ULTRASONIC DRILLING OF NORMAL GLASS AND PYREX COMPARATIVE STUDY

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Abstract: *Usually, when the classic methods reach their limit or have a dissatisfactory productivity, the use of the non-conventional methods imposes. Can be obtained a better quality of the workpiece surfaces and small residual tensions and these are the main advantages of ultrasonic machining. Performing of holes in different types of materials is one of the market requests, which lead us to increase the research in this field of glass ultrasonic drilling processes.*

Keywords: *keywords ultrasonic drilling, glass, pyrex*

1. Introduction

The current literature study results revealed that ultrasounds can directly determine the process machining or may be used to assist other technological processes.

Among the properties that have favoured the ultrasounds use, can be mentioned:

1. the relatively small wavelength;
2. the possibility of creating particle large acceleration (can be achieved accelerations with values of 105 times higher than the one corresponding to the gravitational acceleration),
3. the capacity of directing the ultrasounds radiation in narrow areas - including inaccessible areas - ;
4. the ability to achieve concentrated and focused ultrasonic energy in clearly defined spaces [5].

During the ultrasonic drilling process three important phenomenon's are revealed:

- microcutting ;
- microcracking;
- cavitation.

Sharpened abrasive granules, in their vibratory motion, are hitting the workpiece zone and microcutting process is developed. The hitting force of the ultrasonically activated abrasive particles is ten thousand times bigger than the granules weight.

When the tool exert the pressure force on the abrasive granules that are in direct contact with the working surfaces it determine material microcracking.

The ultrasonic waves presence in a fluid determine the cavitation bubbles formation.

Since surpassing the resonance frequency we can state the bubble volume increasing, until reaching the frequency upper limit, at 10 MHz [3]. Thus, the cavitation bubbles implosion leads to the development of high pressure forces which will cause the workpiece superficial layer erosion. The particles detached from the workpiece or tool are removed by the cavitation bubbles and unused abrasive material is brought in the active area. A research work in the field of ultrasonic machining, in Romania, was first made by Tudor Inclănzan, in 1976.

In 1976 Gheorghe Amza developed researches in the plastic deformation in an ultrasonic field, and in 1999 Mihăiţă Peptănaru developed some microdrilling tools [6].

In 2002, Joseph McGeough presented aspects about the ultrasonic machining process, and showed that by using of ultrasonic drilling a 0,2 mm diameter hole can be achieved with 0,01 mm dimensional accuracy and the roughness value Ra = 0,4µm can be obtained [4].

2. Premises of the experimental research

The experimental research was made in the Non-Traditional Technologies Laboratory, Department of Machine Manufacturing Technology, the "Gh. Asachi" Technical University of Iaşi, using an ultrasonic machine with a piezoceramic transducer (Fig. 1).

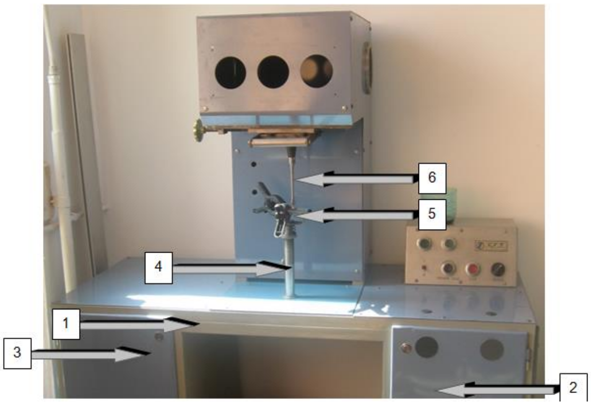


Figure 1 *Ultrasonic drilling machine*

The workpiece was clamped on a circular worktable. The working pressure developed between the tool and the workpiece is generated by helical spring, as shown in Fig 1 [2].

