To the New Frontier of Nano-Precision Mechanical Manufacturing Technology (from Form Generation to Function Generation)

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To survive in the current economic climate after Lehman Crisis and the Great East Japan Earthquake, research and development works in manufacturing processing technology must be changed to the creation and development of new manufacturing principles and technologies to contribute to the competitiveness of Japanese manufacturing industry. This report reveals one of the solutions to exploit the new frontier of manufacturing, such as nano-precision micro/meso mechanical manufacturing (M^4 process) for a generation of functional interface on the machined surface.

Key Words: *micro/meso mechanical manufacturing, M^4 process, nano-precision, functional interface*

1. Foreword

The Great East Japan Earthquake which struck on March 11, 2011, inflicted tremendous damage to all of Japan and drastically effected people's lives. In particular, the disaster at Fukushima No.1 nuclear power plant led to nuclear power plants across Japan ceasing operation, and as a result, power supply shortage has become a serious problem. This situation presented the opportunity to rethink energy issues. It is likely that in the future there will be heightened interest in technologies which utilize and store reusable energies such as solar light, solar heat, wind, geothermal energy, etc., and accordingly R&D activities in this space will gain more momentum. Meanwhile, amidst heightening interest in this type of energy harvesting, there is also a lot of action on the R&D front regarding energy-saving technologies. This is because energy-saving is relatively equivalent to producing energy. In this way, the development of systems and devices to solve energy issues is attracting more and more interest as one way to revive Japan's industry in the wake of the Lehman Crisis. As such, the questions of "What exactly is Monozukuri technology?" and "What is the technology that can give Japan the advantage amongst global competition?" need to be urgently addressed.

Any future discussions on Monozukuri must take into consideration the future demographics of Japan. **Figure 1** shows the forecasted Japanese population shift$^{1), 2)}$. As can be seen from this figure, from last year the population began declining from 128 million, forecast to fall below 100 million in 2050 and be only one-third of the current population 100 years from now in 2100 at 48 million. This number is almost the same as 100 years ago around the turn of the 20th century. However, the major difference between 100 years ago and 100 years from now is the change in the population's age structure. The percentage of the population aged 0 to 14 and the working population aged 15 to 64 will decrease significantly. Furthermore, the average life span in Japan is predicted to increase and become 84.19 years for males and 90.93 years for females by the year 2060$^{2)}$. In other words, the number of elderly people will increase dramatically, changing the current statistic of 1 in 4 people being over the age of 65 to 1 in 2.5 people by the year 2060, meaning that more than one-third of Japanese citizens will be 65 years old or above.

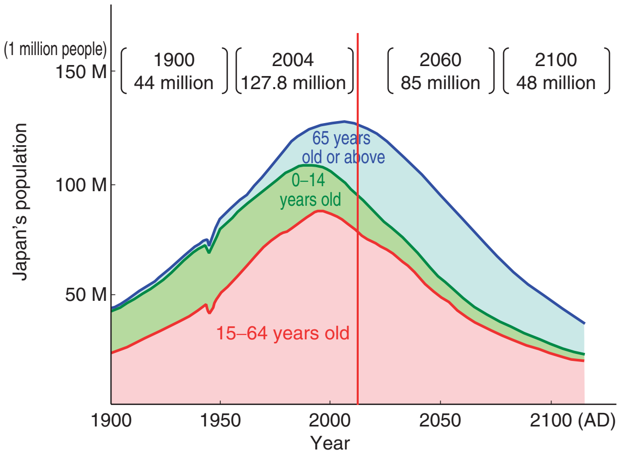


Fig. 1 Demographics of Japan

This changing situation surely marks the end of the mass-production, mass-consumption style of Monozukuri that has been practiced until now and calls instead for a diversified type of Monozukuri that responds to various values. We are right in the middle of a turning point in Japan's industrial structure and we must recognize that now is a time to think seriously about what we will leave behind for future generations. Consequently, when we think about Monozukuri, we must also think about what kind of products will be sought in the future, sufficiently predict what will sell, and "backcast" what kind of technology will be needed to create such products and which technological issues need addressing now.

