# 光加工機 Lasermeister1000SE/1000S の開発

江上茂樹

# Development of the Lasermeister1000SE/1000S Optical Processing Machine

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光加工機はニコンの半導体露光装置の技術を応用して開発された加工機であり，2021年 9 月に初の光除去加工機である「Lasermeister1000S」をリリースした．Lasermeister1000S の座標系は高精度・広範囲に管理されており，加工データを忠実に再現することができる．光源には超短パルスレーザーを採用しており，あらゆる材料に対して非熱のレーザーアブレーション加工を実現できる．さらに，機上には3D 光計測機を搭載しているため，計測結果を精確にフィードバック加工することが可能である．加工パスは CAD データ，加工パラメーター，対象物の3D 計測結果から自動生成されるため，作業者のスキルに依存せずにサブマイクロメートルの高精度加工も実現できる．本稿では，これらの Lasermeister1000S の開発要素と，アプリケーションとして考えているきさげ，精密金型，セラミックス材料の加工事例を解説する．

An optical processing machine has been developed by applying Nikon's semiconductor lithography technology. The first optical subtractive processing machine, "Lasermeister1000S," was released in September 2021. The coordinate system of the Lasermeister1000S is adjustable with high accuracy over a wide range. Therefore, model data can be accurately reproduced with high fidelity in processing. An ultra-short pulse laser is used as the light source, with which non-thermal laser ablation processing can be applied to almost all materials. Furthermore, because a high-precision three-dimensional (3D) optical measuring device is mounted on-machine, accurate feedback of the measurement results to the laser processing for improved process quality is realized. The machining path is automatically generated from computer-aided design (CAD) data, processing parameters, and 3D measurement results of the object; hence, sub-micrometer processing accuracy can be achieved without relying on the operator's skill. In this paper, the development of the aforementioned elements is explained and processing examples with scraping, precision molding and processing on ceramic material are discussed, which are areas of application for this optical processing machine.

**Key words** 光加工機，超短パルスレーザー，レーザーアブレーション，機上3D 計測
optical processing machine, ultra-short pulse laser, laser ablation, on-machine 3D measurement

## 1 Introduction

As the first optical processing machine, the metal 3D printer "Lasermeister100A" was developed in April 2019 by applying the semiconductor lithography technology that Nikon has built up over the years. This optical processing machine, which can realize high-precision metal additive manufacturing at low cost and footprint, has wide applicability to market needs. A model with enhanced functions, such as five-axis machining, was also released in 2020, with titanium alloy support further added in 2021.

Nikon's optical processing machines are not limited to the additive manufacturing processing of this metal 3D printer "+ (plus)," but have also been advancing product development of subtractive processing of "− (minus)." The subtractive optical processing machine can realize high-precision surface-shape processing by repeating 3D precision measurements with an on-machine optical measuring device and


Fig. 1 High-precision surface-shape processing machine: Lasermeister1000S.

non-thermal/non-contact processing together with an ultra-short pulse laser. This high-precision surface-shape processing machine was released in September 2021 as “Lasermeister1000SE” and “Lasermeister1000S” (hereafter collectively referred to as “Lasermeister1000S”) (Fig. 1).

## 2 Concept of Lasermeister1000S

The Lasermeister1000S is a new processing machine that achieves high-precision surface-shape processing and microfabrication based on the concept of “remake manufacturing.” This processing machine can simplify or automate the processing setup such as computer-aided manufacturing (CAM), conditions setting, chucking, or reference surface setting. These processes, typical in conventional processing machines, enable the realization of machining that was difficult owing to the wear of cutting tools and constraints of the target object in terms of, for instance, material, shape, and rigidity, with a micro-to-submicrometer precision and requiring no additional operator skill.

“Lasermeister1000SE” constitutes an entry model equipped with an ultra-short pulse laser and a processing/measurement system that uses an on-machine non-contact 3D optical measurement to realize high-precision subtractive processing. In addition to this basic performance, the standard model “Lasermeister1000S” is equipped with more precise positioning mechanism and coordinate correction system, and it is capable of accurate surface-shape finishing and microfabrication over a wide range. This article describes the features and applications of Lasermeister1000S.

