Computational imaging for drill bit wear estimation

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***Abstract*—Aerospace and automotive industries make more and more use of carbon fiber laminates. They offer high advantages in terms of mechanical performance but are difficult to work on and need precise and expensive tools. Drilling is the most common operation; drill bits must be accurately verified before use to avoid damages during the process. This paper proposes an optical inspection system for drill bits wearing estimation based on a custom-designed illumination device and a processing algorithm based on computational imaging. The elaboration of the computational image is used to measure the drill bit cutting profile. Drill bits have been worn on carbon fiber laminates, and a tool wear model has been extracted using the proposed system. The proposed method has been tested on drill bits, both used and new, used in the aerospace industry.**

***Index Terms*—Computational imaging, drill bit**

I. Introduction

The use of carbon fibers laminates is becoming increasingly common in industrial application such as aerospace and automotive applications, due to their superior mechanical properties, associated with their light weight and corrosion resistance. Machining operations on these materials, with particular reference to perforation, are critical and can cause damages when the laminate is subject to heavy stress. The stresses and vibrations during the drilling process can cause widespread damage that compromises the mechanical properties of the finished piece. However, composite materials' drilling is a conventional machining process in the aerospace industry. The holes made on these materials reduce the resistance of the laminate to stress and are subjected to stringent quality requirements.

The holes must be in the correct position regarding the geometric requirements, have the right shape, and the diameter's expected tolerance. Other quality parameters are related to surface integrity and roughness. When drilling, both the shear strength and friction between the drill bit and the composite piece can cause various types of damage such as delamination, blurring, and chipping [1]. Delamination caused by perforation is one of the most commonly used parameters for evaluating hole quality as it affects the structural integrity of the laminate and can deteriorate long-term performance.

The drill bits' wear measurement represents a critical point in industrial production processes and reflects the tools' average lifetime. An excessively worn drill bit can damage the perforated material's surface and the size of the drilled hole. It is necessary to develop quantitative tool wear measurement techniques to determine the precise timing for tool replacement. In this respect, several studies suggest techniques based on image processing [2]–[4].

A measurement system based on computational imaging To estimate drill bit wear is proposed in this paper. A short review of state of the art about methods used to evaluate drill bit wear is reported in the following paragraph. The proposed system will be described, followed by the description of the experiments and results.

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II. State of the Art

Computers and sensors control the wear monitoring of components and mechanical tools. Tool wear is caused by physical and chemical interactions between the drilling object and the workpiece. It can be described as the removal of small pieces of material from the cutting edge of the tool as a result of these interactions. The component wear' measuring methods can be divided into direct and indirect methods [5]. Indirect methods measure the degree of tool wear through sensors that generate signals that indirectly provide information on the state of the object. In contrast, with direct methods, the information is obtained directly by analyzing drill bit.

A. *Indirect measurement methods*

Indirect measurement techniques generally require the reception of continuously acquired signals. They are widely used thanks to their ease of installation on industrial machines, which does not affect the machinery's function and does not alter the production process. Indirect measurement methods can use several sensor and principles to detect the wear of the tool:

- Torque measurement and push force measurement requires special tooling of the drill system and can influence the dynamics and the overall performance and characteristics of the machining.
- The acoustic emissions (AEs), also known as "stress wave emission" or "microsismic activity", are a phenomenon of sound and ultrasound wave radiation where elastic energy is released in the form of mechanical vibration from a material (tool, workpiece, machine body) as it undergoes deformation and fracture processes [6]. Acoustic emission sensors are generally more expensive and require a higher

sampling rate and computing performance resolution than industrial accelerometers [7].
- Accelerometers are easy to mount and use on industrial machinery. They do not compromise the drilling system's rigidity, and they present good immunity to electromagnetic interference. They are cheap and can be easily substituted.

In indirect measurement, to overcome the single sensor's weakness, a multi-sensor platform can be used as described in [8]. The amount of data produced by indirect methods is so large that it requires neural networks and high-performance computing devices to be analysed. Regarding this point, a comparison between different architectures of a multilayer feed-forward neural network is presented in [9]. They use a training and posterior propagation algorithm for monitoring the wear conditions of a twist drill. The algorithm uses the vibration trace as the only source of information on the machining process. At the input to the neural network, different tip wear conditions are introduced. The frequency-domain characteristics, such as average harmonic wavelet coefficients and the peaks of the spectrum at maximum entropy, are more efficient in training the neural network than statistical moments in the time domain. The results suggest that vibrational signals have a significant impact on tool condition monitoring and manufacturing process diagnostics.

