution. The GA is illustrated in Fig. 4. The algorithms were run on a workstation equipped with an Intel Core i7-10700 CPU operating at 2.90 GHz and 32 GB RAM.

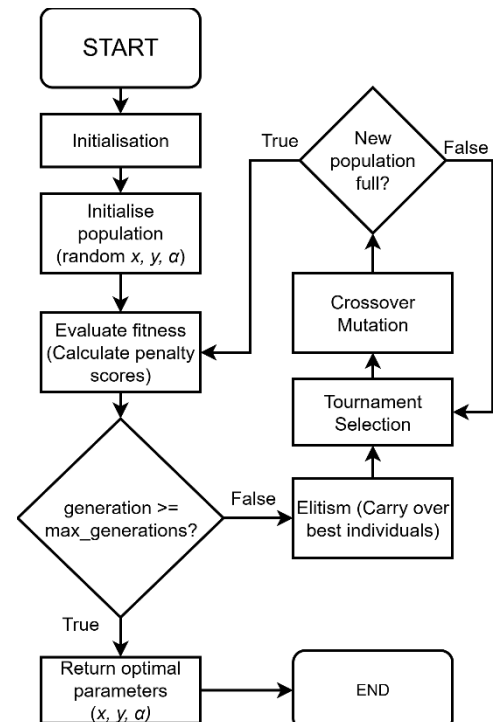


Fig. 4. Illustration of the genetic algorithm (GA)

3. Results and discussion

Representative outputs of the FPAM algorithms are shown in Fig. 5, where the contour colour indicates the fibre cutting angle, whereas the sum of penalty score (SPS), together with the optimal conditions (x, y, α) and the corresponding running time (t), are reported in the upper-left corner of each image. The generated results were subsequently qualitatively assessed to confirm their plausibility, and the findings were summarised in scatter plots (Fig. 6) and bar charts (Fig. 7).



Fig. 5. Representative outputs of the FPAM algorithms obtained using (a) MC, and (b) GA optimisation approaches.

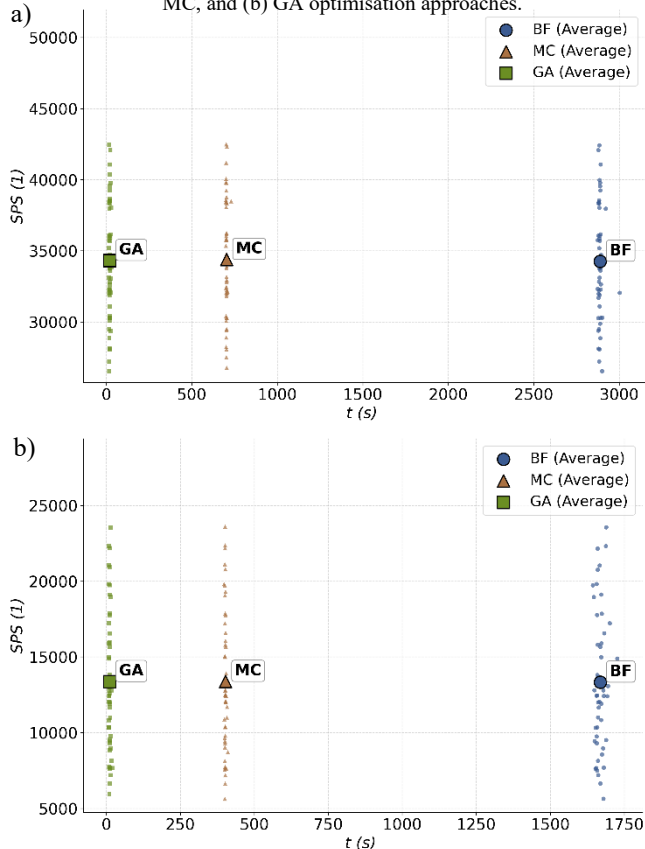


Fig. 6. Scatter plots of computation time (t) versus the sum of penalty scores (SPS) for the investigated optimisation algorithms (BF, MC, and GA) in the case of the (a) 2×2 hole pattern and (b) groove geometry.