Table 1 The spring calibration

Nr.	*F* [N]	*Δl* [mm]
1	0,50	0,31
2	1,00	0,63
3	1,50	0,94
4	2,00	1,39
5	2,50	1,72
6	3,00	2,19

After the calibration and data processing, the regression equation (Eq. 1), that highlights the dependency relationship between the workforce and movement arc, was obtained.

$$\Delta l = 2{,}2998 \cdot 10^{-2} + 5{,}4221 \cdot 10^{-3} \cdot F + +5{,}9285 \cdot 10^{-6} \cdot F^2 \quad (1)$$

where,
Δl - spring deformation value, [mm];
F - the force that compresses the spring, [N].

In order to machine small diameters it was designed and performed a elastic sleeve that was screwed on the threaded end of the horn. After the preliminary experiments, three tools diameters were chosen: 0.6, 1.3, 2 mm.

The tool is clamped by the elastic elements of the sleeve by using a special nut that screws the threaded end of the horn [1].

We calculate the mathematical relation (Eq. 2) for the working force, with constant pressure maintained at 1 N/mm^2, for all three values of the working surface.

$$F = P \cdot A \quad (2)$$

where,
F - the working force, [N];
P - the working pressure, [N/mm^2];
A - the working surface area, [mm^2]

Table 2 *The working force and the specific deformation values, characteristic to each tool diameter*

	d [mm]	*A* [mm^2]	*P* [N/mm^2]	***F* [N]**	***Δl* [mm]**
1	0,6	0,2826	1	**0,28**	**2**
2	1,3	1,3250	1	**1,32**	**10**
3	2	3,14	1	**3,14**	**23**

The hole depth value was measured with a 0.5 mm diameter drill attached to a dial comparator. An image of the device is shown in the Fig. 2.

Figure 2 *The holes depth measurement device*

3. Experimental results processing

In order to minimize errors that may arise, both during the experiment, as well as in the hole depth measurement, were carried out a number of three experiments for the same combination of working parameter values. In the experimental data processing were taken into account the averages values. Thus, there were made a total of 72 ultrasonic drilling experiments in normal glass and Pyrex.

A equal combination of two abrasive materials, 21C and 22C, with 400, respectively 800 granulation, was used. Abrasive solution concentration used was 40%.

Table 3 *Pyrex ultrasonic drilling experimental data*

Nr. exp.	*d* [mm]	gr	*t* [s]	*h* [mm]
1	0,6	400	15	2,81
2	0,6	400	45	3,3
3	0,6	800	15	2,13
4	0,6	800	45	2,42
5	1,3	400	15	1,53
6	1,3	400	45	3,12
7	1,3	800	15	0,94
8	1,3	800	45	2,21
9	2	400	15	0,33
10	2	400	45	0,49
11	2	800	15	0,07
12	2	800	45	0,15

The main experimental values summarized in Tab. 3 were processed using DataFit program and the statistical results are synthesized in Tab. 4.

Table 4 *Statistical data of the pyrex ultrasonic drilling*

Variables	***d***	***gr***	***t***	***h_c***
Nr. of points	12	12	12	12
Missing Points	0	0	0	0
Max. value	2	800	45	3,3
Min. value	0,6	400	15	0,07
Range	1,4	400	30	3,23
Average	1,3	600	30	1,625
Standard Deviation	0,5969	208,8931	15,6669	1,1951

Correlation Matrix

	d	***gr***	***t***	***h_c***
d	1	-6,4749E-18	1,0791E-17	-0,858072
gr	-6,4749E-18	1	0	-0,266553
t	1,07916E-17	0	1	0,2825758
h_c	-0,858072	-0,266553	0,282575	1

Standard Deviation	Sum of Residuals	Average Residual	R^2
0,4706931	-1,5709E-14	-1,30914E-15	0,8871

The significant relationship between the independent variables (d, gr, t) and the dependent variable (h_c) was confirmed by - R^2 value 0.887188414 (Tab. 4) and we can say that 88.71% of the hole depth variation is determined by the tool diameter.

