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ORIGINAL ARTICLE

Investigation on diamond wire break-in and its effects on cutting performance in multi-wire sawing

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Abstract Multi-wire sawing with diamond wire is used to slice hard and brittle materials such as sapphire, silicon carbide, or silicon into thin wafers. Compared to traditional slicing methods, multi-wire sawing with diamond wire has many advantages, including reduced kerf loss, efficient machining, and improved form accuracy. However, the process is associated with several unexpected problems, including considerable kerf loss and inefficient cutting during the initial cutting step. Thus, materials cannot be constantly removed due to the instability of the cutting performance of the diamond wire. These phenomena are defined as the break-in characteristics of diamond wire. This paper focused on the break-in characteristics of diamond wire and the effects of these characteristics on the cutting performance. In an experiment, a single-wire sawing machine equipped with a monitoring system was used to analyze the horizontal and vertical cutting forces which arose during the cutting process. The cutting performance was evaluated by means of cutting profile measurements. The wires used were analyzed by the newly developed vision measurement system and through scanning electron microscope (SEM) imagery. On the basis of results, it was found that the break-in characteristics of diamond wire are strongly correlated with the wear behaviors of the diamond wire.

Keywords Multi-wire sawing · Diamond wire · Break-in · Process monitoring · Cutting force · Wear · Cutting performance

1 Introduction

Loose abrasives and bare wire are used in early forms multi-wire sawing in the 1990s. This process was utilized for the production of silicon wafers with minimum warpage, uniform thicknesses, and low kerf loss wafers for semiconductors [1–3]. The growth of the photovoltaic and light-emitting diode (LED) industries in the 2000s increased the importance of multi-wire sawing technology and has accelerated the technical advances in this field. However, multi-wire sawing with loose abrasives is associated with a number of serious problems at present. The first of these is the transition of the dimensions of the silicon wafer. Wafer sizes have increased, and wafers have gotten gradually thinner. Therefore, it is more difficult to keep the surface integrity uniform within a wafer and to prevent the wafer from breaking when it is machined. One of the main causes of this problem is that the abrasives used do not uniformly exist in the contact area between the workpiece and the bare wire as the wafer size increases. Moreover, this phenomenon induces an unstable cutting condition and fluctuations in the cutting performance. The second issue is caused by the higher demand for machining efficiency. Specifically, single-crystal materials for LEDs, such as sapphire, silicon carbide, and gallium nitride, are harder and more difficult to cut compared to silicon, and machining these materials requires a considerable amount of time. It is also necessary to improve the throughput by minimizing the kerf loss, as these materials are typically very expensive. Owing to these problems, fixed abrasive wires have been utilized recently in the multi-wire sawing process. The appearance of diamond wire helped to overcome the above problems [4, 5]. However, multi-wire sawing with diamond wire continues to be plagued by problems such as considerable kerf loss and inefficient cutting during the initial cutting step [6].

