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Evaluation of Y_2O_3 surface machinability using ultra-precision lapping process with IED [†]

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Abstract

Prospects of Y_2O_3 have been more extended as a great promising and creditable material for optical, electronic and mechanical purposes. Y_2O_3 has been more observed as a fine ceramic which has great material properties: high light transparency, excellent thermal resistance and chemical inertness. But in terms of effective application of Y_2O_3, its hard and brittle nature needs to be overcome during the surface machining process. Therefore, the surface machining control of Y_2O_3 should be conducted carefully. The evaluation for stable and continuous machining should also be investigated in various industrial fields as there are only limited studies on the subject. The lapping process with in-process electrolytic dressing (IED) is widely used for surface machining of hard and brittle materials. In this study, Y_2O_3 surface machinability was evaluated by using the ultra-precision lapping process with IED method by changing three major variables: applied force, wheel speed and machining time. The most suitable value of Ra 92nm surface roughness was acquired with smooth surface quality from the following machining condition: 7kg of applied force, 60rpm of wheel speed and 30minutes of machining time. After the lapping process, the machining tendency and surface characteristics were analyzed with fracture toughness and Vickers hardness for the evaluation of Y_2O_3 surface machinability.

Keywords: Y_2O_3; Surface machinability; Ultra-precision lapping; In-process electrolytic dressing (IED); Evaluation

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1. Introduction

The engineering applications of ceramic materials have been increasing in the electronics industry, optical application, biotechnology and other engineering fields because the ceramic materials have excellent thermal resistance, chemical inertness and wear condition.

Y_2O_3 (Yttria) is a great promising and creditable material for optical, electronic and mechanical purposes. Y_2O_3, which is composed of cubic(c-type) crystal structure, has been used as a light-transmitting material in various fields such as lenses, prisms or glass with high temperature environment. Y_2O_3 has a comparatively high index of refraction and its light transparency is similar to Al_2O_3 (Alumina) which possesses high transparent property and the range of wavelengths is wider than Al_2O_3 ceramics [1-3].

Y_2O_3 has been considered as a suitable buffer layer in metal-ferroelectric-insulator-semiconductor(MFIS) structure for single transistor FeRAM (ferroelectric random access memory) because the Y_2O_3 buffer layer has excellent characteristics: low lattice mismatch, low leakage current, high dielectric constant and chemical stability [4].

Moreover, Y_2O_3 is well worth considering as a high strength and heat resisting material. Among the oxide ceramics, Y_2O_3 has ionic and covalent bonding. These kinds of bonding make the microstructure of Y_2O_3 tough and crowded [1]. High melting point (2430℃) and thermal conductivity (13.6W/cm at

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30℃) of Y_2O_3 make for a useful host material for high power industrial lasers [5].

Y_2O_3 has been more observed as a fine ceramics because of these promising properties. But for the effective application of Y_2O_3 ceramic, the imperfection of its hard and brittle nature needs to be overcome during the surface machining process. Therefore, the surface machining control of Y_2O_3 ceramic should be conducted carefully for efficient application. Furthermore, stable and continuous surface machining should be evaluated in various industrial fields. However, the investigation of Y_2O_3 ceramic surface machining does not exist to any great degree.

In this study, Y_2O_3 surface machinability was evaluated. For assuring surface machinability, atomic purity 97% Y_2O_3 ceramic was machined by ultra-precision lapping process with in-process electrolytic dressing (IED) method. The ultra-precision lapping with IED method is widely used for surface machining of hard and brittle materials [6,9,10]. The lapping with IED was conducted by changing three main variables: applied force, wheel speed and machining time. The machining characteristics and capability were investigated along with material characteristics, which include fracture toughness and Vickers hardness for the evaluation of Y_2O_3 surface machinability.

2. In-process electrolytic dressing (IED)

Super-abrasive lapping is widely used to accomplish a mirror-like surface on hard and brittle materials. This lapping process can be potentially ultra-precision machining. A metal-bonded lapping wheel more than 1,000 grit-sized super-abrasive is suitable for a high quality surface finish. But conventional lapping wheel should overcome defects such as loading and glazing on a lapping wheel. Stable and periodic dressing is requisite to put away these defects. Thus the in-process electrolytic dressing method was proposed.

The IED method is a way of using electrolysis. The worn abrasive grains are removed and new grains are protruded from the wheel surface during lapping process. A high quality machined surface can be obtained because it is possible to lap with new grains.