2. The Fusion of Extreme Form Generation and Function Generation

In order for Japan's Monozukuri creative design and manufacturing to continue to lead the world, we must strongly promote the development of products with even higher accuracy and added-value to an extent that cannot be achieved by overseas technology. Conventionally, the evaluation criteria of a machined product were form accuracy and surface roughness and it was sufficient as long as these were as per design. However, when pushing processing accuracy to the extreme limit, a wavy pattern of the nano-order remains on the machined surfaces and it is difficult to obtain a uniform machined surface. A machining method to remove this wavy pattern and obtain a uniform machined surface is essential. This report uses the example of aspherical grinding and introduces various grinding methods developed with the aim of obtaining a form accuracy of 25 nm just on the ground surfaces. The report first introduces the "Parallel Grinding Method" which improves finished surface roughness, then the "Arc Envelope Grinding Method" which improves form accuracy and finally the "Fluctuation-free Aspherical Grinding Method" used to obtain uniform machined surfaces.

Currently, this sort of demand for form accuracy has already reached its limit in the nuclear-order. Surely now a demand will emerge for Monozukuri that comprises ideas to create machined surfaces with new functions through generating microscopic structures on the obtained machined surfaces and controlling crystal structures in the proximity of the machined surfaces. In other words, the fusion and advancement of a new type of monozukuri technology which does not merely focus on form generation, but also incorporates function generation. That is why this paper also introduces nano-precision micro/meso mechanical manufacturing.

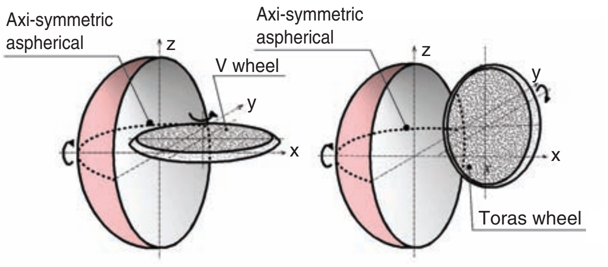
3. Nano-precision Grinding of Aspherical Optical Components

3. 1 Parallel Grinding

Figure 2 (a) shows the conventional grinding method currently being used for axi-symmetric aspherical surfaces. The figure shows that machining is carried out through 2-axial simultaneous control of the x and y axes in a configuration whereby the wheel spindle and the workpiece spindle are perpendicular[3)]. The feature of this form of grinding is that the rotational direction of the workpiece and peripheral vector of the grinding wheel cross at the grinding point, and grinding marks are formed in the workpiece radial direction, as shown in **Fig. 3** (a). This grinding method is known as "cross-grinding".

In many cases, cross-grinding uses an abacus ball-shaped grinding stone edge that has been made into a V-shape formation as the working surface. This method is problematic because wheel wear and collapsed abrasive grain is concentrated in one area due to grinding being performed in one spot on a wheel cross-section vertical to the grinding direction. This means that if the workpiece is high hardness material such as ceramic or has a large diameter, it is practically impossible to grind efficiently.

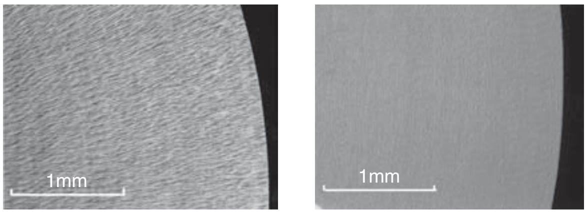
That is why the grinding method shown in **Fig. 2** (b) was devised, where the workpiece rotational direction and the wheel periphery vector are parallel. This grinding method is known as "parallel grinding". The only difference between cross-grinding and parallel grinding is the cutting direction of the abrasive cutting edge. If a spherical wheel is used, the two methods can be regarded as being completely identical geometrically-wise. However if grinding theory[4)] is used to calculate finished surface roughness theoretically, a completely different result could be obtained. In other words, because parallel grinding has more active cutting edges than cross-grinding, it was discovered that parallel grinding has better surface roughness under all grinding conditions[5)]. **Figure 3** (b) is a Nomarski photomicrograph



(a) Cross-grinding method (Conventional grinding method)

(b) Parallel-grinding method (New grinding method)

Fig. 2 Comparison of aspherical grinding methods of ground surfaces of a carbide die. As is apparent when a comparison is made with the cross-grinding shown in **Fig. 3** (a), despite the exact same wheel and grinding conditions being used, the finishing surface roughness obtained with parallel grinding is smaller by approximately half. Parallel grinding is the grinding method which improves ground surface roughness.



