

Characterization of abrasive waterjet processed surfaces

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ABSTRACT: This paper describes the effect of different abrasive waterjet (AWJ) process parameters on the aesthetical results, such as roughness, waviness, main texture direction, and enhancement of material defects of marble samples. Surfaces have been digitalized by optical profilometry. About one hundred samples of White Carrara and Perlato of Coreno have been characterized using standard surface parameters extracted from the digital surface profiles. Statistical analyses have shown the correlation with the main process parameters, particularly with the waterjet head angle. An interpretation of the aesthetical meaning of the surface parameters is also given in the paper.

1 INTRODUCTION

Surface processing in the stone industry is a fundamental manufacturing phase because the aesthetical properties of products are proportional to their value. On one side polishing aims to make surfaces as smooth and reflective as possible. On the other side, new technologies are emerging to obtain rugged surfaces. Among alternatives to more traditional bush-hammered, sand-blasted, flame-finished, are waterjet and laser processed surfaces.

Among the reasons for the demand of rough surfaces is the invariance of brightness when exposed outdoor, specific architectural effects like shadings and anti-slipping properties for floorings.

New processes require the characterization of results for the optimization of the technological parameters. This paper examines the case of abrasive waterjet of stone products (Carrino et al. 2002, 2003, Ravasio & Monno 2003), in Figure 2.

The order of magnitude of the average surface features in commercial stone products can be as low as $R_a = 0.01 \mu\text{m}$ with waviness $W_t < 0.2 \mu\text{m}$ in the case of polished slabs or tiles and reach peak valley differences P_t for the primary profiles in the order of few millimeters with the other processes mentioned.

Surface acquisition and measurement methods, particularly focusing on processed stone, have been reviewed by Tantussi & Lanzetta (2007). New optical methods, including stereo vision, the use of structured light and the one used in this work, which

is validated as described by Lanzetta, Tantussi & Zambardi (2008), have been proposed.

According to the classification proposed, stone surfaces belong to three groups in terms of R_a (roughness of filtered profiles) and P_t (difference in level between the highest peak and the lowest valley in a random primary – unfiltered – profile sample, with negligible errors of form).

The lower and upper bound of the proposed classification are

- *smooth* surfaces: $R_a < 1 \mu\text{m}$
- *rugged* surfaces: $P_t > 100 \mu\text{m}$

and by difference, it also includes an intermediate group addressed as *rough* surfaces (e.g. semi-

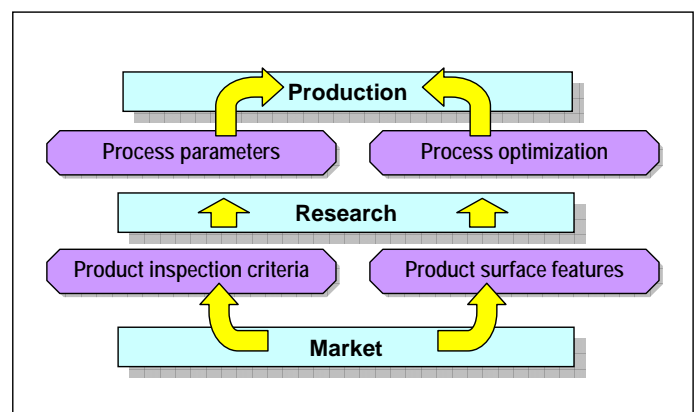


Figure 1. From the product users' criteria, to define the process parameter an intermediate step is required: the objective characterization of the aesthetical features and their quantitative correlation.

Table 1. Abrasive waterjet parameters used in the factorial design of experiments. Passes are spaced 1 mm.

| | Head velocity [mm/min.] | Abrasive flow rate [g/min.] | Head angle [°] | Head setup [mm] ($\varnothing_{\text{foc.}}/\varnothing_{\text{orif.}}$) | Sample material |
|------|----------------------------|--------------------------------|----------------|---|-------------------|
| High | 2000 | 150 | 45 | 1.02/0.33 | Perlato of Coreno |
| Low | 1000 | 50 | 0 | 0.76/0.20 | White Carrara |

finished products), which is concerned in this paper.

The suggested evaluation length depends on the sampling length, which is

- the standard 0.8 mm for smooth surfaces, or lower if required and
- 2.5 mm for rough and rugged surfaces, considered in this paper.

