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Paper

ANALYSIS OF THE EFFECT OF WATER JET PARAMETERS ON THE PERFORMANCE DURING PREPARATION OF CUTTING TOOL EDGE BY FINE ABRASIVE WATER JET

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ABSTRACT

Preparation of cutting tool edge using fine abrasive water jet (FAWJ) was proposed. A specific designed water jet machine tool with four axes was developed. Experiments on preparation of cutting edge of carbide chasers for petroleum steel pipes using FAWJ have been carried out. Taguchi test method was applied in design of experiments. The effects of process parameters on the radius of cutting edge as well as the surface roughness of the cutting tool were investigated and analyzed. Based on the range analysis, among the five process parameters selected, the traverse velocity of the FAWJ exhibits the greatest significance on the prepared cutting edge radius, followed by abrasive flow rate, size of abrasive, pressure and stand-off distance. Nevertheless the most significant impact factor of the designed parameters on the prepared surface roughness is abrasive flow rate, followed by the traverse velocity, stand-off distance, size of abrasive and water pressure. From the analysis of variance, the abrasive flow rate has the most significant impact on both the prepared cutting edge radius and the surface roughness. The traverse velocity also has important impact on the prepared cutting edge radius and the surface roughness.

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1. INTRODUCTION

Cutting tool plays an important role in the machining process. Carbide chaser is an important tool for manufacturing thread of the petroleum steel pipes. Generally a carbide chaser has more than one tooth, as shown in Figure 1. The cutting teeth of the carbide chaser play a significant role in the machining process. In order to improve cutting efficiency, extend tool life and therefore reduce manufacturing costs, a lot of work has to be done . This includes optimization of structure of cutting tool, modification of the tool edge geometry, development of new tool materials as well as tool coating technology[1-5]. The early research shows that most of the defects on the cutting tool, such as micro cracks, burring, chipping etc. can be eliminated by preparation procedure[6]. Therefore researchers have paid enough attention to cutting tool preparation.

The picture of a tooth on the carbide chaser under measuring microscope 107JPC is shown in Figure 2. It can be seen that the cutting edge is very sharp and zigzag burring exists on the cutting edge. On the other hand, linear waviness appears on the surface of the carbide chaser.

The purpose of cutting edge preparation is to strengthen the cutting edge or prepare a surface for deposition of hard coatings. There are three types of cutting edge for cutting tool, i.e. sharp edge, honed or round edge and T-land/chamfer edge in most commercial applications [5], as shown in Figure 3. A chamfer edge combined with additional hone is also available. Round edges are usually employed in finish cuts and it can reduce the initiation of notch wear. Chamfer edges are used in heavy chip loads and interrupted cuts because it can further strengthen tool edge. Thereafter the working life of cutting tool can be greatly improved.

Preparation of cutting edge using abrasive water jet (AWJ) was proposed in our early research. The experimental study has shown the feasibility of preparation of the cutting edge of carbide inserts using AWJ [6]. The zigzag burring existing on the cutting edge was successfully eliminated through preparation by AWJ. Also the very sharp cutting edge was rounded after preparation by AWJ compared with the original one. Thus the cutting edge strength can be enhanced during this course. The results show that preparation of cutting edge of the tool by AWJ is efficient, environmental friendly and higher quality compared with other preparation method. The further experimental study on the preparation of cutting edge using FAWJ is necessary and the effects of experimental parameters on the radius of cutting tool edge as well as surface quality were analyzed in this paper.

2. EXPERIMENTAL SETUP

The experimental setup for preparation of cutting edge of carbide chaser was based on HJ300 abrasive water jet machine, as shown in Figure 4. The AWJ machine has four axes, i.e. linear axis X/Y/Z and rotary axis A. The X, Y, and Z axes are numerically controlled. The abrasive nozzle assembly was driven by X/Y/Z axies. Therefore the abrasive nozzle can map any 2D shape on the machine table.

The rotary (A) axis is used to hold the fixture for carbide chaser and adjust the carbide chaser to perpendicular to the abrasive water jet. Because the fine abrasives were used, it is difficult for the fine abrasives to entrain into the nozzle. So an auger mechanism was designed and used to feed the fine abrasives. The flow rate of abrasives can be precisely controlled by regulating the rotating speed of the electrical motor of the auger mechanism[7], as shown in Figure 5.

