様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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研究課題名（和文）Electro-acoustic stimulation assisted nano-abrasive blasting system

研究課題名（英文）Electro-acoustic stimulation assisted nano-abrasive blasting system

研究代表者

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交付決定額（研究期間全体）：（直接経費）　　3,300,000円

研究成果の概要（和文）：本研究では、砥粒均質化法を研究・実施した。この方法は、超音波振動による円筒形キャビティ内の音響流の生成に基づくものである。この方法は、ワークピースに衝突するナノブラストノズルに、バラバラになった砥粒を噴射する前に適用することができます。
実験では、一次粒子径が2μm以上の粒子の凝集を良好に解砕できることを確認した。2μmより小さい粒子の場合、一部の凝集体が残りました。
このプロセスにより、粒子堆積と材料除去の境界付近の条件で、表面のブラスト加工ができることが示された。2μmの砥粒をガラス加工に用いた場合、ほとんどの加工条件において、超音波振動を加えると表面粗さが顕著に小さくなることがわかりました。

研究成果の学術的意義や社会的意義
超精密研磨方法には、流体ジェット研磨（FJP）やイオンビーム研磨（IBF）など、いくつかの種類があります。 これら 2 つの特定のプロセスでは、材料除去する粒子のサイズと速度、および実装コストが大きく異なります。 FJPとIBFの中間の粒径と速度の砥粒を空気中で使用する方法を開発することで、装置の複雑さとコストを簡素化しながら、表面仕上げ粗さの向上を実現しました。
ナノブラストプロセスは日本の光学製造産業に適用できる。光学を使用する他の産業に利益をもたらすことが期待されています（例えば：車用の HUD、エンターテイメント用の AR ヘッドセット)。

研究成果の概要（英文）：In this study, an abrasive grain homogenization method was studied and implemented. The method is based on the generation of an acoustic streaming flow inside a cylindrical cavity by ultrasonic vibration. It can be applied before injecting the disaggregated abrasive grains in a nano-blasting nozzle that is impiging a workpiece.
Experiments confirmed that the agglomeration of particles with a primary particle size larger than 2μm can be well broken down. In the case of particles with a primary diameter smaller than 2μm, some agglomerates remained while the rest of the agglomerates were broken up.
The process was shown to allow blasting of surfaces at conditions near the boundary between particle deposition and material removal. When abrasive grains with a primary grain diameter of 2μm were used for processing glass, the surface roughness became noticeably smaller when ultrasonic vibration was applied, under most processing conditions.

研究分野：超精密仕上げ

キーワード：ナノブラスト　超精密仕上げ　砥粒均質化法　超音波振動　音響流

１．研究開始当初の背景

Ultra-precision polishing is usually employed to finish the surfaces of optical components such as microscope lenses and telescope mirrors, as well as artificial joint components used in the medical field, to a surface roughness of the order of magnitude of Ra 1 nm. There are several types of ultra-precision polishing methods that can be used for this purpose, including Fluid Jet Polishing (FJP) and Ion Beam Figuring (IBF). The particle size and velocity differs greatly between these two particular processes. On the one hand, the velocity of particles is limited by the velocity of the carrier fluid in FJP. The velocity of the jet is about 10 m/s when the water pressure is around 1.0 MPa. In addition, the smaller the grain size, the more difficult it becomes for the abrasive grains to penetrate the stagnant layer of fluid near the workpiece, so it is necessary to use relatively large abrasive grains of 1 micron or more in diameter. On the other hand, in IBF the maximum speed at which particles are ejected is about 10,000 m/s. Ionized atoms are used which are several orders of magnitude smaller than the micro-abrasives used in FJP. Therefore, the finished surface roughness can be very smooth. However, FJP has much simpler implementation requirements, consisting only of a pump and nozzle, whereas IBF requires a hard vacuum and other expensive equipment. Therefore, the development of a method that uses abrasives with a particle size and speed intermediate between those used in FJP and IBF may allow an improvement in surface finish roughness while simplifying the complexity and cost of equipment, as shown in Table 1.

Table 1. Key characteristic of fluid jet polishing, ion beam figuring, and topic of this research.

	FJP	Proposed	IBF
Particle size	>1 µm	~1 µm	<1 nm
Particle speed	~ 10 m/s	~ 1,000 m/s	~ 10,000 m/s
Operating fluid	Water	Air	Vacuum
Typical finish	>1 nm Ra	~1 nm Ra	<1 nm Ra
Equipment cost	<100K USD	<100K USD	>1M USD

２．研究の目的

The material removal rate and the surface roughness are typically used to evaluate the characteristics of machining processes. The removal rate determines the efficiency of the processing method, and the surface roughness evaluates how smoothly the workpiece is processed. In AAJM, the machining conditions influencing these factors include injection pressure, abrasive grain size, impingement angle, stand-off distance, hardness of the abrasive grains and workpiece, and the amount of abrasive grains injected per unit time, as shown in Fig. 1.