## 3 Features of Lasermeister1000S

The features of the Lasermeister1000S with emphasis on its newly developed elements are introduced below.

### 3.1. Highly Precise and Widely Managed Global Coordinates

The processing machine must construct and manage an accurate coordinate system to reproduce with fidelity computer-aided design (CAD) data (Fig. 2). The coordinate system of a general-purpose processing machine is not always constructed accurately, in particular over wide range, due to insufficient operator skill and unsuitable setup. However, the coordinate system of Lasermeister1000S includes advanced correction systems (tilt, scaling, orthogonality, etc.) developed by using Nikon's semiconductor lithography equipment technology that can construct an accurate global coordinate system regardless of operator skill (Fig. 3). Conventional high-precision processing machines require significant effort to suppress drift caused by environmental temperature fluctuations, but the Lasermeister1000S can correct and manage the highly corrected coordinate system. In addition, this processing machine utilizes an air bearing based work stage, as the optical measurement and processing techniques renders mechanical contact unnecessary. Friction-less sliding of the air bearings installed on the stage against the surface plate finished with a high flatness ensures high running reproducibility throughout the stroke without the vibration or loss of precision that may be caused by mechanical driveshafts.

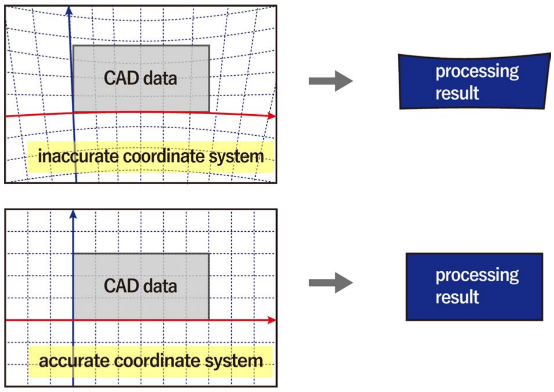


Fig. 2 Effect of coordinate system on processing.

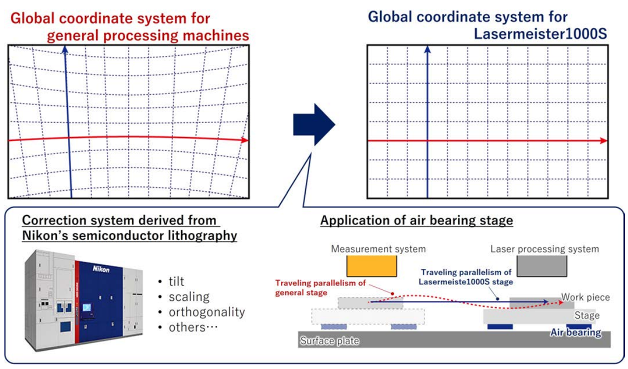


Fig. 3 Lasermeister1000S’s global coordinate system.

### 3.2. Processing for a Wide Range of Shapes and Materials by Ultra-short Pulse Laser Ablation

Laser ablation is a phenomenon in which the surface of an object is explosively scattered and evaporated by irradiation of a high-intensity pulsed laser. Ablation processing using an ultra-short pulse laser (ranging from femtoseconds to several picoseconds) of pulse width shorter than the time required for heat conduction can remove the material without converting the laser energy into heat. Consequently, processing can be performed without causing thermal deformation or including a heat-affected zone (HAZ) of the target object

(Fig. 4), as opposed to CW laser and nanosecond laser processing. In addition, given that laser processing is non-contact and enables processing with almost zero reaction force, a chuck is unnecessary. Therefore, high-precision processing can be realized on the work pieces of thin plates and low-rigidity parts without causing deformation due to that might otherwise be caused chucking and machining force, which is a problem in conventional processing machines.

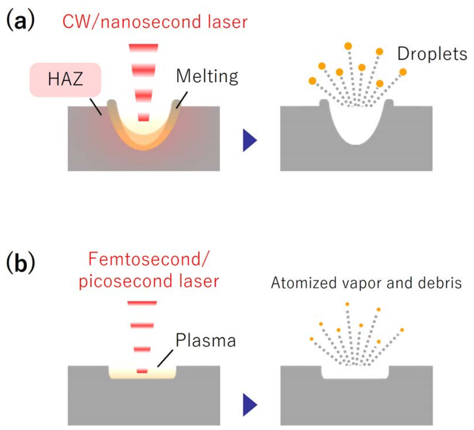


Fig. 4 Differences in processing as a function of laser pulse width: (a) Thermal processing with CW/nanosecond laser; (b) non-thermal processing with femtosecond/picosecond laser.