In order to prepare of cutting edge of carbide chaser for petroleum steel pipes, a specially designed abrasive nozzle (focusing tube) with rectangular inside profile was designed, as shown in Figure 6. The inside profile of abrasive nozzle was composed of three sections, i.e., the contraction section, the cylinder section and the diffusion section. The detailed parameters are showed in Table 1.

In the experiments, carbide chaser for the production of petroleum steel pipes was used as a specimen, as shown in Figure1b. Because of its relatively small size, specially designed fixture for carbide chaser was used during cutting edge preparation with FAWJ. The detailed experimental parameters are listed in Table 2.

3. MEASUREMENTS

An optical 3D measuring device for the cutting tool (MikroCAD) from GFM was used for measuring the radius of prepared cutting edge of carbide chaser, as shown in Figure 7. MikroCAD is a customized system for automated measurement of cutting edge rounding. The profile of the cutting edge of the carbide chaser can be easily scanned by a narrow laser. Equipped with specialized software, it has image processing, data acquisition and data analyzing functions. Therefore the rounding radius of the cutting edge along carbide chaser can be reported by MikroCAD system.

4. EXPERIMENTAL RESULTS AND ANALYSIS

More than 100 thread carbide chasers were prepared in experiments. The prepared samples of carbide chasers are as shown in Figure 8. One of the tooth's camera images of the carbide chaser after preparation with FAWJ was shown in Figure 9a. And the rounding radius for specific section between the blue lines after preparation with fine abrasive water jet was shown in Figure 9b.

Figure10 depicts the variation of rounded radius of the cutting edge along the one tooth of the carbide chaser after preparation by FAWJ. As shown in Figure10, the rounded radius is uneven along the cutting tooth of the carbide chaser, although the variation of the radius is limited. The detailed data of radius after preparation are listed in Table 3.

The comparison of radius of the cutting edge before and after preparation is shown in Figure11. It can be seen from the profile of cutting edge that there are significant changes compared with the original tool edge. The very sharp cutting edge was rounded after preparation by fine abrasive water jet.

In order to explore the performance of preparation of cutting tool edge by fine abrasive water jet and find the effects of process parameters on the radius of cutting edge as well as the surface roughness of the cutting tool, detailed experiments are needed.

4.1 Design of Detailed Experiments

Taguchi test method was applied in design of experiments. According to the preliminary results on preparation of the cutting tool edge, three levels and five factors were considered, as shown in Table 4. The interactive influence of five independent factors was neglected, therefore an final test design of $L_{27}(3^5)$ was applied in this work, as shown in Table 4. The rounded radius of the cutting tool edge and the surface roughness of the cutting tool were considered as the performance during preparation by FAWJ. The results are presented in Table 5.

4.2 Analysis of the Effects of Process Parameters on the Radius of Cutting Edge

In order to enhance the strength of cutting tool edge, the rounded radius of the cutting edge of carbide chaser in the range of 40-70μm is expected. Based on our experiments, the rounded radius is a little bit smaller. From this point, higher water pressure or coarser abrasive should be used during preparation. It should be pointed out that coarser abrasive will be result in higher surface roughness on the rake face and the flank face. Therefore two steps of preparation of cutting edge of carbide chaser for petroleum steel pipes maybe suggested.

4.2.1 The Range Analysis of the Prepared Cutting Edge Radius

The range analysis was used for the analysis of prepared cutting edge radius based on Taguchi experiments in Table 5. The range analysis results for prepared cutting edge radius obtained was shown in Table 6.

In Table 6, K_i is the sum of experimental results r_i based on Taguchi Table 5 when process parameter is at level i. A_i is the average of K_i and R is max-min difference among A_i. Thus they are given in equations (1), (2) & (3).

$$K_i = \sum_{i=1}^{9} r_i \quad (1)$$

$$A_i = \frac{1}{9}\sum_{i=1}^{9} r_i \quad (2)$$

$$R = max(A_i) - min(A_i) \quad (3)$$

Based on the range analysis for prepared cutting edge radius in Table 6, the significant impact factor of design parameters on the prepared cutting edge radius was distinguished and the optimal combination of design parameters in test conditions was found. As shown in Table 6, among the five process parameters, the traverse velocity of the FAWJ exhibits the greatest significance, followed by abrasive flow rate, size of abrasive, water pressure and stand-off distance. The results suggest that the cutting edge radius during preparation is most sensitive to the traverse velocity of the FAWJ and abrasive flow rate.

