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Spatial Objects Shaping with High-Pressure Abrasive Water Jet Controlled By Virtual Image Luminance

P. J. Borkowski, and J. A. Borkowski

***Abstract*—The paper presents a novel method for the 3D shaping of different materials using a high-pressure abrasive water jet and a flat target image. For steering movement process of the jet a principle similar to raster image way of record and readout was used. However, respective colors of pixel of such a bitmap are connected with adequate jet feed rate that causes erosion of material with adequate depth. Thanks to that innovation, one can observe spatial imaging of the object. Theoretical basis as well as spatial model of material shaping and experimental stand including steering program are presented in. There are also presented methodic and some experimental erosion results as well as practical example of object's bas-relief made of metal.

***Keywords*—High-pressure, abrasive, water jet, material shaping.

I. Introduction

The development of high-pressure abrasive water jet (AWJ) machining method is mainly a result of tool elasticity and the fact that the technique never causes any structural changes in the substrate. Water jets were first used in the 1980s, and since then, much research has been done to optimize the technology [1] and improve the cutting efficiency. Examination of abrasive grain interaction in the treatment zone led to an understanding of the mechanism of abrasive erosion [2], making it simpler to characterize and execute specific boring processes such as slender holes [3]. Precision and quality of the treated surfaces were analyzed. Water jet techniques can be applied to ductile materials and to assorted brittle materials [4], [5].

A number of experiments [6] have clarified the mechanisms of AWJ cutting that define eroded grooves shape, process characteristics, as prediction of cutting parameters [7]. This knowledge led to simulations of efficiency and cost [8]. As a result of better understanding the cutting mechanism, techniques such as surface treatment and polishing [9], have become possible.

Recently, a new own method of automatic AWJ sculpturing [10], [11] of different materials was presented. It enables the production of a spatial shaping of an object based on a photograph [12]. In order to manipulate the position of the jet, a principle similar to image rastering was employed [10]. Here, the color of a pixel in the image is correlated to a specific jet feed rate that induces erosion of the substrate to a particular depth [13]. Thanks to this innovation method, one can observe development of many new technologies [14], [15], [16], [17] of spatial imaging of the object.

The paper presents complete method of water jet sculpturing additionally completed with detailed theory. Thanks to that one can explain physical basis of the method.

P. J. Borkowski is with the Institute of Unconventional HydroJetting Technologies at Koszalin University of Technology, Raclawicka 15-17, 75-620 Koszalin, Poland (48-94-3478294; fax: 48-94-3478200; e-mail: przemyslaw.borkowski@tu.koszalin.pl).
J. A. Borkowski is with the Institute of Unconventional HydroJetting Technologies at Koszalin University of Technology, Raclawicka 15-17, 75-620 Koszalin, Poland (e-mail: jozef.borkowski@tu.koszalin.pl).

II. Theoretical Basis

A. The Basis of Shaping Material

The essence of this method consists of properly specifying the erosion depth and working head positions in relation to the minimum resolution required to capture the target feature. The method relies on image rastering to address each pixel and to construct the whole image. Owing to the similarity between this method and data manipulation of rastered images, the bitmap file format was used as the standard. For such bitmaps, respective pixel colors are correlated to specific erosion depths. The concept of this method is illustrated in Fig. 1.

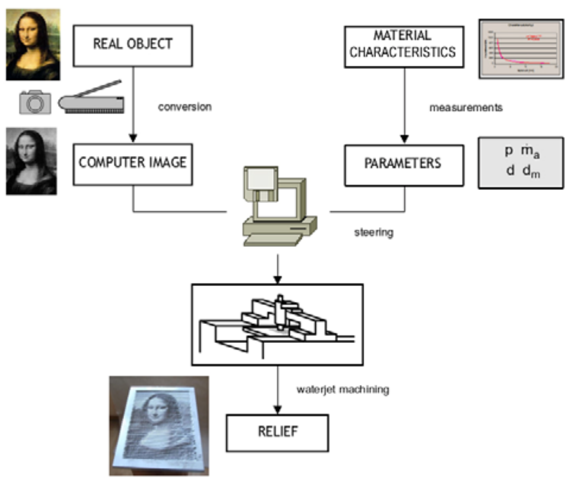

Fig. 1 3D material forming with utilization of flat virtual object luminance

Taking the above conditions into consideration, one can calculate the required interaction time as:

$$\Delta t_i = \frac{d_m}{v_i} \tag{1}$$

where d_m is focusing nozzle diameter while v_i is velocity of the jet movement above chosen elementary cell (i) of shaped material.