According to the results presented in Figs. 6 and 7, the brute-force algorithm exhibited the longest average computation time ($t_{BF,h} = 2889$ s and $t_{BF,g} = 1669$ s for the hole pattern and the groove, respectively) for determining the optimal configuration, followed by the Monte Carlo algorithm ($t_{MC,h} = 703$ s, $t_{MC,g} = 402$ s) and the genetic algorithm ($t_{GA,h} = 20$ s, $t_{GA,g} = 12$ s). As expected, the computational demand of the algorithms' approaches remained essentially constant across individual runs; minor variations in computation time were attributed to fluctuations in background system processes. The MC algorithm was 311.0% and 315.2% faster, while the GA algorithm was 14345% and 13809% faster than the BF for hole patterns and grooves, respectively.

Regarding optimisation performance, the BF algorithm yielded the lowest average sum of penalty score ($SPC_{BF,h} = 34284$, and $SPC_{BF,g} = 13332$ for the hole pattern and groove, respectively), followed by the MC ($SPC_{MC,h} = 34396$, and $SPC_{MC,g} = 13383$) and GA ($SPC_{GA,h} = 34318$, and $SPC_{GA,g} = 13371$) approaches. Nevertheless, the relative differences between the obtained average SPS values remained limited, with deviations of approximately 0.33–0.38% and 0.10–0.29% for the MC and GA approaches, respectively, relative to the BF solution. These results indicate that the proposed MC and GA approaches represent computationally efficient alternatives to exhaustive BF optimisation, substantially reducing computation time while maintaining acceptable solution quality.

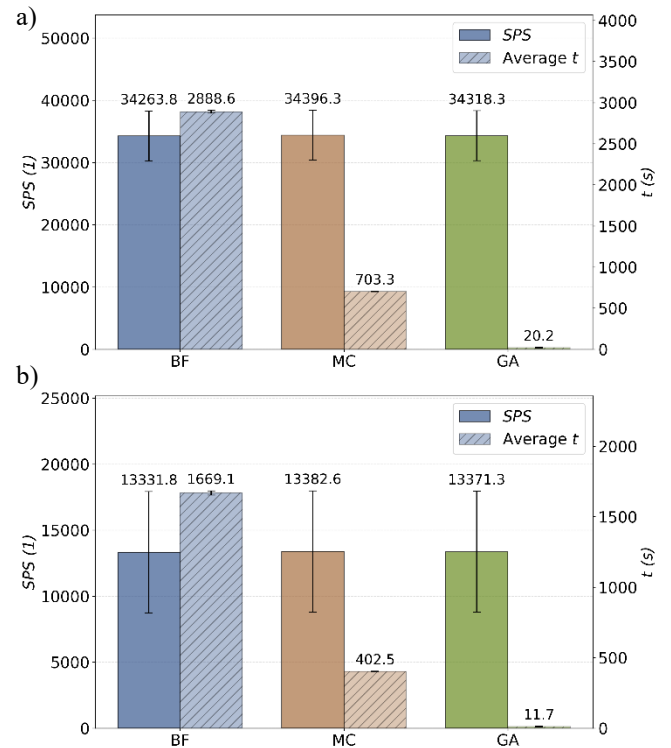


Fig. 7. Bar charts of average computation time versus the sum of penalty scores (SPS) for the investigated optimisation algorithms (BF, MC, and GA) in the case of the (a) 2×2 hole pattern and (b) groove geometry.

Figure 8 illustrates the practical potential of the FPAM algorithms by comparing the SPS values of geometrical features located at their nominal positions, defined as the centre of the parameter space ($x = 0$ mm, $y = 0$ mm, $\alpha = 0^\circ$), with

those obtained at the optimised positions. Points located on the red dashed line indicate cases in which FPAM does not provide an improvement over conventional machining planning strategies that neglect fibre-pattern information. In contrast, the farther a point lies below the dashed line, the greater the achievable improvement in the expected machining quality. In the present numerical study, all evaluated cases demonstrate that FPAM consistently yields lower SPS values than the nominal feature placement. The highest-quality improvements, reaching approximately 63%, were observed for the groove geometry. Furthermore, 90% of the improvement values were found within the ranges of 10.9–35.10% and 19.3–51.5% for the hole pattern and groove geometries, respectively. These results highlight the considerable potential of fibre-pattern-aware machining planning for improving the expected quality of CFRP machining operations.

From an industrial perspective, the proposed FPAM framework offers a practical strategy for reducing machining-induced damage in CFRP components. Since the method operates at the process-planning level by optimising the position and orientation of geometrical features according to the local fibre pattern, it can be integrated into existing CAD/CAM workflows with minimal additional hardware requirements. Furthermore, the reduced computational demand achieved by the stochastic optimisation approaches increases the feasibility of applying FPAM in industrial offline process planning for complex composite structures. Although the proposed penalty-based optimisation framework demonstrated promising numerical performance, further experimental validation is required to establish quantitative correlations between the calculated penalty scores and actual machining-induced damage.