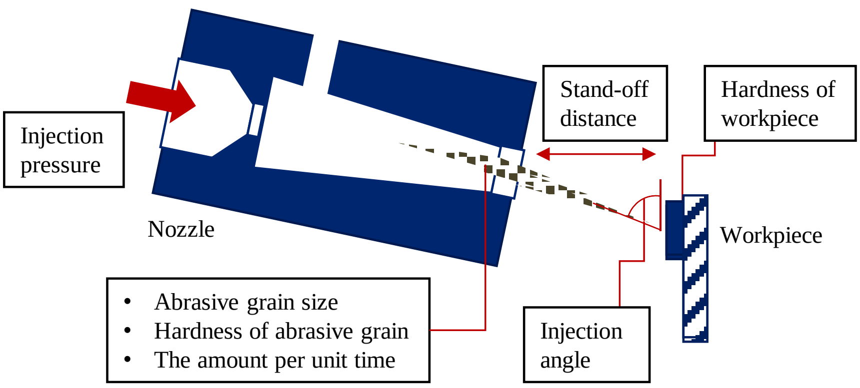
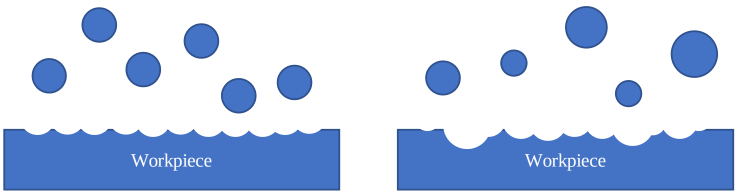


Figure 1. Process parameters in abrasive air jet machining.

The removal rate and the surface roughness increase as function of most processing parameters, except for the jet angle. For a polishing process, the removal rate should ideally be high and the surface roughness low, resulting in a trade-off relationship. When particles are agglomerated, the diameter of the agglomerated particles can vary randomly according to a distribution. As shown in Fig. 2, since the amount of material that abrasive grains cut from the workpiece depends on the size of the impacting particles, the roughness on the workpiece surface may become inconsistent if abrasive grains of various size collide with the surface. Therefore, in order to achieve a better and more consistent surface roughness, it is proposed to make the size distribution of abrasive grains smaller and more uniform by breaking the agglomeration of abrasive grains. In order to break the agglomeration, an acoustic flow is formed by ultrasonic vibration inside a homogenizer cavity, and an acoustic radiation force is applied to the abrasive grains moving along the acoustic flow. The disintegrated abrasive grains can then be injected into the nozzle and impact on the workpiece. By achieving well controller processing conditions, it can be investigated whether polishing is possible near the boundary between the removal and deposition process methods.



(a) Abrasive grains with uniform grain size (b) Abrasive grains with non-uniform grain size

Figure 2. Roughness of workpiece surface due to variation of abrasive grain size.

３．研究の方法

3.1 Interaction forces between abrasive particles

Generally speaking, as the grain size of abrasive grains reduces, the surface roughness of the processed workpiece also reduces. However, as the particle size decreases, the ratio of the surface area to the volume of the particles increases, and the adhesion force, which is a surface force, becomes a dominant factor affecting the behavior of the particles. Thus, the smaller the particle size, the more likely the particles are to agglomerate. There are 3 main interaction forces that can play a role: the capillary (liquid crosslinking) force, Van der Waals force, and electrostatic force. Fig. 3 shows the relationship between particle size and the relative strengths of adhesion forces, of which the liquid crosslinking force is the largest. The liquid crosslinking force can be controlled by the type and amount of liquid molecules adsorbed on the particle surface, and can be typically reduced by desiccating the particles to reduce the number of water molecules.

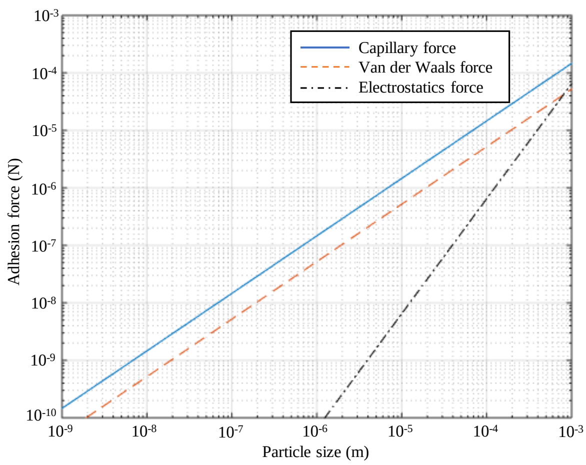


Figure 3. Relative strength of three types of adhesion forces as function of particle size.

