Parameter Optimization by Taguchi Methods for Polishing $LiTaO_3$ Substrate Using Force-induced Rheological Polishing Method

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Abstract. In order to achieve high efficiency and low damage to the surface of the workpiece in the process of polishing, Force-induced Rheological Polishing (FRP) as a novel ultra-precision machining method is proposed and used to polish the $LiTaO_3$ substrate in this study.Taking the surface roughness (Ra) of the workpiece as evaluation index, the influence of four key parameters including diamond abrasive size, diamond abrasive concentration, polishing speed and SiO_2 concentration on the FRP process of $LiTaO_3$ substrate were analyzed by Taguchi method, and the optimized results were verified through experiments. Diamond abrasive size has the most significant effect on Ra, followed by diamond abrasive concentration, polishing speed and then SiO_2 concentration. Based on the S/N average response analysis, the surface quality is the best under the conditions with 8000# diamond abrasive, 5%wt diamond abrasive concentration, 90rpm polishing speed and 10%wt SiO_2 concentration. After 4 mins , the surface roughness is reduced rapidly from Ra 200.5 nm to Ra 4.5 nm.

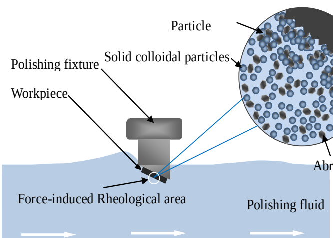
Introduction

As a versatile material, $LiTaO_3$ has excellent piezoelectric, ferroelectric, pyroelectric, acousto-optic, electro-optic, nonlinear optical properties, and have broad application prospects in the fields of laser, electronics and integrated optics. At present, there are few research reports on processing characteristics and ultra-smooth surface processing technology of $LiTaO_3$ substrate at home and abroad. The main processing methods are chemical mechanical polishing methods to polish $LiTaO_3$ substrate. Polishing is the main processing method to improve the surface quality of $LiTaO_3$ substrate, remove damage layer and obtain smooth, low / no damage surface[2,3]. At present, advanced polishing methods include: Chemical Mechanical Polishing [4,5], Magneto-rheological finishing[6], Water Jet Polishing[7], Plasma Polishing[8], Laser Polishing[9] and so on. With the rapid growth of $LiTaO_3$ crystal demand and the continuous improvement of its performance, high efficiency and high quality polishing technology has attracted extensive attention.

In order to improve polishing efficiency and high quality surface of the workpiece, authors put forward the Force-induced Rheological Polishing (FRP) method[10,11], which can achieve high efficiency and low damage to the surface of the workpiece using the force-induced rheological effect produced in the process of polishing fluid and fine abrasive grains. In order to study polishing performances of FRP in $LiTaO_3$, this paper apply Taguchi method to analyze the influence of diamond abrasive size, diamond abrasive concentration, polishing speed and SiO_2 concentration on the $LiTaO_3$ substrate surface roughness to determine the optimum process parameters of $LiTaO_3$ crystal FRP method.

1. Principle of Force-induced Rheological Polishing (FRP)

The principle of FRP for planar workpiece is shown in Fig. 1, the polishing abrasives are dispersed in force-induced rheological fluid. In the process of polishing, due to the relative movement of the workpiece and polishing fluid, the contact part between polishing fluid and workpiece conduct force-induced rheological phenomenon, colloidal particles dispersed in the solution polymerized into a large number of clusters, in which the abrasives are wrapped. The viscosity of polishing fluid in contact area increases rapidly. The holding force applied on abrasive is enhanced, and a flexible "fixed abrasive" in the polishing position is formed. Fig. 2 is a schematic illustration of micro FRP material removal. When the shear force of microscopic outburst is more than the yield stress of the workpiece, the workpiece material will be removed, so as to achieve the purpose of polishing.



