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Optimization of FAP in Nano Machining Process

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To achieve the nano precision surface quality of LBO crystal, the fixed abrasive polishing technology was adopted to realize the nano machining process. The machining tool plays a key role in nano machining process and the same as the fixed abrasive polishing pad (FAP) for the polishing process. The effect of the matrix hardness and polishing powder concentration of the FAP on material removal rate, surface topography, microscopic appearances and surface roughness were investigated in nano machining LBO crystal. The results show that the matrix hardness B and the concentration of the polishing powder 150% of FAP are the optimization characteristics for the maximum material removal rate and the best surface quality in fixed abrasive polishing of LBO crystal. The maximum material removal rate is 71.4 nm/min and the optimal surface roughness Sa is 0.657 nm. The nano precision surface quality with nanoscale material removal was obtained in nano machining LBO crystal.

Keywords Nano machining; fixed abrasive pad (FAP); LBO crystal; fixed abrasive polishing; material removal rate; surface quality

1. Introduction

The nonlinear optical (NLO) crystals are mainly used for frequency conversion of lasers. Lithium triborate (LiB_3O_5 or LBO) crystal is a very important and also the most widely applied NLO crystal [1, 2]. A high surface quality of LBO crystal is urgently needed because of its applications in high energy laser system. Nano machining technology was adopted to achieve nanometer precision surface quality.

Fixed abrasive polishing technology which is one of the nano machining directions, can achieve the surface quality of the nanometer precision and nanoscale material removal [3, 4]. The polishing pad plays a key role in polishing process and the same as the machining tool for nano machining process [5]. In fixed abrasive polishing process, the abrasives are fixed in the polishing pad and the slurry that does not contain abrasives is only D. I. water. Fixed abrasive polishing is a two-dimensional touch friction and leads to a high material removal rate (MRR). A better surface quality can be obtained and clearing is easy because of no abrasive. And cost of manufacture is cut [6–8]. Then, the function of the fixed abrasive

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pad (FAP) appears more important. The FAP supports the wafer and the abrasives and the properties of a FAP play a significant role in polishing process. The support ability and the mechanical action of the FAP in polishing process are dependent on the matrix hardness of FAP. The number of the abrasives taking part in polishing process is related to the concentration of the polishing powder (CPP) in the FAP. Also the material removal rate and surface quality of the wafer in fixed abrasive polishing process is affected by the matrix hardness and CPP of FAP. The FAP is one of the most important consumable materials in fixed abrasive polishing process since the pad characteristic changes during wafer polishing and substantially influences the actual contact conditions [9].

The pad characteristic which directly affects on the MRR and surface quality of the wafer were studied in conventional polishing process. There were such as pad surface pattern and texture [9, 10], groove shape and distribution [11–13], surface roughness [14], hole ratios [15] and so on. Tsai et al. presented a hydrophilic polishing pad that uses a submicron graphite-particle impregnated polyurethane matrix to enhance slurry absorption and indicated that a graphite content of approximately 15 wt% is optimal for maximizing MRR and the wear rate of the hydrophilic pad is reduced by approximately 20–30% [16]. Then, the matrix hardness of FAP and the concentration of polishing power in FAP were seldom involved in polishing process.

Aiming to increase the MRR and enhance the surface quality of the wafer, nano machining LBO crystal was studied. The effect of matrix hardness and polishing powder concentration of FAP on MRR, surface topography, microscopic appearances and surface roughness will be discussed. The optimized FAP parameters for fixed abrasive polishing and the best surface quality of LBO crystal will be obtained in nano machining process.

2. Experiments

All experiments were conducted on LBO crystal (110) surface in this study. The lapping and polishing experiment was performed on CETR CP-4 CMP test system. Fixed abrasive lapping and polishing pad and the slurry without the abrasives were selected. The crystals were lapped by 30 μm diamond FAP before each polishing experiment. Three matrix hardness (A, B and C) and two kinds of polishing powder concentration (100% and 150%, FAP main composition and polishing powder mass ratio) were used to prepare six kinds of FAP with 1 μm CeO_2 for the polishing experiment [17]. The polishing process parameters were showed in Table 1.