An additional advantage of ablation processing by ultra-short pulse laser is that there are few constraints on the materials that can be processed. Ultra-short pulse lasers can process even materials having band gaps larger than the photon energy (i.e., materials that do not absorb light) due to non-linear photon behavior at extremely short pulses. The ultra-short pulse laser adopted in Lasermeister1000S enables processing of general metals and a wide range of materials such as those that are hard and difficult-to-process, e.g., cemented carbides and diamond, and also easy-to-break brittle materials, e.g., ceramics and optical glass (Table 1).

In conclusion, laser ablation using an ultra-short pulse laser can minimize adverse effects on the work piece and is effective for machining of a wide range of shapes and materials.

Table 1 Materials that can be processed with the Lasermeister1000S.

| Typical metals | Highly reflective metals | Difficult-to-cut metals | Ceramics/ Semiconductors/ Sintered materials | Others |
|---|---|---|---|---|
| Austenitic stainless steel | Aluminum | Die steel | Silicon | Borosilicate crown glass |
| Martensitic stainless steel | Copper | Tungsten | Silicon carbide | Fused silica glass |
| Ferritic stainless steel | Gold | Titanium | Silicon nitride | Single crystal diamond |
| Carbon steel | Platinum | Titanium alloy | Aluminum nitride | Polycrystalline Diamond |
| Chromium molybdenum steel | | Nickel alloy | Alumina | |
| Zinc | | | Zirconia | |
| Aluminum alloy | | | Cemented carbide | |
| Cupper alloy | | | | |

Processing accuracy and safety depend on materials. Processing of materials other than the above is also possible.

### 3.3. On-machine Feedback Processing by On-machine 3D Measurement

The on-machine 3D measurement equipment installed in Lasermeister1000S employs optical interference technology, which enables high-precision and high-throughput 3D measurement. By measuring the surface shape of the target object with high accuracy, it is possible to accurately enable machining feedback according to the target shape. As a result, it is possible to obtain the desired high-precision surface easily by repeating the machining feedback using this high-precision measurement (Fig. 5).

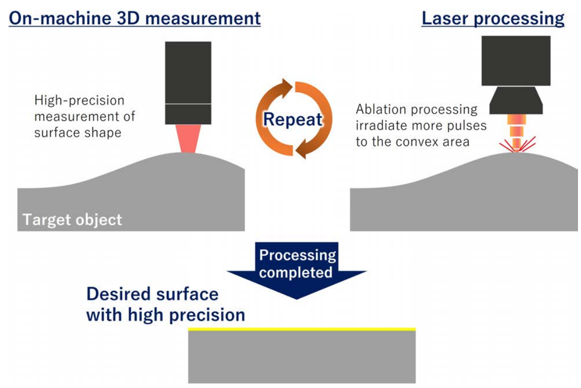


Fig. 5 On-machine feedback processing by on-machine 3D measurement.

Figure 6 shows a typical example of common flat surface processing (processing to achieve uniform flatness over multiple locations) using on-machine feedback machining. The work piece was a thin plate of stainless steel: SUS304 (80 mm x 75 mm x 1 mm thick), and common flat surface processing of 10 mm x 10 mm was performed on these four corners. This stainless steel thin plate exhibited a swell of approximately 100 um before processing. However, as can be seen from the color contour diagram, the targeted area was processed to have a very high precision common flatness (0.4 um) with submicrometer geometric tolerance. It is difficult to realize such ultra-high precision processing of thin

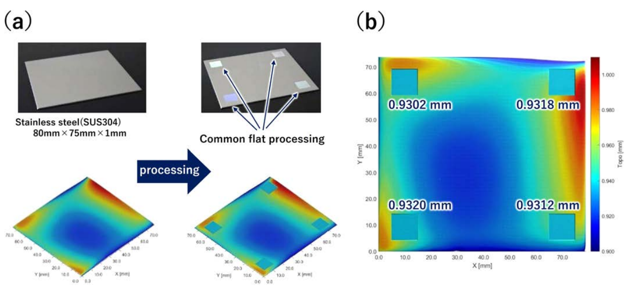


Fig. 6 Common flat surface processing of SUS304 thin plate: (a) Photograph of the target object before and after machining and diagonal contour diagram of height; (b) planar contour diagram after machining; common flatness of 0.4 um was achieved.

plates with grinding machines, but the Lasermeister1000S can readily achieve this without chucking and particular operator skill.

