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Automatic Wear Measurement of Ti-Based Coatings Milling via Image Registration

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Abstract

the purpose of this research is to use the machine vision, and combine with image registration mutual information spatial transformation technique for the automatic wear measurement of Ti-Base coated milling. Provide on-line detecting the mill state during the milling processes in order to obtain a better surface quality.

The experimental results indicated that the TiAlN-surface multilayer coated mill had the best performance under the different milling conditions.

Keywords: machine vision, Image Registration, Ti-Based Coatings, Flank Wear.

1 Introduction

The cutting process is a core factor of machining technology in the development of "manufacturing automation". So, to ensure surface quality of cutting workpieces, on-line detection for cutting-tool wear is currently an important research direction of automatic processing know-how. Thanks to its high rigidity, excellent wear resistance and extremely low friction coefficient, Ti-Based Coating is widely applied to cutters' coating materials in order to increase the tool life of cutters.

At present, there are two on-line monitoring methods against the damage of cutters: vision detection, optical or radioactive detection in linear measurement method. However, some efforts shall be made to resolve the problems in terms of reliability, accuracy and barrier of cutting point. Sawai[1] and Maeda[2] et al., measured and estimated the wear parameters of cutters via two-dimensional image processing technology, and obtained the wear conditions by three steps such as comparatively increasing noise, filtering and boundary tracking, while modifying and comparing the geometrical shape before and after wear. BOPP[3] et al., stressed the need of image processing technology to automatically measure the corner wear of drill heads in order to estimate the tool life of drill heads. Besides, Teshima[4] evaluated the remaining tool life of cutters under known cutting environment, and based on neural network, developed a system for evaluating the tool life and wear patterns of cutters from cutting image data and cutting environment. And, according to indirect measurement method, emphasis is placed on the measurement of cutting resistance, cutting force [5~7], relative distance and contact resistance of cutting workpieces, etc. It's very difficult to detect accurately the damage of cutters in the presence of noisy environment or flexible deformation.

Image registration [8] is a key technology in many fields such as computer vision, picture identification or medical image analysis, etc. Recently, image registration method and know-how have played a bigger part in terms of image joining of aerial remote reconnaissance, building identification, comparison and identification of features, fingerprints and footprints for criminal investigation, recovery of fossil's bone and feature in archaeology, dynamic image identification& tracking of unmanned carriers with automatic navigation function, slice registration and pathologic changes identification in medical treatment as well as manufacturing quality control and detection of industrial products, etc. Therefore, there are a number of research efforts in image registration technology.

The research upon registration measurement via mutual information is traced back to early of 1990. As for multiple modality images, Woods et al.[9] firstly introduced the method of registration measurement. Hill et al.[10] improved the method of Woods, and built up a feature space, which is a two-dimensional plane figure showing all corresponding points and gray-level value combination of two images. The difference lies in the definition of area, namely, similar organizations within images are replaced by the areas within feature space. Additionally, Marti et al.[11] put forward a method of calculating the gross quantity of mutual information by Gray-Level Co-occurrence Matrices in lieu of bar chart distribution, whereby the information of image space is added to establish a more universal measurement method.

According to this research, the technologies of Image Registration and Mutual Information, along with similarity analysis and Spatial Transformation technological analysis as well as measurement methods of wear patterns and wear loss, shall replace the method of microscope off-line measurement of wear patterns and wear loss.

2 Experiment Methods

Through three removable coating surface milling slices commercially available, this research has carried out milling test of TiN, TiCN and TiAlN in dry cutting state in

Table 1. milling conditions used in the experiments

No.	Factor	1	2	3
A	coated	TiN	TiCN	TiA1N
B	Speed(rpm)	2546	3183	3820
C	Feed(mm/s)	0.1	0.16	0.25
D	Depth(mm)	0.15	0.3	0.5

parallel with Taiwan Liwei V30 comprehensive cutting machine, namely, cooling without addition of any cutting agent. The workpiece for testing is JIS S45C carbon steel sheet of $100 \times 200 \times 30\,\mathrm{mm}$. And, the optional milling conditions are determined according to the recommended data of coating cutter manufacturers. Meanwhile, three consecutive milling shall be required under different milling conditions, with the milling conditions for experiment plan shown in Table 1.