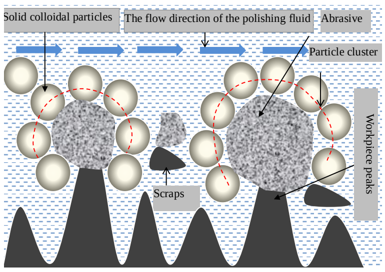


Fig.1-Schematic illustration of FRP Principle   Fig.2-Micro schematic illustration of FRP material removal

2.Experimental methods and conditions

The experimental device is shown in Fig.3. The $LiTaO_3$ substrate is fixed on the workpiece fixture, and has an inclination angle 15° to workpiece driver(definite the angle between the surface of the substrate and the level for the workpiece inclination angle), the $LiTaO_3$ substrate was immersed in polishing liquid and rotated though the Z axis; the polishing slurry moves relatively to the substrate, so that the polishing slurry produces force-induced rheological effect, achieve Force-induced Rheological Polishing on the surface of $LiTaO_3$ substrate.

The size of the $LiTaO_3$ substrate surface is 10mm×10mm, the initial average roughness of the surface of the $LiTaO_3$ substrate Ra is 200±10nm. The average size of solid colloidal particles in the force-induced rheological fluid is about 13μm. Table 1 shows the specific processing conditions.

Due to the small size of $LiTaO_3$ substrate in this experiment, the difference of linear velocity on different point of the surface is very little. After polishing, the surface roughness of 5 positions on the surface was measured (4 on the corner and 1 on the center) and the average value was counted.

The surface roughness is measured by Form Talysurf i-Series (TAYLOR HOBSON) with the resolution 0.1nm.

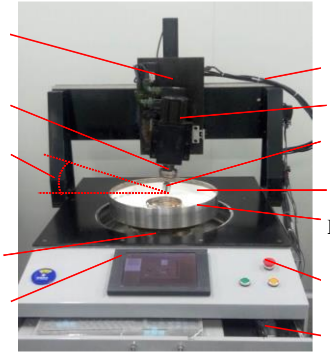


Fig.3-Experimental device for FRP

Tab.1 Optimal experiment condition of FRP

Experimental conditions	Parameter
Abrasive	Diamond abrasive, SiO_2
Abrasive size	3000#, 5000#, 8000#
Abrasive concentration[wt]	4%, 5%, 6%
Polishing speed[rpm]	80, 90, 100
SiO_2 concentration	0, 10%, 15%
Experimental time[min/ group]	4

Tab.2 Table of the Taguchi method

Experime -ntal NO. *i*	Horizontal combination	A	B	C	D
1	$A_1B_1C_1D_1$	3000#	4%	80	0
2	$A_1B_2C_2D_2$	3000#	5%	90	10%
3	$A_1B_3C_3D_3$	3000#	6%	100	15%
4	$A_2B_1C_2D_3$	5000#	4%	90	15%
5	$A_2B_2C_3D_1$	5000#	5%	100	0
6	$A_2B_3C_1D_2$	5000#	6%	80	10%
7	$A_3B_1C_3D_2$	8000#	4%	100	10%
8	$A_3B_2C_1D_3$	8000#	5%	80	15%
9	$A_3B_3C_2D_1$	8000#	6%	90	0

In this study, the influences of 4 key parameters including diamond abrasive size (A), diamond abrasive concentration (B), polishing speed (C) and SiO_2 concentration (D) on the surface roughness were investigated . The experimental design followed the Taguchi method, and a L9(3^4) orthogonal table, as shown in Table 2 was used.

The signal-to-noise ratio (S/N) analysis was used to obtain the optimal combination of polishing parameters[12]. When the evaluation standard is the *Ra*, formula (1) is used:

$$S/N_i = -10\log\frac{1}{r}\sum_{j=1}^{r} R_{ij}^2 \qquad (1)$$

(where, *i* is experiment number, *r*=5 is the number of detection points on the surface of the substrate)

3 Experimental results and analysis

3.1 S/N average response analysis

The measured data were calculated by the signal-to-noise ratio (S/N), through the analysis, Table 3 shows the S/N results of *Ra*. The optimal value and the absolute changes in *Ra* can be confirmed by the average of 3 group experiments under a certain level of factor A. The optimal value of B, C and D can be also determined.