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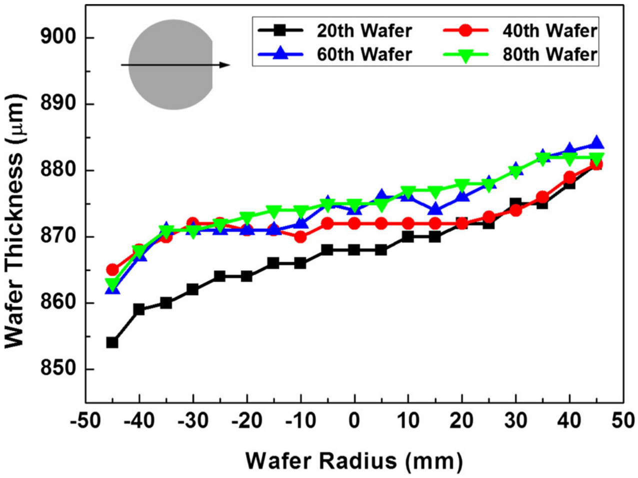
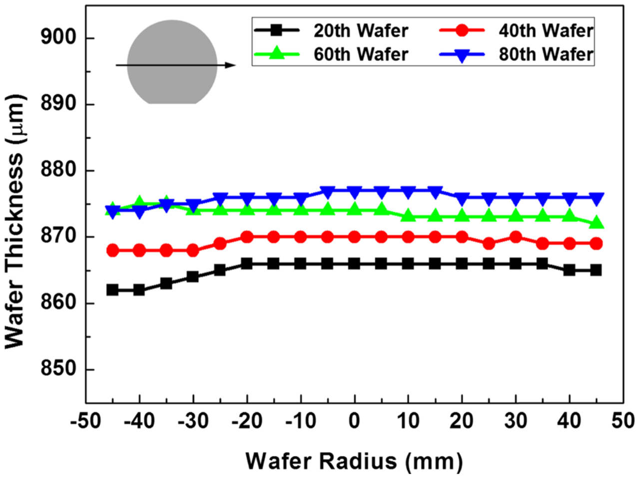
In this paper, these phenomena are defined as the break-in characteristics of diamond wire. To investigate the break-in characteristics and its effects on the cutting performance, experiments were carried out using a single-wire sawing machine with a monitoring system. During the machining process, the cutting forces applied to workpiece were monitored and analyzed. The wear characteristics of the wires used were analyzed by the newly developed vision measurement system. This was done to determine the correlation among the cutting force, the amount of wear to the diamond wire, and the break-in characteristics.

2 Multi-wire sawing with diamond wire

Figure 1 shows the cutting results of a 4-in sapphire ingot for a LED. The wire travel speed was 900 m/min, and the feed rate of the ingot was controlled in accordance with the contact length between the diamond wire and the ingot. The results show that a large percentage of the thickness variation within the wafer occurs in the cutting feed direction. Moreover, the wafer thickness increases along the cutting feed direction. For this reason, the diamond wire is gradually worn during the cutting process. The decrease in the diameter of the diamond wire causes a decrease in the amount of kerf loss. Specifically, the wafer thickness changes rapidly in the region of the wire cutting inlet due to the break-in characteristics of the diamond wire.



(a) Cutting feed direction



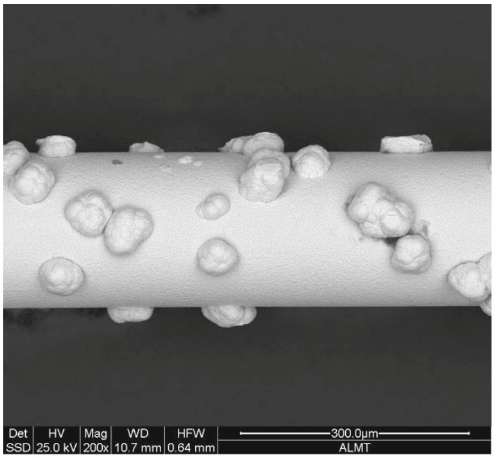
(b) Wire travel direction

Fig. 1 Thickness variation of the as-sawn wafer

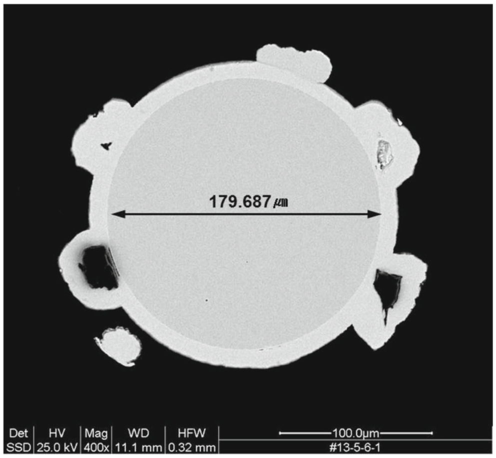
To manufacture diamond wire for multi-wire sawing, various methods can be used. The method used depends on whether the type of bonding material between the wire and the diamond abrasive is a metal or a resinoid material. For metal bonding, the following methods can be used: (1) nickel-diamond composite electroplating and (2) a mixed coating of an alloy with a low melting point and diamond abrasives [7, 8]. With resin bonding, the mixture of the resinoid and the diamond abrasives is coated onto the wire and cured by thermal or light energy [9]. Between the two methods, nickel-diamond composite electroplating is most commonly used because it has good wear resistance and a long lifetime. In addition, when using this method, it is relatively easy to control the characteristics of the diamond wire, such as the diamond density and bonding strength, by changing the electric conditions. Figure 2 shows the surface and a cross-section image of diamond wire processed by means of nickel-diamond composite electroplating.