Tab. 5. *Regression coefficients*

	Value	Standard Error
a	-1,71785714285714	0,237735964055593
b	-0,001525	6,793871063523E-04
c	2,155555555555E-02	9,058494751364E-03
d	4,12654761904762	0,5949735349566
	t	Prob(t)
a	-7,225903534	0,00009
b	-2,244670212	0,05502
c	2,379595744	0,04457
d	6,935682642	0,00012

The regression equation (Eq. 3) is a decreasing function (a<0), which summarizes the correlations between the independent variables (tool diameter, abrasive material granulation, working time) and dependent variable (hole depth).

$$Y=ax_1+bx_2+cx_3+d \tag{3}$$

$$h_{pc}=-1{,}717857\cdot d_s-0{,}001525\cdot gr+2{,}15555\cdot 10^{-2}t+4{,}126547 \tag{4}$$

where,
h_{pc} - the hole depth calculated value for pyrex;
d_s - the tool diameter;
gr - abrasive material granulation;
t - working time.

The equation 4 shows that the Pyrex hole depth value increases with decreasing of the tool diameter- d_s and abrasive material granulation - gr, and will increase with the working time - t enlargement.

The estimated Standard Error is low, according to Tab. 5, which shows that all points are very close to the regression line.

Thus, small values of *t - test* and the corresponding probability, *Prob (t)* reveals a statistically significant relationship between the variables, of which the strongest is the reverse relation of the hole depth value and tool diameter.

Table 6 *ANOVA*

	df	**Sum of Squares**	**Mean Square**
Regression	3	13,93888333333	4,646294444444
Error	8	1,772416666666	0,2215520833333
Total	11	15,7113	
		F	**Prob(F)**
		20,97156738	0,00038

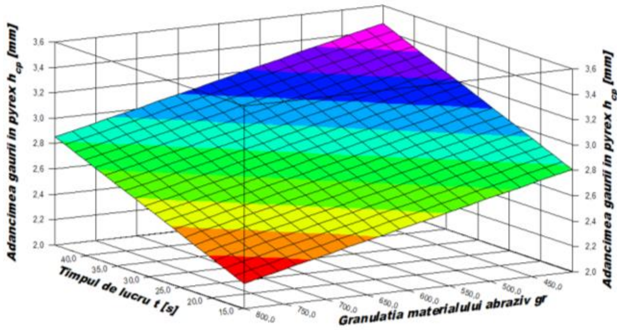
After applying ANOVA for regression it is noted that the calculated value for F (20.97156738) is significant and Prob (F) value, corresponding to the F statistics, is low (0.00038 <0.05) which shows a significant linear relationship between variables.

Table 7 *Calculated hole depth values for pyrex*

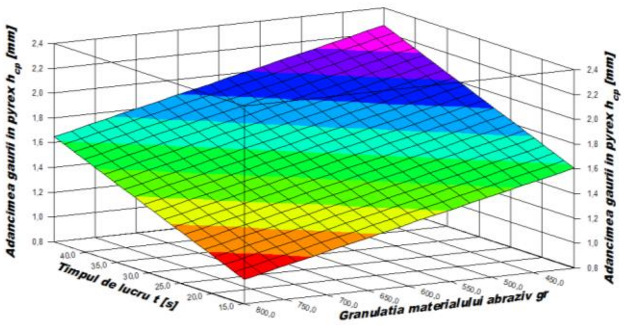
h_p *[mm]*	***h_{pc}*** ***[mm]***	***Residual***
2,81	***2,809167***	0,000833
3,3	***3,455833***	-0,15583
2,13	***2,199167***	-0,06917
2,42	***2,845833***	-0,42583
1,53	***1,606667***	-0,07667
3,12	***2,253333***	0,866667
0,94	***0,996667***	-0,05667
2,21	***1,643333***	0,566667
0,33	***0,404167***	-0,07417
0,49	***0,550833***	-0,06083
0,07	***0,020583***	0,055833
0,15	***0,240833***	-0,09083

Table 7 reveals the very small differences between the experimental values and the depths calculated based on the regression equation.

