Characterization and measurement of stone engravings

M. Lanzetta, F. Fanti & G. Tantussi
Department of Mechanical, Nuclear and Production Engineering – University of Pisa, Italy

M. Annoni
Mechanical Department – Politecnico di Milano, Italy

S. Turchetta
Department of Industrial Engineering – University of Cassino, Italy

ABSTRACT: Engraving by waterjet and laser processing is an emerging stone process for product identification and traceability (characters or codes) and for decoration (inlay). The main characterization and measurement issues for the optimization of the engraving process and for product inspection are discussed. Stylus measurement is not suitable for accessibility and for the very steep surfaces, so an optical profilometer and a specific setup, has been developed. A special measurement method and algorithm is proposed to define the main geometric features of engravings at microscopic level. Based on our analysis the conventional engraving width and several quality measures have been defined.

1 INTRODUCTION

Engraving is an emerging process for the identification and traceability of both (alphanumeric) characters and codes (barcodes, data matrix) and for decoration (inlay) of stone products. Growing demands for identification and traceability (ISO 9000) often find a solution in marking codes directly on products.

Among new technologies are waterjet and laser engraving, which require the characterization of results for the optimization of the technological parameters and for inspection purposes.

The result of stone engraving is usually a groove with a given two dimensional shape on a polished plane surface (Figure 1).

The analysis of engravings can be approached at two levels:

1. macroscopic analysis, regarding the adherence of the actual engraving path to the designed one;
2. microscopic analysis, approached in this paper.

2 MACROMETRIC ENGRAVING ANALYSIS

The macroscopic analysis of an engraving path represents a two dimensional visual inspection problem, which can be approached with pattern matching or blob analysis methods in artificial vision. For instance, observing the corners of the sample in Figure 1 it can be noticed that they are not sharp. This phenomenon is absent in laser processed samples and is due to head angle and to the sudden direction changes producing accelerations of the water jet. The adherence between designed and actual path problem can be simply approached by

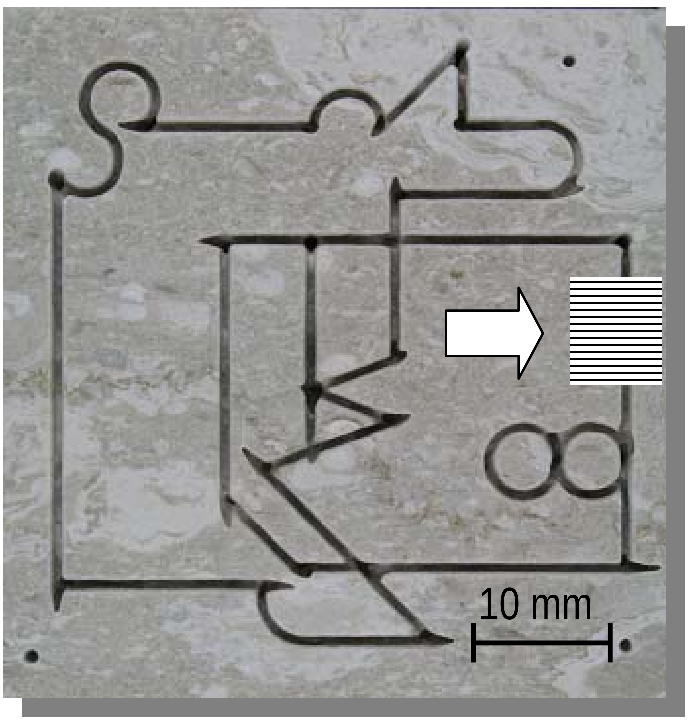

Figure 1. Top view of a sample (n. 18) of Perlato of Coreno engraved by abrasive waterjet, water pressure 1200 MPa, abrasive flow rate 50 g/min., head velocity 500 mm/min., head setup 1.02/0.30 mm (Table 1). The area and direction of the profile acquisition is enhanced.