B. Direct measurement methods

These methods provide immediate evaluation of the actual wear of the objects that may require their removal. The measurement methods most used in the inspection processes of mechanical components are the direct ones. With direct measurement, the tool blade is monitored using, for example, an artificial vision system, an optical microscope, or a touch sensor.

Advances in computer vision and image processing technology have led to the development of various vision sensors that can be used to obtain information about the drilling tool and the perforated surface. One of the most important advantages of machine vision-based measurement systems is that the drill bit is not in permanent contact with the machined part. Monitoring can be achieved with vision systems without any physical contact.

An example of digital image analysis method for tool wear is presented in [10]: it measures the relevant parameters representing the quality of the drilled hole, focusing attention on the geometry of the hole and the measurement of selected indices that characterize the relative delamination phenomena both at the entrance and at the exit of the hole. The results show that the hole diameter generally decreases as the number of holes increases. The delamination at the exit of the hole is more correlated to tool wear progression during drilling.

An automatic optical inspection system for drilling tips for PCB (Printed Circuits Boards) is presented in [11]. A specifically designed lighting system ensures high image quality of the tips. A modified version of the SUSAN (Small Univalue Segment Assimilating Nucleus) algorithm is used [12]. Through the use of a differential operator based on the spatial moment, it is possible to obtain a precision on the position with an uncertainty lower than a pixel. The algorithm returns curves that discreetly approximate the edges of the cutting surfaces of the tip. The angles of the tip are instead determined with suitable precision from the intersections of the extrapolated curves. Once all inspection items have been identified, flaw detection is performed on the tip blade surface. The results show that adopting the automated optical tip inspection method for PCBs results in increased product quality and reliability. The small size of the printed circuits and their respective tips, however, make it necessary to use acquisition devices with a very high resolution.

In most vision-based measurement techniques, the drill bit is framed from the front. In [13] the authors present an inspection system in which the image acquisition module is equipped with a 14 MPixel CMOS camera, a bi-telecentric lens, and a LED ring illuminator with adjustable intensity. The image processing system includes a comparison algorithm and the corresponding graphic interface with the user. The thicknesses of each cutting edge are calculated and the maximum value of these widths is used as an indicator of tool wear through the approximation to the least-squares. The use of a very high resolution camera and telecentric optics, however, can require high and, sometimes, excessive costs.

It is possible to analyze the drill bit from the front side and from the lateral side, and several researches have been published. *A. Volkan Atli and M. Sonmez* in [14] propose a system for monitoring the conditions of drilling tools based on artificial vision conducted with a high-speed CCD camera, placed on the side of the tip. Canny's algorithm [15] is used to extract the necessary information from the acquired images, particularly suitable for detecting contours. This technique is quite sophisticated but provides a good compromise between noise reduction and image edge localization. However, to obtain a measure of the tip wear, a linearity deviation metric (DEFROL) is proposed, which measures how far the contour of the tool flank differs from the straight line.

The inspection of the tip and the estimation of wear focus mainly on the cutting plane, which is determined if the camera that acquires the image to be processed is placed in front of the tip. As for the optical control of the tips in the production of printed circuits, the increasing integration density entails the microminiaturization of the drilling tips and the need to resort to a vision system with an increasingly high resolution. When the diameters of the tips reach the decidimes or even the hundredths of a millimetre, we resort to the use of microscopes for image acquisition. If the cutting plane cannot be segmented exactly, it is impossible to obtain an accurate measurement result with the proposed method.

Most image edge detection algorithms work well if the cutting plane is clear and the tip is clean. During the manufacturing processes, however, traces of dust and smudging stains may be deposited on the tips, which camouflage the cutting plane and cause errors in the analysis of the single image.

The authors in [16] propose an iterative algorithm that uses a series of levels to segment the cutting plane and determine the blades' surfaces without the dirty regions affecting the measurement. This algorithm is based on the idea to start from a zero-level function, defined in a space of a higher dimension than that of representing the image contours, and to follow the evolution of the function through a discrete differential equation. It is a flexible method that can include additional features, and that returns good results as the number of iterations increases; however, this strategy may require too much processing time and excessive computational complexity.