The influence of designed process parameters on the prepared cutting edge radius based on the sum of experimental results K_i was depicted in Figure12. Apparently a larger rounded radius on the cutting edge of the carbide chaser is expected. Therefore the optimal combination of designed parameters under experimental conditions was determined, i.e., $p=120$ Mpa, $u=100$ mm/min, $m_a=1.0$ g/s, $s=240\#$, $s_d=12mm$, as shown in Figure12.

4.2.2 Analysis of Variance of the Prepared Cutting Edge Radius

Analysis of variance (ANOVA) is a statistically based, objective decision–making tool for detecting any differences in average performance of groups of parameters tested. It helps formally test the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels.

With the help of ANOVA, the influence of experimental parameters on the cutting edge radius could be obtained. The results for the cutting edge radius by ANOVA based on experimental data in Table 5 were represented in Table 7.

The F ratio is generally used to determine the significance of the factor effects, which is defined as the ratio of the mean square and the error mean square. From Table 7, at 95% confidence level，the experiment parameter that has the greatest F value (2.08) is abrasive flow rate. It indicates that the abrasive flow rate has most significant impact on the prepared cutting edge radius, while the traverse velocity and the size of abrasive also has the important impact on the prepared cutting edge radius. The significance of water pressure and stand-off distance is relatively small. The water pressure has less impact on the prepared cutting edge radius may be due to the less difference among the three levels.

4.2.3 Regression Analysis of the Prepared Cutting Edge Radius

Regression analysis can determine the relationship between dependent and independent variables. Here it was used to predict the prepared cutting edge radius as a function of the process parameters of preparation of cutting tool edge by FAWJ, i.e., water pressure, traverse velocity, abrasive flow rate, stand-off distance and the size of abrasive.

In this analysis, the prepared cutting edge radius was considered to be a response (output), while parameters such as water pressure, traverse velocity, abrasive flow rate, stand-off distance and the size of abrasive were considered to be independent (input) variables[10]. Generally there is a nonlinear relationship for the multi-factor model, the nonlinear function of the prepared cutting edge radius was given in equation 4.

$$r = a_0 p^{a_1} u^{a_2} m_a^{a_3} S^{a_4} s_d^{a_5} \tag{4}$$

Where a_0 is a constant coefficient; a_1, a_2, a_3, a_4, and a_5 are undetermined coefficient.

With the help of MATLAB toolbox, nlinfit function was used to find the undetermined coefficient based on the Taguchi experiment results shown in Table 5. The regression analysis results obtained are shown in Table 8.

Therefore the regression equation of the prepared cutting edge radius r on the carbide chaser was expressed as follows.

$$r = 26.0676 p^{0.0309} u^{0.1300} m_a^{-0.2023} S^{-0.1985} s_d^{0.0934} \tag{5}$$

In order to verify the regression analysis of he prepared cutting edge radius, 6 set of experimental data were selected. The relative error between the experimental values and predict values based on the regression equation(5) are around 5.189%-7.5897%.

4.3 Analysis of the Effects of Process Parameters on Tool Surface Roughness

4.3.1 The Range Analysis of the Tool Surface Roughness

The range analysis results for prepared tool surface roughness obtained was shown in Table 9. Based on the range analysis results in Table 9, the significant impact factor of design parameters on the prepared surface roughness is abrasive flow rate, followed by the traverse velocity, stand-off distance, size of abrasive particles and water pressure. In order to achieve better surface finish on the carbide chaser after preparation, The better the smaller of the surface roughness R_a is. Therefore the optimal combination of designed parameters under experimental conditions is as follows, i.e., $p = 80$ Mpa, $u = 80$ mm/min, $m_a = 2.0$ g/s, $s = 400\#$, $s_d = 9mm$, as shown in Figure13.

4.3.2 Analysis of Variance of the Tool Surface Roughness

Analysis of Variance of the prepared tool surface roughness based on Taguchi experimental data in Table 5 were represented in Table 10.

As shown in Table 10, the experiment paremeter that has the greatest F value (21.31) is abrasive flow rate. It indicates that the abrasive flow rate has most significant impact on the surface roughness during the preparation of cutting tool by FAWJ, while the significance of traverse velocity, stand-off distance and the water pressure is relatively small. The interesting result is that the size of abrasive has the least impact on the surface roughness. This is probably due to the small difference among the three types of abrasive size. Thus the surface roughness of the cutting tool is more sensible to the changes in the abrasive flow rate than that of abrasive size.