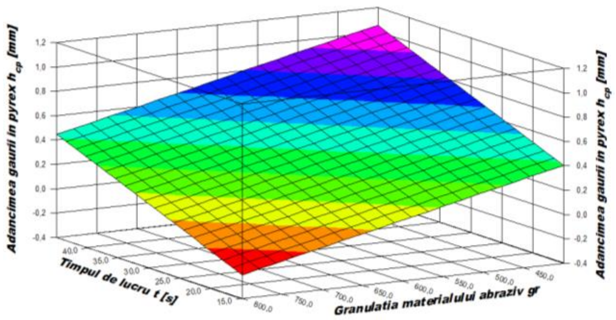
To reveal the cumulative influence of two parameters on the Pyrex hole depth value we have sequentially selected experimental data characterized by constant values of the diameter (Fig. 3), the working time (Fig. 4) and the abrasive material granulation (Fig. 5).



d=0.6 mm

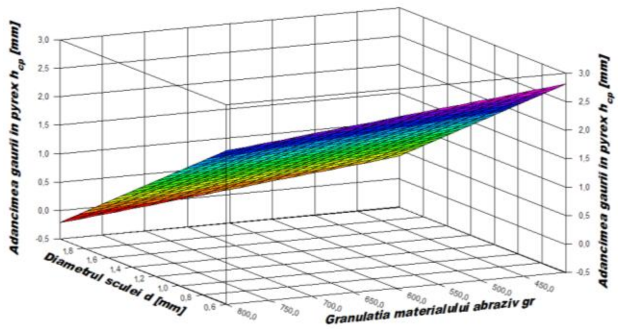


d=1,3 mm

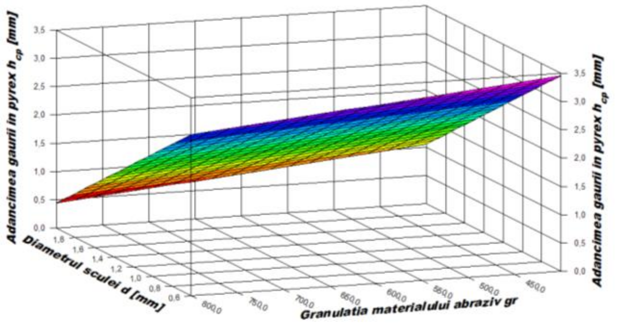


d=2 mm

Figure 3 *The influence of the working time and the abrasive material granulation on the Pyrex hole depth value, maintaining constant the tool diameter*



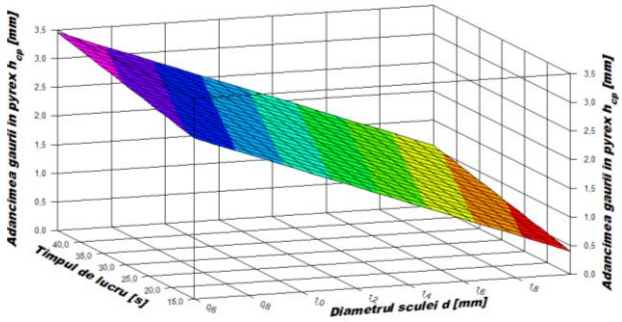
t=15s



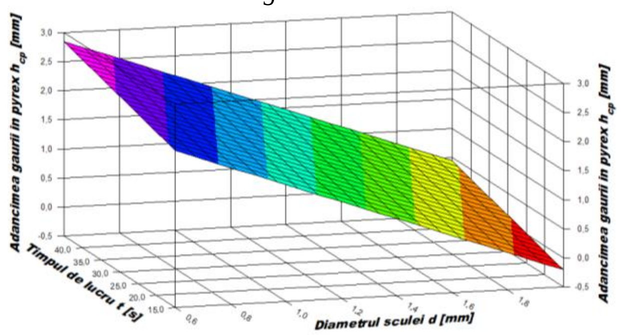
t=45s

Figure 4 *The influence of the tool diameter and the abrasive material granulation on the pyrex hole depth value, maintaining constant the working time*

It can be seen that the hole depth values reaches the lowest value with the 2 mm tool, 800 abrasive material granulation and 15s working time.



gr=400



gr=800

Figure 5 *The influence of the working time and the tool diameter on the Pyrex hole depth value, maintaining constant the abrasive material granulation*

The highest hole depth value - 3.3 mm is obtained with the 0.6 mm tool and the lowest - 0.07 mm with 2 mm tool.