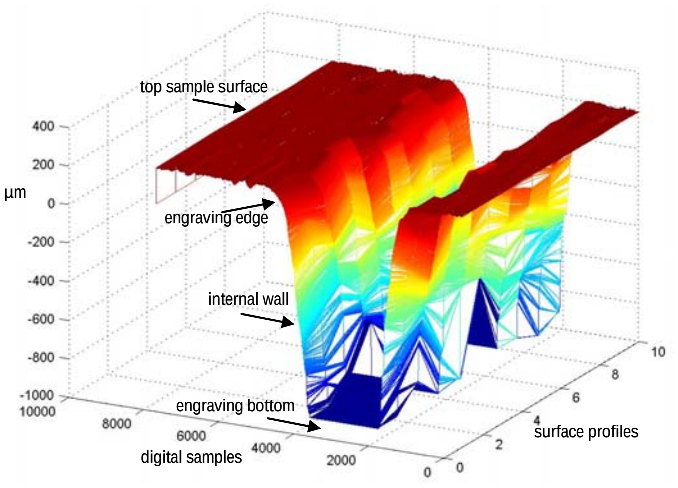

Figure 2. Three dimensional view of the digitalized engraving surface of the sample in Figure 1.

image analysis of a top view of the sample, as the one shown in Figure 1.

Suitable lighting and filling engravings with a cement are possible methods to increase the engraving contrast (visibility) both during use and/or for inspection purposes.

2.1 *Automatic inspection of engraved characters*

Focusing the exemplary sub case of the (visual) inspection of alphanumerical codes, their variability poses problems due, for example, to different types of lettering (*fonts*), not to mention the great number of ciphers, letters, symbols, accents and punctuation signs present in various languages.

The shape of printed characters is also defined by international standards, such as ISO 1073.1 & 2:1976, which permit easy definition of algorithms for recognition. In particular, the ISO relate to inkjet and similar printing methods, specifying the shapes, dimensions and tolerances for the purposes of character recognition. In addition, the ISO 1004:1995 describes the various types of printing defects and other printing considerations, together with the tolerances permitted, and also contains specifications for signal level measurement and references to Optical Character Recognition (OCR).

The various operations involved in character recognition are implicitly performed by an employee assigned to product inspection in the case of manual systems, while they require special algorithms for the development of automatic systems.

The legibility of printed characters (OCR) has been recently dealt with by Lanzetta, Fanti & Tantussi (2008).

For an automatic inspection system, legibility problems can be solved using methods well established from the scientific and industrial standpoints, given the presence of widely used commercial products such as OCR software for PC and considering the existence of dedicated OCR functions in common artificial vision systems.

2.2 *Micrometric engraving analysis*

Controlling an engraving process or developing a new technology can be dealt with by examining the feature generated in engraving the character itself.

And different marking technologies create further difficulties due, for instance, to contrast between the engraving and the background on different stone types or to problems caused by uneven engraving. This latter aspect is also considered in this paper by proposing objective measurement criteria.

The microscopic analysis aims to characterize the section of the engraving path (Figure 2), i.e. the edge and depth of the groove, in order to improve the cleanliness of the engraving, from which the contrast effect and the legibility are a direct consequence.

Table 1. Abrasive waterjet parameters used in different combinations for engraving 24 marble samples. Garnet mesh is 80. * and ** denote material specific parameters.

Number of s amples	Head velocity [mm/min.]	Abrasive flow rate [g/min.]	Water pressure [MPa]	Head setup (∅foc./∅orif.) [mm]	Sample material
5* + 5** exploratory	500, 800, 1000, 2000	0**, 30, 50	100, 150, 200, 250	1.02/0.30*, 0.76/0.25**	Perlato of Coreno*, White Carrara**
3 × 2^5 conditions 2* + 12** measured	500, 1000	25, 50	700, 1200	1.02/0.33, 0.76/0.2	Perlato of Coreno*, White Carrara**

Table 2. CO_2 laser parameters used in different combinations for engraving 21 marble samples.