4.3.3 Regression Analysis of the Prepared Surface Roughness of Carbide Chaser

Generally there is a nonlinear relationship for the multi-factor model, the nonlinear function of the cutting tool surface roughness was given in equation 6.

$$Ra = c_0 p^{c_1} u^{c_2} m_a^{c_3} S^{c_4} s_d^{c_5} \tag{6}$$

Where c_0 is a constant coefficient; c_1, c_2, c_3, c_4, and c_5 are undetermined coefficient.

With the help of MATLAB toolbox, nlinfit function was used to find the undetermined coefficient based on the Taguchi experiment results shown in Table 5. The regression analysis results for coefficient obtained are shown in Table 11. The regression equation of the surface roughness R_a on the prepared carbide chaser is as follows.

$$Ra = 0.0106 p^{0.2319} u^{0.4319} m_a^{-0.8371} s^{0.0039} s_d^{0.5809} \quad (7)$$

According to the experimental data of verification, the maximum relative error of the regression equation(7) is 7.55%.

5. CONCLUSIONS

Experiments on preparation of cutting edge of carbide chaser for petroleum steel pipes using FAWJ have been carried out. The experimental results show that the micro defects on the cutting tool surface, such as micro cracks, waveness, burring, chipping etc. were elimilated. The very sharp edge with irregular zigzag shape was rounded to a radius around 20-30μm by FAWJ. Based on the analysis from the Taguchi experiments, the following conclusions can be drawn.

1) From the range analysis, among the five process parameters selected, the traverse rate of the FAWJ exhibits the greatest significance on the prepared cutting edge radius, followed by abrasive flow rate, size of abrasive, pressure and stand-off distance. Nevertheless the significant impact factor of design parameters on the prepared surface roughness is abrasive flow rate, followed by the traverse velocity, stand-off distance, size of abrasive and water pressure.

2) Based on analysis of variance, the abrasive flow rate has the most significant impact on both the prepared cutting edge radius and the surface roughness. The traverse velocity also has important impact on the prepared cutting edge radius and the surface roughness.

3) Under experimental conditions, the nonlinear relationship between the prepared cutting edge radius and the process parameters was given by $r = 26.0676 p^{0.0309} u^{0.1300} m_a^{-0.2023} S^{-0.1985} s_d^{0.0934}$. The relative error between the experimental values and predict values are around 5.189%-7.5897%.

4) Under experimental conditions, the regression equation for the surface roughness was determined by $Ra = 0.0106 p^{0.2319} u^{0.4319} m_a^{-0.8371} s^{0.0039} s_d^{0.5809}$. According to the experimental data of verification, the maximum relative error for the regression equation is 7.55%.

6. ACKNOWLEDGEMENT

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8. NOMENCLATURE

d - Mixing tube inside diameter /mm
D - Mixing tube outside diameter /mm
a, b -The lenth and width of mixing tube outlet
L_1, L_2, L -The lenth of entrance segment, cylinder segment and whole respectively
p - Water jet pressure/ Mpa
u - Traverse velocity/ mm/min
m_a - Abrasive flow rate/ g/min
s - Abrasive particle size/ mesh
s_d - Stand-off distance/mm
r_0 , r - the cutting edge radius before ande after prepared respectively

R_a - surface roughness after preparation
K_i - the sum of experimental results r_i when process parameter is at level i
A_i - the average of K_i
R - max-min difference among the A_i
a_0, c_0 -constant coefficient
a_1, a_2, a_3, a_4, a_5 -undetermined coefficient
c_1, c_2, c_3, c_4, c_5 - undetermined coefficient

Table 1. Parameters of Rectangular Abrasive Nozzle

α_1(°)	60	d(mm)	0.15
L_1(mm)	5.75	D(mm)	6.35
L_2(mm)	15	a×b(mm)	2.0×0.5
L(mm)	50.8	α_2(°)	30

Table 2. Experimental Parameters for FAWJ

Water Jet Pressure p **/ MPa**	120
Stand-off Distance s_d **/mm**	15
Abrasive Flow Rate m_a **/ g/min**	90.61
Abrasive Type	SiC
Abrasive Particle Size s **/ mesh**	240-400
Traverse Velocity u **/ mm/min**	80-160

Table 3. Measured Radius of the Cutting Edge

Radius	**Unit**	**Min**	**Max**	**Mean**	**Standard Deviation**
r	μm	24.4	28.1	25.9	0.79