3 Experiment method and conditions

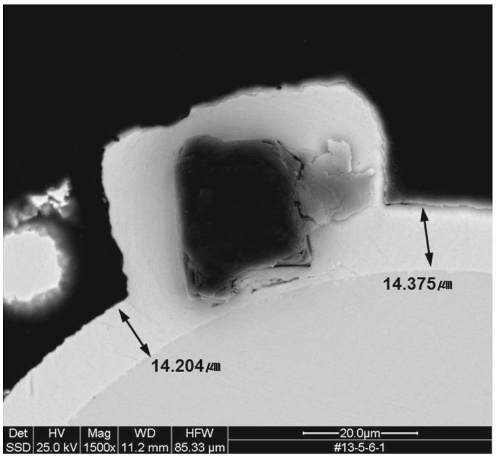
Figure 3 shows the single-wire sawing machine and a schematic of the monitoring system. This test machine is equipped with two wire spools between which diamond wire runs back and forth periodically. The driving motor to wind the spool also produces the wire speed, and the driving motor which unwinds the spool provides tension to the wire. The controllable wire speed with the system is as high as 600 m/min. The wire tension is controllable between 10 and 50 N. The wire tension is monitored by two load cells and is maintained by tension control servo dancers and by the motor which unwinds the spool. The size of the workpiece which can be installed onto the system is up to 100 mm, and the cutting recipe is programmable up to as many as 30 steps. Two force sensors are implemented in the workpiece mounting stage to monitor the horizontal and vertical force in real time, and the sensors are moved with a saddle. One of the sensors is fixed along the wire travel direction to monitor the horizontal force, and the other is fixed along the cutting feed direction (i.e., perpendicular to the wire travel direction). The raw signals of the force sensors are followed by signal processing steps such as amplification and filtering. The processed data can be monitored and saved automatically on a computer.