The multipoint crystal thickness before and after the polishing process were test by micrometer caliper. The material removal rate is calculated through the difference of the

Table 1
Process parameters of fixed abrasive polishing

Polishing parameter	Parameter settings
Pressure	21 kpa
Crystal speed	95 rpm
Pad speed	100 rpm
Slurry flow rate	80 ml/min
Slurry pH	11

average material thickness between before and after polishing, divided by the process time. Mitutoyo MF Measuring Microscope was used to measure surface topography and damages. CSPM3000 Atom Force Microscope (AFM) was used to test surface roughness and micro damages. And surface roughness using the parameter Sa, the average roughness calculated over the entire measured area, were compared and the scan area is 20 μm × 20 μm.

3. Results and Discussion

3.1. Material Removal Rate

The material removal rate of LBO crystal polished by six kinds of FAP is showed in Fig. 1. The maximum MRR of LBO crystal is 71.4 nm/min polished by the FAP with matrix hardness B and CPP 150%, and the minimum is 40.7 nm/min by the one with hardness C and CPP 100%. From Fig. 1, there is the larger MRR polished by FAP with CPP 150% than 100% when the matrix hardness of FAP is identical. When the polishing powder concentration of FAP is identical, the MRR of LBO crystal polishing by the big to small order is hardness B, hardness A and Hardness C of FAP matrix.

3.2. Surface Topography

Figure 2 shows the surface topography of LBO crystal after nano machining process by six kinds of FAP was tested by Microscope. There are some scratches and pits on LBO crystal surface polished by FAP with hardness A and CPP 150% and hardness C and CPP 100% from Fig. 2b and 2e. And there are only some pits polished by other FAP. The best surface quality with very little and small pits is the one polished by FAP with hardness B and CPP 150%. However, the worst surface quality with big scratches and pits is the one polished by FAP with hardness C and CPP 100%.

There is the better surface quality and smaller surface damages of LBO crystal polished by FAP with CPP 150% than 100% when the matrix hardness of FAP is identical. When the

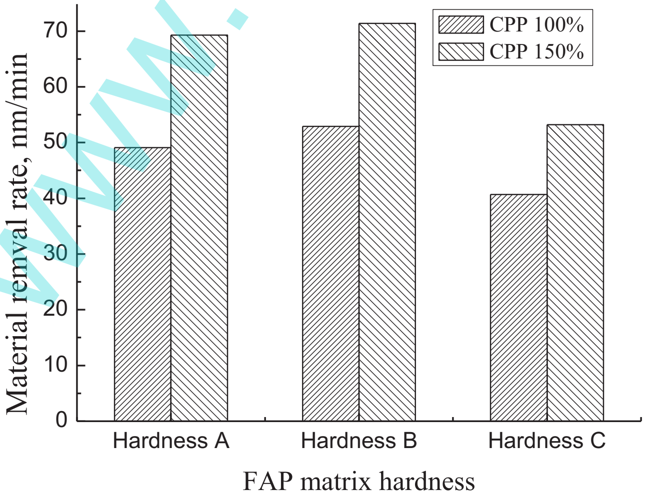
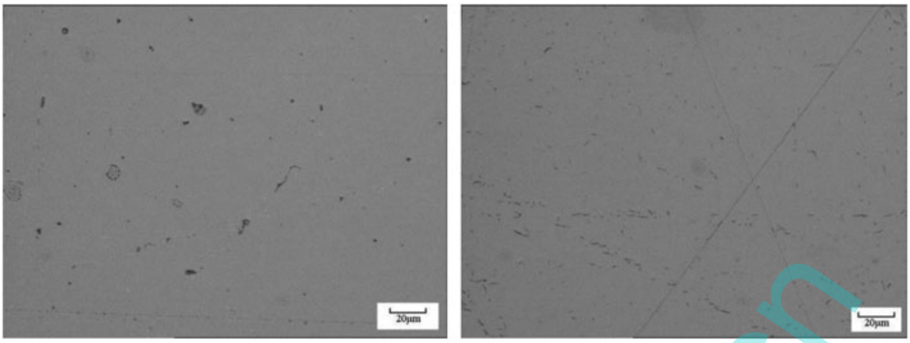
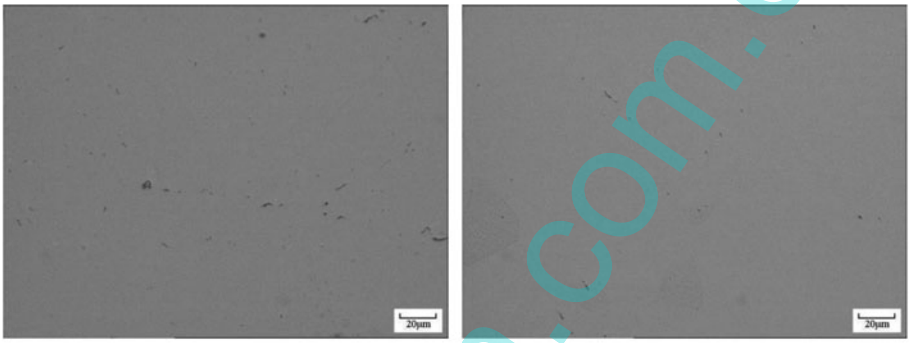