Table 4. Taguchi Test Design

Factors / **Level**	p / MP_a	$u / mm / \text{min}$	$m_a / g / s$	$s / mesh$	s_d / mm
1	120	80	1.0	240	9
2	100	120	1.5	325	12
3	80	160	2.0	400	15

Table 5. Prepared Results by FAWJ

Test No.	p/MP_a	$u/mm/\min$	$m_a/g/s$	$s/mesh$	s_d/mm	$r/\mu m$	$R_a/\mu m$
1	1	1	1	1	1	24.5	0.821
2	1	1	1	1	2	22.9	0.837
3	1	1	1	1	3	23.7	0.907
4	1	2	2	2	1	18.4	0.812
5	1	2	2	2	2	22.1	0.925
6	1	2	2	2	3	23.5	1.397
7	1	3	3	3	1	21.1	0.556
8	1	3	3	3	2	20.4	0.563
9	1	3	3	3	3	20.5	0.554
10	2	1	2	3	1	19.3	0.404
11	2	1	2	3	2	17.1	0.492
12	2	1	2	3	3	16.0	0.843
13	2	2	3	1	1	24.9	0.748
14	2	2	3	1	2	21.2	0.595
15	2	2	3	1	3	19.8	0.556
16	2	3	1	2	1	16.4	0.944
17	2	3	1	2	2	28.5	1.001
18	2	3	1	2	3	17.9	1.418
19	3	1	3	2	1	15.3	0.446
20	3	1	3	2	2	14.2	0.514
21	3	1	3	2	3	22.8	0.294
22	3	2	1	3	1	20.9	0.924
23	3	2	1	3	2	25.7	0.941
24	3	2	1	3	3	26.4	1.307
25	3	3	2	1	1	22.8	0.740
26	3	3	2	1	2	23.3	0.756
27	3	3	2	1	3	21.9	0.951

Table 6. Range Analysis for the Prepared Cutting Edge Radius by Taguchi

	$r/\mu m$				
	p	u	m_a	s	s_d
K_1	197.10	175.80	206.90	205	183.60
K_2	181.10	202.90	184.40	179.10	195.40
K_3	193.30	192.80	180.20	187.40	183.50
A_1	21.90	19.53	22.99	22.78	20.40
A_2	20.12	22.54	20.49	19.90	21.71
A_3	21.48	21.42	20.02	20.82	21.38
R	1.778	3.011	2.967	2.878	1.311
the Order of Significance of the Factors: $u \to m_a \to s \to p \to s_d$					

Table 7. Analysis of Variance of the Prepared Cutting Edge Radius

Variance Source	Degrees of Freedom (DF)	Sum of Square (SS)	Mean Square (MS)	F Value (F)	P Value (P)
p/MPa	2	15.529	7.764	0.7	0.509
u/mm/min	2	4.682	20.841	1.89	0.183
m_a/g/s	2	45.807	22.903	2.08	0.157
S/mesh	2	38.869	19.434	1.76	0.203
S_d/mm	2	8.402	4.201	0.38	0.689
Error	16	176.331	11.020		
Total	26	326.62			

Table 8. Regression Analysis of Prepared Cutting Edge Radius

a_0	a_1	a_2	a_3	a_4	a_5
26.0676	0.0309	0.1300	-0.2023	-0.1985	0.0934

Table 9. Range Analysis for the Prepared Surface Roughness by Taguchi

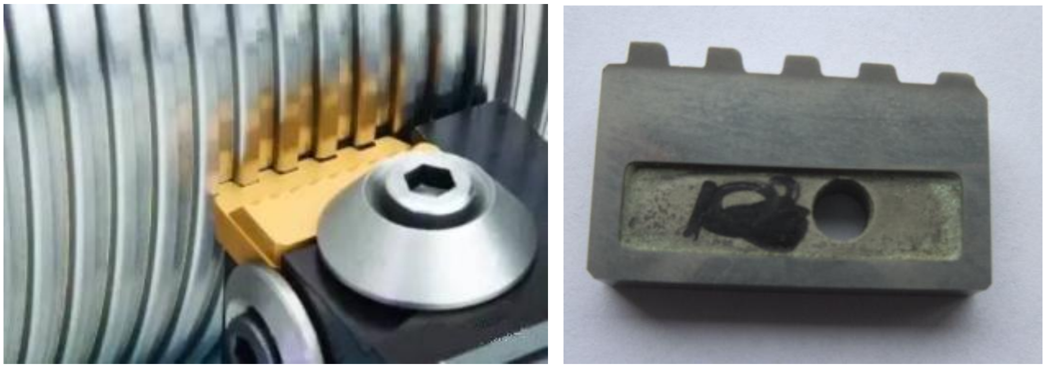
	$R_a / \mu m$				
	p	u	m_a	s	s_d
K_1	7.372	5.558	9.1	6.911	6.395
K_2	7.001	8.205	7.32	7.751	6.624
K_3	6.873	7.483	4.826	6.584	8.227
A_1	0.8191	0.6175	1.011	0.7678	0.7105
A_2	0.7778	0.9116	0.8133	0.8612	0.736
A_3	0.7636	0.8314	0.5362	0.7315	0.9141
R	0.0554	0.2941	0.4748	0.1296	0.2035
the Order of Significance of the Factors: $m_a \to u \to s_d \to s \to p$					