Number of samples	Head velocity [mm/s]	Laser power [W]	Laser spot ∅ [μm]	Sample material
3 replications × 7 conditions, 2* + 12** measured	10, 20, 50, 70, 100, 150, 200	25	180, 240, 400	Perlato of Coreno*, White Carrara**

3 PROBLEM STATEMENT

The final purpose of this research is to characterize the performance of innovative waterjet (Carrino et al. 2002, 2003, Ravasio & Monno 2003) and laser engraving by objective criteria, in order to correlate them to the main process parameters.

These new processes require the characterization of results for the optimization of the technological parameters. To optimize the process parameters a special benchmark has been designed (Figure 1) containing the typical features of alphanumeric codes. About 60 samples of size 65 × 65 mm^2 have been engraved by combination of different process parameters by abrasive waterjet, in Table 1, and laser processing, in Table 2.

The average size of engravings is greater than 3 mm as for the width, and ranges between 0.8 and 1.2 mm as for the depth.

This study focuses on the characterization and measurement of engraving, both for the optimization of the engraving process and for product inspection.

In this paper we approach the micrometric features of engravings, in particular the shape of their cross section (Figure 2).

An objective characterization of engravings is proposed, based on the analysis of profiles perpendicular to the engraving. The acquisition strategy is described and the parameters that can be extracted from profiles are outlined and discussed.

4 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 as in Figure 1. An example of reconstructed engraving is displayed in Figure 2 with the definition of the main engraving features: top sample surface, engraving edges, internal walls and bottom.

The engraving depth and the bottom shape is not the focus of this work and is not displayed because of the measuring range setting of the optical profilometer.

In a recent paper (Tantussi & Lanzetta 2007) surface acquisition and measurement methods for processed stone have been reviewed. New optical methods including stereo vision, the use of structured light and the one used in this work have been proposed.

The digital surface acquisition of samples 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 3 and described in detail in Lanzetta, Tantussi & Zambardi (2008) has been used. The profile errors correction is also discussed there.

The commercial optical profilometer used is claimed to be able to measure absolute distances on glass and rubber surfaces. For these extreme capabilities, it has been selected for application on stone surfaces, where the translucent material may pose measurement problems. The working principle is the analysis of the light reception distribution.

As recommended in case of sudden distance changes, the profilometer axis is perpendicular to the scanning direction. It should be noted that the low translation velocity is due to acquisition errors

Table 3. Parameters of the optical profilometer (Omron ZS-LD20T) for the acquisition of engraving surface profiles. Profile scans are perpendicular to the engraving passes. [*] denotes specific instrument settings.

Number of profiles per sample	10
Spacing between profiles [mm]	0.25
Profile length [mm]	4.2
Measurement distance [mm]	20
Measuring range [mm]	±1
Laser spot ∅ (red), nominal resolution [μm]	25
Sampling frequency [samples/s]	512
Translation velocity [mm/s]	0.2625
Linear spatial resolution [samples/mm]	1950
Number of samples per profile	8192
Light emission*	Auto
Measurement method*	Standard
Measuring target*	Mirror

