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Advanced allowance planning of CFRP composites exploiting the pattern of chopped carbon fibre reinforcement clusters

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Conventional allowance planning of carbon fibre-reinforced polymer composite plates that must be mechanically machined is based on mainly the analysis of the precision of composite manufacturing technologies. This approach neglects the impact of randomly oriented and positioned chopped fibre reinforcement clusters leading to unpredictable fibre cutting angles and inconsistent quality during machining. To address this issue, we developed an innovative allowance planning method for polymer composites reinforced with chopped fibres. Our approach optimizes the size of the non-uniform allowance to minimize machining-induced burrs on the machined edges by detecting fibre reinforcement clusters on the composite surface through digital image processing and employing a convolution-based optimization of geometric feature patterns. Validation through drilling experiments demonstrated that our method improved the average burr factor by 50% compared to a conventional allowance planning technique. Although the proposed method is recommended to be improved to manage the effects of three-dimensional fibre clusters on burr occurrence, it encourages a novel direction in allowance planning of composites having non-defined directional reinforcements.

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Keywords: CFRP; Composite; Machining; Burr; Optimisation**1. Introduction**

Polymer composites reinforced by chopped carbon fibres are increasingly popular in secondary applications within the automotive, consumer goods, and sports industries [1–4]. This growing preference is due to their lower price and more uniform strength and thermal properties compared to composites reinforced by continuous unidirectional or multidirectional fibres [5]. Additionally, these composites boast an aesthetically pleasing forged carbon appearance, enhancing their appeal in various applications [6]. While these composites are often manufactured nearly to their final shape in a single operation, mechanical machining processes such as milling and drilling are frequently necessary to manufacture precise geometric features like pockets and holes [7,8]. In addition to the well-known challenges associated with machining continuous carbon fibre-reinforced polymer composites—such as

significant tool wear [9,10], machining-induced delamination or burr formation [11–14], and fibre direction-dependent machinability [15]—the prediction of fibre cutting angles, which critically impact chip removal mechanisms [16], is even more complex. This complexity arises because the orientation and position of chopped carbon fibre clusters cannot be consistently planned and maintained during the lay-up process. Therefore, the machining-induced geometric defects will be significantly influenced by the unknown local pattern of chopped fibre clusters.

Detection of fibre direction in fibrous polymeric composites is challenging due to the textured and semi-specular surface of the composite. Stokes-Griffin and Compston [17] pointed out that the carbon fibres dominate the light scattering behaviour as long the matrix polymer is transparent to light, and the surface of the composite is smooth. Vas and Balogh [18] developed a digital image processing method capable of detecting the

directions of single glass fibres by analysing the gradient vector of 5x5 pixel areas. Blanc et al. [19] proposed an image processing approach to estimate directions and fibre orientation distribution through image analysis of a single composite section. They validated their method in CFRP composites. Their method requires a careful preparation of composite specimens, as the geometry of cross sections of fibre reinforcements are analysed and evaluated. Krause et al. [20] presented a method for computing the three-dimensional fibre orientation distribution through the analysis of CT images. They utilized a structure tensor to determine directions in which the image information is constant, i.e., fibre directions.

We [21] developed a digital image processing-based method for detecting the chopped fibre clusters on the top and bottom surfaces of the composites to map the distribution of fibre cutting angles (i.e., the angle between the cutting speed vector and direction of fibre reinforcement) around the circumference of the holes to be drilled. Our method exploits the different reflection properties of the differently oriented carbon fibres and the principle of the total internal reflection of light. Therefore, we captured multiple images on the composite specimen using different lighting conditions and superpositioned the computed information. Our initial results on predicting machining-induced burrs based on the detected fibre clusters indicate that knowledge of the positions and orientations of these clusters on the composite surface is crucial. However, despite our method's ability to predict the amount of machining-induced burr, effective control of the burr formation remains challenging.

Therefore, we aim to introduce in this paper a novel approach for minimising the probability of machining-induced burrs formation in polymer composites reinforced by chopped carbon fibres. This approach is based on advanced allowance planning for machining, taking into account the calculated distribution of fibre cutting angles on the machined contours derived from the detection of chopped fibre clusters. Our proposed advanced allowance planning method is presented in Section 2, and its experimental validation is presented and discussed in Section 3.