Fig. 1 shows a schematic diagram of the mechanism of the IED lapping process. After truing, the grains and bonding material of the lapping wheel are flattened. Truing process is required so that the incipient eccentric is reduced. And a pre-dressing process is carried out before the IED lapping process is started. Electric power is supplied to the electrolyte which is located between electrode connected to the cathode and lapping wheel connected to the anode. An electrolyte is provided continuously. During pre-dressing process, bond materials gush out from the surface of the lapping wheel and form hydroxide or oxide insulating layer along with stable grain protrusion. After pre-dressing process, IED lapping is started. The insulating layer and grains are worn away and removed from the wheel surface during the lapping process. After the lapping process, suitable quantities of bond materials gush out again from the wheel surface. Thus the worn grains are removed and new grains protrude forming an insulating layer on the wheel surface. The mechanism of the IED process is repeated during machining time.

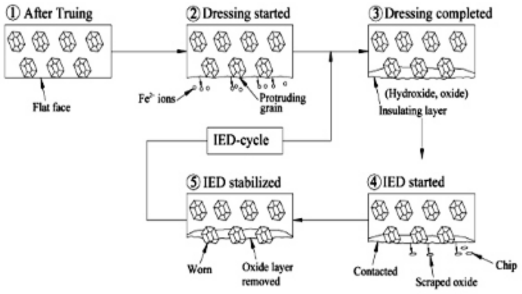


Fig. 1. The mechanism of the IED lapping process.

With conventional lapping, there are numerous disadvantages that are overcome by IED lapping. The machining ability is decreased when machining time is increased because of worn abrasive, chip discharge instability and remaining lapping compound. The above disadvantages deteriorate the lapped surface quality. Therefore, the IED method is needed for stable and continuous lapping process. A high quality smooth surface can be obtained by the IED method [7-10].

3. Experiment and Y_2O_3 Ceramic

3.1 Experimental system and procedure

Fig. 2 shows an actual experimental system and Table 1 shows the specifications of the IED lapping system. A #4000 mesh grit sized cast-iron metal-bonded diamond abrasive wheel having electric conductivity was used because the electrolysis occurs in the electrolyte located between the electrode and lapping wheel during the lapping process. The electrode,

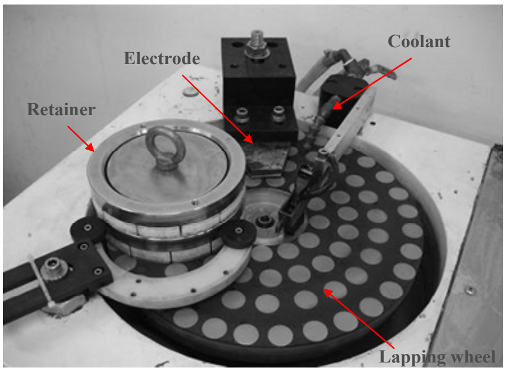


Fig. 2. Experimental IED system.

which is composed of pure copper having purity 99% and located above the lapping wheel, connects from the negative side of the power supply and covers 12.5% area of the lapping wheel. The electrolyte is composed of N3 electrolytic fluid and DI water rated 1:15 ratio and continuously supplied. This solution type of electrolyte has also the role of coolant during the lapping process.

For the provision of electric power, an electric current formed of square pulse wave was supplied from the IED power supply. The experiment was carried out under a peak current of 25A, pulse-time(τ on/off) 20/10 μs. The small gap between the electrode and lapping wheel was adjusted 0.2mm for the efficient generation of electrolysis.

The workpiece was situated in a retainer above the lapping wheel. A retainer has the workpiece keep moving on a stable rotating area. A weight was put on the workpiece and pressed on the surface of the workpiece. The workpiece and weight in a retainer rotate together during machining time.

Before starting the pre-dressing and lapping process, the truing process was previously implemented. The truing process flattens and balances the wheel surface. A wheel after truing can reduce the other damages so the truing process is significantly needed for acquiring high quality machined surface.

At fixed state of the power condition, the lapping processes of Y_2O_3 were conducted varying three major variables: wheel speed, applied force and machining time. A range of wheel speed condition is from 40rpm to 60rpm at 10rpm intervals. An applied force was controlled with 5kg, 7kg and 9kg by putting a weight on the workpiece. Finally, machining time was adjusted from 20min to 40min at intervals of 10min apart. Above conditions were selected through previous experiments and other results of ceramic lapping.

Table 1. Specifications of the IED lapping system.