The process result will be generally addressed here as surface quality. The concept of perceived quality will become explicit in § 5. A number of parameters has been defined in international standards (ISO, AFNOR, DIN) to synthesize surface features, including the ones cited above and the others used in this work.

The main purpose of this research is to characterize the visual features of abrasive waterjet processed samples by objective criteria and to find a quantitative statistical correlation with the main process parameters. This connection has been determined in this work following the (reversible) path (Figure 1)

- abrasive waterjet process parameter
- standard surface profile parameters
- surface quality perceived by the product user.

2 SURFACE ACQUISITION

The first step of this project has been the surface measurement, starting from the acquisition of micrometric digital profiles along parallel line scans (Figure 3). Each profile can be synthesized by a single surface parameter. Multiple profiles for each sample are necessary because of the surface variability in order to calculate statistically significant averaged surface parameters.

96 samples (some visible in Figure 2), size 20×40 mm² corresponding to three replications of a factorial design of 5 parameters on two levels according to Table 1 have been analyzed.

The digital surface acquisition of samples (Figure 3) has been based on optical profilometry, because contact methods are not suitable for accessibility reasons and for the risk of damaging the stylus for steep surfaces. A digital profilometer with the features summarized in Table 2 and described in detail by Lanzetta, Tantussi & Zambardi (2008) has

been used. Profile processing and the filters used are also described in Tantussi & Santochi (1992).

As experimentally verified, profile acquisitions not perpendicular to the primary texture are completely dispersed and depend on the micrometric positioning of profiles with respect to the groove created during each pass by the waterjet head.

Table 2. Parameters of the optical profilometer (Omron ZS-LD20T) for the surface profile acquisition. As recommended by norms, profile scans are perpendicular to the abrasive waterjet passes (primary texture). [*] denotes specific instrument settings.

| | |
|---|----------|
| Number of profiles per sample | 25 |
| Spacing between profiles [mm] | 0.5 |
| Profile length [mm] | 12.8 |
| Wavelength of cut λ_c [mm] | 2.5 |
| Evaluation length [mm] | 3 × 2.5 |
| Measurement distance [mm] | 20 |
| Measuring range [mm] | ±1 |
| Laser spot \varnothing (red), nominal resolution [μ m] | 25 |
| Sampling frequency [samples/s] | 512 |
| Translation velocity [mm/s] | 0.8 |
| Linear spatial resolution [samples/mm] | 640 |
| Number of samples per profile | 8192 |
| Light emission* | Auto |
| Measurement method* | Standard |
| Measuring target* | Normal |

3 SURFACE CHARACTERIZATION

The surface parameters considered in this analysis are reported in Table 3.

The roughness parameters are obtained from the original (primary) profile by filtering at a given wavelength (Figure 3). The waviness is obtained by difference.

As for the physical meaning of Ra, Wa, Wt, Pa, Pz, Dz_DIN, they express the amplitude of profiles,

Table 3. Standard surface parameters tested to characterize the surface profiles. Roughness (R) and Waviness (W) parameters are determined according to ISO 4287:2002. Primary profiles (P) are unfiltered. (*) denotes a non-ISO parameter.

| Roughness profile | Waviness profile | Primary profile |
|-------------------|------------------|-----------------|
| Ra, Rku, Rsk, Rmr | Wa, Wt | Pa, Pz, Dz_DIN* |

Table 4. Abrasive waterjet and surface parameters of the samples displayed in Figure 2.