2. Allowance planning

Our new approach originates from the realization that as long as the external contour and each internal geometric feature of the CFRP composite part (such as holes, pockets, and grooves) are manufactured by machining, varying the lateral outer margin (i.e., the allowance) of the CFRP preform appropriately allows for optimizing the position of the machined geometric feature patterns considering the chopped fibre clusters. This optimization aims to minimise the probability of machining-induced burr formation.

Figure 1 illustrates two types of allowance plans. In both cases, the size of the composite preform (50x50 mm) and the nominal geometry of the machined part (plate size of 40x40 mm and a hole with diameter $\varnothing 10$ mm at the position of (12; 20) mm from the zero point P) are the same. However, due to the difference in the allowance shapes, the relative positions of chopped fibre clusters to the hole contour differs. Therefore, the fibre cutting angle (θ) diagrams are also significantly

different, resulting in significantly different expected risk of burr formation along the contour of the machined hole.

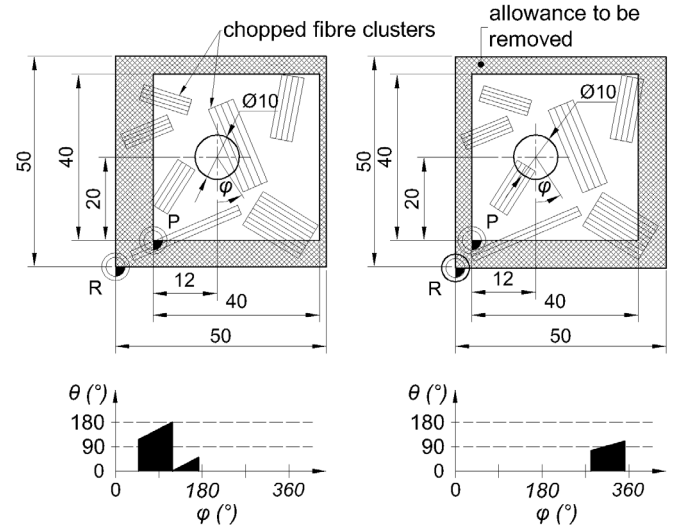


Fig. 1. A schematic illustration of the effect of the allowance design on the fibre cutting angle (θ) along the hole contour, in a polymer composite reinforced by randomly positioned and oriented chopped carbon fibre clusters, where φ is a running parameter. The allowance design in the right is better, as the fibre cutting angle avoids the critical range of $\theta_c = 135^\circ \pm \delta^\circ$, where the chip removal is governed by fibre buckling and macro fracture

The main steps (i ... ix) of the proposed advanced allowance planning method are presented below.

- i. Calculate the minimum size of the uniform external allowance (U) using conventional techniques and own experiences, considering the achievable composite manufacturing quality and precision.
- ii. Set the composite manufacturing technology and design the mould to provide an external allowance of $U+W$ mm on the composite part, where W is comparable to the average width of chopped fibre clusters, i.e., $W=2 \dots 10$ mm.
- iii. Capture q number of images on the top and bottom surfaces of the composite plate using different lighting conditions as described in [21] (Fig. 2a).
- iv. Convert the images to grayscale, segment them using the Otsu method and filter the noise according to the digital image processing algorithm presented in [21]. The output of these processing steps is realized in a $\mathbf{P}_q$ matrix as expressed by Eq. (1), where i denotes the rows and j denotes the columns, and q is the number of illumination setups (Fig. 2b).

$$\mathbf{P}_q = \begin{pmatrix} p_{11} & \cdots & p_{1m} \\ \vdots & \ddots & \vdots \\ p_{n1} & \cdots & p_{nm} \end{pmatrix}_q, p_{ijq} \in \{0; 1\} \quad (1)$$

- v. Calculate the submatrix of $\mathbf{P}_q$ matrix ($\mathbf{S}_q$) according to Eq. (2), i.e., delete the pixels which are out of the range of interest.