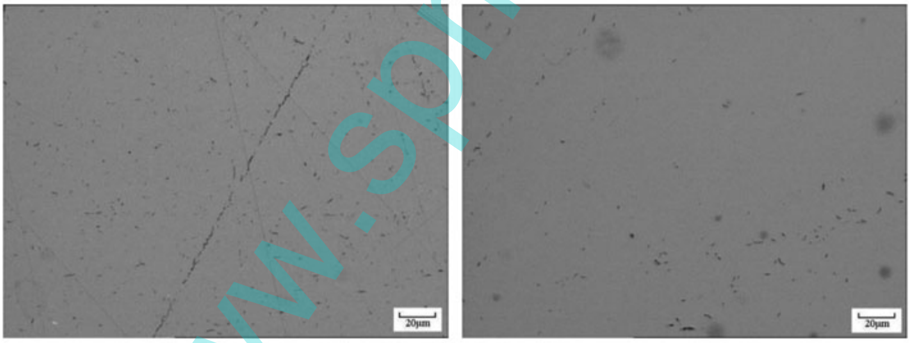
Figure 1. MRR of nano machining LBO crystal by six kinds of FAP.



(a) Hardness A and CPP 100% (b) Hardness A and CPP 150%



(c) Hardness B and CPP 100% (d) Hardness B and CPP 150%



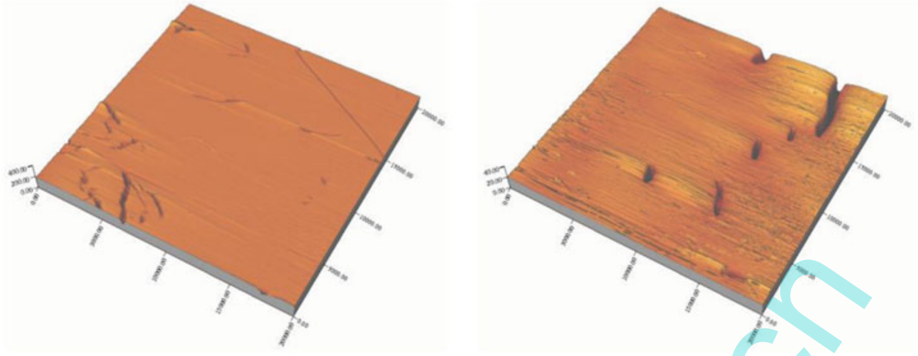
(e) Hardness C and CPP 100% (f) Hardness C and CPP 150%

Figure 2. Surface topography of LBO crystal after nano machining.

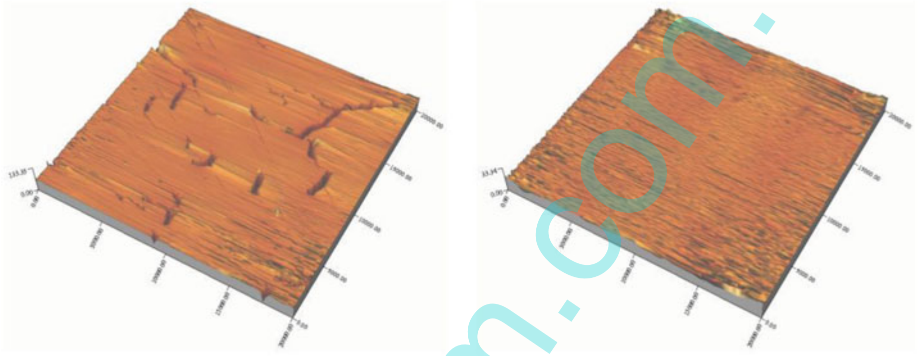
polishing powder concentration of FAP is identical, the best surface quality and the smallest surface damages of LBO crystal is the surface polished by FAP with matrix hardness B. And the worst surface quality and the largest surface damages of LBO crystal is the surface polished by the one with hardness C.