(a) Cross-grinding method (84 nm *Ry*) (b) Parallel-grinding method (44 nm *Ry*)

Fig. 3 Nomarski photomicrographs of ground surfaces

3. 2 Arc Envelope Grinding

As already mentioned, in the conventional grinding method, the grinding point on the wheel cross-section does not change, causing wear concentrates of the point where grinding is carried out. Consequently, life between dressings is shorter and the efficient grinding of large workpieces is practically impossible. Even more fatal is the fact that this triggers degradation of the aspherical form accuracy. If the grinding point that is fixed to one spot is moved in the wheel width direction, these problems could be solved. In order to do that, it would be sufficient to use a wheel with an arc cross-section as shown in **Fig. 4** to generate an aspherical surface by the envelope of that arc cross-section[6]. In such a case, the active grinding width would be larger and wheel wear would be dispersed. As a result, with the arc envelope grinding method it would be possible to reduce wheel wear significantly, as shown in **Fig. 5**, and greatly improve form accuracy in aspherical grinding.

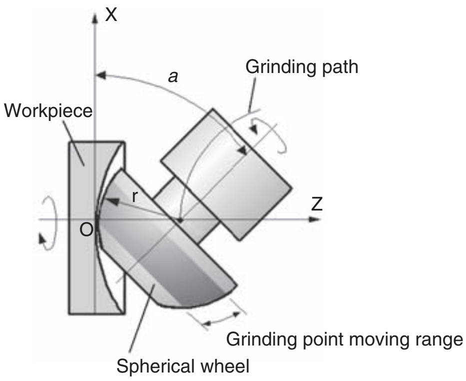
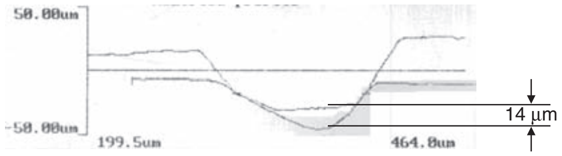
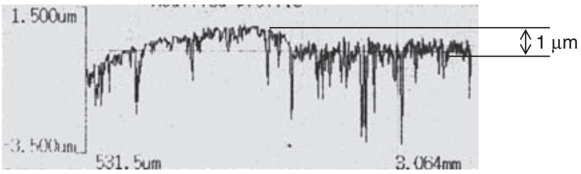


Fig. 4 Arc-envelope grinding method



(a) Fixed grinding point. (Conventional grinding method)



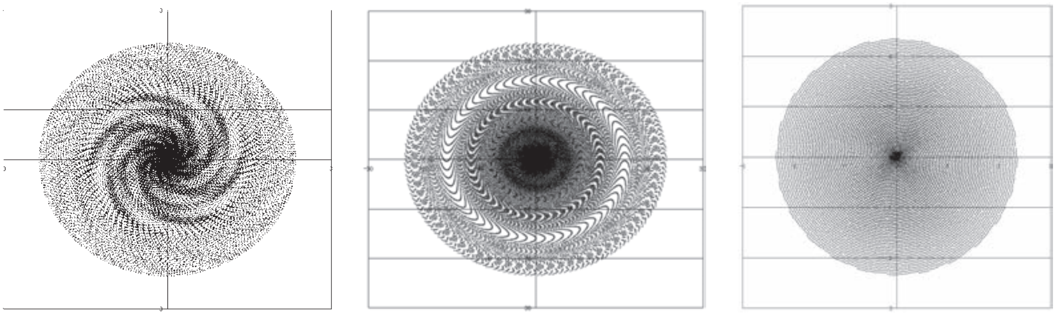
(b) Moving grinding point. (New grinding method)