(a) Surface

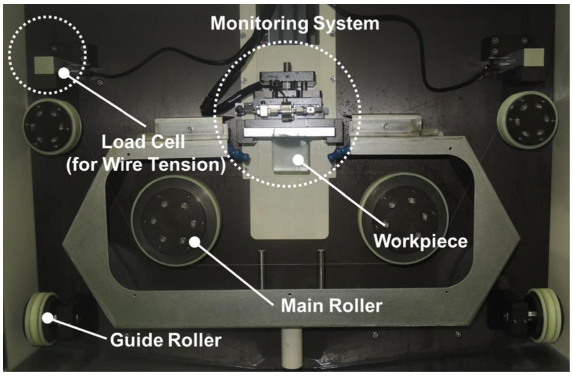


(b) Cross-section

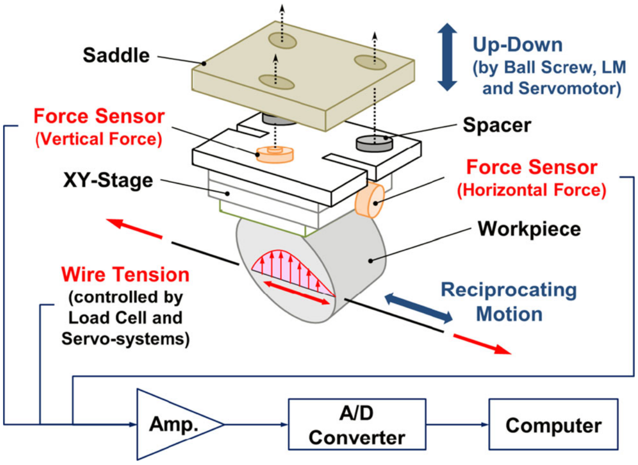


(c) Detail of the cross-section

Fig. 2 SEM images of diamond wire



(a) Single-wire sawing machine



(b) Schematic of the monitoring system

Fig. 3 Single-wire sawing machine with a monitoring system

In the experiment, a glass block was sawn by two different types of diamond wire. The diamond wires were chosen from the commercial products that are most commonly used in sapphire multi-wire sawing. The diamond abrasives, with a primary particle size of 30–40 µm, were fixed onto an Ø180-µm core wire by Ni electroplating. The apparent specifications and properties of the two wire types were nearly identical. The characterization step found a difference in the number of diamond abrasives per unit of wire length through observations with a digital microscope. Wire B had approximately 1.5 times more abrasives than Wire A. The wire travel speed was 400 m/min, and the wire tension was 40 N. The cutting feed and the total feed depth were 0.5 mm/min and 6.67 mm, respectively. The number of contact times between the wire and the glass was 100 per run, and 6 runs in total were carried out for each diamond wire. Table 1 shows the experimental conditions in more detail.

A vision measurement system and a scanning electron microscope (SEM) were used to observe and analyze the surface conditions of the diamond wires. The vision measurement system was newly developed to investigate the wear characteristics of diamond wire during the cutting runs. SEM or digital microscope is one of the most general methods to measure the diamond wire quantitatively. However, this method is possible to obtain data for a certain point, while it is impossible to measure the profile of diamond wire. The diamond abrasives are irregularly positioned on the wire, and the

Table 1 Experimental Conditions

Parameters	Conditions
Workpiece	Glass block, 50×50×15 t [mm]
Wire type	Ni-electroplated diamond wire A and B Core wire Ø180 [μm], diamond size 30–40 [μm]
Wire travel speed and tension	400 [m/min] and 40 [N]
Cutting feed and amount	0.5 [mm/min] and 6.67 [mm]
Contact times per run	100 (a total of six runs for each wire)
Cutting water	DKW-1P (dilution ratio with water=1:10)

bonded shapes are different from each other. The wear of diamond wire is not uniform during the cutting process because the twisted wire while being traveled changes the wire surface in contact with workpiece continuously. In this conditions, the profile data of diamond wire helps to analyze the diamond wires more effectively.

Figure 4 shows a schematic of the vision measurement system and its measurement algorithm to measure the profile of diamond wire quantitatively. The vision measurement system for diamond wire was composed of a digital vision camera, a macroscopic lens, a lighting system, and a motorized rotary stage. Also included were precision adjustment units, in this case a goniometer, a micro XY-stage, and a wire position aligner. This system was placed on the wire travel path, and in-line measurements were taken. A backlight image was captured to measure the diamond wire, with all cases undergoing image processing steps such as gray scaling, image binarization, and gradient correction. The effective data were extracted from the processed image, which were summarized statistically. After each run, diamond wire measurements were carried out with an interval of 1 m, with 40 measurements overall. The evaluation length within the captured image was 1 mm. During the data processing step, the wire surface was excluded from the measured results, and the distribution of the diamond extrusion height was expressed as a percentage.