Lapping machine	In-process electrolytic dressing lapping machine
Lapping wheel	Cast-iron metal-bonded diamond lapping wheel (CIB-D) (Φ380 x W25 mm #4000 conc. 100)
Power supply	Voltage (0-90V) Peak current Ip (0-30A) Pulse on/off (0-999μs)
Electrolytic fluids	N3 : DI water (1:15)
Workpiece	Y_2O_3 (Yttria)

Table 2. Element composition of Y_2O_3.

Element	Weight %	Atomic %
Y	75.02	46.38
O	14.78	50.80
Ir	5.70	1.63
Pb	4.50	1.19
Total	100.00	100.00

3.2 Y_2O_3 (Yttria) ceramic

For engineering applications of Y_2O_3 ceramic, some of material properties were investigated. Table 2 shows the element composition of Y_2O_3 ceramic conducted in the experiment. It represents element weight ratio and atomic ratio of Y_2O_3. Two elements (Y and O) compose 89.8% weights and 97.12% atomic ratio of the workpiece. Fig. 3 shows the spectrum of Y_2O_3 element composition.

Sintered Y_2O_3 ceramic was cut by conventional ceramic cutting machine for experiment in this study. Its plane dimension was 20mm x 20mm and thickness was 8mm. After ceramic cutting, the lapping process with IED was conducted.

Ceramics are difficult to manufacture because of their hard and brittle nature. The material properties of Y_2O_3 as a kind of ceramic also need to be investigated.

Before the lapping, hardness and fracture toughness of Y_2O_3 ceramic were measured because these material properties have a close relationship with ceramic surface removal mechanisms: crack propagation along a grain boundary and surface grain wear [10]. The indentation fracture method was used to measure

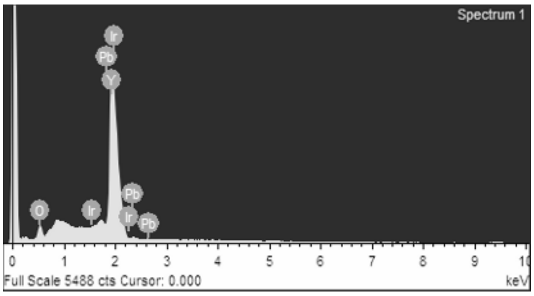


Fig. 3. Spectrum of Y_2O_3 element composition.

hardness and fracture toughness.

Hardness of Y_2O_3 was gauged by Vickers hardness testing machine (Akashi Inc., AVK-C0 Model). 98N of load was applied and maintained during 15 seconds on the workpiece.

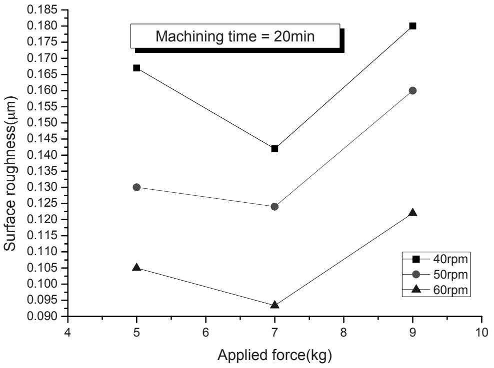
The indentation on the workpiece was observed after the duration time. Measurements were conducted 10 times to gauge Vickers hardness and the average value obtained was $H_v = 653.91$ kg/mm^2 with the function ($H_v = 1.8544\ F/d^2$). Here, F is the load value and d is the diagonal length on the indentation.

Using the measured Vickers hardness, crack length and diagonal length, the fracture toughness K_{IC} was also obtained with the function ($K_{IC} = 0.203(c/a)^{-2/3} H_v a^{1/2}$). Here, c is half value of the crack length and a is half value of the diagonal length [8]. The measured value was $K_{IC} = 5.68$ MPam$^{1/2}$. These measured Vickers hardness and fracture toughness data are lower than ZrO_2-Y_2O_3, ZrO_2-CaO and ZrO_2-MgO which are widely used as structural ceramic materials. And these values are similar with Si_3N_4-BN [1, 11].