For a feature of the object under inspection to appear in the image acquired by an optical measurement system, the object must be suitably illuminated. In industrial vision systems, light must be supplied in a controlled manner so as to highlight the characteristics of interest and reduce the presence of unwanted ones. Lighting is one of the most critical aspects of an automatic vision system, for this reason the choice of the lighting method and setup is extremely important. *R. Ramzi and E.A. Bakar* [17] propose an optical inspection method for the wear of the drill bits used in the assembly sector of the aeronautical industry, from which important considerations can be drawn on the orientation of the rays that illuminate the surface of the focus, on the nature of the light and on the alignment of the tool with respect to the objective. The monitoring system used by the authors consists of a very complex hardware part, consisting of a digital microscope for image acquisition with its own lighting, two strips of LED illuminators to further improve the image quality, pair of servomotors used to adjust the rotation angle of the supplementary illuminators and by a spindle that fixes the position of the drill bit in order to align it with the microscope.

The tip is placed in a vertical position and framed from top to bottom. In this way, the drill bit axis of symmetry coincides with the image acquisition instrument's optical axis, whether this is a microscope or a generic camera. The drill bit image can be divided into different regions: the cutting blade and the chisel edge are the two main cutting edges of the four edges into which the cutting plane is divided. The cutting blades correspond to the edges through which the tip removes material from the perforated surface. The edges of the chisel are placed on the line of intersection between the cutting surface and the lateral surface.

III. Proposed system and method

The use of microscopic imaging for a drill bit with a size of $4\,\mathrm{mm}$ or bigger is not feasible or useful. Moreover, the use of moving illumination systems or complex setup is not applicable in production environments or to have a fast check of the wear state of a drill bit. To solve these problems, the proposed solution uses a custom-designed lighting system, as in Fig. **??**. The custom illumination system and the digital camera were set up on an optical bench to ensure the alignment of the tip with the camera and the symmetry of the supports with respect to the optical axis, as in Fig. 2. The drill bit is placed in an horizontal position and aligned with the camera

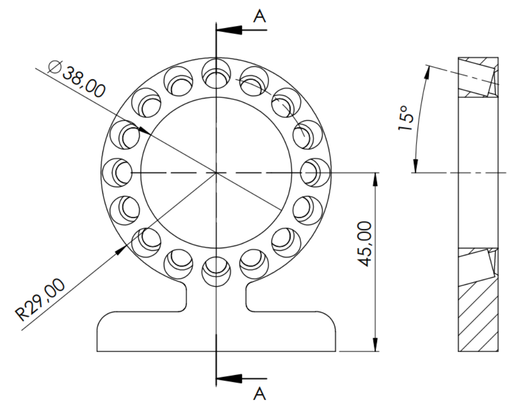


Fig. 1: Dimensional drawing of the custom ring illuminator. All the measures are in mm.

and optic center through two alignment supports. At the same time the ring illuminator axis is aligned with the drill bit axis and so with the camera. A end stop is placed to keep the drill bit tip in the focal plane. The supports that make up the system have been physically sized and made through a 3D printer, using PLA (poly lactic acid).

It has been experimentally found that the light produced by a single white LED is able to uniformly illuminate the region of a cutting blade when the orientation of this region falls within a certain angular range and does not excessively stand out the remaining regions of the surface of the drill bit. A specific ring illuminator has been designed, whose operating principle adopts the image computation technique. The illuminator consists of a support in the shape of a circular crown, specially printed and perforated in 16 points; inside each of these a white light LED has been inserted. The emission of the single LED, due to the lens in the shape of a spherical cap, is of the radial type but each hole is inclined in such a way that the direction of its axis intersects the optical axis at the point where the drill bit is in focus. A detailed drawing of the designed illumination system is reported in Fig. 1.

Taking advantage of the computational image processing technique, the LEDs that make up the system are turned on sequentially, and at each step of the sequence, an image is acquired. The 16 images obtained following this procedure represent the front surface of the tip subjected to the measurement, always oriented in the same position but illuminated from a different direction. The images are all different from each other. By choosing a generic pair from the overall set of 16 elements, the two images can differ even only for a limited number of pixels. Some images highlight the details sought or one of the two cutting surfaces; the others contain superfluous information for the purpose of the measurement. The designed lighting system allows to vary the source's angle with a resolution equal to one sixteenth of the round angle, that is, about $23°$. This rotation step guarantees at least the presence of a pair of images in which the first and