| <i>Abrasive waterjet parameters and surface parameters</i> | <i>Sample n. 43</i> | <i>Sample n. 11</i> | <i>Sample n. 83</i> | <i>Sample n. 86</i> | <i>Sample n. 53</i> | <i>Sample n. 14</i> |
|--|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| Head velocity [mm/min.] | 1000 | 1000 | 1000 | 1000 | 1000 | 2000 |
| Abrasive flow rate [g/min.] | 150 | 50 | 150 | 150 | 150 | 50 |
| Head angle [°] | 0 | 0 | 0 | 0 | 0 | 45 |
| Head setup | 1.02 | 0.76 | 1.02 | 1.02 | 0.76 | 1.02 |
| Material | Coreno | Coreno | Carrara | Carrara | Coreno | Carrara |
| Ra [μm] | 23.5 | 20.1 | 24.6 | 18.6 | 19.2 | 11.6 |
| Rku | 3.028 | 2.707 | 3.795 | 4.204 | 2.860 | 3.467 |
| Rsk | 0.505 | -0.014 | 0.849 | 0.879 | 0.194 | 0.242 |
| Rmr | 10.47 | 13.39 | 9.53 | 8.18 | 10.24 | 10.50 |
| Wa [μm] | 100.3 | 61.8 | 166.0 | 116.6 | 63.1 | 69.9 |
| Pa [μm] | 138.6 | 72.7 | 184.5 | 122.7 | 74.6 | 75.7 |
| Pz [μm] | 513.4 | 325.3 | 693.3 | 474.8 | 328.8 | 282.7 |
| DZ_DIN [μm] | 206.3 | 148.2 | 261.1 | 190.6 | 146.1 | 118.0 |
| Directionality [grades 0 to 3] | 0 | 3 | 0 | 0 | 1 | 0 |
| Material removal [mm] | -3.9 | -1.5 | na | na | -2.2 | na |

with a different consideration of local maxima. A higher value represents a rougher surface, or the presence of occasional irregularities.

Skew and kurtosis (suffix sk and ku of P, W or R) are central moments of the third and fourth order. They are able to measure the material ratio on a profile. In particular, the skew shows the degree of symmetry of the profile, while the kurtosis shows

the amount of profile points near (narrow profile) or far (flat profile) from the mean. As for the perceived quality, the skew shows the material concentration on the upper (negative, full profile) or lower (positive, empty profile) part of the profile, while the kurtosis shows the degree of pointedness (> 3) or bluntness (< 3) of the waveform.