The hole depth values obtained by Pyrex ultrasonic drilling are lower with the use of an 800 abrasive material granulation but it gives a superior surface roughness quality.

The main experimental data of the normal glass ultrasonic drilling process are synthesized in Tab. 8.

Table 8 *Normal glass ultrasonic drilling experimental data*

Nr. exp.	*d* [mm]	gr	*t* [s]	*h* [mm]
1	0,6	400	15	2,58
2	0,6	400	45	2,98
3	0,6	800	15	1,81
4	0,6	800	45	2,21
5	1,3	400	15	1,58
6	1,3	400	45	2,14
7	1,3	800	15	0,78
8	1,3	800	45	1,77
9	2	400	15	0,19
10	2	400	45	0,55
11	2	800	15	0,07
12	2	800	45	0,11

Table 9 *Statistical data of the normal glass ultrasonic drilling*

Variables	***d***	***gr***	***t***	***h_c***
Nr. of points	12	12	12	12
Missing Points	0	0	0	0
Max. value	2	800	45	2,98
Min. value	0,6	400	15	0,07
Range	1,4	400	30	2,91
Average	1,3	600	30	1,3975
Standard Deviation	0,5969	208,8931	15,6669	1,1951

Correlation Matrix

	d	***gr***	***t***	***h_c***
d	1	-6,4749E-18	1,0791E-17	-0,858072
gr	-6,4749E-18	1	0	-0,266553
t	1,07916E-17	0	1	0,282575
h_c	-0,858072	-0,266553	0,282575	1

Standard Deviation	Sum of Residuals	Average Residual	R^2
0,2593481	-1,72085E-14	-1,43404E-15	0,9529386

R^2 value - 0,9529386 showed that between the independent variables (d, gr, t) and the dependent variable (h_c) is a significant relationship (Tab. 9) and we can say that 95,29% of the hole depth variation is determined by the tool diameter.

$$Y=ax_1+bx_2+cx_3+d \qquad (5)$$

Tab. 10. *Regression coefficients*

	Value	Standard Error
a	-1,54642857142857	0,237735964055593
b	-0,0013625	6,793871063523E-04
c	1,52777777777777E-02	9,058494751364E-03
d	3,76702380952381	0,5949735349566
	t	Prob(t)
a	-11,80564607	0,0
b	-3,63977041	0,00659
c	3,060968999	0,01556
d	11,4909384	0,0

$$h_{sc} = -1{,}546428 \cdot d_s - 0{,}001362 \cdot gr + +1{,}527777 \cdot 10^{-2} t + 3{,}767023 \quad (6)$$

where,
h_{sc} - the hole depth calculated value for normal glass;
d_s - the tool diameter;
gr - abrasive material granulation;
t - working time.

The equation 6 shows that the normal glass hole depth value increases with decreasing of the tool diameter- d_s and abrasive material granulation - gr, and will increase with the working time - t enlargement.

The most significant relationship is the reverse relation of the hole depth value and tool diameter.

Table 11 *ANOVA*

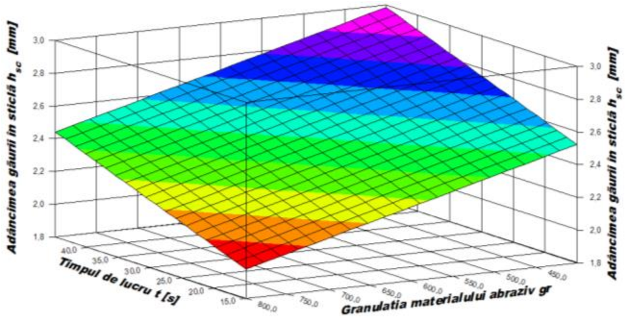
	df	**Sum of Squares**	**Mean Square**
Regression	3	10,8957333333	3,63191111111111
Error	8	0,53809166666	6,726145833333E-02
Total	11	11,433825	
		F	**Prob(F)**
		53,9969129	0,00001

We can noticed that the calculated value for F (53,99691296) is significant and Prob (F) value, corresponding to the F statistics, is low (0,00001<0,05), this fact demonstrate the significant linear relationship of the variables.