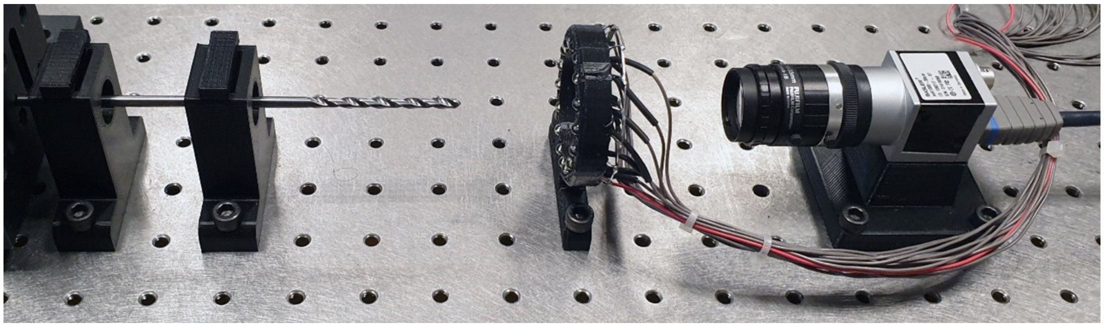


Fig. 2: Realized measurement system on the optical bench. From the left: two drill support, the ring illuminator and the camera on the camera support.

second cutting blades stand out respectively. By appropriately processing the 16 images, it is possible to obtain a definitive image, whose amount of information is much greater than a single acquisition of the sequence.

The measurement system is composed by the custom illuminator driven by an Analog Discovery 2 board [18] and a Raspberry PI, a low-power single board PC that controls the system. The camera used is a *Basler ace acA1300-30uc*; a monochromatic camera with a 1.3MP *Sony ICX445* CCD sensor [19] with a $35\,\mathrm{mm}$ *Fujinon HF35HA-1B* optic designed for 1.5MP sensor [20].

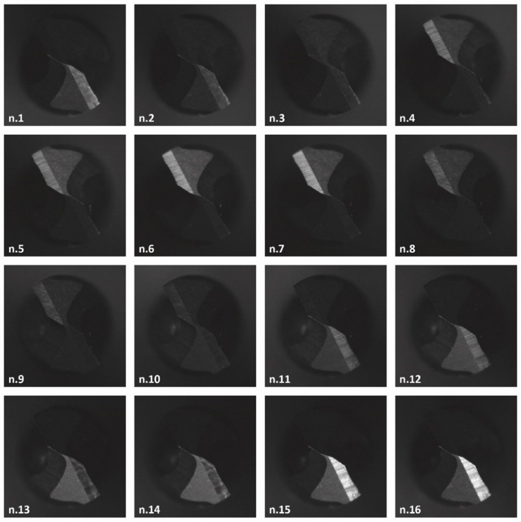
The images are acquired from the camera via the USB 3.0 connection on the Raspberry PI with a *Python* script. The script manages both the capture from the camera and the illumination system. When the acquisition is completed, the images are processed still via a *Python* and *Open CV*. The acquisition time is about $5\,\mathrm{s}$ while the execution time on this platform is about $30\,\mathrm{s}$ without any particular optimization technique.

A. Computational image processing

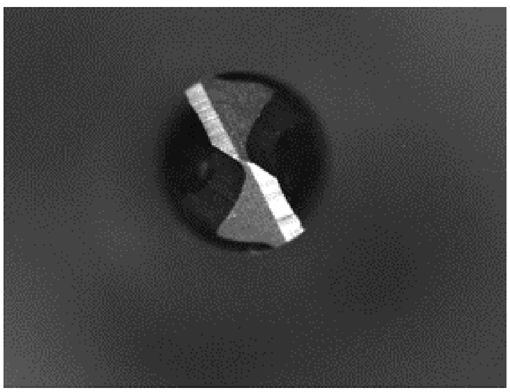
The goal of the implemented algorithm is to extract the two geometric shapes of the surfaces of the cutting edges, aligned on the transverse axis and arranged symmetrically with respect to the center of the tip. The drill bit, during its operation, rotates clockwise around its axis of symmetry. Therefore, in the image depicting the tip, the rotation takes place counter-clockwise and the wear of the cutting edge is reflected directly on the cutting blade. The blade profile is expected to vary depending on the wear of the tip and the thickness of the surface. The algorithm can be divided into the following steps:

1) The computation of the sixteen images is based simply on the arithmetic sum (example in Fig. 3a). The camera used is monochromatic, so each image is in grayscale and the value of the single pixel varies from 0 to 255. All the images have the same size, the pixels are arranged in a two-dimensional matrix with 960 rows and 1280 columns. The arithmetic sum of sixteen grayscale images yields an overall image in which the (i, j) element has a value given by the sum arithmetic of the sixteen values of the pixels corresponding to the same position. Since the maximum limit of the gray level is equal to 255, when the sum of the sixteen values exceeds this number it is approximated precisely to 255. If the brightness of the lighting system did not guarantee a good contrast of the single image, the arithmetic sum would return as a result an incorrect image.
2) A threshold operation is performed to obtain a binary image. The choice of the threshold value depends on the computed image's pixel values and can be conducted by analyzing the histogram of the computed image. The oversizing of the field of view, necessary to make the system adaptable to larger sized tips, means that the tip image occupies a limited region of the overall size. The excessive number of pixels belonging to the background makes the histogram single-mode.
3) The angular position of the drill bit is arbitrary and not controllable. A scan is carried out on the binary image without isolated points to determine the pixels' coordinates corresponding to the extremes of the drilling tip in each of the four directions. A rectangular mask is then applied, the sides of which correspond to the two pairs of abscissas and ordinates found by scanning. Subsequent processing is carried out exclusively on the pixels inside the mask to reduce the algorithm's computational complexity.
4) A straight edge search is performed on the grayscale image since it contains information on the gradient. The transverse axis's position on which the two cutting surfaces lie and with respect to which the blades are aligned is sought. The value to be calculated is the orientation angle of the axis with respect to the Cartesian plane on which the image of the drill bit lies.
5) Each image is rotated clockwise by an angle equal to the value returned in the previous step. In this way, the two cutting edges are aligned vertically, and, in the rotated images, the rectilinear contour coincides with a central column. To trace the two cutting edges' profiles with respect to its transverse axis, just add the pixels arranged on the lines.

In Fig. 3a an example of all the 16 acquired images is reported, in particular, this figure refers to a light pattern



(a) Example of acquired images with a specific light pattern.



(b) Example of computed drill bit image.

Fig. 3: Example acquired images in 3a and obtained computational image 3b.

formed by two adjacent LED turned on simultaneously. Each photo corresponds to a specific position of the chosen light pattern with respect to the 16 possible positions. The drill bit tip computed image is reported in Fig. 3b.

IV. Tests and Results summary

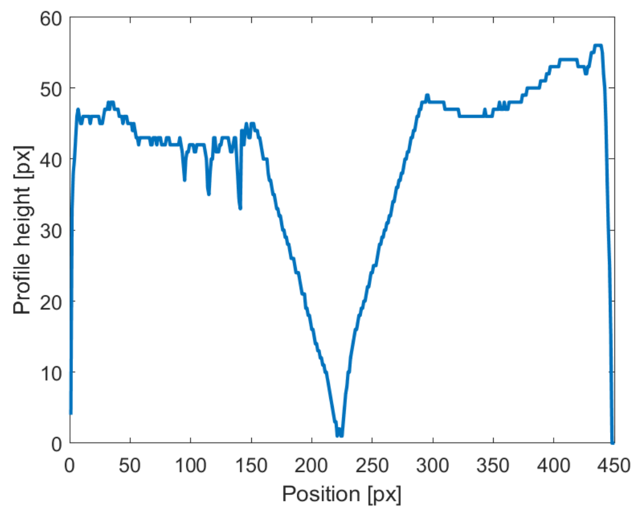
To obtain an indication on the number of holes that have been made with a generic drill bit an extrapolation has been made. A new drill bit was taken into consideration and wore, making holes on a carbon fiber laminate pice using a drill press. The drill bit used for the tests have a diameter of 6 mm (Fig. 4) and are commonly used for aeronautical applications. Every five holes, the drill bit was analyzed, and the result stored to be further compared and to check the degree of wear and observe any variations in the value of the average thickness, standard deviation, and integral profile.

The proposed method and system associates each set of sixteen images with an array of values that identifies the surface profile of the two cutting edges with respect to the axis on which they are aligned. Each value of the output array gives a measure, in pixels, of the cutting edges' thickness while the number of elements in the array gives a measure of the length of the cutting edges.