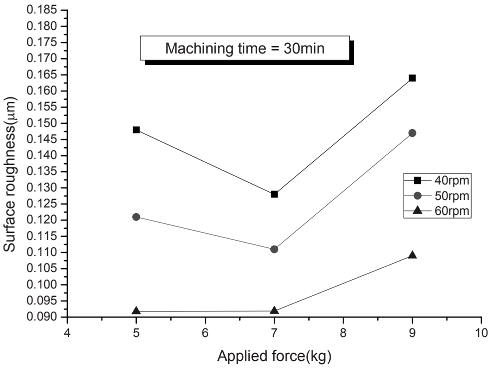
4. Results and discussion

4.1 Surface roughness characteristics

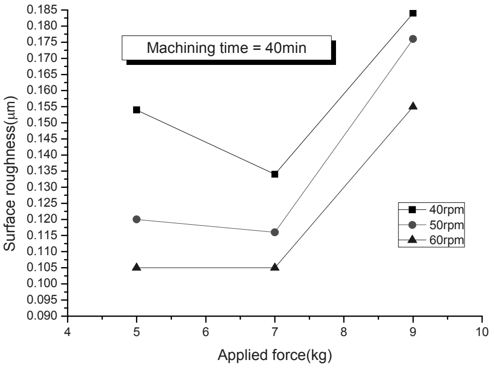
Y_2O_3 ceramic was machined by the lapping process with the IED method. Conditions of each machining are represented above in section 3.1. The average surface roughness before the lapping process was Ra 1.5 ㎛, and surface roughness data after lapping process were measured by using Ra data under various machining conditions. Measurements from each workpiece were conducted 10 times with a surface roughness testing machine (Taylor Hobson Ltd., Surtronic 3+ Model). Fig. 4 shows the Ra value of the surface roughness results in relation to applied force and each wheel speed.



(a) Surface roughness after 20 minutes lapping with IED



(b) Surface roughness after 30 minutes lapping with IED



(c) Surface roughness after 40 minutes lapping with IED

Fig. 4. Surface roughness of Y_2O_3 after IED lapping process.

Fig. 4 shows a tendency that the surface roughness was decreased or similar when the applied force was increased from 5kg to 7kg. But the surface roughness was increased under pressing 9kg. This tendency indicates that an excessive applied force can interfere with the stable surface abrasive removal machining. For the case that excessive force is pressed, the electrolyte flow cannot be harmonious on the surface of the workpiece. For the above reason, the electrolyte

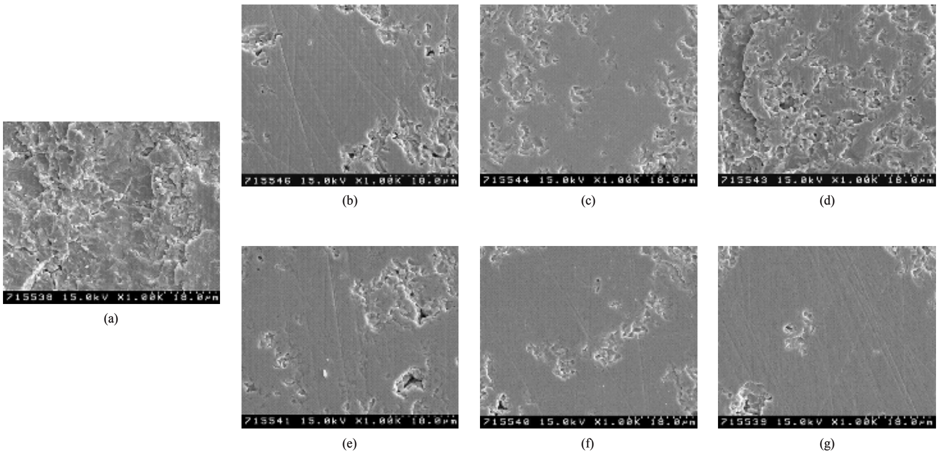

(a) (b) (c) (d) (e) (f) (g)

Fig. 5. SEM images of Y_2O_3 (a) before lapping (b) after lapping surface with machining condition; 5kg, 50rpm and 40minutes (c) 7kg, 50rpm and 40minutes (d) 9kg, 50rpm and 40minutes (e) 5kg, 40rpm and 30minutes (f) 5kg, 50rpm and 30minutes (g) 5kg, 60rpm and 30minutes.

cannot act as a lubricant and coolant. Moreover, a chip on the surface is not transpired stably during machining time. Chips remaining on the surface scratch and interfere with the machining by other abrasives. These phenomena make the results of surface roughness increased.

Y_2O_3, which has correlatively lower fracture toughness than other structural ceramics, requires more sensitive machining condition of applied force during abrasive removal machining. Optimal condition of applied force was obtained at 7kg in this study.