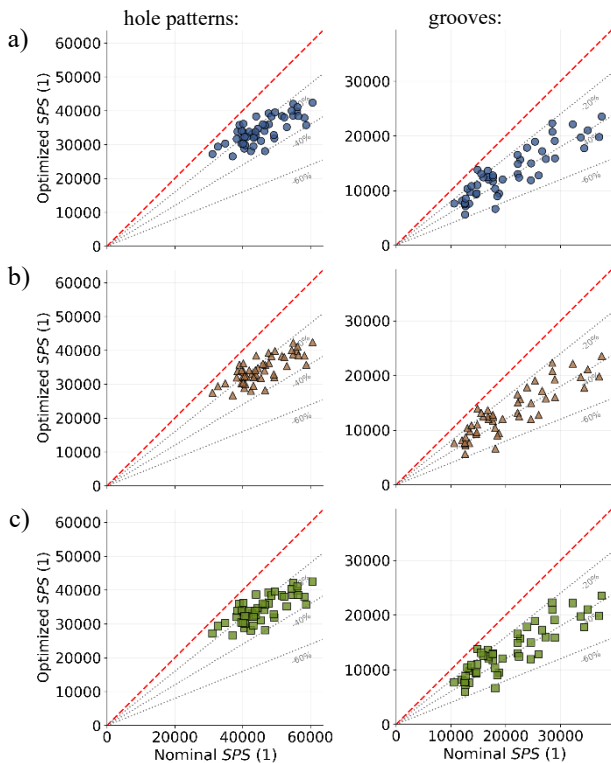


Fig. 8. Penalty scores of the geometrical features located at the nominal vs optimal position, calculated by the (a) brute-force (BF), (b) Monte Carlo (MC), and (c) genetic algorithm (GA) optimisation approaches.

4. Conclusions

The present study proposes a fibre-pattern-aware machining (FPAM) framework for optimising geometric feature placement in CFRP composites using local fibre-pattern information. The previously developed fibre-orientation-driven optimisation concept was extended by incorporating rotational degrees of freedom and by introducing stochastic optimisation approaches, namely Monte Carlo (MC) and genetic algorithm (GA), as computationally efficient alternatives to exhaustive brute-force (BF) optimisation. A database containing 250 synthetic fibre-pattern images was generated and used to evaluate the performance of the proposed algorithms.

- The numerical results demonstrated that the BF algorithm provided the reference optimum solution but required the highest computational effort. In contrast, the MC and GA approaches reduced the computation time by approximately 75% and 99%, respectively, while maintaining comparable optimisation performance. The differences in average SPS values remained limited to approximately 0.33–0.38% and 0.10–0.29% relative to the BF solution for the MC and GA approaches, respectively.
- Comparison of nominal and optimised feature locations revealed the practical potential of FPAM. All evaluated cases showed lower SPS values after optimisation, demonstrating that the local fibre pattern significantly influences the expected machining quality. The largest improvement was approximately 63%, while 90% of the improvement values were within the ranges of 10.9–35.10% and 19.3–51.5% for the hole-pattern and groove geometries, respectively.
- The proposed FPAM framework provides a practical route for integrating local fibre-pattern information into CAD/CAM-based process planning. The results indicate that substantial improvements in the expected machining quality can be achieved without modifying tooling or cutting parameters, highlighting the industrial relevance of fibre-pattern-aware machining. Future work will focus on experimental validation and on establishing quantitative correlations between the calculated penalty scores and actual machining-induced damage.

Acknowledgements

This research was partly supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences No. BO/00508/22/6. This research was implemented thanks to the support of the 2024-1.2.5-TÉT-2024-00032, which encourages scientific and technological cooperation between China and Hungary.

