To the New Frontier of Function Creation Processing for High Value Manufacturing

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We have shown that the future of manufacturing will not be limited to "the creation of form", but will also include "the creation of function" by creating structures that express functions on or inside the machined surface. This kind of "functional creation processing" is exactly what we are aiming for in "high value manufacturing", and we believe that it will become increasingly important. In this report, we introduce the UV-assisted tape grinding technology for gallium nitride substrates, plasma shot technology for creating low-friction and low-wear surfaces, and new surface function creation technology (ex. lattice coating) and functional material creation technology based on 3D modeling technology.

***Key Words**: high value manufacturing, function creation processing, UV-assisted tape grinding, gallium nitride, plasma shot*

1. Introduction

Since manufacturing has always been one of Japan's cornerstones, creating a vision for the future of domestic manufacturing is an important need. Organizations such as universities along with public testing and research laboratories, private enterprises and government agencies are responding to this need by stepping up their nationwide initiatives. Recent examples include calls to set and achieve major goals such as creating a carbon neutral economy and coping with Japan's highly aging population. But how should the manufacturing sector respond? A previous report[1)] presented some of the keywords that should be important when considering the future of manufacturing. It discussed how manufacturing will be going beyond just the shape formation processes it has focused on so far. Instead, function formation processes that create structures generating surface or internal functions will likely take on a more important role. Proposed processing methods for these function formation processes will aim to create high value-added manufacturing. These types of proposals should grow in importance in the coming years. Subsequent to the report, the author's lab has been working on pico precision-level processing (a precision level exceeding nano precision) and surface function formation technology. Work is also being done on the application of a blasting technology to dentistry, while testing the technology in a clinical trial. Among these areas, this report presents UV-assisted tape grinding technology for gallium nitride substrates, plasma shot technology for forming surfaces with low friction and abrasion, new surface function formation technology that applies 3D modeling technology, and functional material formation technology.

2. UV-Assisted Tape Grinding Technology for Gallium Nitride Substrates

Semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN) are attracting interest as new materials for power electronics devices surpassing the limits of silicon (Si). For example, practical applications of GaN devices have started to appear in the form of white LEDs that are coming into widespread use in standard lighting and vehicle light sources such as headlights. Researchers have also started looking into using them in power devices for applications such as air conditioners and electric vehicles (where future demand growth is anticipated). But creating technologies for manufacturing high-quality, large-diameter GaN substrates at low cost will be an essential requirement for speeding the widespread adoption of these GaN devices. Satisfying this requirement will be difficult since GaN materials are harder and more chemically stable than Si materials, so need to be processed for nearly 10 times longer (100 to 150 hours).

CMP (Chemical Mechanical Polishing) is the method conventionally used to polish Si substrates. CMP is a combined processing method that does most of the polishing by chemical removal while ensuring flatness through mechanical action. Colloidal silica particles are used in a highly alkaline environment to polish Si substrates, for example. But the chemically stable nature of GaN single-crystals makes them much less efficient to process than Si. To address this issue, we worked with a team led by professor Momoji Kubo of Tohoku University[2]. Tight-binding quantum molecular dynamics simulations were used to explicate the types of reactions that take place for each type of abrasive grain acting on the GaN substrate, and to understand how Ga atoms are separated from the surface of the GaN substrate. These simulations showed that when nanodiamond (ND) abrasive grains were used in a neutral environment, boosting the OH radicals resulted in the separation of surface Ga atoms originating from the bond between the abrasive grains and the substrate. In an alkaline environment, the OH- action encouraged bond formation between the abrasive grains and the substrate, suggesting that polishing would be accelerated. These findings were used to devise a method that uses ND abrasive grains for processing while irradiating hydrogen peroxide (HP) solution with ultraviolet (UV) light to generate OH radicals.

The standard polishing method places the surfaces of the workpiece (substrate) and polishing surface plate in contact with each other, making efficient UV irradiation impossible during polishing. OH radicals usually have a very short life, enabling UV irradiation near the polishing area. We created a prototype of the UV-assisted tape grinder shown in **Fig. 1** as a way to continuously supply ND abrasive grains to the polishing area in a more effective manner[3-5]. This device presses the polishing tape against the GaN substrate through urethane contact holes. By changing the contact conditions (such as the contact hole diameter, modulus of elasticity, pressing force and polishing speed), this structure enables precise control of the surface area in contact with the GaN substrate to control the number of effective cutting edges. The substrate undergoes reciprocating motion while affixed to a hydrostatic-pressure reversing table with ultra-precise, high-speed operation (of up to 1 000 strokes per minute). The polishing tape used in the device polishes by a fixed abrasive grain method, so feeding the tape creates the benefit of successively supplying new abrasive grains to the polishing area. The device is ultimately expected to enable all the commonly used processes for polishing substrates with free abrasive grains to be replaced by fixed abrasive grain methods, resulting in significantly simplified processes.