Fig. 5 Decrease in wheel wear due to the movement of grinding point

3. 3 Fluctuation-free Grinding

The difficulty of aspherical grinding lies in the fact that a ground surface roughness in nano-order is demanded at the same time as a high accuracy profile. The above sections showed that the combination of parallel grinding and arc envelope grinding was extremely effective in solving this problem. This solution has made it possible to achieve a form accuracy of 50 to 100 nm and a surface roughness of 10 to 30 nmRy. However, year after year higher accuracy is being demanded of aspherical lenses in order to obtain an even clearer, finer optical image. Hence, now there is a demand for a form accuracy of 25 nm or less and a surface roughness of only a couple of nm. In order to achieve this kind of high accuracy grinding, the high accuracy countermeasures that have conventionally been implemented on processing machines is no longer sufficient. One example of this is the fact that the control resolution of processing machines is already at 1 nm, approaching its limit. That is why it is necessary to look at improving the accuracy of machined surfaces from a different perspective.

The current outstanding issue with aspherical grinding is that the 3-dimensional form (form error pattern) of the waviness which occurs on the lens machined surface cannot be reproduced. For example, a spiral pattern shown in **Fig. 6** (a), or a concentric circle pattern as in **Fig. 6** (b) appears, and these patterns are unstable. Through fundamental research relating to the nano topographical generation mechanism of ultra-precision ground surfaces, the author determined that the instability of the form error pattern was affected significantly by the unevenness of wheelspindle and workpiece spindle rotation as well as wheel unbalance[7]. This means that due to the instability (unevenness) of processing machines it would be difficult to achieve an even form error pattern and form accuracy of 25 nm with practically all of the commercially available ultra-precision aspherical grinding equipment. In order to solve this problem and achieve an even form



(a) Spiral pattern (b) Concentric circle pattern (c) Uniform and fine pattern

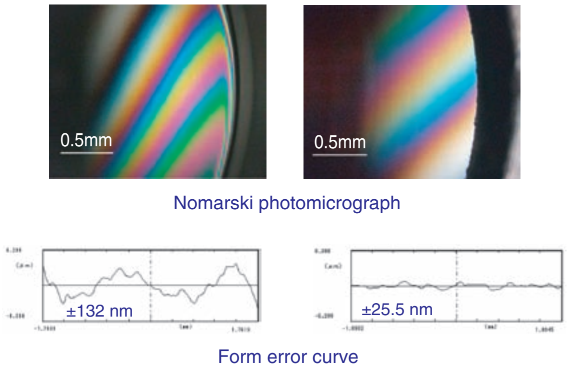
Fig. 6 Grinding marks generated on axi-symmetric aspherical ground surfaces

error pattern on machined surfaces, a form of machining where all the parameters which affect machining results are entirely controlled at predetermined values and do not fluctuate, vary or waver whatsoever, in other words fluctuation-free machining, is necessary.

3. 4 Development of a Fluctuation-free, Ultra-Precision Aspherical Grinding System

Fundamental research relating to nano topographical generation mechanisms showed that if the fluctuation of workpiece and wheelspindle RPM is 0.1% or less, the error form pattern would not be obvious (**Fig. 6** (c)). That is why a new fluctuation-free, ultra-precision aspherical grinding system was developed which allows the abovementioned parallel grinding (improved ground surface roughness) and arc envelope grinding (improved form accuracy) to be performed simultaneously at the same time as maintaining rotation fluctuation during grinding below 0.1%. The newly developed system is shown in **Fig. 7**. We used this grinding machine to grind aspherical glass lenses (4mm dia.) for an endoscope (rigid scope). The resulting form accuracy was ±25.5 nm and the surface roughness was 21 nmRy, meaning that form accuracy was improved by approximately one-fifth of the conventional product while surface roughness was improved by two-thirds. Moreover, as shown in **Fig. 8**, the form error pattern was dramatically less than conventional products. The author also ground a cemented carbide concave aspherical die (die dia. = 25.0mm, lens aperture dia. = 24.4mm) used to form aspherical glass lenses for high-definition digital cameras. This achieved a form accuracy of ±25.5 nm and a surface roughness of 18 nmRy. Moreover, there were no form error patterns on the machined surfaces and results of a resolution assessment of a sagittal image and a meridional image confirmed improvement compared to the conventional method.