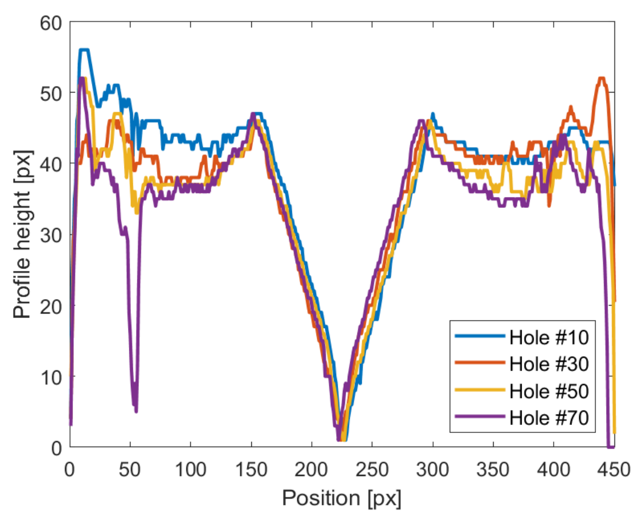
In Fig. 5a, the profile of a new drill bit is reported, while in Fig. 5b a comparison of the profiles of the same drill bit in different wear condition is reported. On the

Seventy holes were made to age the drill bit and build the wear profile reported in Fig. 6. A decreasing trend in the

Fig. 4: Drill bits used for the tests.



(a) A profile af a new and clean drill bit.



(b) Comparison of drill bit profiles with increasing wear.

Fig. 5: Drill bit profiles measured with the proposed method.

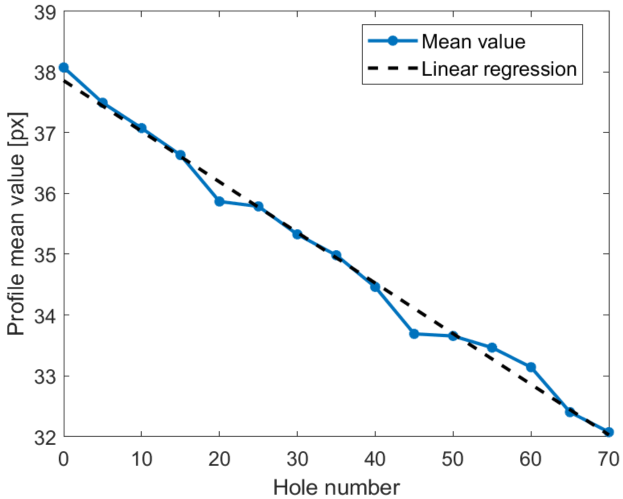


Fig. 6: Mean value of the profile at varying number of hole and its linear regression.

cutting edges' average thickness was observed as the number of holes increased. The wear model that can be obtained with this method is expressed in equation (1), where $\hat{h}$ is the estimated hole number while m is the measured profile average value.

$$\hat{h} = \frac{m + 0.083}{37.85} \tag{1}$$

The measurement with the greatest sensitivity regarding the number of holes made is that of the average of the points of the zero derivative profile. The information to which this type of measurement refers is limited exclusively to the cutting edges' blades, which become thinner as the degree of wear of the tip increases. Measurements of the mean and integral of the algorithm's output array overall profile provide a more complete description of the cutting edge surfaces but have lower sensitivity as the remaining surface regions, such as the center and corner edges of the cutting edges, during the drilling process they are not eroded as much as the blades.

V. Conclusions

A method for tool wear measurement based on computational imaging and custom illumination system has been presented. The systems allows an offline measure of the drill bit tip. The ring illuminator with 16 LEDs allows the creation of good images for the computational imaging procedure that has been presented. The extraction of the profile from the computed images can be done with appropriate rotations and accurate thresholding operation. The linear regression obtained with the wearing of the tool can be adopted as a wear model.

References

[1] G. Mihoc, P. Pop, H. Geaman, C. Diana, and L. Mitu, "A review of the drilling processes of composite materials," 05 2011.