3.3. Microscopic Appearances

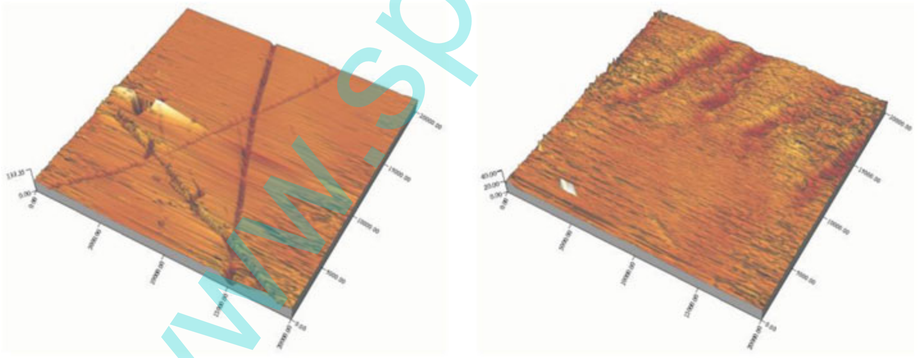
The microscopic appearances of LBO crystal by AFM were showed in Fig. 3. There are some big micro scratches and pits on LBO crystal surface polished by FAP with hardness



(a) Hardness A and CPP 100% (b) Hardness A and CPP150%



(c) Hardness B and CPP 100% (d) Hardness B and CPP 150%



(e) Hardness C and CPP 100% (f) Hardness C and CPP 150%

Figure 3. Microscopic appearances of LBO crystal after nano machining.

C and CPP 100%. And there are some micro pits one the surface polished by FAP with hardness A and CPP150% and hardness B and CPP 100% from Fig. 3b and 3e. The best surface quality is the one polished by FAP with hardness B and CPP 150%. However, the worst surface quality with big micro scratches and pits is the one polished by FAP with hardness C and CPP 100%.

There are the bigger microscopic damages on LBO crystal surface polished by FAP with CPP 100% than 150% when the matrix hardness of FAP is identical. When the polishing powder concentration of FAP is identical, the largest surface microscopic damage and the worst surface quality of LBO crystal is the surface polished by FAP with hardness C. And the smallest surface microscopic damage and the best surface quality of LBO crystal is the surface polished by the one with matrix hardness B.

3.4. Surface Roughness

The surface roughness of LBO crystal polished by six kinds of FAP is showed in Fig. 4. The optimal surface roughness Sa is 0.657 nm polished by FAP with matrix hardness B and CPP 150% and the worst is 3.33 nm by the one with hardness C and CPP 100%. From Fig. 4, there is the better surface roughness polished by FAP with CPP 150% than 100% when the matrix hardness of FAP is identical. When the polishing powder concentration is 100%, the surface roughness of LBO crystal by the big to small order is hardness C, hardness B and Hardness A of FAP matrix. When the CPP is 150%, the surface roughness of LBO crystal polished by FAP with hardness A and Hardness C are nearly. And they are worse than hardness B.