Table 10. Analysis of Variance of the Tool Surface Roughness

Variance Source	Degrees of Freedom (DF)	Sum of Square (SS)	Mean Square (MS)	F Value (F)	P Value (P)
p/MPa	2	0.081	0.0403	1.68	0.218
u/mm/min	2	0.416	0.2080	8.66	0.003
m_a/g/s	2	1.024	0.5121	21.31	0
S/mesh	2	0.015	0.0075	0.31	0.737
S_d/mm	2	0.221	0.1107	4.61	0.026
Error	16	0.384	0.0240		
Total	26	2.142			

Table 11. Regression Analysis of Prepared Surface Roughness

c_0	c_1	c_2	c_3	c_4	c_5
0.0106	0.2319	0.4319	-0.8371	0.0039	0.5809



a) Carbide Chaser in Production Thread b) Carbide Chaser

Figure 1. Carbide Chaser for Manufacturing Thread of a Petroleum Steel Pipe

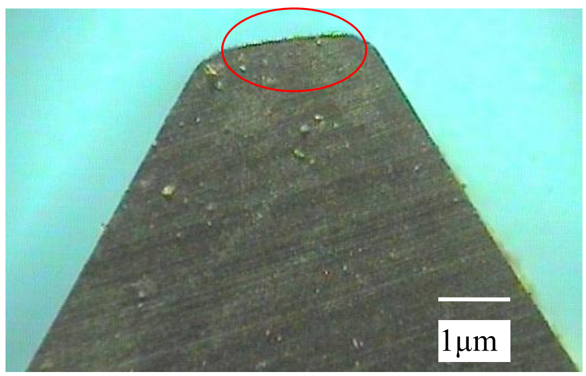
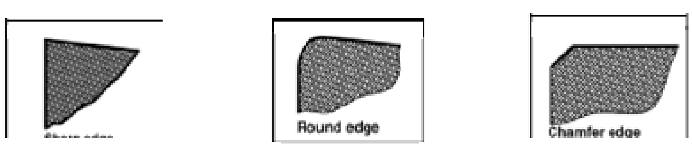


Figure 2. Picture of One Tooth of Carbide Chaser (Magnification of 40×400)



a) Sharp edge b) Round edge c) Chamfer edge

Figure 3. Typical Types of Cutting Edge for Cutting Tool

Figure 4. Experimental Setup for Cutting Edge Preparation

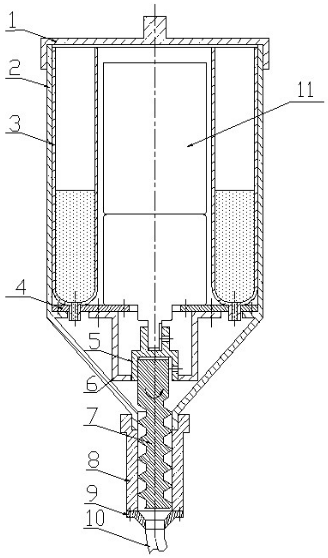


Figure 5. Fine Abrasives Precise Feed System
1-cover 2-shell 3-cavity 4-Support 5-coupling
6- blocking tube 7-auger 8-sheathing 9-joint
10-hose 11-geared motor