[2] A. G. Rehorn, J. Jiang, and P. E. Orban, "State-of-the-art methods and results in tool condition monitoring: a review," *The International Journal of Advanced Manufacturing Technology*, vol. 26, no. 7, pp. 693–710, Oct 2005. [Online]. Available: https://doi.org/10.1007/s00170-004-2038-2

[3] J. Jurkovic, M. Korosec, and J. Kopac, "New approach in tool wear measuring technique using ccd vision system," *International Journal of Machine Tools and Manufacture*, vol. 45, no. 9, pp. 1023 – 1030, 2005. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0890695504003128

[4] J.-H. Kim, D.-K. Moon, D.-W. Lee, J.-s. Kim, M. C. Kang, and K. Kim, "Tool wear measuring technique on the machine using ccd and exclusive jig," *Journal of Materials Processing Technology*, vol. 130-131, pp. 668–674, 12 2002.

[5] S. Kurada and C. Bradley, "A review of machine vision sensors for tool condition monitoring," *Computers in Industry*, vol. 34, no. 1, pp. 55 – 72, 1997. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0166361596000759

[6] Yuchen Zhou, P. Orban, and S. Nikumb, "Sensors for intelligent machining - a research and application survey," in *1995 IEEE International Conference on Systems, Man and Cybernetics. Intelligent Systems for the 21st Century*, vol. 2, 1995, pp. 1005–1010 vol.2.

[7] M. Mannan, A. A. Kassim, and M. Jing, "Application of image and sound analysis techniques to monitor the condition of cutting tools," *Pattern Recognition Letters*, vol. 21, no. 11, pp. 969 – 979, 2000. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0167865500000507

[8] J. A. Duro, J. A. Padget, C. R. Bowen, H. A. Kim, and A. Nassehi, "Multi-sensor data fusion framework for cnc machining monitoring," *Mechanical Systems and Signal Processing*, vol. 66-67, pp. 505 – 520, 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0888327015002010

[9] I. Abu-Mahfouz, "Drilling wear detection and classification using vibration signals and artificial neural network," *International Journal of Machine Tools and Manufacture*, vol. 43, no. 7, pp. 707 – 720, 2003. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0890695503000233

[10] A. Caggiano, R. Angelone, and R. Teti, "Image analysis for cfrp drilled hole quality assessment," *Procedia CIRP*, vol. 62, pp. 440 – 445, 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2212827117301890

[11] W. J. Zhang, D. Li, F. Ye, and H. Sun, "Automatic optical defect inspection and dimension measurement of drill bit," pp. 95–100, 2006.

[12] C. Gao, H. Zhu, and Y. Guo, "Analysis and improvement of susan algorithm," *Signal Processing*, vol. 92, no. 10, pp. 2552 – 2559, 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0165168412000801

[13] Q. Hou, J. Sun, and P. Huang, "A novel algorithm for tool wear online inspection based on machine vision," *The International Journal of Advanced Manufacturing Technology*, vol. 101, no. 9, pp. 2415–2423, Apr 2019. [Online]. Available: https://doi.org/10.1007/s00170-018-3080-9

[14] A. V. Atli, O. Urhan, S. Erturk, and M. Sönmez, "A computer vision-based fast approach to drilling tool condition monitoring," *Proceedings of The Institution of Mechanical Engineers Part B-journal of Engineering Manufacture - PROC INST MECH ENG B-J ENG MA*, vol. 220, pp. 1409–1415, 09 2006.

[15] J. Canny, "A computational approach to edge detection," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. PAMI-8, no. 6, pp. 679–698, 1986.

[16] G. Duan, Y.-W. Chen, and T. Sukegawa, "Automatic optical flank wear measurement of microdrills using level set for cutting plane segmentation," *Machine Vision and Applications*, vol. 21, no. 5, pp. 667–676, Aug 2010. [Online]. Available: https://doi.org/10.1007/s00138-010-0259-y

[17] R. Ramzi and E. A. Bakar, "Optical wear inspection of countersink drill bit for drilling operation in aircraft manufacturing and assembly industry: A method," *IOP Conference Series: Materials Science and Engineering*, vol. 370, p. 012041, may 2018. [Online]. Available: https://doi.org/10.1088%2F1757-899x%2F370%2F1%2F012041

[18] Digilent. Analog Discovery 2 Reference Manual. [Online]. Available: https://reference.digilentinc.com/reference/instrumentation/analog-discovery-2/reference-manual

[19] Basler. Basler ace USB 3.0 - Product Documentation. [Online]. Available: https://docs.baslerweb.com/basler-ace-usb-30

[20] Fujifilm. HF-HA-1S Series Specification Sheets. [Online]. Available: https://www.fujifilm.com/us/en/business/optical-devices/machine-vision-lens/hf-ha-1s-series