Fig. 7 Newly-developed fluctuation-free ultra-precision aspherical grinding machine



(a) Conventional grinding method (b) Fluctuation-free grinding method

Fig. 8 Ground aspherical glass lenses

4. Nano-precision M^4 Process Technology

The last chapter introduced fluctuation-free machining which raises form accuracy to extreme limits. This chapter will introduce M^4 processes, which are one function generation method to add even more functions.

The nano/micro/meso hybrid structure such as that shown in **Fig. 9** is one of the structures for expressing function. This was formed by forming a micro-sized functional microscopic structure on top of a macro-sized free-form surface (or surface) with a smooth surface in the nm order then overlapping a further microscopic structure of the nano size to that surface. There are expectations that this kind of nano/micro/meso hybrid structure will express particular functions optically, electrically, thermally or mechanically. The generation of such functions is not achievable with conventional ultra-precision mechanical machining technology, therefore the creation of a new machining technology covering the area shown in **Fig. 10** is necessary. That is why, regarding various mechanical machining technologies which have developed and advanced independently, there is a high expectation of micro/meso mechanical manufacturing (hereinafter referred to as nano-precision M^4 processes) as being able to machine sizes as small as several μm and at the same time raise machining accuracy to the nano order.

Table 1 shows typical types of nano-precision M^4 processes. It is expected that the machining mechanisms are practically the same as conventional mechanical machining methods however the following new challenges will arise as a result of the machining target getting smaller.

1. Development of an M^4 processing machine/system: It would be necessary to develop a multi-axes control nano-precision micro processing machine which would be capable of controlling machining force.
2. M^4 process combination technology: The development of a unit which could support combination machining would be necessary.
3. M^4 process tool development: Because the tools would be thinner, a new fabrication technology for such tools would be necessary.
4. M^4 process measurement assessment technology: Because the machining force itself would get smaller, micro-force measurement and control technology would be necessary. Also, because the machined profiles would be small, new profile measurement technology would be necessary. Finally, developing a way to assess sub-surface damage of the machined surfaces is essential.
5. Clarification of M^4 process machining mechanisms and functionality generation mechanisms: In order to minimize the removal unit it is necessary to assess the removal property of the material itself, and that is why it is essential to develop new analytical methods such as machining simulations, large-scale molecular level simulations combining FEM and molecular dynamics or multiphysics simulations able to comprehensively analyze multiple physical phenomena such as material distortion and thermal behavior.

Also, in this type of nano-precision M^4 process machining, the chips themselves are of the nano order. Consequently, it is easily predicted that chemical elements will also strongly affect the removal mechanism of material, and there are many points which cannot be clarified with the mechanical engineering approach taken until now. In other words, rather than merely looking at actual physical and chemical phenomena in the nano region from a mechanical engineering perspective, a mechanical scientific approach which sees things from a quantum mechanics perspective incorporating nuclear bonding state change and the electromagnetic or chemical mutual effect which triggers such changes. In this way, even more emphasis will be placed on machining simulation technology as a common fundamental technology and R&D of nano-precision measurement assessment technology.

