ABRASIVE-WATER JET SHAPING OF BAS-RELIEF

P. Borkowski, A. Szpakowicz
Unconventional HydroJetting Technology Center
Koszalin University of Technology
Koszalin, POLAND

ABSTRACT

The paper presents new original method of different materials surface spherical shaping using high-pressure abrasive-water jet basing on flat image conversion. General concept of this method consists in row scanning of the sample with the working head forming abrasive-water jet. Steering of the jetting duration is crucial for erosion depth and it consists in selective choose of the head positioning. This method makes use of object light intensity differences that are stored in the photo. Final bas-relief is an effect of respective adjacent rows cutting with the jet. Experimental stand and spherical shaping methodic as well as main tasks of steering program are presented in. There are also presented some experimental results showing examples of objects bas-relief made in metal.

1. INTRODUCTION

High-pressure abrasive-water jet is an elastic tool designed for surface forming with wide range of applications thanks to unusual forming features of water jet that never causes any structural changes of forming material. From the early 80's, when that technology has started, optimization of technological conditions as well as efficiency of different high-pressure abrasive-water jet types were defined. Thanks to that such technologies may be competitive to traditional methods of material separation.

Original research of precise abrasive-water jet [8, 10, 20] surface processes, moreover abrasive grains interactions in the collision zone with treated material [14, 22, 23] let to optimize AWJ machining factors [11] and milling [12, 13, 17]. Thanks that it was possible to elaborate the mechanism of abrasive-water jet cross-cut [14], model shaping [13, 15, 16] and simulation of their run [3, 19, 21] as well as to predict machined surface topography [12, 13] and consequently its quality [9, 24, 25]. Taking above achievements into account original idea of spatial object reproduction was elaborated that is based on its flat image [1, 4]. Particular importance in this case plays accuracy and quality of treated surface [2, 5] that are crucial for smooth methods of surface treatment.

On the other hand basing on earlier experiments [6. 7] the steering movement process of the jet was modified taking the similarity of this method compared to raster image way of record and readout [4]. It enables to use bitmap, which adopts respective depth of material erosion for individual pixel color [5] and consequently is the form of standard for final shape of sculptured object.

The paper presents the essence of this method of material spatial shaping utilizing high-pressure abrasive-water jet.

2. THE MATTER OF MATERIAL SPATIAL SHAPING

The method concept of spatial material shaping with high-pressure abrasive-water jet utilizes different light intensity of the object that is stored in the form of picture. In practice, the process is realized by computer steering programm that reads in the object image and then by respective steering of working head feed rate on the sample. Its longitudinal movement is realized with different velocities and ensures analogical different time intervals for high-pressure abrasive-water jet influence on treated material. It is transmitted into respective depth cut out located along eroded trace of the jet. In the effect of following versifying jet movements that are shifted on scale equal to jet diameter, it is possible to receive depth mosaic analogical to virtual image.

Thanks to that by selection of such interaction jet time on material, taken as important parameter for receiving expected erosion depth, material processing is an effect of adequate working head feed rate usage on treated sample (Fig. 1). For such conditions, the smallest elementary area formed with this method, characterized with analogical erosion conditions, is equal to abrasive-water jet diameter. The sum of such elementary jet interactions that represents assumed model creates spatial bas-relief of real object.

Instead of difficult in realization dynamic process control, adequate model [1] of direct coupling of feed rate (v) and erosion depth (h) was applied. The most universal and precise one is model expressed in the form of following power equation:

$$h = b \, v^{-a} \tag{1}$$

So the essence of this method consists in selective erosion depth choose and working head positioning, taking into account minimum accuracy close to the size of such elementary area. It reminds raster image notation in which all pixels are positioned one after another creating verses and finally their sum gives an image. Because there is similarity of this method to the way of record and readout of raster image, bitmap form was used as standard for final sample shape. For such bitmap, respective pixel colors are ascribed to adequate erosion depth.

For that purpose realization an x-y steered plotter was used. Adequate feed rate of working head is guaranteed by computer signals used in especially own written programm for process steering.

3. EXPERIMENTAL STAND

For spatial material shaping realization with this jetting technology, a special experimental stand was elaborated and built, which general view is presented in Fig. 2. Two precise rolling ways are the base of this construction which supports are driven by rolling screws equipped with stepping motors type WX6 08500 made by Isert Electronic. Analogically same type rolling way was mounted crosswise and is the base for abrasive-water jet working head mount. Such gantry construction of these three ways works with positioning accuracy of ±0,005 mm in the table area of 1 m^2. Stepping motors applied in this plotter are steered by four-channel controller type SLIM-4S made by MIXPOL, which also is responsible for operation of end switches and abrasive feed container worm engine.