Polishing tests demonstrated that the boost gained from the UV and hydrogen peroxide combined with the tape grinding mechanism reduced an initial surface roughness of 5.3 nmRa to no more than 1 nm after 10 minutes of polishing. An average of 60 minutes was needed to reduce the surface roughness to no more than 1 nm without the use of UV and hydrogen peroxide, indicating that the boost provided by the UV and hydrogen peroxide made polishing at least 6 times faster than when not used (**Fig. 2**).

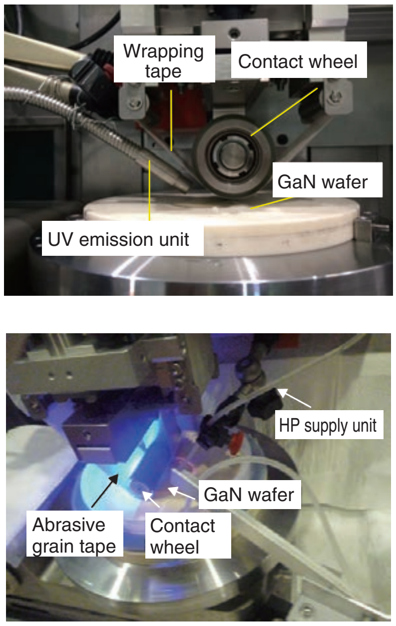


Fig. 1 UV-assisted tape grinding equipment

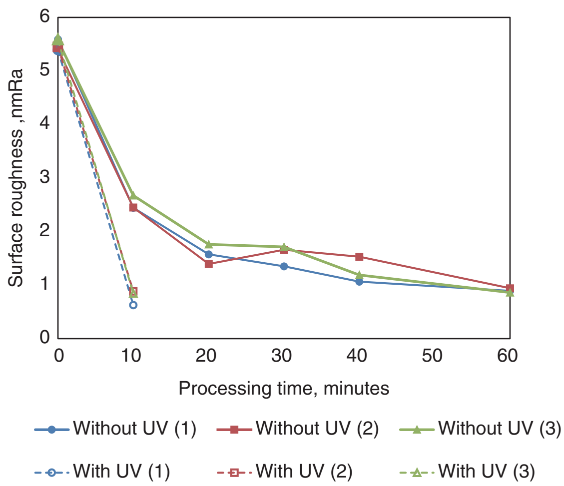


Fig. 2 UV-assisted effects (UV irradiation intensity: 1.0 W, UV wavelength: 365 nm, HP concentration: 98%) (Processing conditions: diamond abrasive #10000, oscillation width ±1.5 mm, oscillation frequency 500 times/min)

3. Using the Plasma Shot Method to Form Surfaces with Low Friction and Abrasion

The plasma shot (PS) method is a surface treatment method that uses electrical discharge machining[6-9]. As shown in **Fig. 3**, the PS method generates continuous pulsed discharges between the electrode and workpiece. These discharges melt the electrode and transfer it to the workpiece to form a modified layer. The PS method repeatedly generates minute pulse-shaped localized discharges, forming minute irregularities on the processed material surface (structures called microdimples that collect oil when lubricated). While this process is occurring, the electrode material moves to the workpiece in a molten state. It partially mixes and fuses with the substrate to form a highly adhesive modified layer. These characteristics should enable the formation of attractive surfaces with low friction and abrasion.

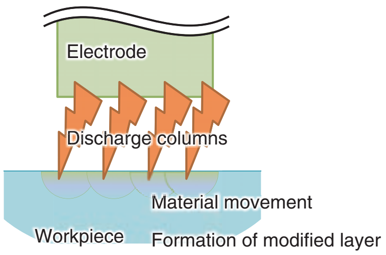


Fig. 3 Schematic diagram of the plasma shot method

Figure 4 shows Vickers hardness measurements for modified surfaces formed using plasma shot processing on stainless steel substrates with TiC or Si electrodes. The use of plasma shot processing was found to make surfaces at least 5 times harder. This method can be used on hardening-resistant items like products cast from materials such as casting iron or aluminum. The microdimples generated on the surface should also improve lubrication. The microdimple irregularities can be removed from the plasma shot surface by grinding or other processes, turning this method into a black box process by hiding the boundaries of hardened areas.