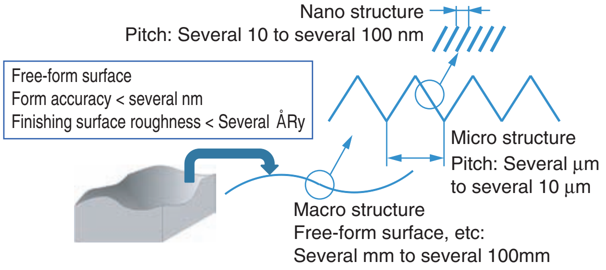


Fig. 9 Nano/micro/macro hybrid-structure

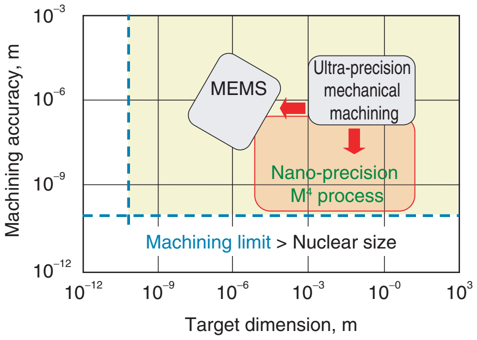
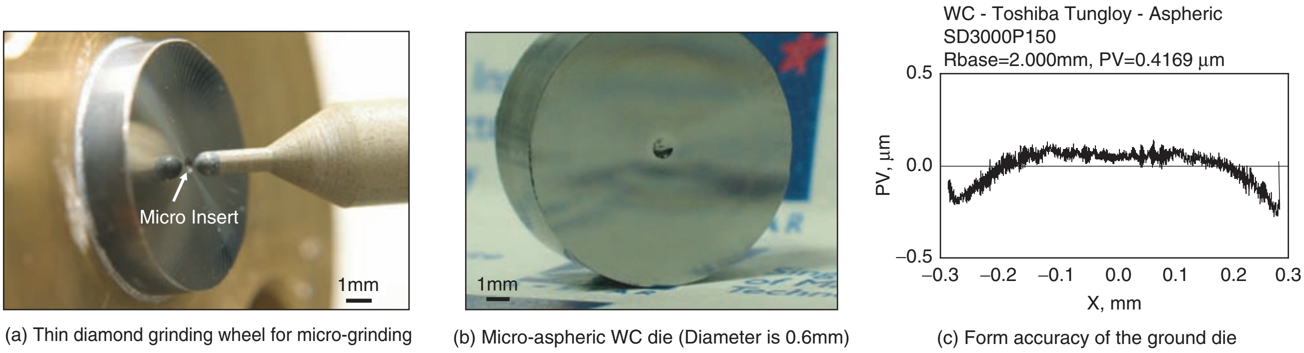


Fig. 10 Object size and machining accuracy focused in nano-precision M^4 processes

Table 1 Various types of nano-precision M^4 processes

Abrasive machining	Micro-grinding Micro-polishing Micro-ultrasonic machining Micro-abrasive jet machining, etc
Cutting	Micro-cutting Micro-milling, etc
Other	Particle jet coating Micro-discharging Micro-adhesion Micro-punching Micro-laser processing Micro-forming, etc



(a) Thin diamond grinding wheel for micro-grinding (b) Micro-aspheric WC die (Diameter is 0.6mm) (c) Form accuracy of the ground die

Fig. 11 Micro-aspherical die generated by micro-grinding process

4. 1 Micro Aspherical Machining

This section will introduce micro aspherical grinding as an example of an M^4 process. The targeted aspherical surface is of submillimeter size. Phenomena which were practically not problems with conventional machining sizes or of the extent which could be ignored, can no longer be ignored in machining this size. For example, if an aspherical surface with a submillimeter sized diameter was micro-grinded with a wheel that had a diameter of 1mm or less, no doubt the truing/dressing of a small diameter wheel and other applied technology would become issues. In order to solve these issues the following would be important.

- Development of a truing/dressing method where there would be more active cutting edges.
- Development of a grinding wheel with an ultra-high degree of concentration.
- Development of a grinding method where wheel wear and surface roughness become smaller.

Also, if the workpieces themselves have small diameters, ways to make the machining force itself smaller (such as ultrasonic grinding, etc) must be examined.

Figure 11 shows a carbide micro-aspherical lens die ground using an SD3000P150 ultra-fine abrasive diamond wheel with a diameter of 1mm. The form accuracy was 0.4 µm and the surface roughness was 62 nm. These are improvements of one-digit compared with grinding results when normal size wheels are used. This is because the number of active cutting edges becomes much smaller when a small-diameter wheel is used.