2.1 Image registration of surface milling

As an optimization process, Registration aims to find out a Spatial Transformation function of optimum space and brightness for realignment of two (or more) two-dimensional (or three-dimensional) images. Thus, Image Registration is defined as the correspondence between the space and brightness of two images. Assuming that I_1 and I_2 represent respectively two-dimensional array of two images of known sizes, and $I_1(x,y)$ and $I_2(x,y)$ represent respectively the brightness value (or other measurement values) of images I_1 and I_2 at position (*x*, *y)*, the correspondence between images can be expressed by the following formula:

$$I_2(x,y) = g(I_1(f(x,y)))$$

Where: f is coordinate conversion in two-dimensional space, which is used to make coordinates x and y correspond to the special coordinate conversion of new coordinates x' and y', namely:

$$(x', y') = f(x,y)$$

And, g is represented by one-dimensional brightness conversion.

2.1.1 Establishment of image sub-area

In this research, the whole image is firstly divided into N×N sub-areas, which are then taken as feature areas and their central points as the feature points.

2.1.2 Searching of matched pairs

The following steps shall be followed to find out the corresponding points via Mutual Information theory:

(1) Calculation of Marginal Entropy

As for continuous or discrete random variables A and B, Shannon-Wiener Entropy *H(A)* and *H(B)* can be defined as:

$$H(A) = -\sum_{a \in A} P_A(a) \log P_A(b) \tag{1}$$

$$H(B) = -\sum_{b \in B} P_B(b) \log P_B(b) \tag{2}$$

Where: $P_A(a)$ and $P_B(b)$ represent Marginal Probability Distribution (MPD) between images A and B, respectively.

(2) Calculation of Joint Entropy

When the joint probability density functions of images A and B $p_{AB}(a,b)$ are known, their joint entropy can be obtained from the following formula:

$$H(A,B) = -\sum_{a \in A}\sum_{b \in B} P_{AB}(a,b) \log P_{AB}(a,b) \tag{3}$$

(3) Calculation of Mutual Information

Mutual Information can be used to measure a variable's information content that's included in another one. After obtaining Marginal Entropy and Joint Entropy of images A and B, the Mutual Information of A and B can be acquired by the following formula:

$$MI(A,B) = H(A) + H(B) - H(A,B) \tag{4}$$

Thus, it's possible to achieve the maximum value of Mutual Information, and find out optimum parameter t for Spatial Transformation T_α leading to Image Registration:

$$T_\alpha = \arg\max_t I(A, B^t) \tag{5}$$

Where: $I(A,B^t)$ is MI of images A and B converted by parameter t, and T_α is the position of $I(A,B^t)$ at its maximum value. When optimum registration parameter T_α is found out, the maximum value of $I(A,B^t)$ is obtained by exhaustive searching.

2.1.3 Measurement of correlation coefficient

The second step for registration option is to choose the method of measuring the similarity level of two images. The similarity measurement is closely related to the matching feature used by feature space. After extracting the information to be matched from every image, calculate the degree of similarity between two images via similarity measurement and find out an optimum spatial coordinate transformation parameter. In other words, the accuracy of registration can be judged according to the similarity level among measured images. In this research, Correlation Coefficient (CC) is used to measure the similarity level between two images.