The following steps are required for this technique:

1. The image, typically a photograph, is scanned in gray–scale.
2. The pixel values in the resulting bitmap are converted to working head feed rates that determine the jet interaction time at each location on the substrate.
3. The feed rates are passed to the water jets, and the image geometry is parsed into the control language of a 2-axis plotter that physically rasters the jets across the substrate.

While this approach requires only a simple 2-axis plotter, position control of the jets is crucial, and a specialized program to parse the image data in the control language of the plotter is required.

B. Photometric Basis of Object Reproduction

Intensity of illumination determines the quality of the resulting image from a photograph. Therefore, special care should be taken when creating the target images because the quality of these images relates directly to the quality of the product. A basic photometric quantity is energy flux (W) per unit time (t) which is described by:

$$\phi = \frac{\Delta W}{\Delta t} \tag{2}$$

Such a light flux value is calculated by integration of the spectral distribution of energy fluxes that are carried by respective wavelengths of the analyzed radiation as follows:

$$\phi = K_m \int_{\lambda_1}^{\lambda_2} e(\lambda)\cdot\varphi(\lambda)\cdot d\lambda \tag{3}$$

Here, K_m is a photometric equivalent of radiation for the quality of target surface, while λ_1=380 nm and λ_2=760 nm are wavelengths of visible light, $e(\lambda)$ is a relative light efficiency of monochromatic radiation and $\varphi(\lambda)$ is a function of the spectral energy flux distribution for respective wavelengths.

Other important quantities that describe a light source are light intensity and luminance. Light intensity is described with the following formula:

$$I = \frac{\Delta\phi}{\Delta\omega} \tag{4}$$

where $\Delta\omega$ is a block angle relating object surface illumination to the light beam.

The luminance of a luminous surface in a given direction can be expressed as:

$$L = \frac{\Delta I}{\Delta S\cos\varepsilon} = \frac{\Delta\phi}{\Delta\omega\Delta S\cos\varepsilon} \tag{5}$$

where ΔS is surface radiation, while ε is the angle between the vector normal to the surface of ΔS and the direction of radiation propagation.

Differences in the surface morphology of the target object cause the ε angle and luminance of each element to have considerably diversified values.

C. Modeling the Spatial Shaping Process

To a certain extent, the automated method of object quasi-spatial sculpturing based on a target image needs to evaluate the relation between photometric conditions of visible light radiation and jet erosion parameters. Therefore both radiation and jet dynamics must be modeled.

Considering formulae nos. 5 and 2, one can evaluate the proper exposure time for a given target object. This time value can be used to define the interaction time of the AWJ with respect to each feature element of the target object (see formula No. 1). This process can also be expressed via following proportion:

$$\frac{d_m}{v_i} = K_m \frac{\Delta W}{L_i\Delta\omega\Delta S\cos\varepsilon_i} \tag{6}$$

where L_i is the luminance of a given element (i) taken from the target image, while ε_i is the angle between the vector normal to the surface and the direction of radiation propagation.

Imaging the target takes place using perpendicular radiation and perpendicular AWJ spraying ($\varepsilon=\varepsilon_i=0^o$). Substituting these parameters into (6), one can evaluate the instantaneous velocity of the jet motion above a given element. This is described by the following equation:

$$V_i = \frac{\Delta\omega\Delta S d_m}{K_m\Delta W} L_i \tag{7}$$

It can be also described in a reduced form which is more useful for analytical purposes:

$$V_i = AL_i, \tag{8}$$

where $A_i = \frac{\Delta\omega\Delta S d_m}{K_m\Delta W}$ is a constant involving photometric conditions and characteristics of working head used for AWJ treatment.

Instead of attempting to model full dynamic process control, a simplified model [10], [12] of the direct coupling between feed rate (V) and erosion depth (h) was applied. The most universal and precise model is expressed in the form of following equation:

$$h = bV^{-a} \tag{9}$$

where a and b are empirical exponent and factor respectively.