### 3.4. Automatic Generation of Machining Data by On-machine CAM/3D Alignment

For typical NC machine tools, it is necessary to create a machining program with CAM based on a design model created with CAD. CAM improves the work efficiency of the process and can handle complicated machining shapes and perform machining simulations. However, it requires specialized knowledge in programming, and the time required for creation and data quality varies depending on the operator's skill.

Lasermeister1000S incorporates CAM-equivalent functionality (on-machine CAM) into the device software (Fig. 7). Only the 3D models of the work piece and the machining target design, together with the machining and measurement parameters, are input into the device. As the machining area and machining path are automatically generated from these model data, parameters, and on-machine 3D measurement results, the operator's specialized knowledge is no longer required, leading to shortened program creation times and stabilized data quality.

Elimination of setup by a "3D alignment" procedure that automatically positions the target object is also a prominent feature of the Lasermeister1000S. In conventional processing machines, the operator fixes the work piece with a jig and performs position measurements involving contact of the measurement stylus at multiple sample points; however, it is typically an extremely complicated procedure. With the Lasermeister1000S having on-machine measurement capability, such procedures can be automatically performed.

Figure 8 shows the process of 3D alignment. First, the work piece is placed at any arbitrary position on the table. Lasermeister1000S is equipped with two types of 3D mea-

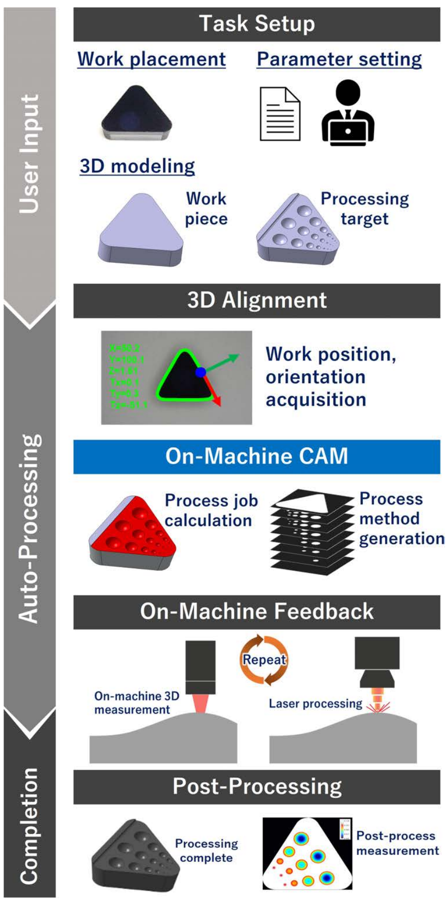


Fig. 7 Processing flow of the Lasermeister1000S.