4. 2 Nano/Micro Structure Generation Utilizing Hybrid-Vibration Assisted Grinding

Generally speaking, nano/micro structure generation is performed using surface generation technologies such as nanoimprint technology or self-assembly, etc. These methods have still many issues such as the difficulty of generation of complicated 3-dimensional surfaces on the large surface, and high costs problem. Here, the author would like to introduce a method which is relatively low in cost and able to mechanically generate structures in the sub-micron order on large surfaces.

Figure 12 (a) shows the principle of hybrid-vibration assisted grinding overlapping low frequency vibration of several Hz with ultrasonic vibration of several 10 kHz[9), 10)]. Ultrasonic vibration in the axial direction is applied using a special-purpose ultrasonic spindle while low-frequency vibration and workpiece feed are executed with NC commands from the processing machine. **Figure 12** (b) shows the cutting trajectory of the abrasive cutting edges and by controlling the position where these cutting edges overlap a fine structure such as that shown in **Fig. 12** (c) can be acquired. **Figure 13** shows a periodic structure with a 500 nm pitch generated on a zirconia ceramic surface using an SD600 small-diameter wheel with a diameter of 1mm. By changing feed rate, vibration frequency and so on, it is possible to generate various forms.

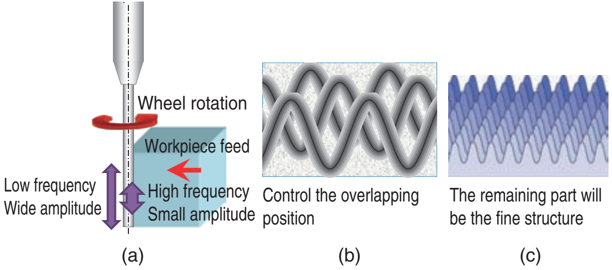


Fig. 12 Principle of fine structure generation utilizing hybrid-vibration assisted grinding

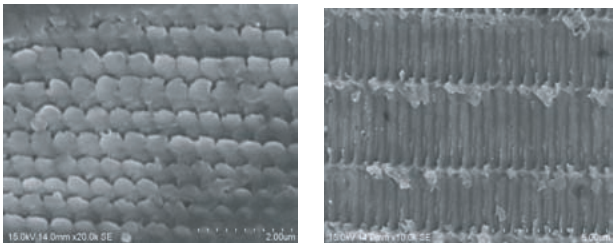


Fig. 13 Periodic structure with 500 nm pitch generated by hybrid-vibration assisted grinding

5. Conclusion

This report has introduced key words thought to be important when contemplating Monozukuri in the future. No doubt from here on more than mere "form generation" will be required. "Function generation", which creates structures possessing various functions in such surfaces or internally, will also play an important role. This report used the example of grinding, one mechanical machining method, to introduce fluctuation-free grinding which increases form accuracy and hybrid-vibration assisted grinding for the generation of fine structures. However, rather than stopping at mechanical techniques in order to generate functions, we should adopt a top-down approach of Monozukuri such as optic machining or MEMS machining in an effective and timely manner. Moreover, it could be said that a bottom-up approach of Monozukuri that efficiently utilizes molecular design and self-assembly would be an effective method.

In this way, in order to realize the machining technology foundation for Monozukuri of the future, it will be essential to construct learning framework and technology achieving "Monozukuri with scientific rationality that understands the essence of phenomena of the nano world" and research foundation for that.

In other words, it will be necessary to strongly promote the following:

1. Clarification from a quantum-mechanical perspective through positioning nuclear level and nano level mechanical behavior as coupled problems with electromagnetic phenomena and chemical reactions.
2. Scientific clarification of the various phenomena related to nano mechanochemistry, nano material and nano processing.
3. Design and construction of micro machines, nano machines and nano systems.
4. Establishment of material/strength reliability assessments at a nuclear/nano-level and energy conversion system safety assessment research.
5. Development of material durable in extreme environments and high-reliability nano machines/systems, etc.
6. Development of nano measurement/assessment technology.

The author looks forward to future advancements in research and development.

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