3.2 Dispersion of agglomerated particles in an acoustic flow

When acoustic radiation pressure is applied to a resonant tube, it creates a pressure difference in the tube. Once a standing wave of ultrasonic pressure in the tube is achieved, an acoustic flow is then induced between the belly and the nodes of the standing wave. The global flow induced outside the boundary layer is called the Rayleigh acoustic streaming. Rayleigh acoustic streaming is the streaming velocities of second order in powers of acoustic Mach number, with vortices that span a quarter of a wavelength. The main mechanisms for disintegration of agglomerated particles in air are acceleration and shearing force by airflow, mechanical disintegration, and collision with walls or obstacles. The particles may disaggregate if the dispersive force exceeds the sum of adhesion forces

3.3 Overview of proposed nano-blasting system

Fig. 4 shows a schematic diagram of a proposed Nano-Blasting (NB) system. Abrasive grains are supplied at an approximately continuous rate from a screw based feeder and sent to the homogenizer cavity. Acoustic vibration is generated by an ultrasonic oscillator connected to the cavity, allowing disintegration and mixing of the abrasive grain agglomerates to take place. These are then sent to the nozzle and sprayed onto the workpiece by the high-speed air flow formed by high-pressure air supplied by a pump connected to the nozzle via a pipe.

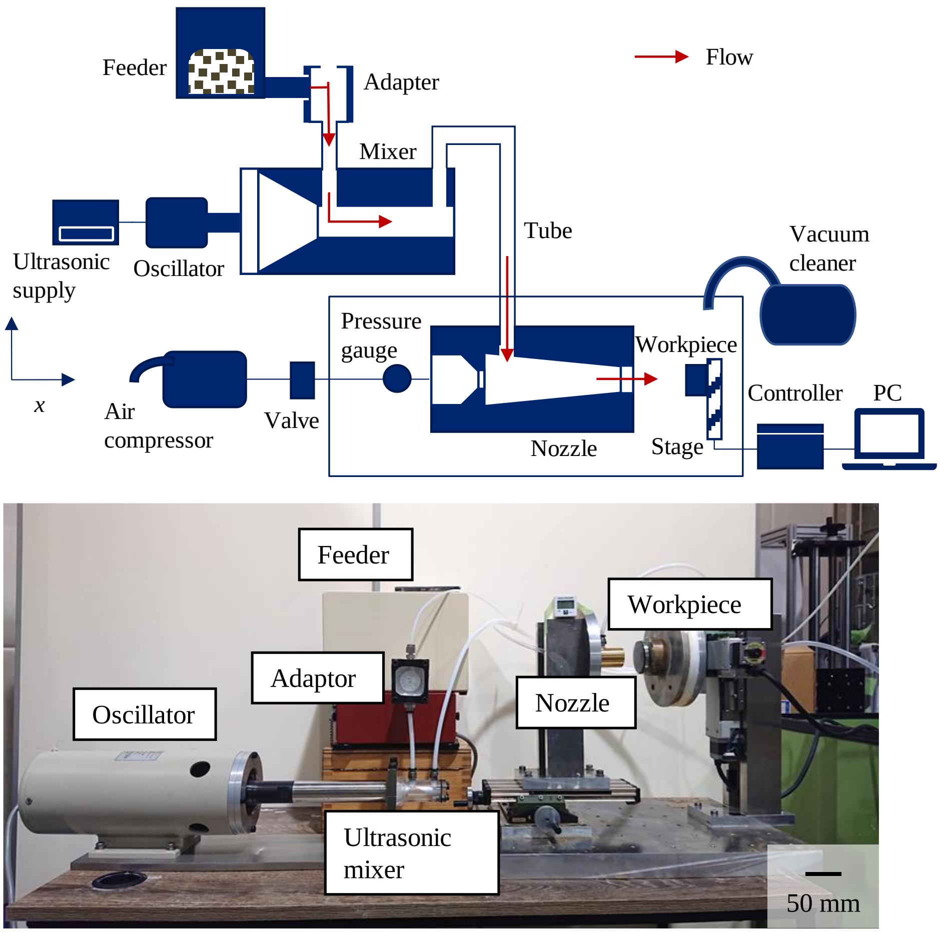
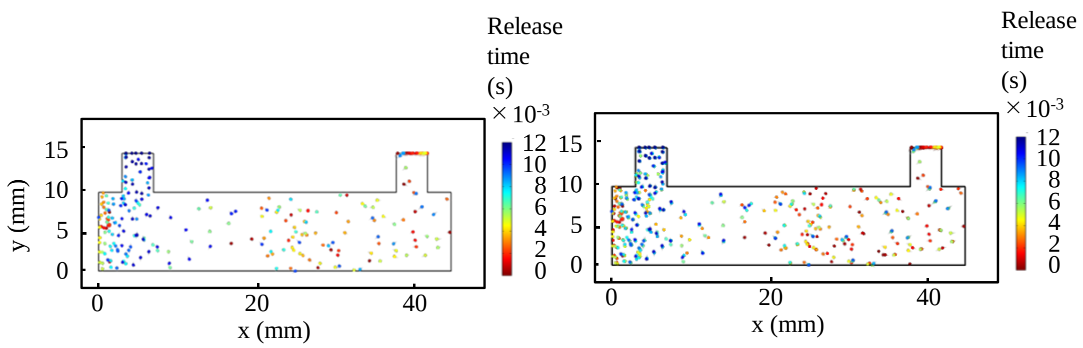