$$\mathbf{S}_q = \begin{pmatrix} s_{11} & \cdots & s_{1m} \\ \vdots & \ddots & \vdots \\ s_{n1} & \cdots & s_{nm} \end{pmatrix}_q, s_{ijq} \in \{0; 1\} \quad (2)$$

$$s_{11} = p_{y_1 x_1} \text{ and } s_{nm} = p_{y_2 x_2}$$

Where x_i and y_i coordinates define the corner points of the submatrix as illustrated in Fig. 2c.

vi. Determination of matrix F_k containing segmented contours to be machined, according to Eq. (3).

$$F_k = \begin{pmatrix} f_{11} & \dots & f_{1m} \\ \vdots & \ddots & \vdots \\ f_{n1} & \dots & f_{nm} \end{pmatrix}_k, f_{ijk} \in \{0; 1\} \\ = \begin{cases} 1, j = g_k(i) \\ 0, \text{otherw.} \end{cases} \quad (3)$$

Where $g_k(i)$ functions describe each contour element to be machined, and k denotes the number of contours, as illustrated in Fig. 3a.

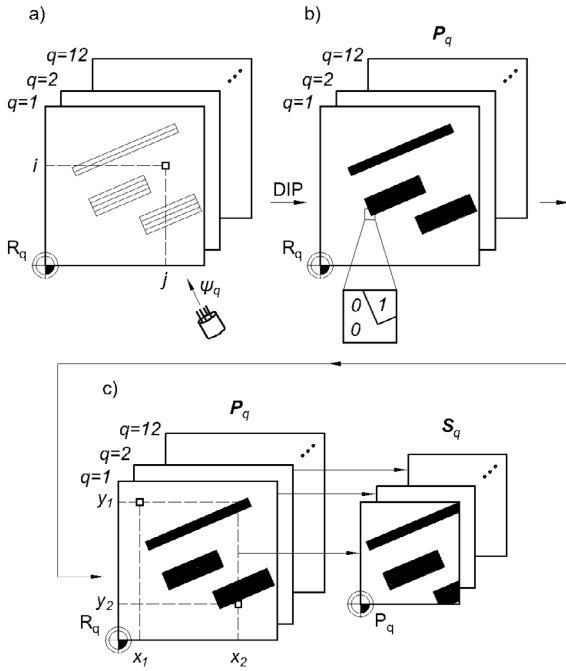


Fig. 2. A schematic illustration of the iii ... v steps of the proposed advanced allowance planning method: (a) original raw images on the composite, (b) segmented-filtered images, (c) cutting of images to define the area of interest

vii. Determination of the VC_k matrix specifying the distribution of the direction of the cutting speed vector along the contours to be machined, as expressed by Eq. (4) and illustrated in Fig. 3b.

$$VC_k = \begin{pmatrix} vc_{11} & \dots & vc_{1m} \\ \vdots & \ddots & \vdots \\ vc_{n1} & \dots & vc_{nm} \end{pmatrix}_k = F_k \cdot C_k \quad (4) \\ vc_{ijk} \in \{0 \dots 360\}$$

Where C_k functions describe the direction of the tangent of the k^{th} contour (i.e., the direction of the cutting speed vector relative to the horizontal axis) to be machined in each (i, j) coordinates.

viii. Calculating the θ_{qk} matrix consisting of the fibre cutting angles along the contours to be machined, considering the fibre direction (perpendicular to the direction of q^{th} lighting setup) and VC_k matrix as illustrated in Fig. 3c.

ix. Determination of probability matrix $P\theta_{qk}$ based on Eq. (5), where the critical fibre cutting angle is $\theta_c = 135^\circ$ and its range is $\delta = 30^\circ$, as illustrated in Fig. 3d.