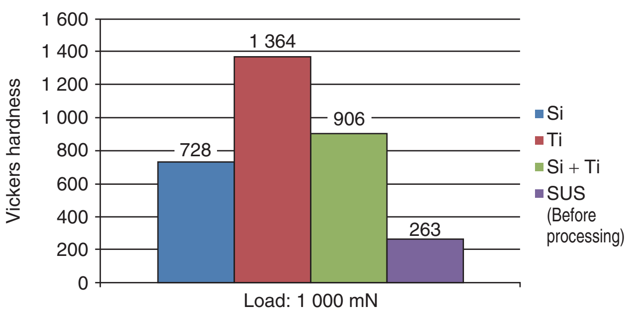


Fig. 4 Increase of hardness by plasma shot treated surface

4. Functional Interface Formation Using Layered 3D Modeling Technology

Layered 3D modeling is a commonly used fundamental technology that can model complex shapes as long as 3D shape information is available for the structures to model. Layered 3D modeling for metals and ceramics has recently become a promising technology for use in creating custom-made implants for medical applications (such as artificial bones and bone fastening materials). But modeled object surface properties, crystal structures and constructions are known to change in accordance with the modeling conditions, causing changes in the mechanical properties of the product also. This report presents technology developed by applying laser-beam layered 3D metal modeling technology. As well as a method of forming shapes, the technology was developed as a method of forming functions such as surface functions.

4. 1 Minute Lattice Coating Technology

Products will gain more added value if it becomes possible to form periodic textures on their surfaces to generate functions such as wettability, lubricating ability, biocompatibility, and anchor effect. We have responded by proposing a method of using layered 3D metal modeling technology to form a texture on the surface of a rough framework created with the dimensions and shape of the product using standard machining processes such as cutting and grinding.

The minute lattice coating method is the new method we have developed to print a minute lattice structure on any freely curved surface. The two most commonly used processes in layered metal modeling are the PBF (Powder Bed Fusion) method and DED (Direct Energy Deposition) method. The PBF method is usually used for modeling complex structures. It models the structure on top of a flat base plate. The DED method is used to model freely curved surfaces, but it makes modeling complex shapes difficult. In contrast, the minute lattice coating method can model complex structures on freely curved surfaces. The minimum modeling width of the structures obtained is about one particle, making it an innovative and unrivaled process[10-12]. **Figure 5** shows an example of a metal cylinder surface textured using the minute lattice coating method.

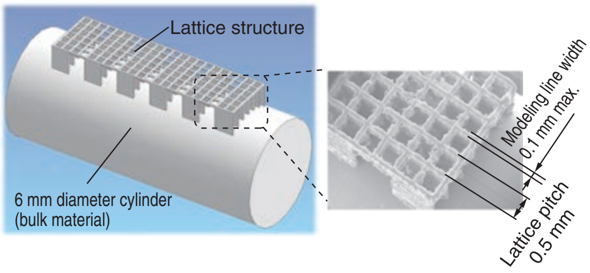


Fig. 5 Sample of micro-lattice coating

4. 2 Technology for Forming Functional Materials

To identify the basic effects taking place at the smallest scale during layered metal modeling, we described the working principle of the modeling process by describing the microscopic melting behavior of a single powder particle and explicating the microeffects taking place during the modeling process. Our findings indicate that the model's internal crystal structure and construction can be arbitrarily controlled by controlling the laser beam's scanning speed and energy density. **Figure 6** is an IPF (Inverse Pole Figure) map with a color-coded display of crystal orientation created by using EBSD (electron backscatter diffraction) to show crystal structure differences in structures modeled with different laser conditions. The results show that the laser conditions can be controlled either to make the crystal structure finer, or to make it coarser in any direction. Controlling the laser conditions should also make it possible to affect the model's mechanical properties or anisotropy.

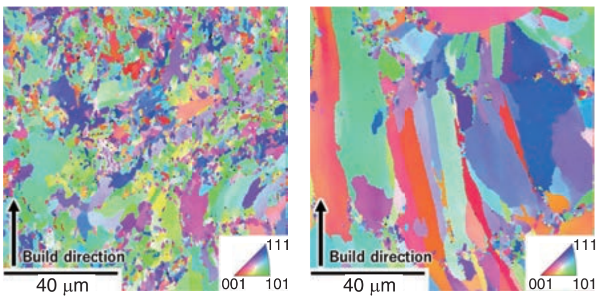
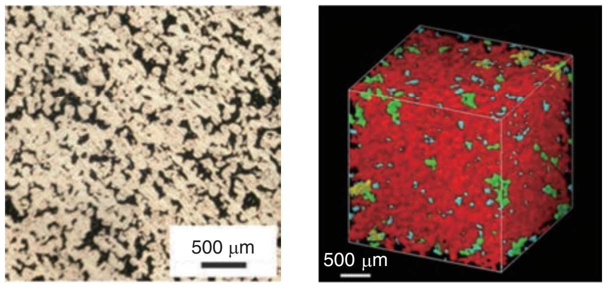