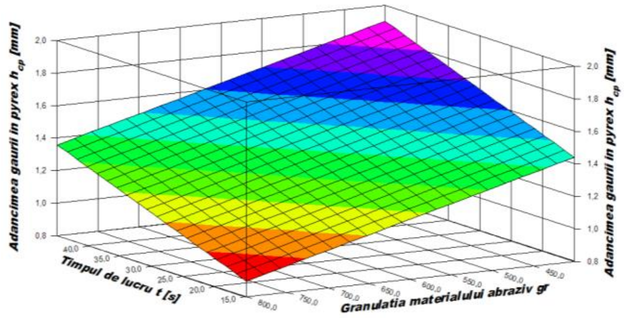
Table 12 *Calculated hole depth values for pyrex*

***h_p* [mm]**	***h_{pc}* [mm]**	***Residual***
2,81	***2,809167***	0,000833
3,3	***3,455833***	-0,15583
2,13	***2,199167***	-0,06917
2,42	***2,845833***	-0,42583
1,53	***1,606667***	-0,07667
3,12	***2,253333***	0,866667
0,94	***0,996667***	-0,05667
2,21	***1,643333***	0,566667
0,33	***0,404167***	-0,07417
0,49	***1,050833***	-0,56083
0,07	***-0,20583***	0,275833
0,15	***0,440833***	-0,29083

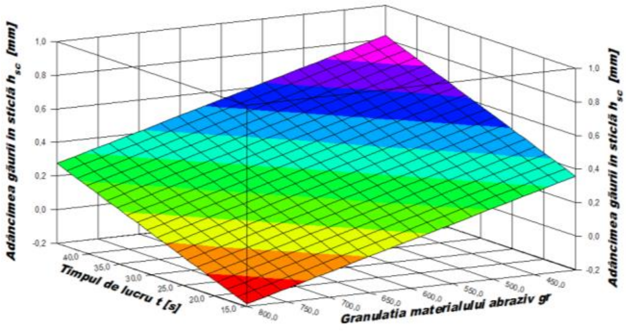
Table 12 reveals the very small differences between the experimental and calculated data.



d=0,6 mm



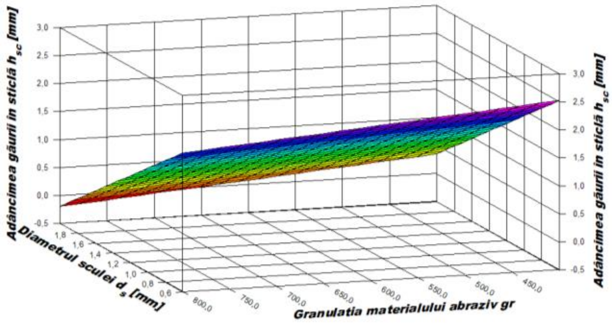
d=1,3 mm



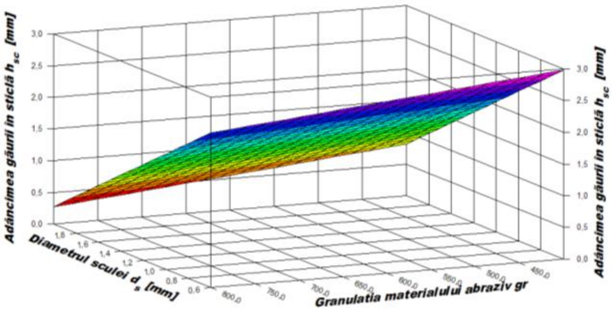
d=2 mm

Figure 6 *The influence of the working time and the abrasive material granulation on the hole depth value in normal glass, maintaining constant the tool diameter*

The hole depth maximum value is reached with a 0,6 mm tool and 400 abrasive material granulation in 15 s.