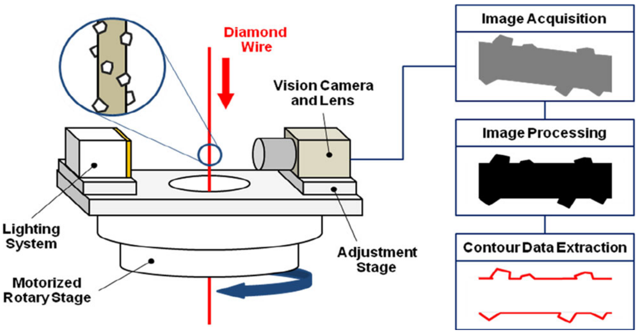


Fig. 4 Schematic of the vision measurement system and its measurement algorithm

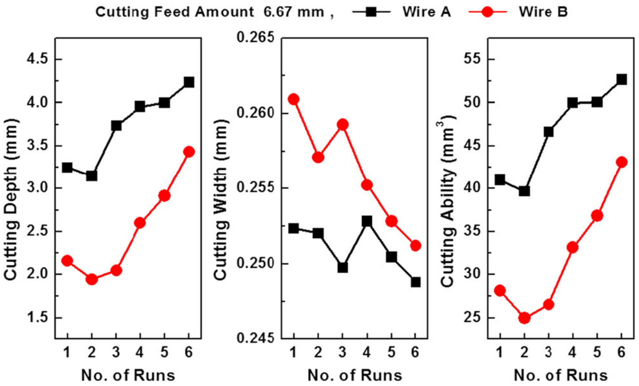


Fig. 5 Cutting performance during cutting runs

4 Experimental results

4.1 Cutting performance and cutting forces

Figure 5 shows the results of the cutting performance as the cutting runs progressed. With regard to the cutting depth, wires A and B had a transition segment near the second and third run, respectively. After the transition segment, Wire A gradually increased and stabilized according to the runs, while Wire B continuously increased. The cutting depth and the transition period of Wire A were larger and shorter, respectively, than those of Wire B, although Wire A had fewer diamond abrasives per unit of length. For the cutting width, Wire B was slightly wider than Wire A. The cutting width as the runs progressed gradually decreased in both wires. The trend of the cutting ability, referring to the cutting volume, was identical to that of the cutting depth. Thus, it was found that Wire A is superior to Wire B with respect to the cutting ability within the range used in this experiment. Wire B needed more process time to match the cutting ability of Wire A.

While the diamond wire saws a workpiece, it is deflected by the action of workpiece feeding and by the elasticity of the diamond wire. The vertical force is the repulsive force applied by the diamond wire to the workpiece. Its amplitude is an important indicator that can determine whether or not the cutting process is suitable. The horizontal force is the frictional force that contributes to material removal, providing information about any changes of the contact condition between the workpiece and the diamond wire. In general, if the contact condition is constant, the horizontal force may be proportional to the vertical force on the basis of Coulomb friction.

Figure 6 shows the variation of the horizontal and vertical forces during the cutting process. In the experiment, the acquired raw signals were presented in the form of the root mean square value (RMS) after signal processing. The vertical force of Wire A and Wire B increased in the second and third run, respectively, and gradually decreased upon subsequent runs. The trend in the variation was opposite to that of the cutting depth, as shown in Fig. 5. This explains why the accumulation

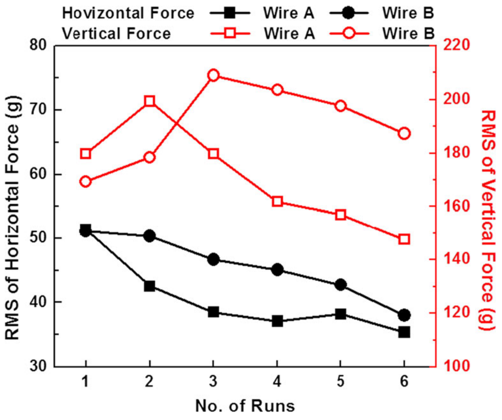
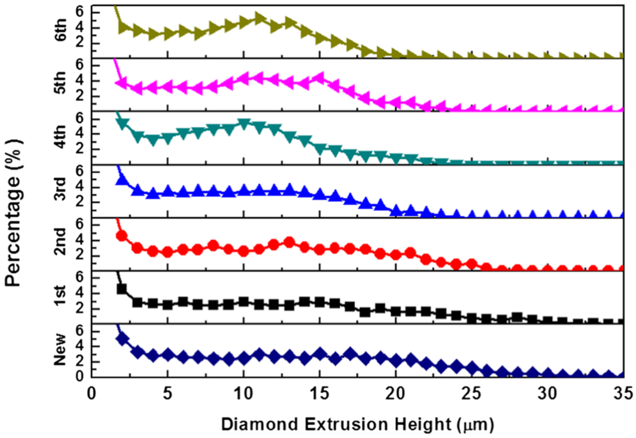
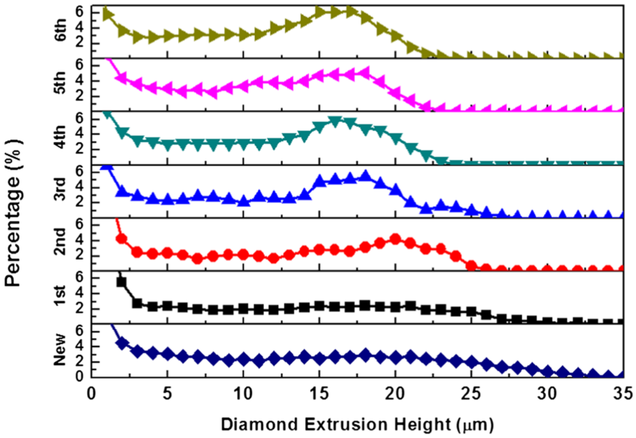