As for the roughness parameters, it should be

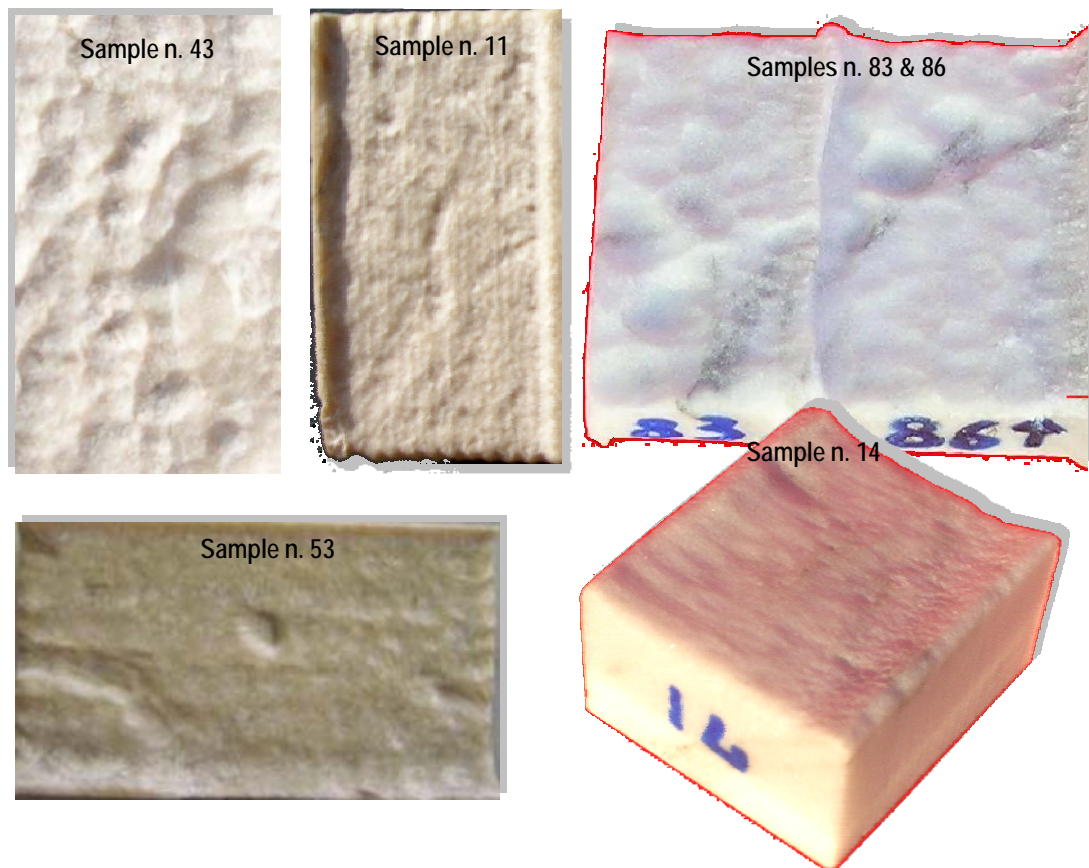


Figure 2. Top views (lateral for sample n. 14) of some of the 96 samples examined, processed by abrasive waterjet. Incident light from different directions enhances the surface roughness. The surface of samples is $20 \times 40 \text{ mm}^2$. Parameters are listed in Table 4.

emphasized that a cutting length of 2.5 mm has been used. Recalling that the spacing between passes is 1 mm and that profiles are taken perpendicularly to passes, all the process induced modifications are practically included in the roughness parameters.

To verify this hypothesis, also several waviness and primary parameters have been considered.

The following two parameters to characterize the perceived surface quality have also been considered.

Directionality. Before considering more complex areal texture or isotropy parameters, a qualitative estimation of how perceivable are individual passes or the cutting direction on a sample (like n. 11 in Figure 2), with the grades from 0 to 3 (4 levels) has been proposed. This may or may not be a desirable product feature. The grading of samples has been repeated by different also non skilled operators and the results averaged.

Material removal. The quantitative parameter associated with material removal is the elevation (negative) of the abrasive waterjet created surface, with respect to the original (semi-finished) product surface (concavity of sample n. 14 or edge between sample 83 and 86 in Figure 2). Of course this is not a perceived feature, except in the cases where steps, patterns or engravings with a given depth are present on the product. Removal is not to be confused with roughness: high roughness can be available also at low removal rates. Removal affects productivity and

the thickness of the final product.

A Matlab script and interface (Figure 3) have been developed. The selected profile parameters in Table 3 for each digital profile of a given sample can be calculated automatically. Profile correction according to different strategies, in the case of spikes during acquisition and filtering, using the standard digital Gaussian filter described by Tantussi & Santochi (1992) and eliminating the profile inclination errors (by subtracting the corresponding coordinates of the best-fit least-squares line) are optional.

4 STATISTICAL ANALYSES

Using each of the standard profile parameters outlined in Table 3 as the response variable, the standardized effect of the abrasive waterjet parameters in Table 1 (individually and as a combination) has been evaluated with a commercial statistics program. For each of the 32 working conditions for the given plan of experiments of Table 1, all the surface parameters discussed in § 3 calculated as the average of the surface parameters extracted from the 25 profiles of each samples, for three replications are used as the input. Results in aggregated form are reported in Table 5 and are discussed in § 5.