Tab.3 The test results of *Ra* and S/N value

Experimental NO.	surface roughness (nm)						(S/N) /dB
	R_1	R_2	R_3	R_4	R_5	average value	
1	146.3	125	124.1	124.3	105.4	125	-42
2	31.5	30.5	27.9	19.6	47.8	31.5	-30.4
3	85	69.8	69	61.2	60.1	69	-36.9
4	26.6	24.5	26.1	25.9	19.2	24.5	-27.8
5	10.4	9.6	10.8	13	10	10.8	-20.7
6	21	12.3	36	17.4	18.4	21	-27.2
7	5.7	5.3	5	4.7	4.3	5	-14
8	5.2	4.3	4	5.8	4.8	4.8	-13.8
9	4.1	3.6	3.6	4.4	6.4	4.4	-13.2

Fig.4 shows the influence curve of *Ra* with the average response of S/N factors. With the increase of the diamond abrasive size, the reduced rate of the surface roughness increase. The average data of the surface roughness of each trial of experiments and the absolute change of *Ra* is shown in Table3. In polishing , under the condition which the initial *Ra* of the $LiTaO_3$ substrate is about 200nm, when the different abrasive sizes (3000#,5000# and 8000#) were used, the different surface roughness *Ra* (75.2nm, 18.8nm, and 4.7nm) were obtained in 4-min polishing. In the polishing, the material removal is mainly caused by micro abrasive machining, therefore, under the condition of same abrasive concentration, the smaller the abrasive size, the more the abrasive number, the improvement of the surface roughness is more obvious. With the increase of diamond abrasive concentration, the reduced rate of the surface roughness first increase and then decrease. In polishing, under the condition which the initial *Ra* of the $LiTaO_3$ substrate is about 200nm, when the different abrasive concentrations (4%, 5%, and 6%) were used, the different surface roughness *Ra* (51.5nm, 15.7nm, and 31.5nm) were obtained in 4-min polishing .With the diamond abrasive concentration increasing, the number of abrasive increases, therefore, the reduced rate of the surface roughness increases. But when the concentration exceeds a critical value (critical abrasive concentration in this experiment is 5%wt), the force-induced rheological effect will be destroyed due to the too much polishing abrasive. With the polishing speed increasing, the reduced rate of the surface roughness first increase and then decrease. In polishing, under the condition which the initial *Ra* of the $LiTaO_3$ substrate is about 200nm, when the different polishing speeds (80rpm , 90rpm and 100rpm) were used , the different surface roughness *Ra* (50.7nm, 20.1nm and 28.7nm) were obtained in 4-min polishing. This is because of the increasing of the shear rate, the rheological property of the polishing base fluid enhances, the force-induced rheological phenomenon is more obvious, therefore, the improvement of the surface roughness is more obvious. When the polishing speed is more than 90rpm, the polishing fluid is thrown into the pool wall. Therefore, the reduced rate of the surface roughness decreases.

Through the average response analysis of S/N, the greater the average signal-to-noise ratio of each factor, the better the polishing effect of the $LiTaO_3$ substrate. Therefore, the parameter combination of the optimum material removal rate is A3B2C2D2(diamond abrasive 8000#, diamond abrasive concentration5%wt, polishing speed 90rpm and SiO_2 concentration 10%wt).