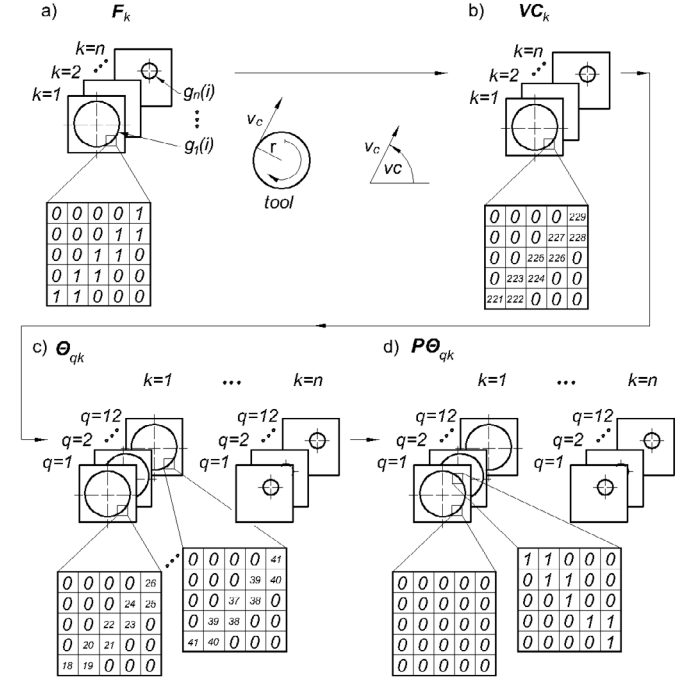


Fig. 3. A schematic illustration of the vi ... ix steps of the proposed advanced allowance planning method: (a) $g_k(i)$ segmented contours to be machined, (b) the cutting speed direction along the contours to be machined, (c) fibre cutting angles along the contours to be machined, (d) probability matrix for expected burr formation

$$P\theta_{qk} = \begin{pmatrix} p\theta_{11} & \dots & p\theta_{1m} \\ \vdots & \ddots & \vdots \\ p\theta_{n1} & \dots & p\theta_{nm} \end{pmatrix}_{qk}, p\theta_{ijk} \in \{0 \dots 1\}, \quad (5) \\ p\theta_{ijk} = \begin{cases} 1, (\theta_c - \delta) < \theta_{ijk} < (\theta_c + \delta) \\ 0, \text{otherw.} \end{cases}$$

x. Summation of k pieces of $P\theta_{qk}$ matrices as expressed by Eq. (6) to meet the degrees of freedom of $P\theta_{qk}$ and S_q matrices for further processing by convolution.

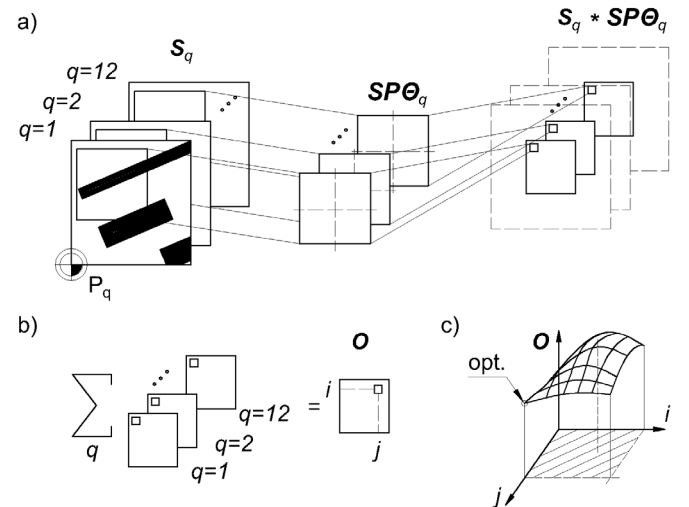


Fig. 4. A schematic illustration of the xi and xii steps of the proposed advanced allowance planning method: (a) convolution of q pieces of S using kernels of $SP\theta$, (b) summation of q number of convoluted matrices, (c)

finding the optimal condition where the probability of burr formation is minimal

$$SP\theta_q = \sum_{k=1}^n P\theta_{qk} = \begin{pmatrix} sp\theta_{11} & \cdots & sp\theta_{1m} \\ \vdots & \ddots & \vdots \\ sp\theta_{n1} & \cdots & sp\theta_{nm} \end{pmatrix}_q \quad (6)$$

$$sp\theta_{ijq} \in \{0 \dots 1\}$$

xi. Convolution of q pieces of S using kernels of $SP\theta$, (Fig. 4a) then summation according to Eq. (7), as illustrated in Fig. 4b.