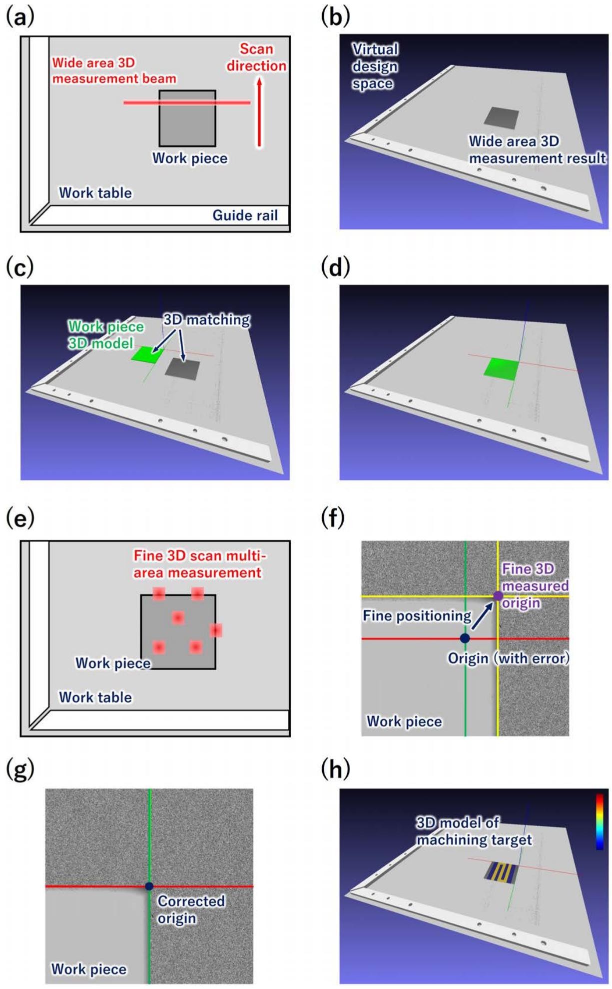


Fig. 8 3D alignment process: (a) Work piece measurement with wide-area 3D scanner; (b) placement of wide-area 3D scanner measurement results in virtual space; (c) 3D matching of base-material 3D model and measurement results; (d) 3D matching results; (e) measurement of edge position and height of the work piece at multiple areas with a fine 3D scanner; (f) fine positioning of the work piece origin based on the measurement results of the fine 3D scanner; (g) fine positioning results; (h) placement of 3D model of machining target in virtual space.

suring machines: a wide-area 3D scanner implementing an optical cutting method and a fine 3D scanner implementing an optical interference method. Next, the wide-area 3D scanner measures the entire image of the work piece in a short time, and 3D matching is performed with the 3D model input into the system. From the result of this matching, the work piece's position and orientation can be automatically aligned, and the actual position and orientation of the work piece can be reproduced in a virtual space on the computer. However, 3D alignment with a wide-area 3D scanner has an error of several hundreds of micrometers; thus, when more precise alignment is required, it is performed with the fine 3D scanner. With reference to the results of the wide-area 3D scanner, by then accurately measuring the edge position and height of the work piece at multiple areas with the fine 3D scanner, it is possible to finely position the model and orientation of the work piece in the processing space with micrometer precision. The 3D model of the machining target is placed in a virtual space based on the actual position and orientation of the work piece on the work table, and then machining can be accurately performed according to the input machining parameters.

## 4 Applications

Lasermeister1000S, which integrates the above-mentioned technologies, can easily realize high value-added processing with micro-to-submicrometer geometric tolerances for various applications. Examples of applications include precision molding, precision surface, cutting tools, grinding wheels, low rigidity parts, difficult-to-cut materials processing (ceramics, diamonds, carbide, optical glass, etc.), and microfabrication. Here we will introduce some of them.

### 4.1. Reproduction Processing of Scraping

Scraping is used in sliding parts of machine tools, such as grinding machines, and as reference flats. It is an important technique indispensable for machine tools. Scraping, which results in an ultra-flat finish that cannot be achieved with conventional processing machines, still requires a traditional processing technique where a craftsman hand-scrapes a surface to induce shallow depressions while maintaining the original flat surface. Oil will readily adhere to this scraped surface, creating an oil sump of several microns, allowing smooth movement when used as a sliding surface. Figure 9 shows the processing that digitally reproduced this scraping.

Gray cast iron (FC300) was prepared as the base material, and the hand-scraping result was reproduced in the center of the work piece with dimensions 60 x 60 mm (laser processing time: 35 min). Figures 9 (a) – (c) show a photograph after processing, the height contour diagram, and the profile, respectively. As can be seen from the profile results in Fig. 9 (c), the shape after processing was faithfully reproduced in submicrometer scale with respect to the target shape, realizing the automation of scraping that typically requires more than a decade of skill mastery. An evaluation of the sliding characteristics was also conducted in another case, and results comparable to hand-scraping made by a craftsman were obtained. Note that it is easy to pattern the oil sump with arbitrary shape and regularity, making it possible to eliminate the quality variation introduced by different operators. Thus, we demonstrated that this processing machine is a powerful tool for realizing digital manufacturing of scraping.