Based on this analysis, the depth of material erosion is proportional to a negative power function of jet feed rate. This implies that the deepest erosion takes place at minimum jet feed rate, while increasing the feed rate leads to reduced erosion according a nearly hyperbolic dependence. This relation is also suitable for instantaneous values of h_i, V_i related to erosion of a given element.

Substituting equation (8) into (9), one can obtain a new formula to determine the instantaneous values of eroded material:

$$h_i = BL_i^{-a} \tag{10}$$

where $B = b\left(\frac{\Delta WK_m}{\Delta\omega\Delta Sd_m}\right)^a$ is a new constant involving photometrical and characteristics of the working head.

Examining this universal model (10) shows that material erosion depth is proportional to a negative power function of a given elements luminance. In the effect, the most shaded parts of an image correspond with the deepest material erosion, while an increase in luminance leads to a quasi-hyperbolic decrease in erosion depth.

Application of such a model simplifies the raster control method and increases treatment accuracy by enabling the erosion depth to be specified.

III. Experimental Methodology

A. Experimental Stand

A special experimental stand was designed and built (Fig. 2) and its details are given in [18], [19]. Two stepper-driven lead screws (WX6 08500 by Isert Electronic) were used as linear actuators to control the planar position of the working head, while an additional lead screw system was affixed to these to provide a base for the working head. This gantry ensures XY positioning accuracy of ±0.005 mm over a table area of 1 m^2. This customized gantry supported a water supply to the working head that was pressurized up to 50 MPa, thereby ensuring constant feed rate of the abrasive material from the reservoir.

Fig. 2 General view of test stand for spatial material machining with high pressure AWJ: 1 – frame, 2 – y direction slideways, 3 – x direction slideway, 4 – abrasive-water jet working head, 5 – abrasive feed container, 6 – steering PC computer, 7 – high-pressure water pump type As500/15A

Longitudinal movements of the head were produced with stepping frequencies of 1-2400 s^{-1} that taking lead screw travel in account, gives a feed rate of approximately 0.005-12 mm/s, allowing a wide range of different cuts to be made. The actual control of the water jet was controlled with custom-made WaterJetLab software that was written in C++. The FreeDOS platform was used to provide access to PC hardware. This system handles all of the aforementioned functions in only 5000 lines of code, has easily obtainable hardware requirements and presents a simple user interface.

B. Steering Software for Sculpturing Process Realization

Proper function of the system requires the following tasks:

- process configuration prior to running the system,
- principal process control,
- calibration of the sample material's erosive properties with respect to a calibration standard,
- user interface manipulation.

All actions related to process configuration are performed by the user according to a strict procedure [13], [19]. Once prepared, the software records the settings and initializes the appropriate modules. Image processing can be performed by using a filter that transforms bitmaps into 256 step gray scale images based on calculating the luminance from an RGB image according to:

$$\textit{Grey depth}=0.3\cdot \textit{Red}+0.59\cdot \textit{Green}+0.11\cdot \textit{Blue} \tag{11}$$

The next group of tasks performed by the software pertains to controlling the actual material shaping process. Here, the user's only role is to monitor the process and shut down the system if a problem occurs. A detailed schematic of the x-axis motor control that regulates material erosion is presented in [13], [20]. The system will raster across the sample and determine the appropriate jet parameters based on the gray scale value of each element in relation to that of the subsequent element. This process occurs repeatedly across a line and rasters back (along the y-axis) to the start of the next line.

The calibration phase includes a variety of different AWJ parameters designed to regulate the erosion parameters based on a given material. The relevant parameters are the length of individual erosion segments, the number of such segments and the assignation of the proper jet feed rate to individual segments. Another algorithm, which is used for position control, creates a database containing material erosion properties. This serves as the calibration standard for determining erosion depths based on a graphical standard. The last task performed by the software is to handle basic computer services such as graphical display and input for the driving computer.

C. Research Conditions

Different ceramics, glasses, plastics and popular metals served as sample materials. Aluminum alloy, 5mm thick AlMg1SiMn, was used most commonly. Depending upon the shape of the object to be reproduced, the maximum erosion depth defined in the WaterJetLab program was set to values ranging from 1.5 mm to 2.5 mm. A water nozzle of 0.7 mm diameter and focus nozzle of 2.5mm diameter was installed in work head, while a standoff distance was set at 5 mm.