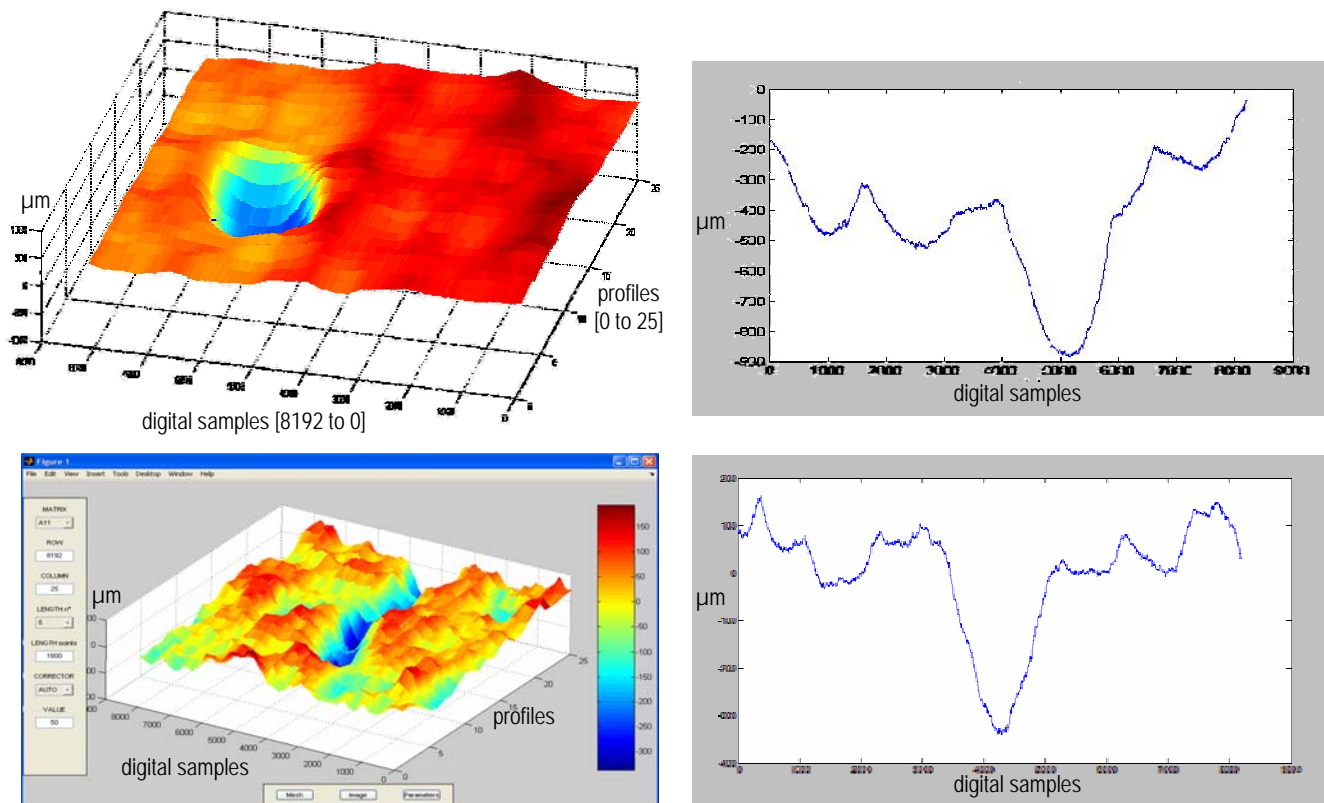


Figure 3. From top, left. The three dimensional view of the digitalized surface of sample n. 53 (hole detail). One of the 25 profiles of sample n. 43 before filtering. The developed software interface: three dimensional surface and a primary profile of sample n. 11.

To explain how table has been built, let us take the Ra column as an example. According to the statistical analysis, the standardized effect of the head angle is 28 (Figure 4). The standardized effect of the other abrasive waterjet parameters and their 32 combinations on Ra is lower than 8, so it is not included in Table 5.

So, Table 5 lists only the most significant abrasive waterjet parameters, e.g. those parameters and their combinations whose standardized effect is over a threshold, which has been fixed as 60% of the highest standardized effect.

The Rmr and Wt parameters in general and the Rsk, Rku and Rmr parameters for White Carrara, have not been included in the analysis because of their sensitivity to disturbances and for the high dispersion due to profile acquisition errors.

The detailed statistical analysis can be found in Bernardelli & Lenzi (2008).

5 RESULTS

The samples analysis has included roughness, waviness and direct profile parameters, and direct observation (§ 4) and is summarized in Table 5.

By comparing the effects of abrasive waterjet parameters on amplitude surface parameters (i.e. Ra, Wa, Wt, Pa, Pz, Dz_DIN) it has been observed that they are similar, even at different cutting length of the filtered profiles (i.e. for roughness, waviness and primary profile). This means that, as hypothesized, the selected cutting length for the roughness parameters is sufficient to preserve the process information about the surface morphology.

Minor differences in the effects of the abrasive waterjet parameters have been found. These differences express the presence of irregularities larger than the cutting length of 2.5 mm. These elements are probably caused by the material inconsistency, which is enhanced during processing. So regarding the differences between the Ra, Wa and Pa columns in Table 5, the head setup and velocity have the ability to enhance the presence of material defects.

The difference between Pa and Pz can be explained because averaged values are less affected by irregularity (like the hole in Figure 3), so they are more informative in regards of the effects of process parameters.

The dominating abrasive waterjet parameter is the head angle.

At 45° samples are practically planed (average Ra ≈ 9) uniformly, with negligible effects of the other parameters.