References

- [1] Ahmad J. Machining of Polymer Composites. Springer US; 2009.
- [2] Geier N, Paulo Davim J, Szalay T. Advanced cutting tools and technologies for drilling carbon fibre reinforced polymer (CFRP) composites: a review. *Composites Part A: Applied Science and Manufacturing* 2019;125:105552. <https://doi.org/10.1016/j.compositesa.2019.105552>.
- [3] Forintos N, Czigany T. Multifunctional application of carbon fiber reinforced polymer composites: Electrical properties of the reinforcing carbon fibers – A short review. *Composites Part B: Engineering* 2019;162:331–43. <https://doi.org/10.1016/j.compositesb.2018.10.098>.
- [4] Geier N, Xu J, Poór DI, Dege JH, Davim JP. A review on advanced cutting tools and technologies for edge trimming of carbon fibre reinforced polymer (CFRP) composites. *Composites Part B: Engineering* 2023;266:111037. <https://doi.org/10.1016/j.compositesb.2023.111037>.
- [5] An Q, Cai C, Cai X, Chen M. Experimental investigation on the cutting mechanism and surface generation in orthogonal cutting of UD-CFRP laminates. *Composite Structures* 2019;230:111441. <https://doi.org/10.1016/j.compstruct.2019.111441>.
- [6] Wang F, Qian B, Jia Z, Fu R, Cheng D. Secondary cutting edge wear of one-shot drill bit in drilling CFRP and its impact on hole quality. *Composite Structures* 2017;178:341–52. <https://doi.org/10.1016/j.compstruct.2017.04.024>.
- [7] Liu C, Ren J, Shi K, Zhang Y. Investigation of fracture mechanism evolution model for UD-CFRP and MD-CFRP during the milling process. *Composite Structures* 2023;306:116585. <https://doi.org/10.1016/j.compstruct.2022.116585>.
- [8] An Q, Ming W, Cai X, Chen M. Study on the cutting mechanics characteristics of high-strength UD-CFRP laminates based on orthogonal cutting method. *Composite Structures* 2015;131:374–83. <https://doi.org/10.1016/j.compstruct.2015.05.035>.
- [9] Wang C, Liu G, An Q, Chen M. Occurrence and formation mechanism of surface cavity defects during orthogonal milling of CFRP laminates. *Composites Part B: Engineering* 2017;109:10–22. <https://doi.org/10.1016/j.compositesb.2016.10.015>.
- [10] Monoranu M, Mitchell RL, Kerrigan K, Fairclough JPA, Ghadbeigi H. The effect of particle reinforcements on chip formation and machining induced damage of modified epoxy carbon fibre reinforced polymers (CFRPs). *Composites Part A: Applied Science and Manufacturing* 2022;154:106793. <https://doi.org/10.1016/j.compositesa.2021.106793>.
- [11] Park KM, Kurniawan R, Yu Z, Ko TJ. Evaluation of a hybrid cryogenic deburring method to remove uncut fibers on carbon fiber-reinforced plastic composites. *Int J Adv Manuf Technol* 2018. <https://doi.org/10.1007/s00170-018-3045-z>.
- [12] Hintze W, Hartmann D, Schütte C. Occurrence and propagation of delamination during the machining of carbon fibre reinforced plastics (CFRPs) – An experimental study. *Composites Science and Technology* 2011;71:1719–26. <https://doi.org/10.1016/j.compscitech.2011.08.002>.
- [13] Kwon B, Mai NDD, Cheon ES, Ko SL. Development of a step drill for minimization of delamination and uncut in drilling carbon fiber reinforced plastics (CFRP). *Int J Adv Manuf Technol* 2020;106:1291–301. <https://doi.org/10.1007/s00170-019-04423-5>.
- [14] Meng Q, Cai J, Cheng H, Zhang K. Investigation of CFRP cutting mechanism variation and the induced effects on cutting response and damage distribution. *Int J Adv Manuf Technol* 2020;106:2893–907. <https://doi.org/10.1007/s00170-019-04667-1>.
- [15] Du Y, Yang T, Liu C, Sun Y. Damage performance in drilling of carbon fiber-reinforced polyetheretherketone composites using drills with different geometries. *Int J Adv Manuf Technol* 2022;121:1743–53. <https://doi.org/10.1007/s00170-022-09430-7>.
- [16] Su F, Yuan J, Sun F, Wang Z, Deng Z. Analytical cutting model for a single fiber to investigate the occurrences of the surface damages in milling of CFRP. *The International Journal of Advanced Manufacturing Technology* 2018;96:2671–85. <https://doi.org/10.1007/s00170-018-1797-0>.
- [17] Geier N. Fibre-orientation-driven defect probability mapping for machining-induced delamination and burr minimisation in carbon fibre-reinforced polymer (CFRP) composites. *Composites Part C: Open Access* 2025;18:100636. <https://doi.org/10.1016/j.jcomc.2025.100636>.