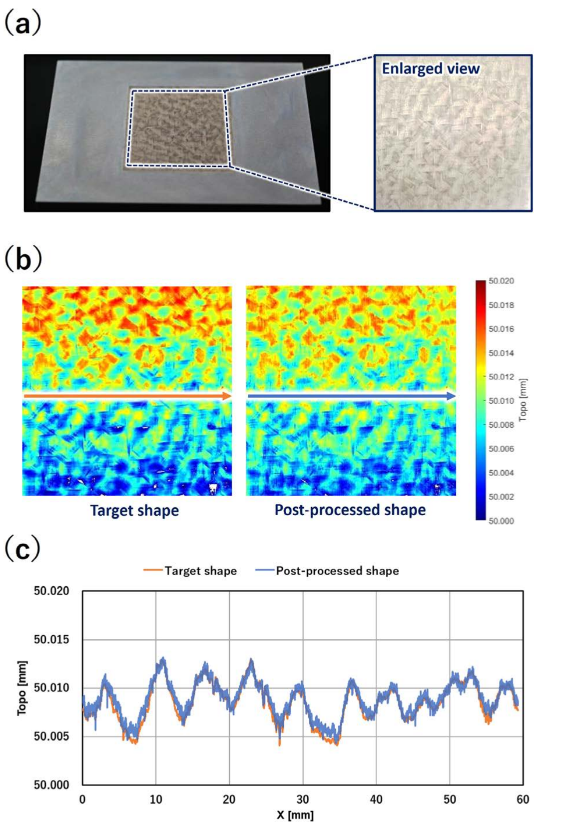


Fig. 9 Reproduction processing of scraping: (a) Photograph of processed scraper; (b) contour diagram of heights of machining target and post-processed shape; and (c) corresponding shape profiles.

### 4.2. Mold Processing of Fuel-cell Separator

Fuel-cell separators are manufactured by press molding, but materials with high hardness and abrasion resistance, such as die steel, high-speed tool steel, and cemented carbide, are used as mold materials. Consequently, it is difficult to realize high-precision machining of the molds with conventional processing machines. In addition, the machining shape of the separator mold is complicated, and the processing difficulty is also high. The separator has a flow path through which gas flows, and to promote gas diffusion, an irregularly shaped flow path may be needed. As the separator is used for stacking, high flatness is also required. Figure 10 shows a processing example model of a hypothetical separator mold.

PD613 (Daido Steel Co., Ltd.), which is a die steel, was used as the base material for this processing objective. In the flow path of the 3D model of the machining target, aperture and taper were included, and a structure with a high degree of freedom was machined for this mold material (laser processing time: 3.3 h). The flow path model has a 45-degree taper, and the processing in Fig. 10 results show that it can be reproduced precisely. The surface shape could be processed with extremely high precision: the average difference between the shape after processing and the target shape to be processed was 1.3 um. The surface roughness was Ra 0.15 um at the deepest point. It was confirmed in another example that similar processing can be carried out even with cemented carbide. Thus, these processes demonstrate the processing of separator molds for fuel cells, which is one of the applications of precision molding.