For the case of increasing wheel speed from 40rpm to 60rpm, the results of surface roughness were decreased. As the lapping wheel speed is increased, material removal by one abrasive is reduced and it helps to draw chips off. And the lapping resistance is decreased more than case of correlatively low wheel speed [8, 12]. Most of the high surface quality was obtained with 60rpm wheel speed during the lapping process.

As the machining time was increased from 20 to 30minutes, the surface roughness was decreased. This tendency can be confirmed in Fig. 4(a) and (b). Because a load is applied all the more on the workpiece, the surface is flattened and increasingly refined.

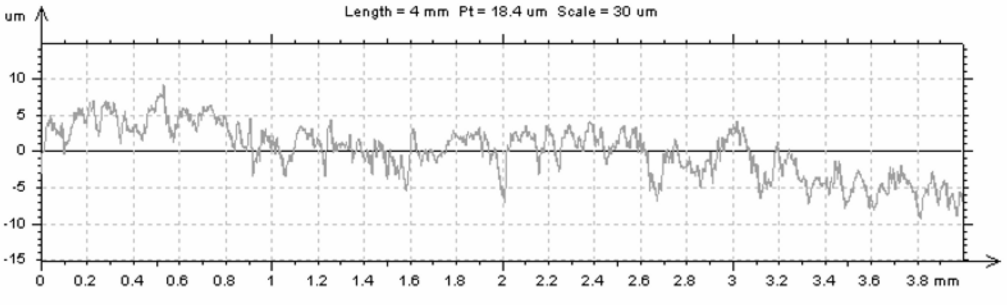
On the other hand, Fig. 4(b) and (c) show that suitable machining time should be controlled during the lapping process. When the machining time is considerably increased, the ability and stability of the IED dwindle away. The number of abrasives conditioning the breakdown of the grain boundary increases on the lapping wheel. These worn-out abrasives rapidly rub the workpiece with high speed and obstruct the protrusion of other new abrasives. An unstable machining is performed for a long time due to this kind of inferiority in the lapping wheel. And defects on the workpiece are increased if these kinds of phenomena are maintained during the lapping process. Consequently, the highest quality of the surface roughness was obtained at 30minutes machining time as a result of this experiment.

Through the analysis of machining results, the optimum conditions of the lapping process with IED were determined. 7kg of applied force, 60rpm of wheel speed and 30minutes of machining time made the finest quality of Y_2O_3 ceramic surface.

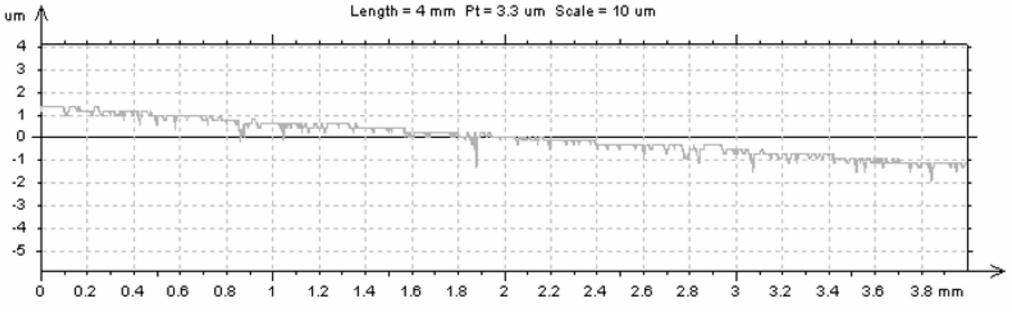
4.2 Analysis of fabricated surface

Fig. 5 shows SEM images on the Y_2O_3 surface. Fig. 5(a) represents the surface of Y_2O_3 before the lapping process. The production of the workpiece for lapping process was achieved by using a conventional ceramic cutting machine with a diamond wheel. The surface condition before lapping process was considerably rough. And it was observed that numerous brittle fractures on the surface occurred. Fig.5(b) through (g) show the surface images of Y_2O_3 fabricated and controlled by various machining conditions.

Most of the fabricated surfaces were performed as a ductile mode surface removal by surface grain wear with some of the brittle mode surface removal caused by crack propagation along the sintered grain boundary. Abrasive machining is a material removal process caused by stress concentration and fracture energy



(a) Before lapping process



(b) After lapping process

Fig. 6. Y_2O_3 surface profile (a) before (b) after lapping with IED.

diffusion on the micro cracks generated by each abrasive machining condition. Flattened areas are the machined regions by abrasives. The quality and removal patterns of machined areas are different from various machining conditions: applied force, wheel speed and machining time.