Fig. 6 Difference of crystal structure by laser condition

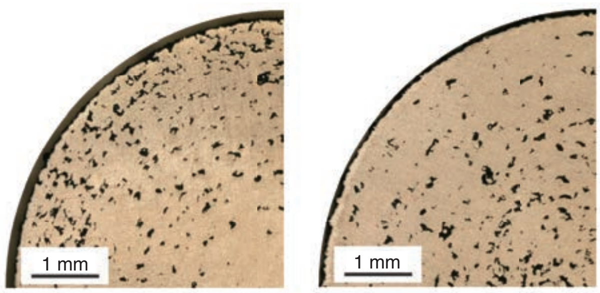
Since holes lead to lower mechanical strength, the common practice is to allow as few holes as possible to remain in modeled objects during layered 3D metal formation. Despite this practice, we decided to create a porous structure inside a modeled object by proactively using the holes that form accidentally during the modeling process. If successful, this approach could be an effective method for forming new functional structures. We have also developed a method of controlling the modeling conditions that can impose organization on the placement, distribution and shapes of these holes generated at random inside the modeled object[13, 14].

Figure 7 shows a cross-section and CT image of a functional structure with connecting holes created by this method (rhizoid porous structure; RPS). As shown, we found that the shape, direction, and distribution of the connected holes can be controlled. **Figure 8** shows an example model created with a hole distribution gradient in the radial direction. This technology could have applications for dentistry. **Figure 9** is a conceptual diagram showing the internal structure of a highly functional implant that we plan to create. Implants featuring this type of RPS structure are expected to provide a large number of benefits, such as better jawbone adhesion and an elastic construction that closely resembles natural teeth.



(a) Cross-sectional image of RPS material
(b) CT image of vacancies (red: connected holes)

Fig. 7 Sample of Rhizoid Porous Structure (RPS)



(a) In the case of rough periphery
(b) In the case of dense periphery

Fig. 8 Porosity gradient distribution of RPS

5. Conclusion

This report has presented a number of technologies developed to provide processing methods satisfying the high value-added manufacturing needs that will be key in determining the future of Japan's manufacturing sector. Specifically, it has discussed UV-assisted tape grinding technology for gallium nitride substrates, plasma shot technology for forming surfaces with low friction and abrasion, technology for forming new surface functions (minute lattice coating method) using 3D modeling technology, and functional material formation technology.

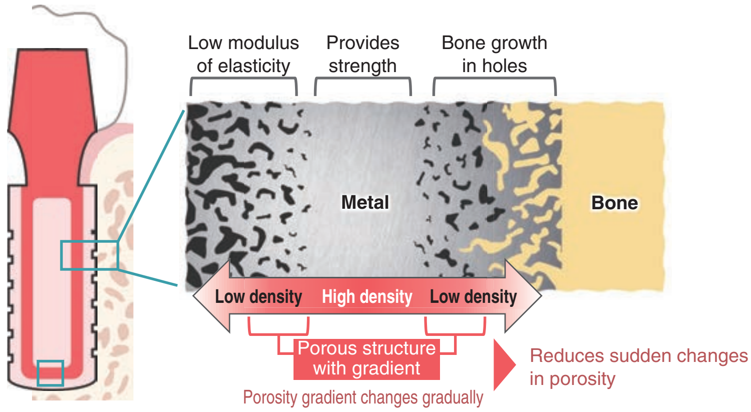


Fig. 9 Proposed new internal structure of high performance dental implant

Creating science-based and rational manufacturing methods rooted in the principles of nanoscale effects will be an essential requirement for creating the processing technology infrastructure that will underpin the manufacturing of tomorrow. The manufacturing sector also needs to avoid an overemphasis on just creating innovative technologies (making more advanced hardware). Hardware development is naturally important, but software development is also crucial for its role in creating ways of combining and getting the most out of hardware.

Manufacturing activities must be rooted in a circular economy that covers processes ranging from production to disposal and recycling (or reuse). It is critically important to design and satisfy life cycle assessments that eliminate CO_2 and other greenhouse gases generated during the series of processes in the life cycles of manufactured products.

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