Statistical evaluation of a fixed diamond wire surface topography using a deep learning

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Keywords: Diamond wire, Abrasive grain, Statistical evaluation, Deep learning, Convolutional neural network, Image processing

Abstract. A fixed-diamond wire is employed to slice semiconductor materials. The wire surface topography influences the roughness of the substrate. Thus, it is very important to measure the distribution of abrasive grains. In this study, a statistical evaluation method of the distribution has been proposed using a method of "deep learning". It is not practical to measure the wire topography in a static state, because the wire length is over a hundred kilometers. For this reason, running wire surface images are captured using a high-speed camera. Abrasive grain imagery extracted by the camera will provide the source for the pattern recognition (deep learning) process. Additionally, location coordinates of those abrasive grains are calculated. Here, assuming that the distribution follows the Poisson distribution, the number of grains in a length of analysis interval is not dependent on any location statistically. Conversely, this means that the length can be employed as a criterion indicating the distribution state. Finally, an effectiveness of those proposed methods is shown in an experiment.

Introduction

Long-term renewable energy sources have been attracting attention because they offer a low environmental load, sustainability and high cost-effectiveness [1]. Photo-voltaic power generation is one of the most famous technologies, and it has been introduced all over the world. The most common construct is many photo-voltaic arrays which are in serial / parallel connection of solar battery cells constituted by a polycrystal or a single crystal silicon wafer. Thus, each cell's conversion efficiency from solar energy to electrical energy is very important [2]. Therefore, it demands that a uniform thickness and a surface roughness of high accuracy for the substrate be retained in order to increase the efficiency. The silicon wafer is conventionally processed by slicing a silicon ingot with a loose grain wire method [3]. However, this method has some problems. One is that a kerf loss is comparatively large because it is difficult to manufacture a thin wire due to damage to the wire surface by the slurry. Another issue is that removing of metal chips from the used slurry is difficult. In contrast, a fixed grain method has been recently employed. In a comparison of the conventional loose grain wire method, this has a high efficiency and a small kerf loss [4]. Additionally, the burden of the waste fluid processing is small. However, the distribution of abrasive grains on the wire surface influences the surface roughness and the thickness of the substrate. This is due to the abrasive grains are bonded to the wire surface in the fixed grain method. Thus, measuring the distribution is very important in order to process with a high degree of accuracy. For this problem, a scanning electron microscope(SEM) is generally employed [5]. This apparatus can obtain a detailed image with extremely high magnification. However, it takes a comparatively long time to capture images since the wire is over a hundred kilometers. Thus, this is not a practical method.

In this paper, a statistical evaluation method of the distribution of the diamond abrasive grain on the wire surface has been proposed using a method of deep learning. A running wire surface image is captured using a high-speed camera. The abrasive grains on the diamond wire are captured via the camera and provide the source for the "pattern recognition" (deep learning) process. Additionally, coordinates of those abrasive grains are calculated. Here, abrasive grains are not uniformly bonded on the wire surface. Thus, the distribution state depends on any measurement points. Therefore, it is very important to determine a suitable length of the analysis interval. When the distribution follows the Poisson distribution, the number of grains in the relevant length is not dependent on any location statistically. This means that the length can be employed as a criterion indicating the wire surface topography. Finally, the effectiveness of the proposed method is verified by an experiment.

Image capturing using a high speed camera

A measurement system is shown in Fig. 1, and the specification is shown in Table. 1. Running wire surface image is captured by a high-speed camera. In this experiment, an electrodeposited diamond wire is employed, and the running speed was fixed at about 200m/min. Furthermore, the frame rate of the camera was set at 20,000fps. This camera has an internal memory of 8 megabytes. In this case, it can take images for about 3.7 seconds. The captured image is shown in Fig.2. In this image, the dark gray part shows an electrodeposition surface, the bright gray small circular part and the dark gray which is bulged from the upper and lower wire edge face show the abrasive grain. From this image, it is found that it has become the blurred image as a whole. Thus, it is easy to ascertain that obtaining accurate abrasive grain data using photo imaging techniques could be difficult. In this proposed method, a convolutional neural network is implemented. This is one type of "deep learning".