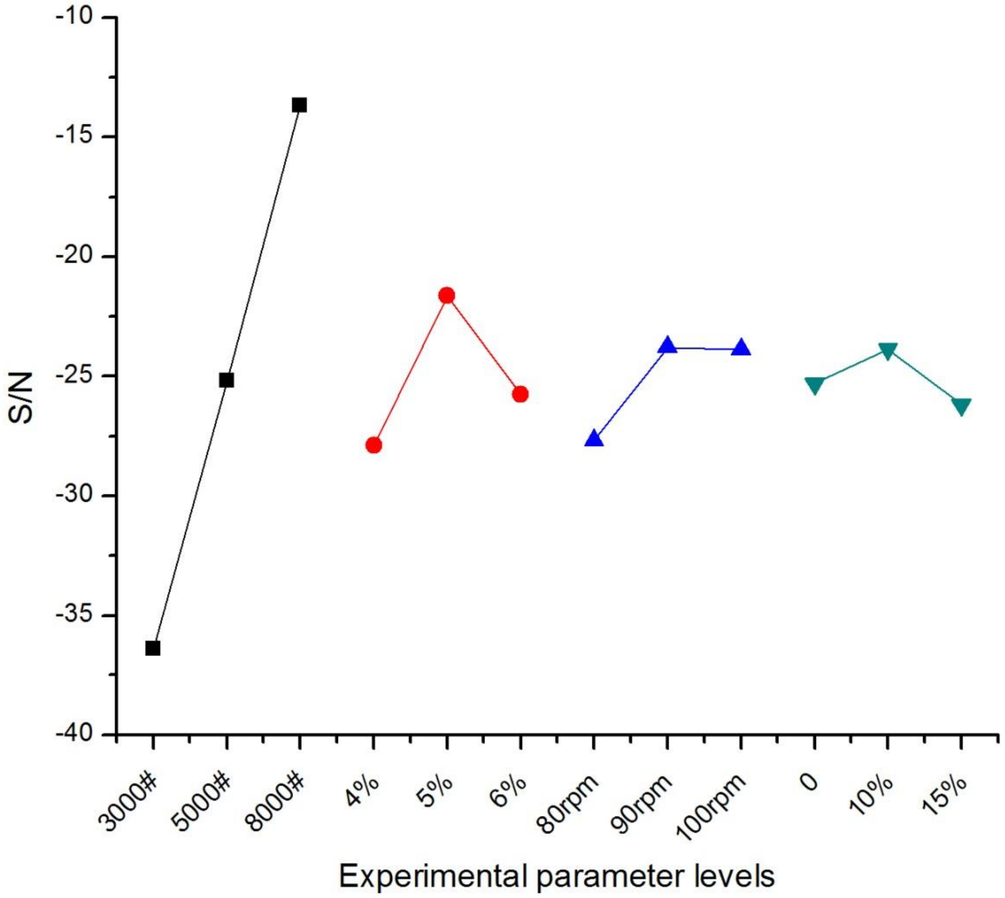


Fig.4 Plots of *S/N* ratio of each parameter level on *Ra*

3.2 Analysis of Variance

Analysis of variance (ANOVA) is used to evaluate the influence of experimental parameters on *Ra* by quantifying the percentage. The ANOVA analysis results of *Ra* are shown in Fig.6. The diamond abrasive size (43%) has the most significant effect on *Ra*, followed by diamond abrasive concentration (22%), polishing speed (18%) and then SiO_2 concentration (17%).

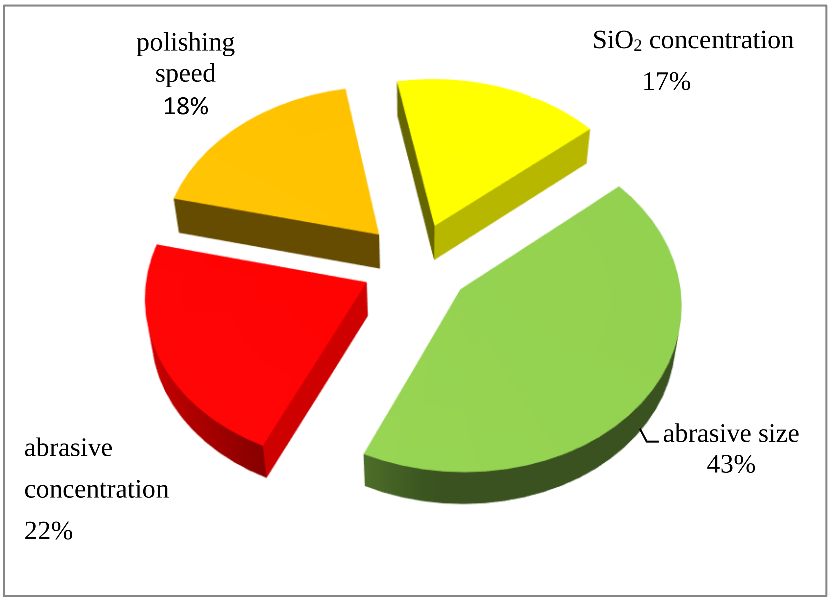


Fig.6 *ANOVA* results

3.3 Optimization of experimental analysis

As far as *Ra* is concerned, the optimal parameter combination is：8000# diamond abrasive, 5%wt diamond abrasive concentration, 90rpm polishing speed and 10%wt SiO_2 concentration. The experiments were repeated in this combination, after polishing 4mins, the surface roughness Ra decreased from 200.5 nm to 4.5 nm. Fig. 7 is a comparison that shows the $LiTaO_3$ substrate before polishing and after polishing. Fig.8 shows ultra-depth of field microscope (HIROX) in the workpiece surface before and after FRP, the initial $LiTaO_3$ substrate surface is not smooth, after FRP, the $LiTaO_3$ substrate surface becomes smooth. Fig.9 shows SEM micro-topographies of the workpiece surface before and after FRP.