Experiments were conducted with a water pressure range of 10-50 MPa, while garnet #80 was used as the abrasive material and was set to output at 0.9 g/s. For such conditions, the dimensions of a mapped gray scale element on sample surface were set to 2x2 mm. Calibration of the material's erosive properties was then conducted. Surface morphology was characterized using a laser gauge (TalySurf CLI 2000 by Taylor Hobson).

IV. Abrasive-Water Jet Sculpturing Effects

Using this system and approach, basic metal shaping experiments were conducted. Two particular types of test were performed to characterize quality and accuracy and to assess the practicality of the technique.

A. Erosion Characteristic of Different Materials

The erosion characteristics of the jet are determined by the physical properties of substrate material. The optimal jet properties such as water pressure, abrasive material type and output, interaction time and the jet spraying angle all depend on the substrate properties. A typical example of this is seen in Fig. 3, which depicts the erosion of AlMg1SiMn under different test conditions. Erosion curves were obtained for both popular metals (Fig. 4).

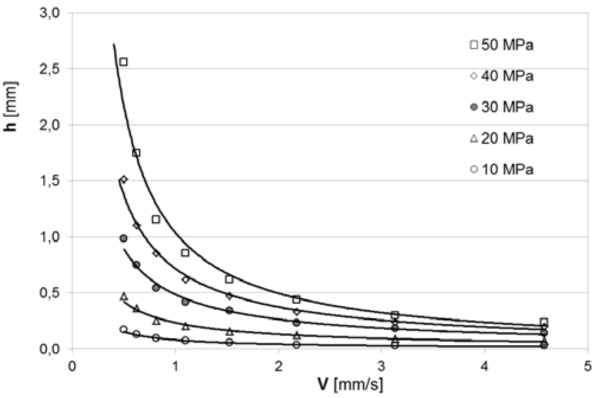

Fig. 3 AlMg1SiMn erosion realized with AWJ technology (garnet #120, m_a=0.90 g/s)

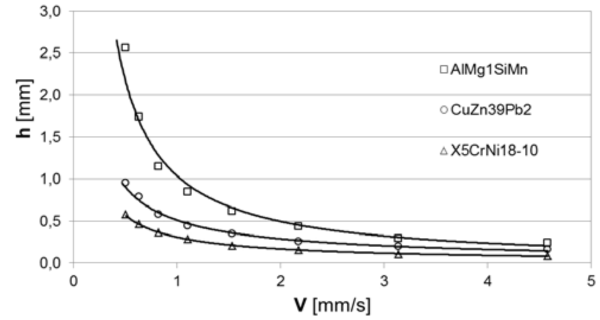

Fig. 4 Metals erosion realized with AWJ technology (p=50 MPa, garnet #120, m_a=0.90 g/s)

B. Examples of Practical Effects

Basing on this jet-machine including original software, a wide array of different uses for AWJ were considered. Despite the inaccuracies mentioned above, the process needs neither complicated process control nor complex position control. Adequate software of such jet machining processes need only ensure the possibility for proper "relocation" between sample material features and AWJ erosiveness and working head feed rate that is finally responsible for material spatial sculpturing basing on the photo.

Fig. 5 presents a photocopy of a well known painting and includes a set of illustrations showing the important phases of its reproduction in a metal plate. The presented images show the phases of converting a real object (Fig. 5(a)) into a virtual 2D matrix (Fig. 5(b)) with the resolution reduced to a level that is reproducible with an abrasive water working head in 3D bass-relief (Fig. 5(e)), scanned that way image (Fig. 5(c)) and its perspective view showing out its real resolution (Fig. 5(d)).