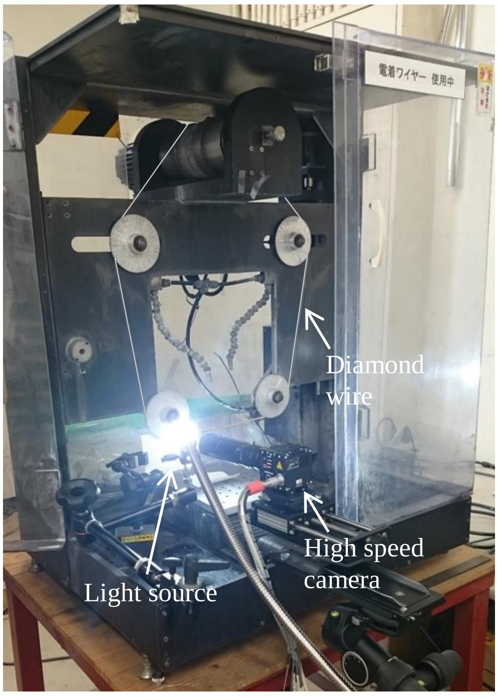


Fig.1 Diamond wire saw

Extraction of diamond abrasive grain by a convolutional neural network

It is difficult to view the abrasive grain from the unclear image with a high degree of accuracy using the conventional image processing method. On the other hand, a convolutional neural network(CNN) is a deep learning technology that can be employed [6]. The neural network has proven very effective in areas such as image recognition and classification. As an application of the CNN network, an image style transfer algorithm has been proposed [7]. The network is generally given such as a structure in Fig. 3. This consists of an input layer, output layer, and multiple hidden layers. The hidden layer also consists of convolutional layers, pooling layers, deconvolution layers, and unpooling layers. The convolutional layer includes

Table.1 Specification

Bond	Electrodeposition
Grain	Diamond
Grain size	30μm
Wire diameter	160 μm
Wire speed	Approx. 200 m/min
High speed camera	nac Image Technology Inc. MEMRECAM Q1v
Frame rate	20,000fps
Resolution	640px x 144px
Image size	3657.1μm x 822.9μm