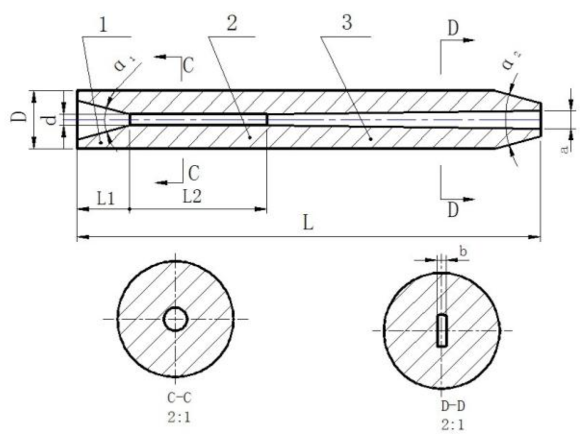


Figure 6. Rectangular Abrasive Nozzle

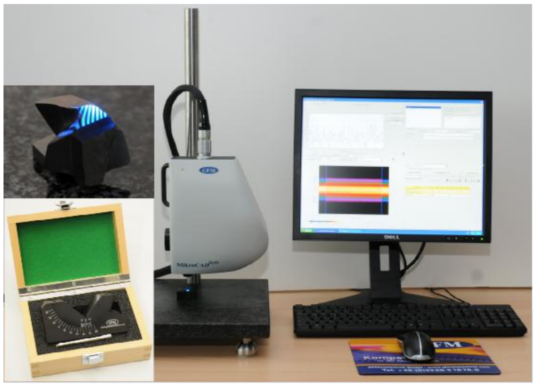
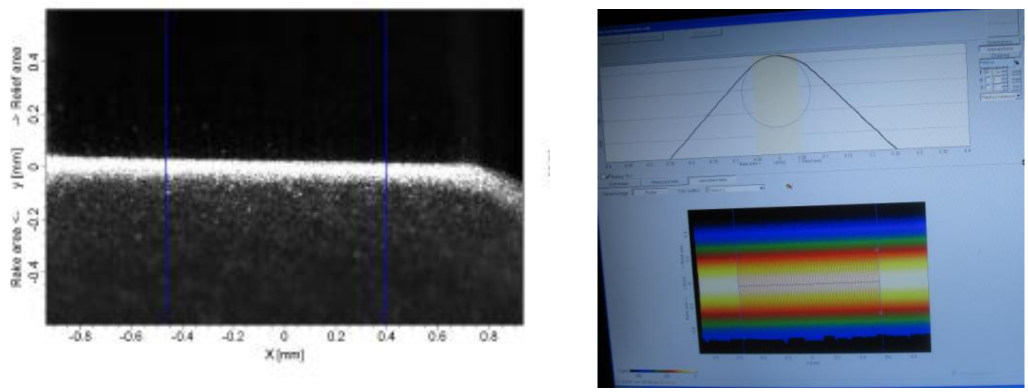