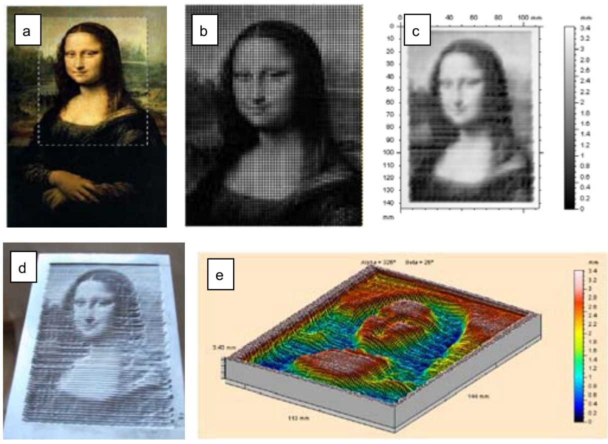

Fig. 5 Images showing important phases of spatial object (Mona Lisa) sculpturing basing on its photocopy: a- picture, b – virtual 2D matrix, , c- image scanned from the relief, d- photo of 3D bas-relief cut in AlMg1SiMn plate. E-perspective scanned view showing depth analysis

C. Surface Finish Quality

While there is enormous advantage in the automated water jet cutting technique presented, inaccuracy was noted in the form of incomplete reproduction of the erosion depth in regions of high contrast compared to the surroundings [13], [20]. It was observed that proper erosion depth can be achieved only when consecutive pixels in a rastered line share fairly similar gray scale values [10], [19]. Moreover, the quality needs to be improved with respect to the boundary leveling that occurs between individual lines (Fig. 6).

Correction of this problem is possible by modifying the algorithm determining positive and negative gradients with respect to the desired erosion depth. Previous measurements of the effects of such a correction demonstrate a marked improvement in quality [10], [11]. One should have in mind that during such AWJ spraying, surface of the sample becomes slightly tarnished based on the roughness parameters shown in Fig. 7.

Surface quality shaped with AWJ jet depends on spray angle (Fig. 8) and its effect is similar to grinding because resultant surface creates mosaic of irregular traces created after abrasive grains stroke.

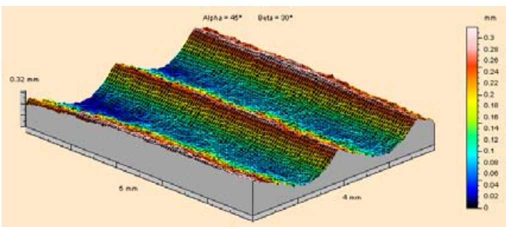

Fig. 6 Shape regularity and edge height of respective jet paths after AWJ treating of AlMg1SiMn for p=40 MPa, garnet #120, m_a=0.56 g/s

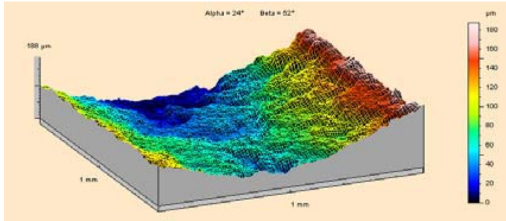

Fig. 7 Quality of the bottom of eroded region for AWJ treating of AlMg1SiMn (p=50 MPa, garnet #120, m_a=0.90 g/s)

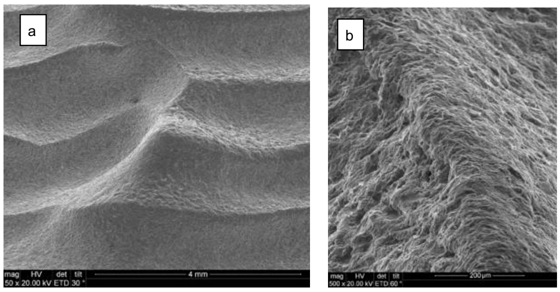

Fig. 8 Typical configuration of macro- (a) and micro- (b) surface eroded in aluminum alloy (AlMg1SiMn, p=40MPa, garnet #120, m_a=0.56g/s)

It can be claimed that, despite the relatively low matrix resolution, the quality of the reproduced image in metal plates is satisfactory. Further, it should be noted that characteristics of the target object are preserved. A particular example of this may be seen in still recognizable subtle smile of La Gioconda presented in Fig. 5d. Despite the problem discussed earlier, these results suggest a good future for this technology.

V. Conclusion

The abrasive water jet based material shaping technique presented here confirms assumptions about AWJ machining and presents a software based procedure for controlling the position of the work head. Based on the presented data, one can generally admit that, despite low matrix resolution, images given in the form of bitmaps were reconstructed relatively well in metal samples. Therefore, the presented method gives satisfactory results.

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