Fig. 6 Cutting force during cutting runs



(a) Wire A



(b) Wire B

Fig. 7 Distribution of the diamond extrusion height during cutting runs

of an uncut amount during the cutting process affected the amplitude of the vertical force. With the cutting runs, the horizontal force of Wire A gradually decreased and became saturated, while that of Wire B continuously decreased. One remarkable finding was that the trend in the variation in this case was not influenced by a change of the vertical force. This indicated that the surface condition of the diamond wire in contact with the workpiece changed continuously during the cutting process.

4.2 Wear characteristics of diamond wire

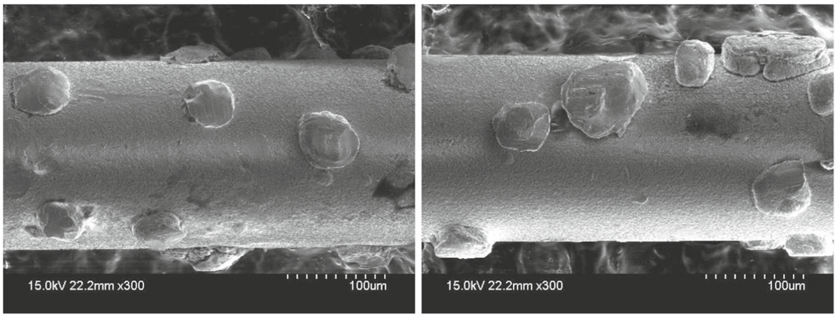
Figure 7 shows the analysis results of the diamond wires using the vision measurement system. For Wire A, wearing of the new wire started from the highest spots as the cutting proceeded. From the first run to the third run, the maximum height was gradually reduced, but the profile of the diamond height distribution was rarely changed. The hill in the profile appeared first during the fourth run, indicating that the distribution of a certain height rapidly increased. Subsequently, the profile including the hill was maintained to the sixth run, and the reduction of the maximum height slowed after the third run.

The wear trend of Wire B was similar to that of Wire A. However, the wear rate was slower than that of Wire A. The appearance of a hill in the profile was noted sooner, in the second run, and its position was, in this case, at a lower height during the third run. The height difference between the peak of the hill and the maximum height was smaller than that of Wire A. The wire surface was observed by SEM in order to investigate the characteristics of the changes in the profile.