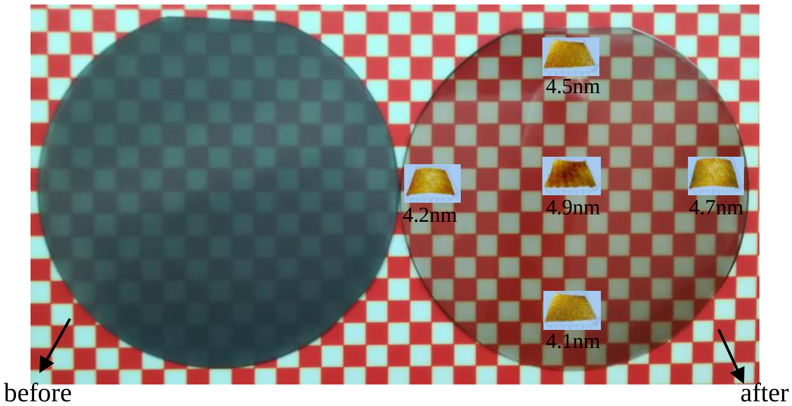
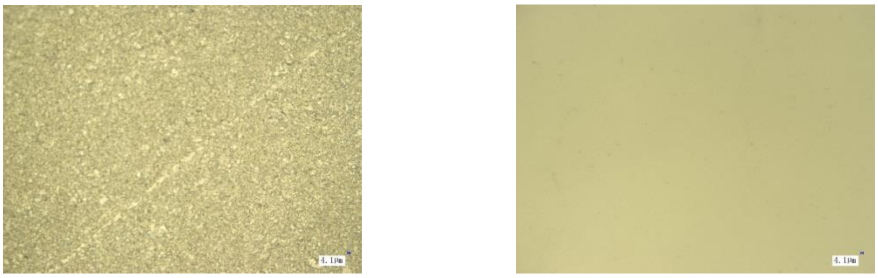
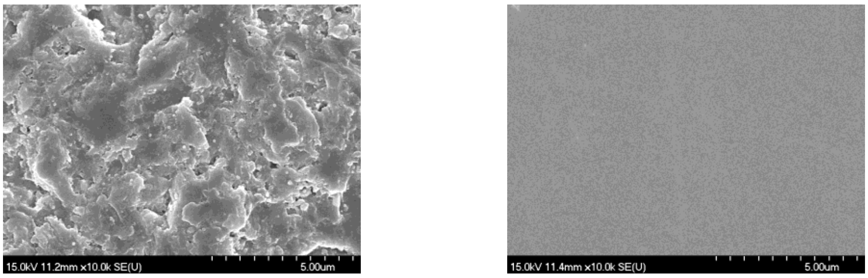


Fig.7 The $LiTaO_3$ substrate before and after FRP



(a) before (b) after

Fig.8 ultra-depth of field microscope (HIROX) in the workpiece surface before and after FRP



(a) before (b) after

Fig.9 SEM micro-topographies of the workpiece surface before and after FRP

4. Conclusion

In the process of polishing $LiTaO_3$ substrate surface with FRP, in order to obtain optimum surface quality, *Ra* is taken as the optimization objective and the Taguchi method is taken to optimize diamond abrasive size, diamond abrasive concentration, polishing speed and SiO_2 concentration 4 key parameters.

(1) From the average response analysis of S/N, when diamond abrasive 8000#, diamond abrasive concentration5%wt, polishing speed 90rpm and SiO_2 concentration 10%wt, the best surface quality of $LiTaO_3$ substrate can be attained, after polishing 4mins, the surface roughness Ra decreased from 200.5nm to 4.5nm.

(2) From the analysis of variance, The diamond abrasive size (43%) has the most significant effect on *Ra*, followed by diamond abrasive concentration (22%), polishing speed (18%) and then SiO_2 concentration (17%).

5. Acknowledges

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6. References

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