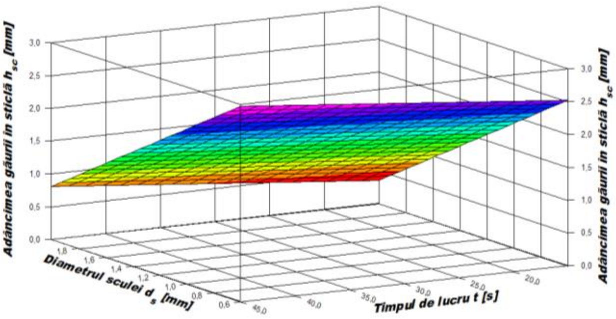
t=15s



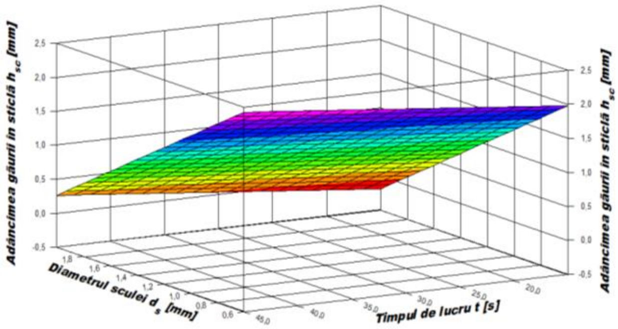
t=45s

Figure 7 *The influence of the tool diameter and the abrasive material granulation on the hole depth value in normal glass, maintaining constant the working time*

Increasing the size of the abrasive granule (from 800 to 400) leads to the significant increase of the hole depth value.

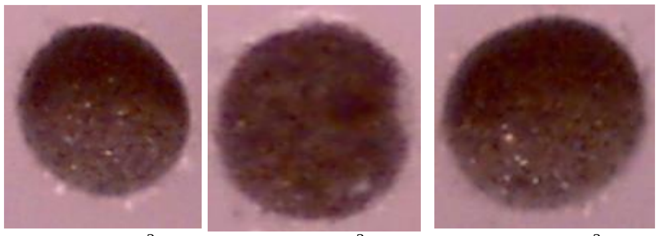


gr=400



gr=800

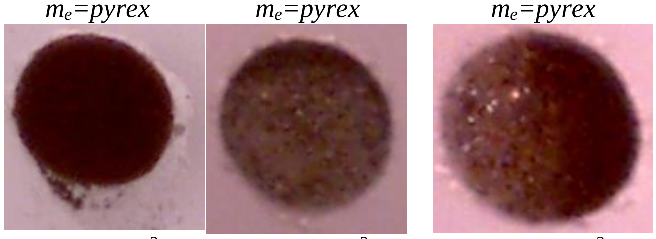
Figure 8 *The influence of the working time and the tool diameter on the hole depth value in normal glass, maintaining constant the abrasive material granulation*