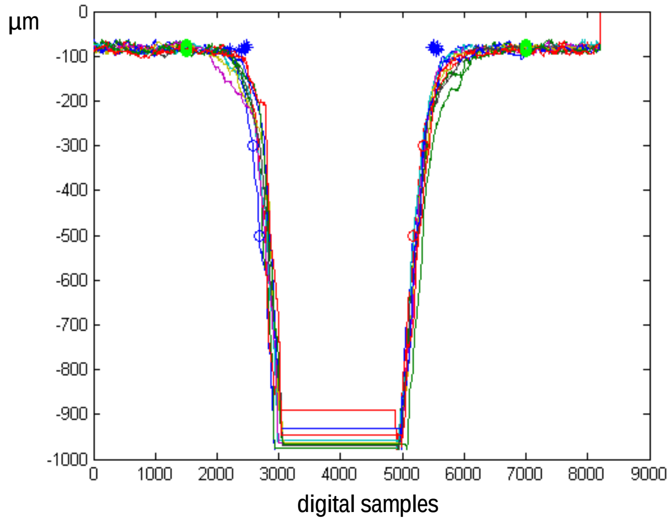

Figure 3. Measurement of the cross section of waterjet engraved sample n. 14 of Perlato of Coreno, water pressure 1200 MPa, abrasive flow rate 50 g/min., head velocity 500 mm/min., head setup 1,02/0.30 mm. 10 profiles are displayed. From Table 3, the calibration factor is 0.513 µm per digital profile sample (horizontal axis).

(spikes) caused by the presence of reflective crystals and very steep surfaces, particularly at higher speed.

Multiple profiles for each sample are necessary because of the surface variability in order to calculate statistically significant parameters as in Figure 2 (three dimensional view) and Figure 3 (in two dimensions).

5 MEASUREMENT METHOD

With reference to Figure 3 and Figure 4, which contains 10 profiles extracted from a sample, the nominal engraving width is defined as the (horizontal) distance between the couples of points enhanced by (blue) asterisks near to the engraving edges. Considering the problem symmetry, we can either refer to single points or to couples.

The profile asymmetry is due to alignment problem between sample and optical sensor or between sample and cutting head.

The measures of each of the 10 profiles represent local measurements of the engraving spaced 0.25 mm.

The mentioned edge points are determined at the intersection between the ideal plane containing the top sample surface and the one containing the internal engraving wall, according to the engraving model in the bottom right corner of Figure 4.

The top sample surface is usually polished (profile roughness can be as low as Ra = 0.01 µm), so it is a plane apart from waviness errors (Wt < 0.2 µm).

Far from the engraving edges and bottom, the internal walls can be also approximated to a plane. This hypothesis is verified in engravings with a high aspect ratio, i.e. with high contrast. Low depth or free form engravings require specific analysis.

Considering that Figure 3 represents a perpendicular section of the mentioned planes, we can either refer to their traces (lines) or to planes.

The top sample surface horizontal (green) line and the internal wall (blue and red) lines are determined using the least square criterion. Assuming an accurate parallel positioning between sample and profilometer translation axis, the top horizontal line is simply given by averaging profile data outside of the top surface nominal bound. This height is calculated using the 10 profile data, because they all have the same top plane in common.

The (green) circles on the top sample surface are located manually outside of the edges to define a bound for the top sample surface. Also the two (blue and red) circles respectively on the left and right internal walls are located manually. They represent the upper and lower bound where the internal walls can be considered almost straight in order to determine the containing plane according to the least square criterion.

The manual positioning of boundaries (circles) does not need to be accurate. It is done only once at setup and depends on the nominal size of engravings and on the positioning of the digital profilometer.

Observing the engraving edge variability from figures, we also propose a quality parameter called edge error as the area between ideal and actual engraving, also displayed in Figure 4. It is considered as an error because sharper edges (as the