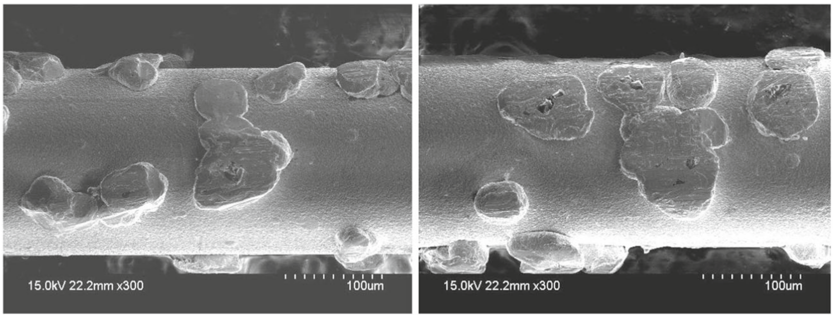
Figures 8 and 9 show SEM images of each diamond wire with the cutting runs. In Wire A, the diamond abrasives of the new wire had a round shape, and they were entirely coated by the electroplated Ni layer. The top side of the diamond abrasives was worn down gradually and flattened during the first and second runs, and pieces of diamond grit were rarely discovered. After the third run, some of the diamond grit was partially exposed from the electroplated Ni layer. As the cutting runs progressed, the number of exposed pieces of diamond grit increased. In Wire B, the wear characteristics were similar to the initial wear behaviors of Wire A; its wear rate was much slower. Wear of most abrasives was observed after the third run, and the flattened area of the abrasive top side gradually increased with the cutting runs. A few pieces of diamond grit were locally exposed at the fifth run. For this reason, the cutting force per unit of abrasive decreased with an increase in the amount of abrasives. In the data of Fig. 6, the horizontal cutting force, which causes the abrasive to wear, was greater in the case of Wire B. However, the applied force per unit of abrasive was lower than that of Wire A.

From the above results, the hill in the diamond height distribution profile was created by the flattened area due to the wear of the diamond abrasives. The position and emergence time of the hill were determined by the wear rate of the diamond abrasive. The difference in the height between the hill peak and the maximum height became larger with the number of exposed diamond grit pieces. The hill (i.e., the flattened area) could make sliding in contact with the workpiece easier, and the horizontal force was reduced.

Fig. 8 SEM images of diamond wire during cutting runs (Wire A)



(a) New wire (b) First run

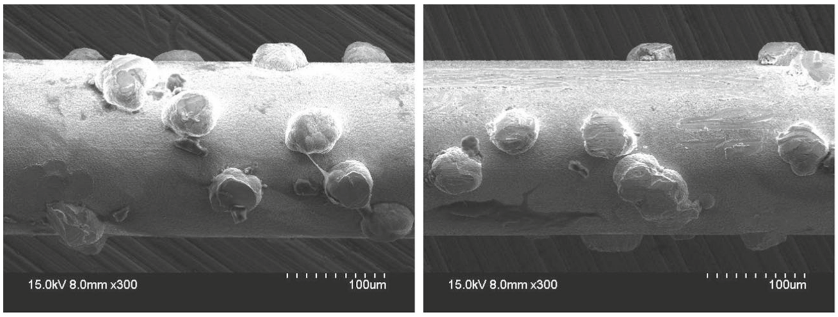


(c) Third run (d) Fifth run

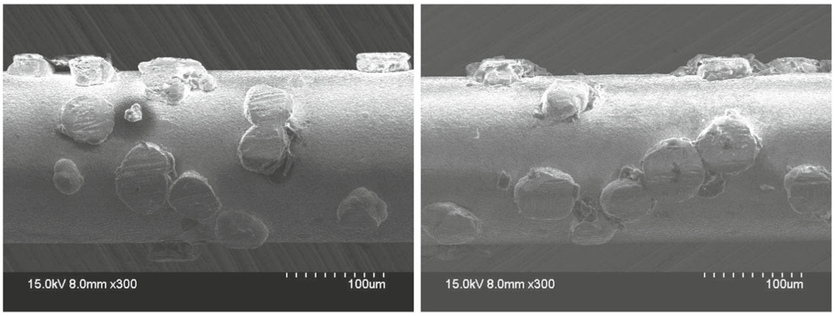
5 Break-in characteristics of diamond wire

In general, the lifecycle of diamond wire can be classified according to the cutting ability of the diamond wire, as shown in Fig. 10. The lifecycle includes the break-in phase, the stable condition phase, and the deterioration phase. The break-in phase of diamond wire is defined as a state during which it achieves its originally designed performance. In the stable condition, a gradual reduction of the diamond height is expected due to wear, and the cutting ability and the cutting forces can be maintained until the wear amount reaches a certain height of the diamond abrasives. After the stable condition, the cutting ability may deteriorate rapidly due to the excessive wear of the diamond abrasives. Then, it is predicted that the vertical force increases quickly and the horizontal force decreases.