3.5. Discussion

The material removal mechanism is the result of a combination of both the mechanical and chemical actions in nano machining process. The mechanical action of polishing agent particles controls the material removal rate whereas chemical action causes breakage of network connections of the sample surface. The action of two elements (water and abrasive grains) allows the formation of the transition soft layer with mechanical properties that differ from the sample. This layer is easily removed by the abrasive grains [18]. Generally, the performance of CeO_2 slurry relies on the chemical activity of the abrasive surface [19]. In an aqueous solution, cerium is most likely to be oxidized to a tetravalent state and given

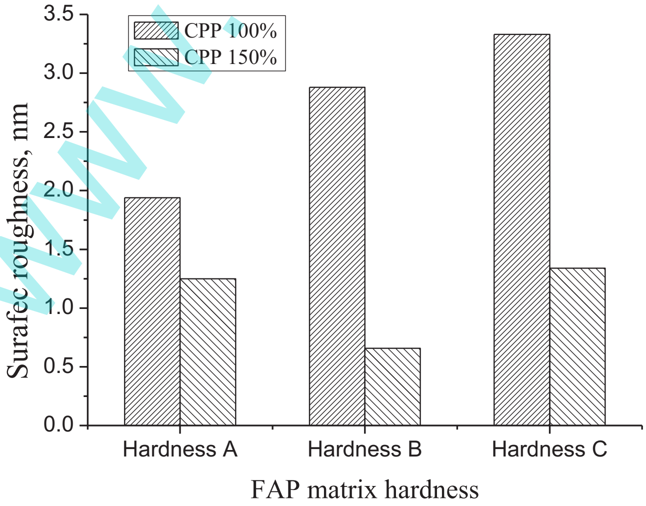


Figure 4. Surface roughness of LBO crystal after nano machining

this property, its separation is generally the easiest. In the tetravalent form, the cerium ion exhibits chemical behavior markedly different from other trivalent rare earth ions [20]. In alkaline solution, $Ce(OH)_4$ was formed easily. It was also proposed that cerium hydroxide (Ce-OH) may react with the crystal surface and form M-OH (M^+ is Li^+ or B^{3+}). In this mechanism, the breaking of O-B-O bond is controlled by chemical depolymerization as well as mechanical tearing. Thus all the mechanisms proposed to explain the ceria propose that a bond is formed between the ceria abrasive and the sample work-surface in its hydrated form [21].

When the matrix hardness of FAP is identical, there are larger MRR and better surface quality of LBO crystal polished by the CPP 150% than 100%. In other polishing parameters are the same, the polishing powder concentration of FAP is high. And the number of ceria taking part in the chemical reaction with the crystal surface is large and the transition soft layer is easily formed in the polishing process. In the meantime, the number of ceria taking part in the mechanical action is also large. The higher the concentration of ceria is, the greater the chemical and mechanical action is and the larger the MRR is. Therefore, the MRR is large and the surface quality of the sample is good because the transition soft layer can be timely removed when the polishing powder concentration of FAP is 150%.

Chemical mechanical polishing is a complex mechanical and chemical process, and the better surface and the larger MRR can be obtained only when there is a balance between the two functions. If the mechanical action is oversupplied, the mechanical action can make abrasive particles to scratch the crystal surface. And if the chemical action is larger than the mechanical action, the transition soft layer that the chemical action generates is not promptly removed by the mechanical action [22].

When the polishing powder concentration of the FAP is identical and other polishing parameters are the same, the ability of the mechanical action and supporting the abrasive are dependent on the matrix hardness of FAP. When the matrix hardness A of FAP is the hardest hardness, the mechanical action of LBO crystal polishing process is oversupplied. Then, the surface damages are the scratches by the mechanical action from Figs. 2b and 3a. However, when the matrix hardness C of FAP is the softest hardness, the chemical action is larger than the mechanical action. Due to the transition soft layer that is not promptly removed by the mechanical action, the MRR is the smallest. The abrasives are easily dropped from the FAP surface and damage the crystal surface from Figs. 2e and 3e. When the matrix hardness of FAP is hardness B, the mechanical and chemical actions are nearly. There is a balance between the mechanical and chemical actions, the largest MRR and the best surface roughness and surface quality can be obtained from Figs. 1, 2d, 3d and 4.

4. Conclusions

The fixed abrasive polishing of LBO crystal was studied for nano machining process. The effect of the matrix hardness and polishing powder concentration of fixed abrasive pad on material removal rate, surface topography, microscopic appearances and surface roughness were discussed. The maximum MRR is 71.4 nm/min and the optimal surface roughness Sa is 0.657 nm in fixed abrasive polishing of LBO crystal. The optimization characteristics for the optimal MRR and the best surface quality are the matrix hardness B and CPP 150% of FAP. The nanometer precision surface quality with nanoscale material removal was obtained in nano machining LBO crystal.

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