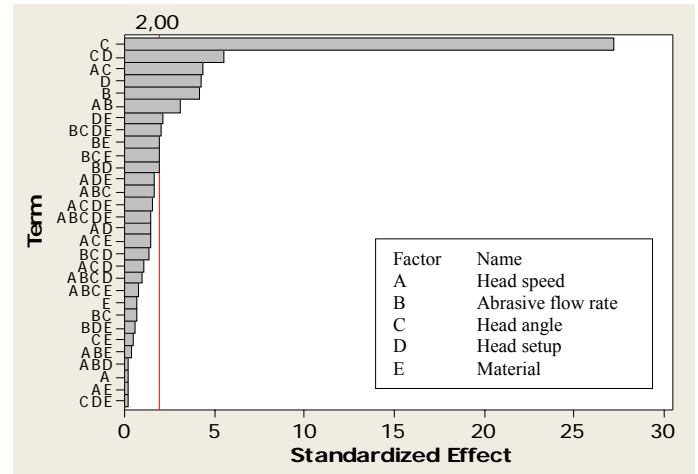


Figure 4. Pareto chart of the standardized effects. Response variable is Ra, Alpha = 0.05, first 30 (out of 32) largest effects shown.

At 0° surfaces are rougher (average Ra ≈ 20). The other parameters become more effective, yielding flexibility in the available morphology, but are not able to achieve low Ra as at 45°.

Observing the head velocity row in Table 5, it can be noticed that it does have a statistically significant effect on the abrasive waterjet of stone surfaces, but this effect is lower than other parameters. This suggests keeping the head velocity high to increase productivity and modify other parameters to achieve the desired surface quality.

In addition to what reported in Table 5, significant interaction abrasive flow-rate and head setup has been found on material removal. The same has been found for head angle and setup in regard to the parameter Rku. The statistically significant interaction of two (or more) parameters means that the change of one parameter is not independent on the other one(s) and the desired effect is achievable by changing all of them.

For the material removal the head angle was not included in the analysis, because it was already recognized as a dominating parameter. The material removal is also inversely dependent on the mechanical properties of the material.

Directionality in general is not desirable and was low on most samples, but it has also been determined how to control it.

It has been noted that the effect of abrasive waterjet parameters are consistent on the two tested materials (marbles).

6 CONCLUSIONS

In this paper the correlation between perceived surface quality of rough surfaces and quantitative parameters has been addressed.

Table 5. To be read by column. Influence of the abrasive waterjet process parameters on the surface profiles statistically analyzed. \uparrow (\downarrow) represents a direct (inverse) correlation, sorted by the circled progressive number, according to the statistical effect of the parameter concerned. (\square , unsorted) denotes a significant parameter not considered in the statistical analysis.

| Increasing surface parameter→ is influenced by parameter(s)↓ | Ra | Rku | Rsk | Wa | Pa | Pz | Dz_DIN | Direction- ality | Material removal |
|--|----|-----|-----|----|----|----|--------|---------------------|---------------------|
| Head velocity | | | ②↓ | ③↓ | ③↓ | | | | ②↓ |
| Abrasive flow rate | | | | | | | | ②↓ | ①↑ |
| Head angle | ↓ | ↑ | | ①↓ | ①↓ | ↓ | ↓ | ①↓ | □ |
| Head setup | | | ①↑ | ②↑ | ②↑ | | | ③↓ | ③↑ |
| Sample material | | | | | | | | | □ |

About one hundred abrasive waterjet processed samples of White Carrara and Perlato of Coreno have been characterized using several standard surface parameters extracted from the digital surface profiles.

A statistical analysis has shown the correlation between surface parameters and process parameters. An interpretation of the aesthetical meaning of the surface parameters has been discussed in the paper. It should be stressed that the practical implication of objective measurement becomes fuzzy if we consider the unpredictable and variable appearance of stone material, which adds some kind of bias to all surface processing.

The signal processing theory predicts that the cutting length must be higher than the double of the maximum wavelength of interest present in a given signal. In this case, it corresponds to the spacing between passes. By this analysis, it has been demonstrated that the roughness parameters are able to describe the surface morphology if a cutting length using this rule is used (the standard 2.5 mm has been selected). This result has an important operative implication, considering that roughness parameters are not only an international standard, but are also of widespread use (Ra is commonly used in mechanical drawing).

It has been shown that among parameters, the head angle affects results most. Future work includes assessing the surface quality at different head angles. Preliminary tests with negative values showed the highest material removal rate.

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