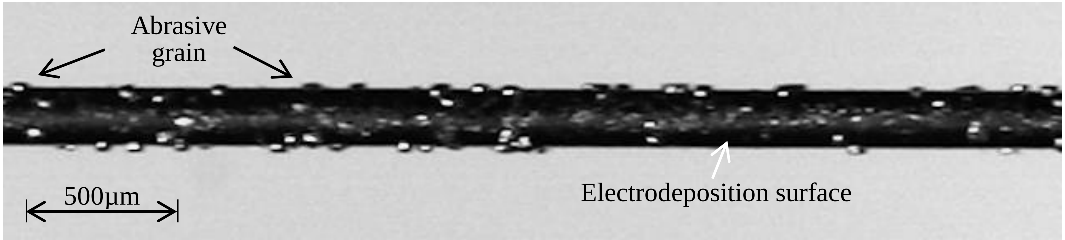


Fig.2 Diamond wire surface

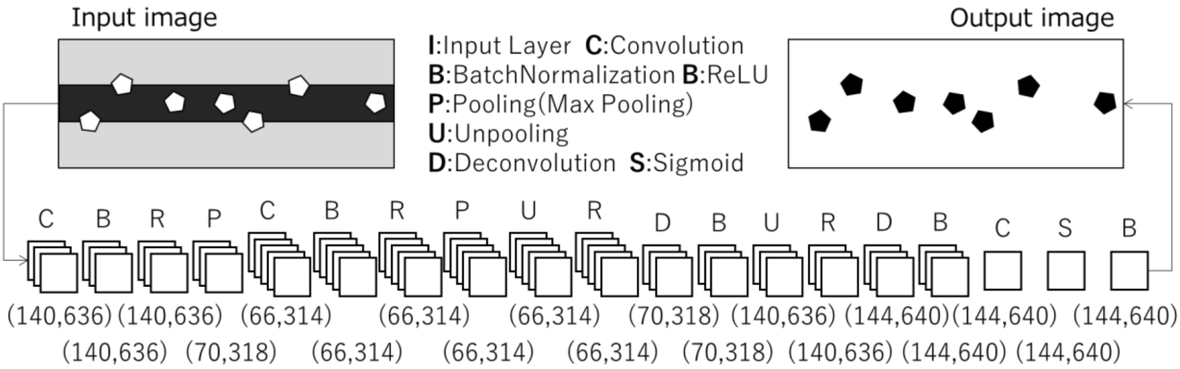


Fig.3 Convolutional neural network

weight parameters which are adjusted outputting the desired results. In our proposed system, the captured wire surface image is given for the input layer. The desired output is set as an extracted image of abrasive grains. Weight parameters are learned to output the desired image when a wire surface image is given to the network. Finally, the location coordinates of all extracted abrasive grains are calculated from transferred style images which are obtained from the learned CNN network.

Statistical evaluation of a variance value of abrasive grain

Abrasive grains are not bonded uniformly on the wire surface. This means that a prescribed processing accuracy is not more likely to be provided. Thus, it is very important to grasp the distribution of the abrasive grains on the wire surface. However, even if the surface topography can be analyzed by the image processing, a measurement of the whole wire surface is not practical, because the length is over a hundred kilometers. Therefore, a suitable

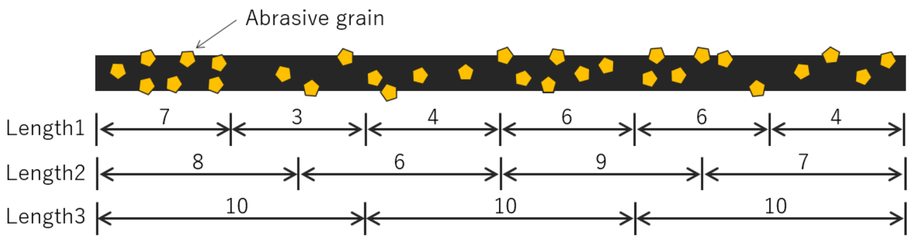


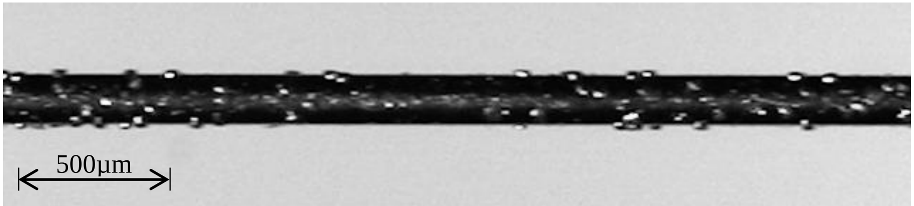
Fig.4 Statistical evaluation of the wire surface topography

measurement length of an analysis interval must be determined numerically. The number of grains in the length is not dependent on any location statistically as shown in Fig. 4, when the distribution of abrasive grains follows the Poisson distribution. For this reason, the length can be employed as a criterion indicated by the wire surface topography. In this method, the suitable length is determined based on the location result using the CNN network and the conventional image processing.