By comparing reference image I_R and registration comparison image I_C, the similarity level can be evaluated, of which dx and dy are lines and columns of images. $I_R(x,y)$ and $I_C(x,y)$ represent respectively the brightness value of center point coordinate (x,y) of reference image I_R and center point coordinate (x,y) of registration comparison image I_C; μ_R and μ_C are average brightness of reference image and comparison image, respectively.

$$CC = \frac{\sum_{x=1}^{dx}\sum_{y=1}^{dy} (I_R(x,y) - \mu_R)(I_C(x,y) - \mu_C)}{\sqrt{\sum_{x=1}^{dx}\sum_{y=1}^{dy} (I_R(x,y) - \mu_R)^2 \sum_{x=1}^{dx}\sum_{y=1}^{dy} (I_C(x,y) - \mu_C)^2}} \tag{6}$$

2.2 Spatial Transformation

In order to remove the spatial difference of two images, this step will, based on preselected spatial correspondence relationship, transform the spatial coordinates of images by the matched pair obtained in aforesaid step. It's worthy to note that, Spatial Transformation model plays a key role in Image Registration. If the selected Spatial Transformation model cannot reflect properly the spatial correspondence relationship of two images, the results of spatial coordinate transformation are unsuitable for subsequent image matching.

Owing to rigid deformation arising from shift of surface milling cutter, the objects within the image will maintain the shape and size. Rigid transformation comprises Rotation(θ), Translation(t_x and t_y) and Scaling(s). As a most commonly used spatial transformation, rigid transformation is fully capable of matching two images obtained from the same viewing angle but at different positions. If assuming (x_1, y_1) represents a certain point of the first image, the corresponding point (x_2, y_2) of (x_1, y_1) on the second image can be obtained from the following rigid transformation equation:

$$\begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = \begin{pmatrix} t_x \\ t_y \end{pmatrix} + s\begin{pmatrix} \cos & -\sin\theta\theta \\ \sin & \cos\theta\theta \end{pmatrix}\begin{pmatrix} x_1 \\ y_1 \end{pmatrix} \quad (7)$$

Where: θ is represented by rotation angle, t_x and t_y by translation amount along the direction of x and y, and s by scaling ratio.

2.3 Image Subtraction and Final treatment

Perform logic subtraction of two images before and after milling, namely, surface milling cutter's wear image XOR(original image of surface milling cutter, image to be measured after milling).

2.4 Analysis of Wear Image

After final treatment of images, you can get an image at one wear position of milling cutter. Next, analyze the wear via the aid of computer. Shall be used to develop a user-friendly window interface program for convenient wear analyze of cutting-tools, etc.

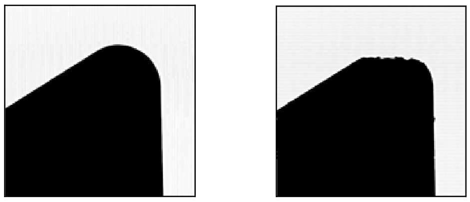
3 Results and Discussion

Based on the principle of Spatial Transformation in collaboration with similarity analysis of Image Registration and Mutual Information, this research strives to explore on how to measure the wear of different Ti-based coating surface milling cutters after Image Registration under different milling conditions. The similarity analysis of Image Registration and wear loss measurement are described below:

3.1 Result of Image Registration

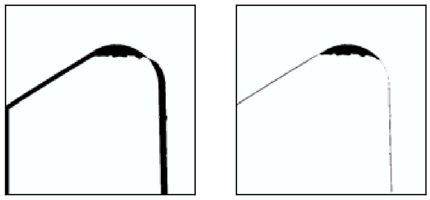
According to different milling conditions of test plan, this research has carried out three consecutive milling of different coating surface milling slices in dry cutting state in parallel with Taiwan Liwei V30 CNC machine center. When every milling program is finished, capture wear image of milling via CCD, and process original images prior to milling. Figure 1 shows the images before and after milling of surface milling cutters, of which (a) shows original image prior to processing of milling cutter, and (b) shows the wear image after three times milling.

The results of image registration analysis are shown in Fig.2. In the case of any offset of position or angle on the captured images of milling cutters before and after milling, it's likely to generate wrong results after image subtraction, leading to increasing difficulty and improper



(a) (b)

Fig. 1. The images before and after milling of surface milling cutters (a) original image (b) the wear image after three times milling.



(a) (b)

Fig. 2. The results of image registration analysis (a) pre- registration (b) post-registration.