$$O = \sum_{q=1}^m (S * SP\theta)_q = \begin{pmatrix} o_{11} & \cdots & o_{1m} \\ \vdots & \ddots & \vdots \\ o_{n1} & \cdots & o_{nm} \end{pmatrix} \quad (7)$$

$$o_{ij} \in \{0 \dots M\}$$

The o_{ij} elements of the matrix O respectively specify how many critical contour points there are where the probability of burr formation is high (assuming a clockwise direction of rotation of the tool).

xii. Selecting the smallest o_{ij} element (Fig. 4c). This smallest value defines the position of the contours to be machined, i.e., the allowance plan. If a global minimum location cannot be clearly established (the value of several o_{ij} elements is also the same as the minimum of the values of the list formed by the matrix elements), then we recommend considering the position closest to the centre as more favourable among the minimum locations, because the closer the position to the workpiece centre, the more uniform the external allowance is.

3. Experimental validation and discussion

The feasibility of our method was tested through drilling experiments in polymer composite plates reinforced by chopped carbon fibres. The epoxy resin of MR3010 and catalyst of MH3124 were used in a ratio of 100:33 as matrix, reinforced by chopped carbon fibres having a nominal fibre length of 6 mm, as in Ref. [21]. The nominal fibre content was set to 20 wt%. The composite was placed in a preheated 60 °C mould and held under 100 bar for 20 min. Two composite plates were produced in this way, having a nominal size of 80x80x4 mm (see in Fig. 5).

Each CFRP panel was fixed into an aluminium fixture (see in Fig. 5) and its corner was applied as a reference point for calculations and positioning holes. Therefore, this fixture was used in the image-capturing setup (where 12 images were captured with different illumination) and the machining setup, without unscrewing screws and changing the relative position of the reference point to the chopped fibre clusters.

The composite plates were divided into 16 sections (the size of one section was 13.5x13.5 mm) as illustrated in Fig. 6a. On the one hand, the hole centre positions in one of the composite plates were optimised within these sections according to the algorithm described in Section 2. A representative response graph of one of such section is illustrated in Fig. 6b, where the lowest o_{ij} value represent a hole centre position where the probability of burr formation is the smallest, and the larger o_{ij} values correspond to higher risks. On the other hand, the hole

centre positions in the second composite plate were set to the centres of the sections without any optimisation, i.e., these positions were defined conventionally.

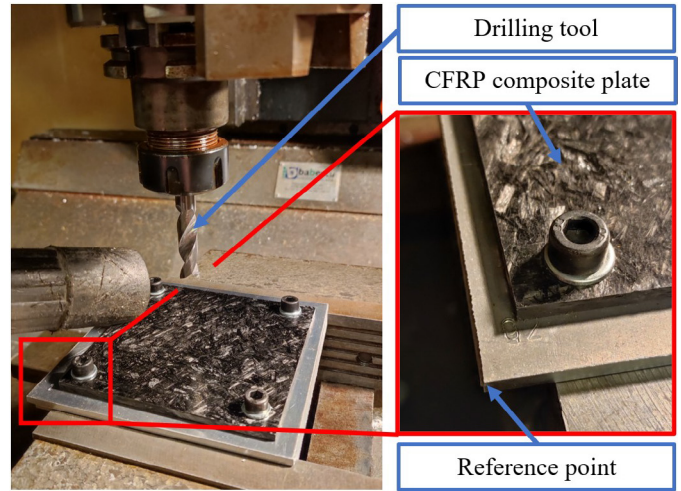


Fig. 5. Experimental setup

The drilling experiments were conducted on a Kondia B640 three-axis machining centre in dry condition. A THOMAS TDM 2L 23C100100 uncoated solid carbide drill (Fig. 5) having a diameter of $\varnothing 10$ mm, a nominal clearance angle of 14° and a nominal rake angle of 30° was used. A Nilfisk GB733 industrial vacuum cleaner extracted the chips from the cutting zone.