Experimental results

First of all, 73,126 wire surface images such as Fig. 5a were captured under the conditions of Table. 1. Next, 3048 surface images which are continued without overlapping were set as the test dataset. Furthermore, 20,000 and 1,000 images respectively were set as a training data set and a validation dataset from images except for the test dataset. Here, the training dataset and the validation dataset don't include any of the same images. The training dataset is employed to adjust the weight parameters in the hidden layers, and the ability of the CNN model is evaluated by the validation dataset. These learning and validation are operated 1 time(epoch). Finally, the performance is assessed by the test dataset. The datasets don't have any of the same captured images in order to give a high versatility to the CNN network. Fig. 5b shows the CNN output image. From this result, it is found that the abrasive grain data was extracted with a high degree of accuracy. The recall factor was 0.95.

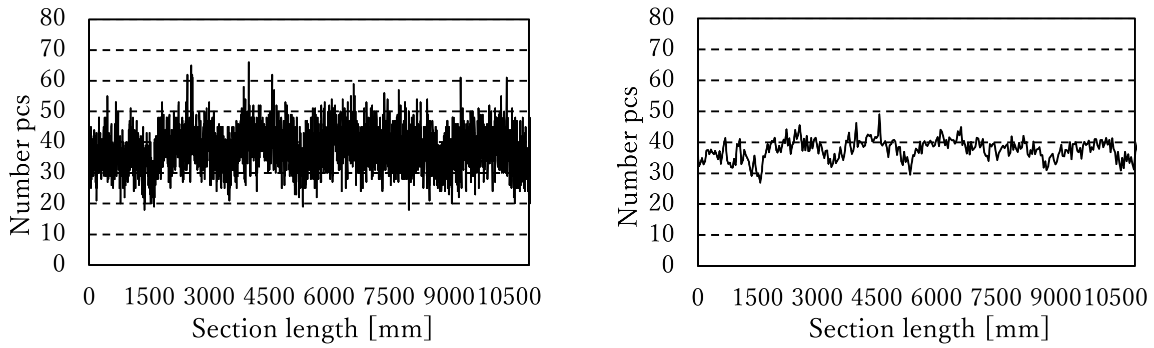
After that, the average number of abrasive grain in 3.65mm was calculated every 3.65mm and 36.6mm based on the location coordinate of all extracted abrasive grain. Moreover, the standard deviation of the distance between nearest abrasive grains was obtained on the same length of the analysis interval. These results are shown in Fig. 6 and Fig. 7. From these results, it is found that the fluctuation range is narrower in the 36.6mm than the 3.65mm. Next, the