Figure 4. Schematic and photograph of the developed nano-blasting system.

In this study, the motion of abrasive particles due to acoustic flow inside the homogenizing cavity was simulated by computational fluid dynamics (CFD). Fig. 5 shows the distribution of the dropped particles in the device. The figure shows the position of the particles in the device every 0.003 seconds from the start of the calculation. The red particles were dropped first, and the blue particles were dropped later. The figure shows that red particles, which were dropped earlier, are still in the device after some time when applying ultrasonic vibration. By comparison, when no ultrasonic vibration is applied the particles go straight from the entrance to the exit.

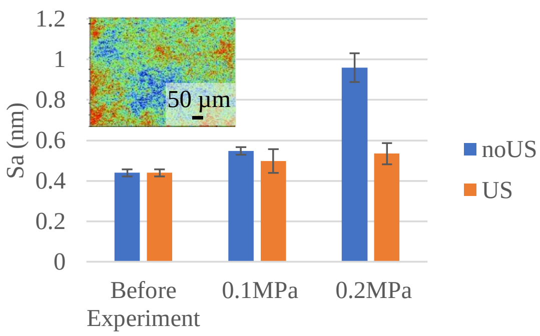


(a) 0.009 s (b) 0.012 s

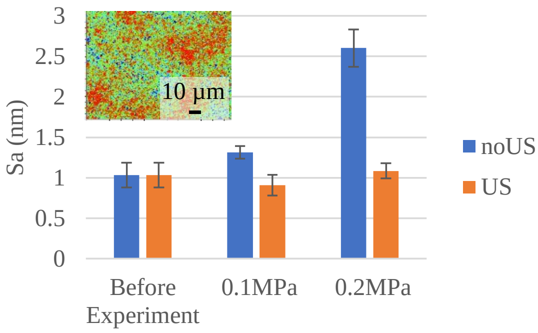
Figure 5. Motion of particles in the homogenizer cavity under the influence of acoustic streaming.

４．研究成果

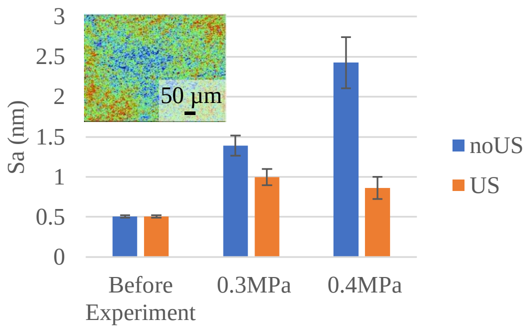
Particles were blasted onto the glass plates with mirror finish. Five points were measured for each machining condition. The measurement results are shown in Fig. 6. The surface roughness can be seen to increase as function of the injection pressure, but it can also be seen to decrease when ultrasonic vibration is applied. In particular, when ultrasonic vibration was applied, the surface roughness was significantly smaller in the measurements at 0.3 MPa and 0.4 MPa.