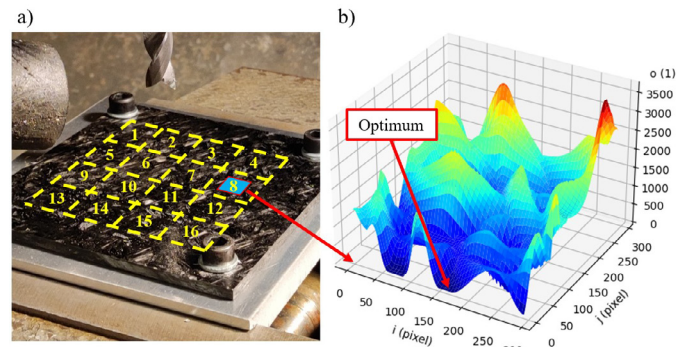


Fig. 6. (a) illustration of the 16 sections where the position of the holes are optimised or put to the middle of each section, (b) response graph for the 8th section where the lowest o_{ij} value represent a hole position where the probability of burr formation is the smallest

The holes were captured by a Mitutoyo QI-A505 microscope and the burr factor (F_b) was calculated through digital image processing to characterize drilling-induced burrs. The pixel density was 14.8 pixel/mm. Holes characterized by smaller burr factors are considered to be of better quality. The results are shown in Fig. 7.

The average of burr factors of holes machined into the conventionally defined positions is 3.41%, while it is only 1.69% in the case of the optimised one. This suggests that the quality of holes drilled into the optimised position is 50% better than the non-optimised ones. This suggests that the proposed method is suitable for burr-minimisation in polymer composites reinforced by chopped carbon fibres. However, the variances compared to the differences in the means are considerable according to the one-way ANOVA test (F -

value=2.29, P-value=0.141). The null hypothesis of the ANOVA was that the influence of whether the hole position was defined using the optimised or the conventional method is not significant on the burr factor. Statistically, the results mean that we fail to reject the null hypothesis of ANOVA at a significance level of 0.05. Nevertheless, it can be rejected at a significance level of 0.15. Therefore, a significant improvement in the experimental validation procedure or measurement setup is required in the future to properly validate the effectiveness of the proposed method at the standard significance level of 0.05.

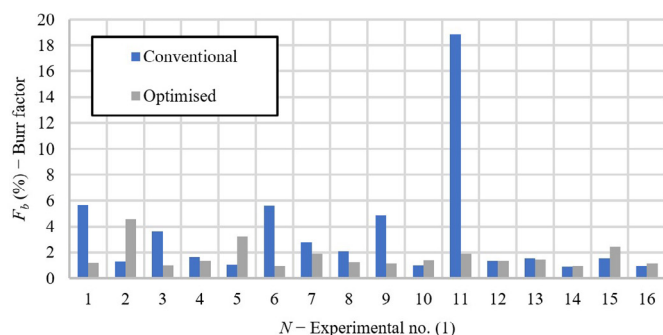


Fig. 7. The diagram on the burr factors (F_b) of holes drilled into optimised and not optimised positions

Although the proposed method is very promising, it has numerous limitations and should be improved further. For example, the algorithm tries to find the best position of machinable contours by moving them along the i and j directions; however, the rotation of complex contours could result in an even better solution, which rotation has not been included yet within our algorithm. There is also significant room for improvement in the experimental validation of the proposed method, as only microscopic images were used to characterise the top and bottom of the composite plates. Therefore, in the future, images will be captured using computer tomography (CT) to determine chopped fibre clusters within the composite plate. In addition, more complex geometrical features and feature patterns will be analysed in the future to test the effectiveness of the method.

4. Conclusions

We developed an innovative allowance planning method for polymer composites reinforced with chopped fibres. Our approach optimizes the size of the non-uniform allowance to minimize machining-induced burrs on the machined edges by detecting fibre reinforcement clusters on the composite surface through digital image processing and employing a convolution-based optimization of geometric feature patterns. Validation through drilling experiments demonstrated that our method improved the average machining quality by 50% compared to a conventional allowance planning technique. However, the variances compared to the differences in the means are considerable according to the one-way ANOVA test (F -value=2.29, P -value=0.141). This means that the significance level of 0.15 enables us to declare that the influence of whether the allowance is planned by the proposed or the conventional method is significant on the burr factor.

Although the proposed method is very promising, it needs improvement in the future to meet industrial requirements. Therefore, we plan to gain 3D information on the chopped fibre clusters using CT, validate the method using more complex geometric features and feature patterns, analyse more cutting tools and technologies, and include the rotation of geometric features in the algorithm.

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