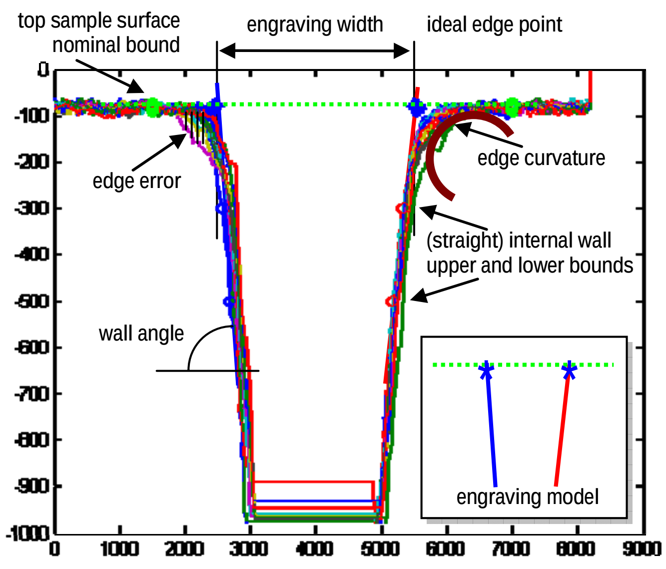

Figure 4. Engraving characterization (bottom right): straight lines + sharp edges. Engraving measurement parameters and construction.

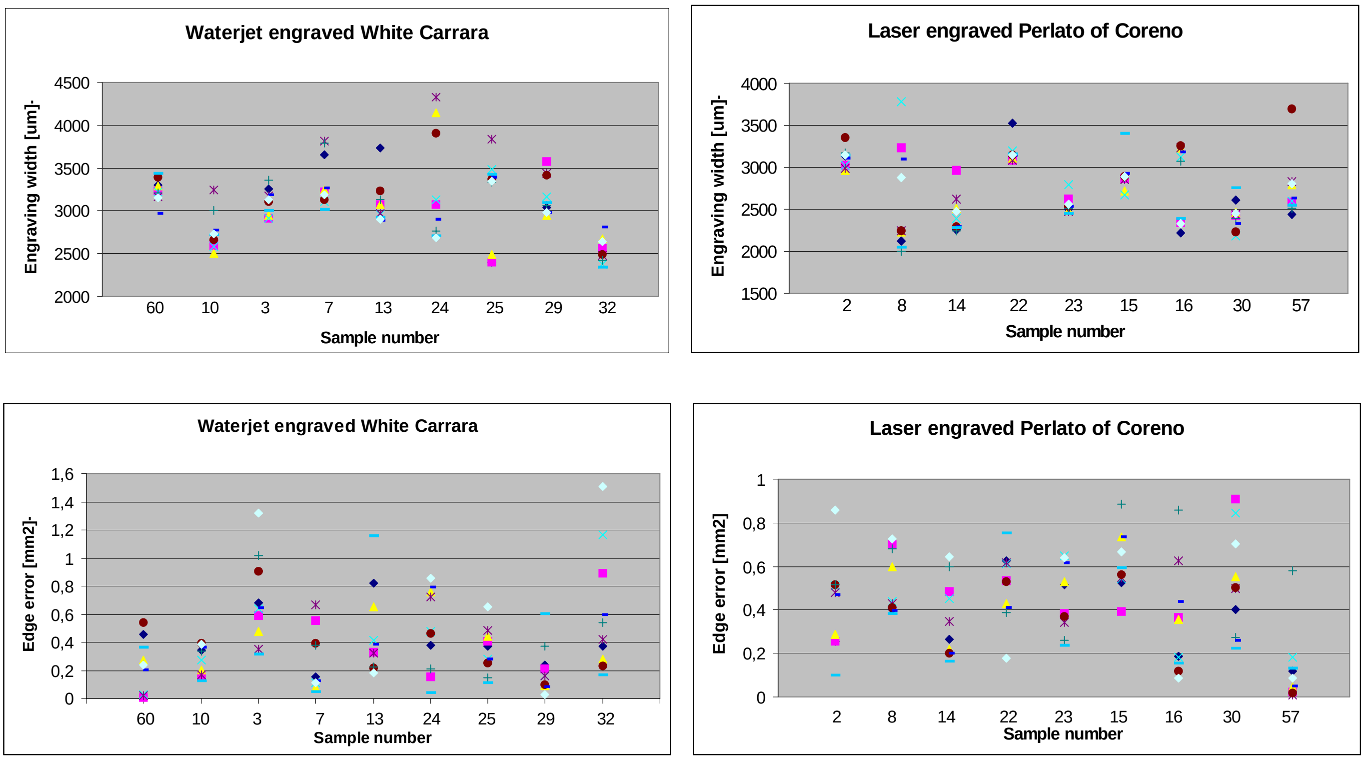

Figure 5. Measurement of samples engraved as in Table 1 and Table 2. Width measurement (top two graphs) and edge error (bottom two graphs) are displayed.