(a) Captured wire surface image

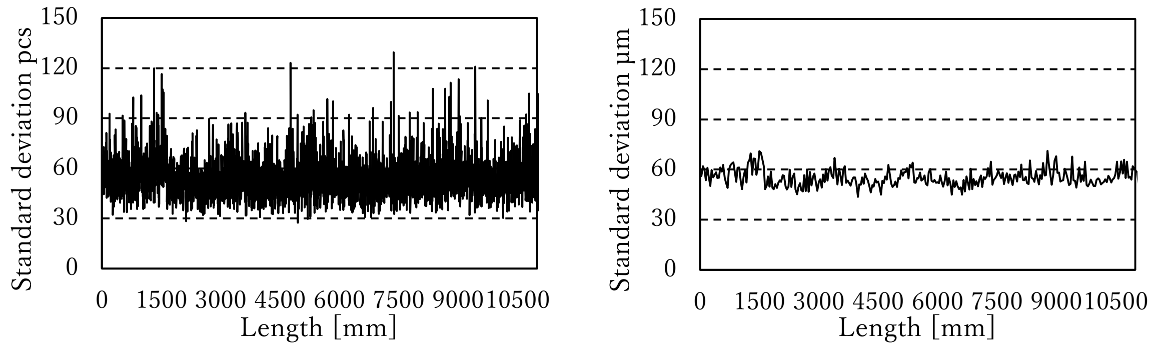
(b) Extracted image of abrasive grain

Fig.5 Extracting result



(a) Every about 3.65mm (b) Every about 36.6mm

Fig.6 Average number of abrasive grains in 3.65mm



(a) Every about 3.65mm (b) Every about 36.6mm

Fig.7 Standard deviation of the distance between nearest abrasive grains

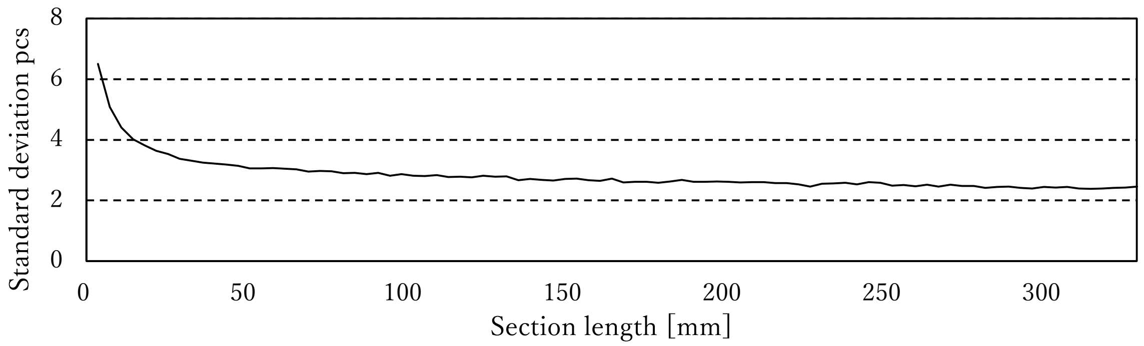


Fig.8 Standard deviation of the number of abrasive grain per section length

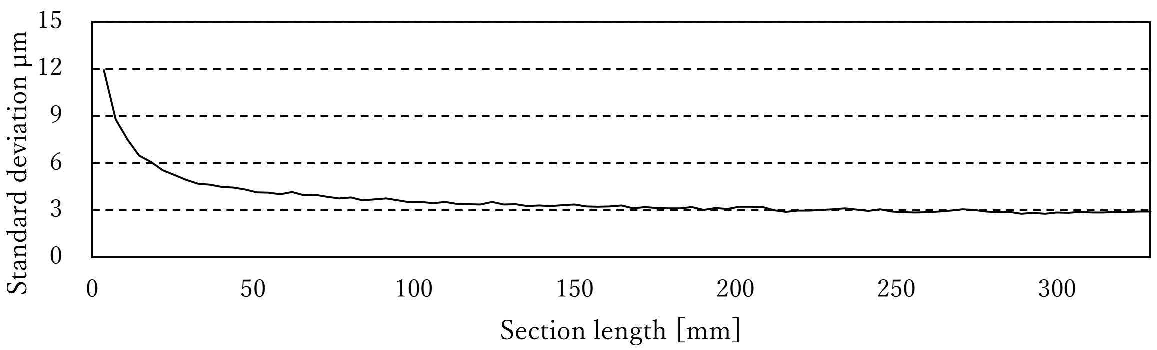


Fig.9 Standard deviation of the distance between nearest abrasive grains per section length

number and the standard deviation were calculated while changing the length of the analysis interval. The results are shown in Fig.8 and Fig.9. From these results, it is found that both chart lines decrease rapidly until the intervals are 50mm, and they remain stable from 250mm. As these results, the criteria value for the distribution of abrasive grains on the wire surface became approximately 250mm.

Summary

In this report, a statistical evaluation of a fixed diamond wire surface topography using a method of deep learning has been proposed. The running wire surface image is captured by a high-speed camera, and abrasive grain pattern data are extracted from the captured image by a CNN. In addition, a suitable measurement range which represents a condition of a wire surface topography is determined by a statistical method. As a result of the experiment, the following facts were verified.

- The running wire surface image can be captured in 200m/min approximately.
- A high degree accuracy in extracting abrasive grain data using a CNN can be obtained more efficiently than the conventional image processing methods alone
- A suitable length of analysis which can evaluate the wire surface topography is determined by the statistical method.

This means that this method has enough plausibility which could be employed for the wire manufacturing process by on-machine.

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