Fig. 9 SEM images of diamond wire during cutting runs (Wire B)



(a) New wire (b) First run



(c) Third run (d) Fifth run

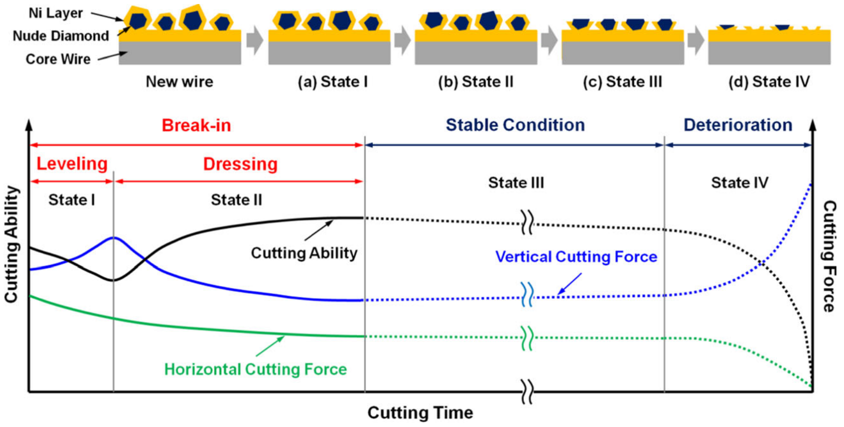


Fig. 10 Break-in characteristics of diamond wire

On the basis of this definition, Wire A reached break-in at the fifth run, and Wire B did not at this point in this work. The correlation between the cutting force and the cutting ability can be explained in terms of the wear characteristics of the diamond wire. The cutting forces and the cutting ability were unstable and included a transition segment during the break-in phase, as the contact condition of the diamond wire was continuously changed. Based on the transition segment, the break-in phase was divided into a leveling step and a dressing step with respect to the wear state of the diamond wire. In the leveling step, the extrusion height of the diamond abrasives in new wire was not uniform, and only a few large diamond abrasives took part in the actual cutting action. The cutting forces could be concentrated on the abrasives, and this may have caused an abnormal contact condition and high vertical and horizontal force between the work and the diamond abrasives. Then, the wearing of the diamond wire selectively occurred, and its rate was faster than in the other states. With an increase in the number of cutting runs, the amount of contact abrasive material and the contact area both gradually increased. The increase in the number of dull abrasives induced inefficient cutting and a decrease in the horizontal force. The vertical force then increased, and the cutting ability decreased due to the unstable cutting action. The dressing step is the period in which some of the diamonds began to be exposed. Although the contact area between the work and the diamond wire increased, the decrease in the vertical force and the cutting ability were improved by the partially exposed diamond grit pieces. As the cutting continued, the number of exposed diamond grit pieces increased. The cutting force and the cutting ability then reached a stable condition.

6 Conclusion

The purpose of this research is to investigate break-in characteristics of diamond wire and the effects of these characteristics on the cutting performance. In the experiment, a single-wire sawing machine equipped with a monitoring system was used to measure the horizontal and vertical forces during the cutting process. The cutting performance was evaluated, and the used wires were analyzed by a newly developed vision measurement system by SEM images.

Based on the results, the break-in of diamond wire can be broken down into the leveling step and the dressing step. It was found that the break-in behavior of diamond wire is strongly dependent on the wear behavior of the diamond wire. The diamond wire with the fewer abrasives has the better break-in characteristics. In the cutting forces, the vertical force can be correlated with the cutting ability, and the horizontal force indicates the wear state of the diamond wire during the break-in phase. To ensure better cutting performance in the break-in phase, most crucial is how rapidly the diamond grit will be exposed. An additional process, such as pre-dressing, is needed in order to accelerate the initial wear of the diamond wire as necessary. However, it is important to remember that the lifecycle of the diamond wire may be shortened in such a case.

To improve the cutting performance in the multi-wire sawing process, more research is needed. The theoretical and empirical methods that are proposed in this paper can help to understand and investigate the multi-wire sawing.

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