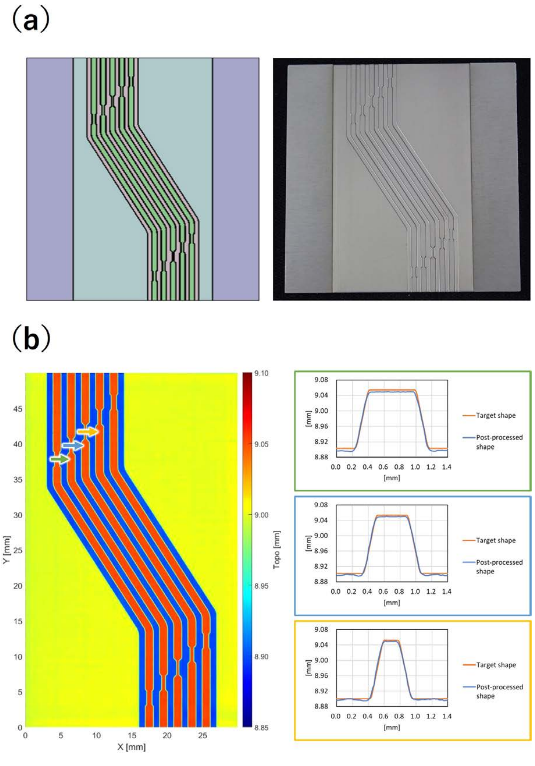


Fig. 10 Processing example of a model of a hypothetical fuel-cell separator mold: (a) 3D model of processing target and work piece after processing; (b) height contour diagram of shape after processing and cross-sectional profile of flow path through the aperture.

### 4.3. Fine Shape Processing of Ceramic Materials

Ceramic materials such as alumina have excellent mechanical strength, wear resistance, and electrical insulation properties and are used as structural materials for electrostatic and vacuum chucks that hold silicon wafers on a flat surface with high accuracy. Tens of thousands of fine pin shapes with a diameter of hundreds of micrometers and a height of tens of micrometers are formed on the surface of these chuck parts to suppress trash traps; but these parts demand high productivity and must be processed in a short time. Blasting is usually employed for this pin formation as it can accomplish surface grinding, satin processing, and surface modification, even in places where machine tools do not reach. However, the setup of the masking and mask peeling process is complicated and difficult to automate. The degree of freedom of the processing shape is also complicated to manage and there are many restrictions. In this context, we introduce an example of ceramics processing by Lasermeister1000S.

Figure 11 shows the results of conducting grooving, common flat surface processing, and fine pins processing on an alumina substrate. Grooving is a machining procedure that assumes a groove for the gas flow path of an air bearing or electrostatic chuck. It can be seen that a target machining depth of 20 um can be achieved in each groove with a machining accuracy of ± 1 um or better (Fig. 11 (b)). Similar to the stainless steel machining example, common flat surface processing could achieve a flatness of 0.4 um even for alumina (Fig. 11 (c)). Pin pattern machining was successful with models of diameters 250 um and 500 um by imagining electrostatic and vacuum chucks. The height of

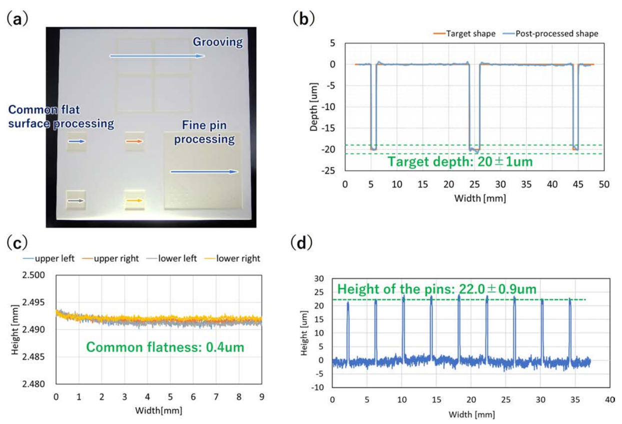


Fig. 11 Fine shape processing on alumina substrate: (a) Photograph of alumina substrate with after fine-shape processed; (b)-(d) cross-sectional profile of grooving, common flat surface processing, and fine pin processing, respectively.

the pins of diameter 250 um was 22.0 ± 0.9 um, highlighting suppression of variation among pins (Fig. 11 (d)). Given that the machining accuracy of chuck parts affects the distortion when gripping the flat surface of the wafer and the temperature controllability for keeping the wafer temperature constant, it is a requirement to process the pin height and groove depth uniformly. Lasermeister1000S controls these parameters on a micro-to-submicrometer scale.

## 5 Conclusions

Lasermeister1000S is a novel processing machine that has a dramatic effect on the design of machining tasks, reduces the waste of “processes that were common so far”, and realizes “processing that was impossible so far.” Being able to easily process a wide variety of machine parts with light will revolutionize manufacturing. Therefore, we will introduce machining support tools, such as automatic processing condition setting and processing unevenness correction, and advance the development of elements such as five-axis stage/laser re-melt to enable the development of more valuable next-generation optical processing machines for users in the future.

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