Table 2. similarity analysis of image registration

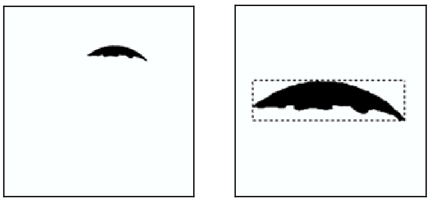
milling	pre- registration		post-registration	
	CC	SSD	CC	SSD
TiN	0.865	5.241	0.903	3.508
TiCN	0.869	3.811	0.945	1.053
TiA1N	0.845	6.404	0.901	0.764

judgment on automatic wear measurement of milling cutters. According to image subtraction in Fig.2, the result prior to registration is shown in (a), wherein wear areas (black portion) cannot be display properly due to offset of position. The result after image registration is shown in (b), wherein the black areas display correct wear position and size of milling cutter. Therefore, it's practicable to obtain correct wear area and wear loss of milling cutter after Image Registration.

3.2 Similarity Analysis of Image Registration

The measurement of similarity level is primarily intended to offer an objective evaluation standard as to whether optimum registration can be realized. In other words, the accuracy of registration can be judged through the similarity level between measured images. In case related coefficient approaches 1, there is a correspondence of height between images. In case related coefficient is equal to 1, there is no difference between two images.

It can be learnt from Table 2 that, the accuracy of registration could be judged through the similarity level between measured images after Image Registration. Meanwhile, it can be leant from the results of Correlation Coefficient (CC) that, CC value is between 0.901~0.945 after registration. Besides, in the case of absence of difference between images, sum of square difference (SSD) is zero. As shown in Table 2, SSD of TiA1N is the smallest and that of TiN the biggest. Accordingly, it's predicted that and that of TiN the biggest. Accordingly, it's predicted that TiA1N can present optimum wear resistance, and then followed by TiCN.



(a) (b)

Fig. 3. The results of morphological process and wear analysis (a) morphological process (b) milling wear analysis.

Table 3 The result of the measurement milling wears

Trial	A B C D 1 2 3	1st milling wears (mm)	2nd milling wears (mm)	3rd milling wears (mm)
1	1 1 1 1	0.046	0.130	0.144
2	1 2 2 2	0.026	0.066	0.108
3	1 3 3 3	0.035	0.093	0.142
4	2 1 2 3	0.031	0.067	0.102
5	2 2 3 1	0.042	0.072	0.099
6	2 3 1 2	0.038	0.094	0.121
7	3 1 3 2	0.027	0.079	0.097
8	3 2 1 3	0.025	0.068	0.093
9	3 3 2 1	0.031	0.077	0.116

3.3 Wear Test of Milling

According to different milling conditions of test plan, three consecutive millings are implemented for wear analysis based on images of milling cutters. Therefore, it's possible to measure the wear loss of cutters in tune with correct wear analysis result of milling cutter from section 3.1 and 3.2. The wear measurement of milling cutters is based on the maximum value (VB_{max}) within wear areas.

Figure 3 shows the results of image final process and wear analysis, of which Fig.3(a) is the result of Fig.2(b) after morphological process, and can present properly the entire wear area and size of milling cutter. Fig. 3(b) is the calculation result of wear area and maximum height (VB_{max}) by means of Blob Analysis and MEAS_BOX in MIL function library.

Table 3 shows the wear measurement results of different Ti-based surface milling cutters under the milling conditions of test plan, of which TiAlN offers optimum average wear loss.

4 Conclusion

According to this research, the technologies of Image Registration and Mutual Information, along with similarity analysis and Spatial Transformation technology as well as measurement methods of cutter's wear loss, can serve the purpose of on-line measurement in lieu of traditional method of microscope off-line measurement. Meanwhile, this paper has given a detailed description of the framework of automatic measurement system and the wear test principle of cutters. The experimental results show that, among three coating surface milling cutters, TiAlN-multilayer coating can offer minimum wear loss and optimum milling performance.

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