Fig. 5(b), (c) and (d) show the effect of applied force. A heavy load was pressed in case of (d) better than (b) and (c).

As other conditions were fixed, it was confirmed that a stable load condition on the whole workpiece was accomplished with 7kg of applied force (Fig. 5(c)) rather than 5kg of applied force (Fig. 5(b)). However, an excessive heavy load (Fig. 5(d)) made the partial surface wear removal condition with much brittle removal with plentiful crack propagation traces. The lapped surface results are from the reduction of electrolyte ability and surface fracture by crack having high fracture energy. Moreover, 40minutes of machining time led to correlatively lower quality of surface condition caused by defects of the wheel surface.

Fig. 5(e), (f) and (g) show the effect of wheel speed. Increasing the wheel speed resulted in a smoother and clean surface condition with other conditions held fixed. For high wheel speed (Fig. 5(g)), the lapping resistance and crack propagation time into the inside of the workpiece are reduced and it can minimize the unstable fracture removal. As a result of high wheel speed, high quality of surface on the Y_2O_3 can be obtained.

The effect of machining time is considered comparing Fig. 5(b) and (f). Fig. 5(b) is an image machined with 40minutes machining time. The excessive machining time decreased the quality of the workpiece surface. Choosing an inappropriate machining time can possibly damage the wheel surface: a wheel surface may crack by excessive continuous pressure and excessive corrosion area by local and continuous electrolysis concentration. These wheel defects decrease the workpiece surface quality. The selection of optimum machining time is important and the best lapping process time was confirmed as 30minutes. This time can reduce the disadvantage of wheel surface defects during the lapping process with IED.

Fig. 6 shows the surface profile before and after the lapping process with optimum conditions in this study: 7kg of applied force, 60rpm of wheel speed and 30minutes of machining time. A phase of Y_2O_3 surface was flattened and balanced after lapping process with IED (Fig. 6(b)). The surface roughness Y_2O_3

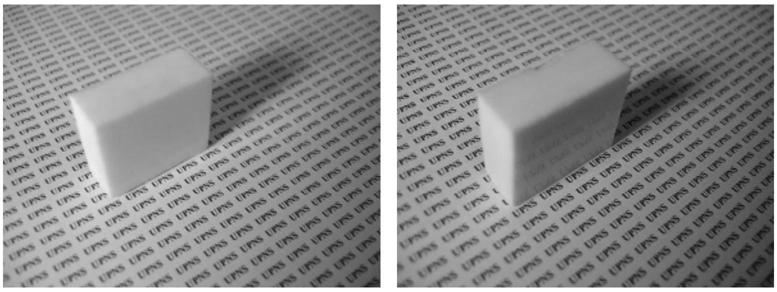


Fig. 7. Comparison of surface quality before lapping and after lapping.

ceramic was improved until 92nm.

Fig. 7 shows that the finest surface of Y_2O_3 was established after the lapping process with optimum condition. The ultra-precision lapping of Y_2O_3 ceramic was achieved resulting from a sufficiently mirror-like surface of Y_2O_3.

5. Conclusions

The ultra-precision lapping process with in-process electrolytic dressing (IED) method was conducted on the surface of Y_2O_3 ceramic to evaluate the Y_2O_3 surface machinability. It was evaluated by the analysis of machined surface characteristics. Three major machining variables were applied force, wheel speed and machining time. The surface characteristics were analyzed from changing the main parameters during the lapping process.

As the wheel speed was increased, the lapping resistance and unstable fracture removal were reduced along with several times of surface wear removal. The finest wheel speed condition was obtained at 60rpm.

It was confirmed that an excessive applied force condition considerably roughens the surface of Y_2O_3 because of the ability reduction of electrolyte and the increment of excessive brittle mode surface removal region with crack having high fracture energy.

Inappropriate machining time gave harmful effects during the lapping process caused by the wheel surface defects: surface cracks and excessive corrosion area on the wheel, worn-out abrasive increment by reduction of IED capability and inferiority of chip discharge.

The finest machining conditions and surface quality were accomplished at 7kg of applied force, 60rpm of wheel speed and 30minutes of machining time. And 92nm of surface roughness was obtained from the above machining conditions.

Measured fracture toughness of Y_2O_3 ceramic was relatively lower than other ceramic as a structural material. It was judged that Y_2O_3 surface machinability using abrasive machining has a more sensitive tendency from the results conducted by lapping process with IED. Also, precision abrasive machining control should be investigated more and more for the effective applications of Y_2O_3 ceramic.

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