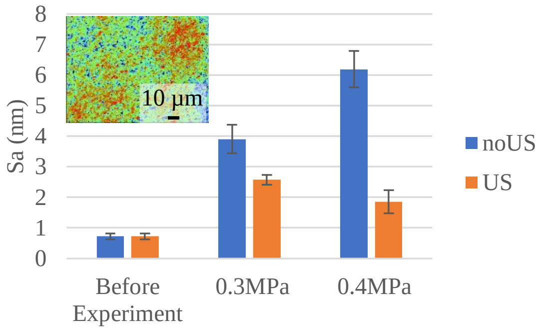
(a) 0.1, 0.2 MPa injection pressure (10x mag.)



(b) 0.1, 0.2 MPa injection pressure (50x mag.)



(a) 0.3, 0.4 MPa injection pressure (10x mag.)



(b) 0.3, 0.4 MPa injection pressure (50x mag.)

Figure 6. Surface roughness of the glass plate after processing with WA #6000.

After measuring the surface form, the material removal rate was calculated as shown in Fig. 7. When ultrasonic vibration is applied, the material removal rate decreases by a factor of 0.62 times when the injection pressure is 0.3 MPa, and 0.56 times when the injection pressure is 0.4 MPa. Clearly, the total mass of particles colliding with the surface is larger when ultrasonic vibration is not applied. If the abrasive grain is large, it will collide with the workpiece without changing its trajectory significantly from the direction of injection, but if it is small, the trajectory will deviate outward from the direction of injection due to the entraining force of the airflow as the air from the nozzle hits the workpiece. Therefore, as abrasive grains become smaller, the range where abrasive grains collide should become wider, and more particles may be unable to penetrate the stagnant near-wall layer of air.

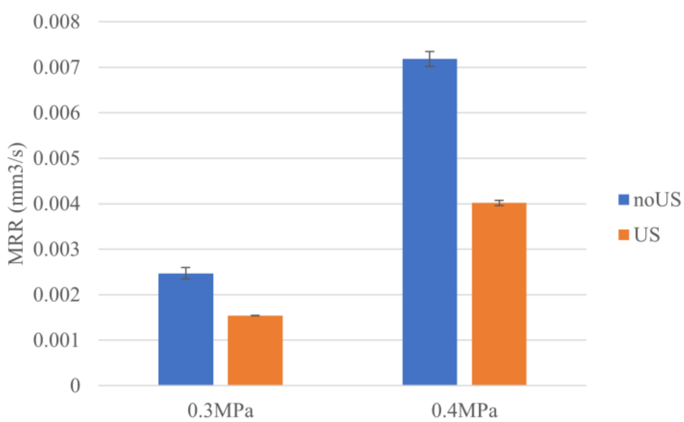


Figure 7. Material removal on the glass plate when processing with WA #6000.

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　3件／うちオープンアクセス　0件）

１．著者名 Mizoue Yuichi, Sencer Burak, Beaucamp Anthony	４．巻 159
２．論文標題 Identification and optimization of CNC dynamics in time-dependent machining processes and its validation to fluid jet polishing	５．発行年 2020年
３．雑誌名 International Journal of Machine Tools and Manufacture	６．最初と最後の頁 103648
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ijmachtools.2020.103648	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Zhu Wule, Beaucamp Anthony	４．巻 172
２．論文標題 Generic three-dimensional model of freeform surface polishing with non-Newtonian fluids	５．発行年 2022年
３．雑誌名 International Journal of Machine Tools and Manufacture	６．最初と最後の頁 103837
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ijmachtools.2021.103837	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Beaucamp Anthony, Mizoue Yuichi, Yamato Shuntaro, Sencer Burak	４．巻 312
２．論文標題 Feed scheduling for time-dependent machining processes by optimization of bulk removal and NC blocks	５．発行年 2023年
３．雑誌名 Journal of Materials Processing Technology	６．最初と最後の頁 117786
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.jmatprotec.2022.117786	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計3件（うち招待講演　0件／うち国際学会　1件）

１．発表者名 Shuntaro Yamato, Burak Sencer, Anthony Beaucamp
２．発表標題 Novel deconvolution based feedrate scheduling towards a new class of CAM for time-dependent processes
３．学会等名 International Symposium on Flexible Automation (ISFA2022)（国際学会）
４．発表年 2022年

１．発表者名 森 有花，松原 厚，Beaucamp Anthony
２．発表標題 ナノブラスト精密研磨装置の試作機の研究と製作
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４．発表年 2021年～2022年

１．発表者名 森 有花，松原 厚，Beaucamp Anthony
２．発表標題 静電気力と超音波振動を用いたナノブラスト研磨用砥粒粒径均一化に関する研究
３．学会等名 精密工学会学術講演会講演論文集 2020 年度精密工学会秋季大会
４．発表年 2020年～2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関