P=1N/mm^2, gr=400, d_s=0,6mm, m_e=pyrex

P=1N/mm^2, gr=400, d_s=1,3mm, m_e=pyrex

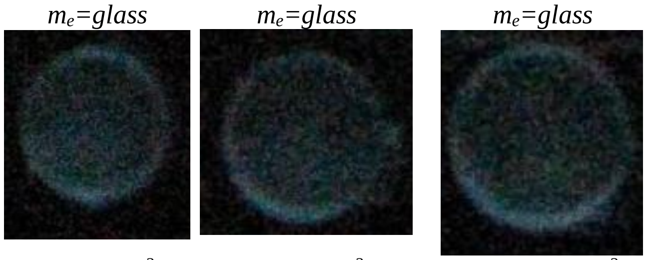
P=1N/mm^2, gr=400, d_s=2 mm, m_e=pyrex



P=1 N/mm^2, gr=400 d_s=0,6mm, m_e=glass

P=1 N/mm^2, gr=400 d_s=1,3mm, m_e=glass

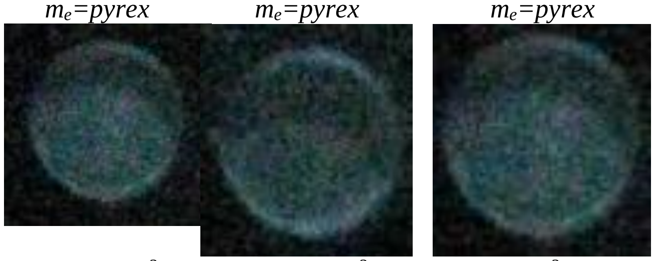
P=1 N/mm^2, gr=400 d_s=2mm, m_e=glass



P=1N/mm^2, gr=800, d_s=0,6mm, m_e=pyrex

P=1N/mm^2, gr=800, d_s=1,3mm, m_e=pyrex

P=1N/mm^2, gr=800, d_s=2 mm, m_e=pyrex



P=1 N/mm^2, gr=800 d_s=0,6mm, m_e=glass

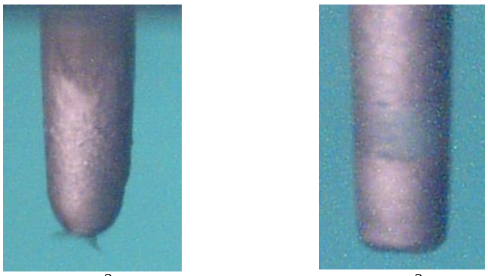
P=1 N/mm^2, gr=800 d_s=1,3mm, m_e=glass

P=1 N/mm^2, gr=800 d_s=1,3mm, m_e=glass

Figure 9 *Exterior form of the ultrasonically drilled holes*

Figure 9 revel the superior form precision that was obtained at pyrex and normal glass ultrasonic drilling process.

In order to increase the hole depth value we tried to use a higher working pressure 1,5N/mm but it has been proven to be a wrong choice. The 0,6mm tool has been broken after 12s. At the same pressure value the 1,3mm tool, the elastic sleeve and the screw nut have been welded. In the ultrasonic drilling process with a the 2mm tool, at 1,5 N/mm working pressure the horn has been broken from the threaded superior zone limit.



$P=1,5 N/mm^2$, gr=400, $d_s=1,3$ mm, m_e=pyrex *$P=1,5 N/mm^2$, gr=400, $d_s=1,3$ mm, m_e=glass*

Figure 10 *Ultrasonically drilled holes*

4. Conclusion

The ultrasonic drilling experimental research were made in pyrex and normal glass samples. The abrasive material had a very important role, thus, we used an equal percent of two material types, 21C and 22C in order to benefit of their proprieties cumulative effect.

There were used two values of the abrasive material granulation, 400 and 800. The abrasive solutions had a 40% concentration. To avoid, as far as possible, the processing and measurement errors, were made three experimental with the same working parameters values. At the experimental data processing we took into consideration the average values. The highest hole depth value was 3,3 mm for pyrex and 2,98 for normal glass, it was obtained in the same working conditions: 0,6 mm tool, 400 abrasive material granulation and 45s the working time.

Mathematical modeling of the experimental results was made using the DataFit program. Were revealed the following main correlations:

- the hole depth value increases with decreasing of the tool diameter - d_s and abrasive material granulation - gr, and increases with the working time - t enlargement;
- the abrasive granule size increasing (from 800 to 400) leads to the significant increase of the hole depth value;
- maintaining constant the working time and the abrasive material granulation the hole depth value will increase with the tool diameter decreasing.

These correlations are valid for ultrasonic drilling of both material types, Pyrex and normal glass.

The main ultrasonic drilling advantages are: high dimensional precision and a superior surface roughness, good working speed and the absence of the intern stresses and local warming accumulation in workpiece. Due to those advantages the ultrasonic drilling process is expanding its applicability area.

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