ideal case in the corner of Figure 4, provide the highest contrast. This area is measured on each profile as the sum of distances between top sample surface and actual profile edge. This sum is calculated between the abscissas of the ideal edge point (blue asterisks) and the conventional end of the engraving (green circles). Although the positioning of the edge of the nominal edge bound is critical, the contributions of further profile data are negligible.

A normalized version of the edge error can be obtained by dividing the calculated area by its base (the mentioned asterisk-circle distance). So the edge error can be assessed by an average height expressed in mm. The problem of this measurement is to define the edge end, to which this normalized parameter is sensitive. For comparative analysis a conventional point like the nominal bound of the top sample surface in Figure 4 can be used.

Same considerations are valid to assess the edge curvature (Figure 4), which can be determined according to the least square criterion. Also in this case the edge bound needs to be defined because the edge curvature calculated is very sensitive to it.

Other geometric information that can be obtained with the constructions described in Figure 4 are: the angles of the internal walls (steepness) and their difference (to assess the engraving asymmetry).

6 MEASUREMENT RESULTS

A Matlab program implements the measurement algorithm described and has been run on the samples listed in Table 1 and Table 2.

Figure 5 shows the measurement of the engraving width and edge error on 9 samples of different materials and processes. A nominal engraving width can be estimated, however the edge variability is evident from the dispersion of data, which depends on the process parameters. In particular, for the waterjet engraved White Carrara samples, the average engraving width is between 2.5 mm (for samples n. 57 and n. 14) and 3.3 mm (for samples n. 15, n. 2 and n. 22). The standard deviation of samples ranges between 0.14 mm (for samples n. 16 and n. 15) and 0.6 mm (for samples n. 2, n. 57 and n. 14), corresponding to 5% and 18%.

Regarding laser engraved Perlato of Coreno samples, the average engraving width is between 2.5 mm (for samples n. 29, n. 3, n. 13 and n. 10) and 3.1 mm (for samples n. 60 and n. 7). The standard deviation of samples ranges between 0.1 mm (for samples n. 13 and n. 60) and 0.6 mm (for sample n. 10), corresponding to 4% and 24%.

At a first estimate, no significant variability difference has been noticed between samples of different materials and processes.

The edge error parameter expresses the distance between ideal and actual engraving and as shown in Figure 5 it varies from 0.14 to 0.62 mm^2 for laser engraved Coreno and 0.20 to 0.69 mm^2 for waterjet engraved Carrara.

7 CONCLUSIONS

A systematic experimental analysis of different geometric features extracted from engraved stone samples has been carried out, to point out those that can be correlated to intelligibility, quality and repeatability of engravings and ultimately with the manufacturing parameters. This correlation has to be established.

The processes considered have shown an intrinsic variability between 5 and 25% of the nominal engraving size, corresponding to a tenth to a half of a millimeter. This defines the accuracy requirements for an on-line inspection or laboratory measuring system.

Engravings have been modeled at microscopic level. Features to measure width, steepness and their variability have been pointed out. The analysis has not been refined further, considering the relative variability of the examined engraving processes. Different engraving processes may require the investigation of additional parameters.

This work is based on the acquisition of straight engraving segments. The analysis of different shapes, like high curvature segments, cuspids and corners may require further investigation for the adaptation of the proposed algorithms.

According to current approach, recommendation or standards for the stone sector, like it has been done in the ISO 1004:1995 for paper printing, could be defined.

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