Figure 7. MikroCAD System

Figure 8. Prepared Samples



a) Camera Image of the Cutting Edge b) Data Acquisition and Processing

Figure 9. Measured Result of One Tooth of the Carbide Chaser After Preparation

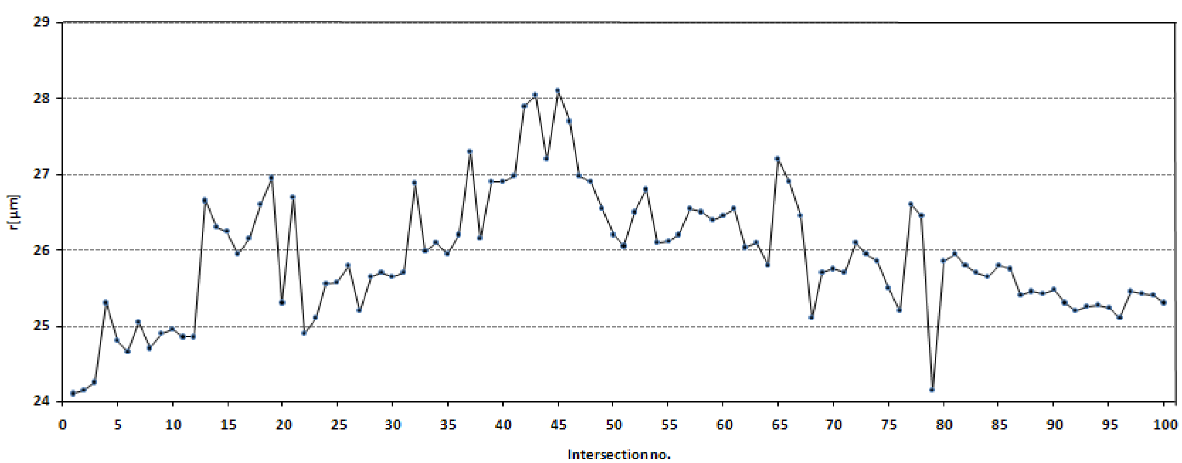
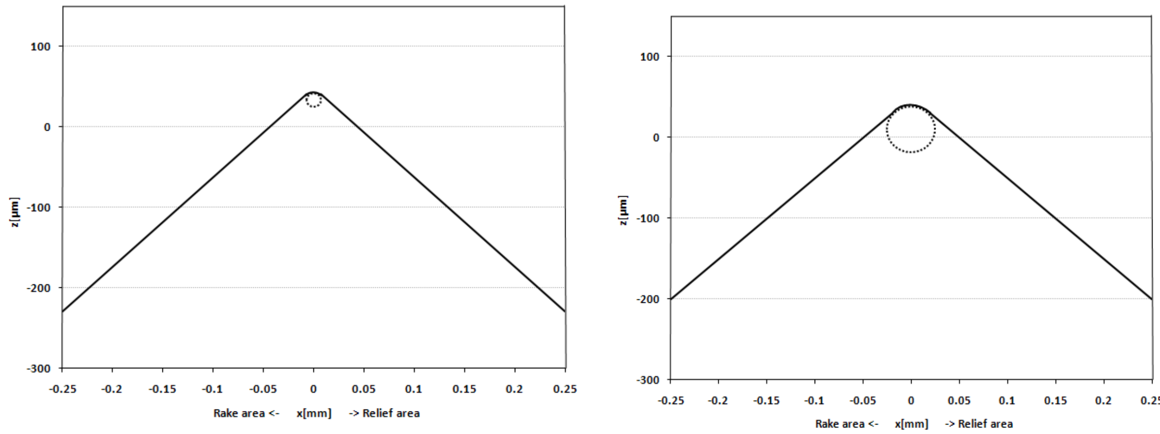


Figure 10. Rounding Radius of the Cutting Edge Along the Tooth After Preparation



a) Before Preparation   b) After Preparation

Figure 11. Comparison of Radius of the Cutting Edge Before and After Preparation

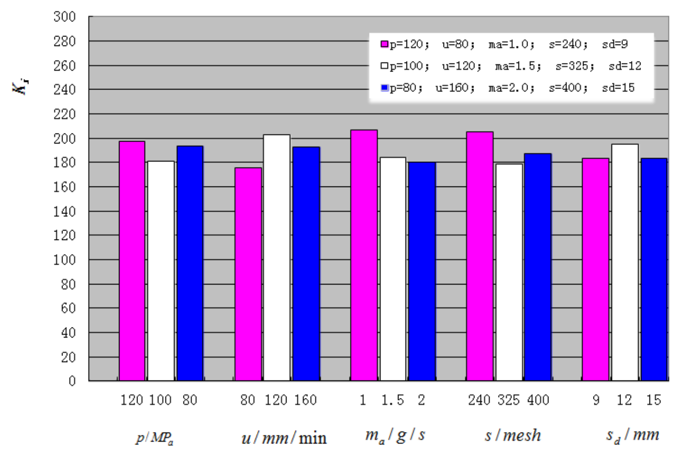


Figure 12. The influence of Process Parameter’s Level on the Prepared Cutting Edge Radius

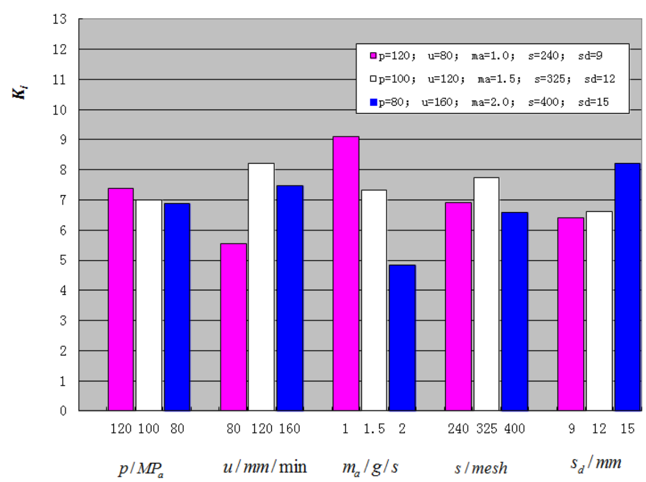


Figure 13. The influence of Process Parameter’s Level on the Prepared Surface Roughness