WEMAA type high-pressure hydro monitor equipped with As500/15A (p_{max}= 50 MPa, Q_{max}= 0,25 dm^3/s) pump produced by Annovi Reverberi is used for supplying pressured water to working system.

Two way (x-y) steering realized according to mentioned above concept are responsible for working head. Longitudinal movements of the head are realized with stepping motor frequencies of 1÷2400 s^{-1} what taking into account rolling screw travel gives in practice the following feed rate range of 0.005÷12 mm/s ensuring proper system work.

This jetting sculpturing process is controlled by own made WaterJetLab programm written in C^{++} language. Operation system is DOS platform enabling direct access to PC hardware. Such WaterJetLab programm realizes all above mentioned functions, taking its minimalistic user interface and involves about 5000 lines of source code [5].

4. EXPERIMENTAL METHODOLOGY

High-pressure abrasive-water jet erosiveness is selected depending on physical properties of treated material. Such important jet feature depends on many process parameters e.g.: water pressure, abrasive material type and its output as well as on jet spraying angle for which adequate nozzle geometry should be chosen and work time that results from working system feed rate etc. Typical example for that can be presented in Fig. 3 showing out erosion of aluminum alloys type AlMg1SiMn. Specific equations describing models presenting chosen metal materials eroded for different conditions are presented in Tab. 1.

Such a spatial material shaping with high-pressure abrasive-water jet basing on its virtual image doesn't need either problematic process control or its complex steering process. Adequate software of such treatment process has to ensure only possibility of proper selection of treated material properties and jet erosiveness as well as working head feed rate that all leads to machine spatial object basing on its photo image.

Different ceramics, glass, plastics and popular metals are sample materials used for the process. Aluminum alloy AlMg1SiMn type of 5 mm thick was the most often one used as a sample among them. Depending on reproduced object shape, the maximum erosion depth realized according to WaterJwtLab programm was set to values range from 1.5 mm to 2.5 mm. Water nozzle of 0.7 mm diameter and focus one of 2.5 mm diameter were installed in work head while standoff distance was set to 5 mm. Experiments were realized with 30 MPa of water pressure while garnet #80 was used as abrasive material with its set up output to 0.8 g/s. For such conditions, dimensions of mapped cell of grey standard (pixel) on sample surface were set to area of 2x2 mm. Calibration of treated material erosiveness is the first stage of the process [5].

Geometrical structure of obtained this way surface was realized with laser gage of TalySurf CLI 2000 analyzer made by Taylor Hobson.

5. STEERING SOFTWARE FOR SCULPTURING PROCESS REALIZATION

Proper function of this prototype jet machine tool operational system and its software requires the following tasks to fulfill:
● process configuration just before its run,
● principal process control,
● calibration of sample material erosive properties respectively to standard sample,
● user interface service.

All actions connected to process configuration are mainly realized by user according to strict procedure [5] whereas programm records all the settings and starts adequate modules. It can be done by using the filter that transforms bitmap into grey depth standard (of 256 gradual scale), basing on the following equation [18] enabling to count the luminance from the model of RGB colors.

$$\text{GREY DEPTH} = 0.3 \cdot \text{Red} + 0.59 \cdot \text{Green} + 0.11 \cdot \text{Blue} \qquad (2)$$

The next group of tasks realized by this programm is the main part that currently controls working process of material spatial shaping. In this part user only can monitor process realization or force its earlier finalization. Detailed schema of x axis motor steering that defines material erosion stage is presented in earlier paper [5]. Every individual sequence of the programm is recall when grey depth value for the next cell of standard table is different from previous one. In this process of every verse creation such sequence is recall repeatedly. When one verse is finished, the programm starts y axis motor to set the working system configuration to new verse and the procedure of x axis direction starts all over again.

This machinery calibration includes also other parameters that adapt treated material flexibility to set erosion parameters [5]. These are: length of individual erosion segment, number of such segments and assignation of proper jet feed rate to individual segments. Another task group algorithm is used for working system movements steering that enables to complete data base with treated material erosive properties and is the base to obtain set erosion depths for respective areas of graphical standard.

The last task group realized by this programm is functions collection that ensures graphical card and keyboard service as well as grouping and ordering of all information projected on monitor screen in text and graphical form.

6. HYDROJETTING SCULPTURING EFFECTS

Examinations of spherical shaping different materials with this high-pressure abrasive-water jet let to collect interesting data. They let to verify if chosen erosion depth are correct and point out satisfactory quality of such spherical object reproduction basing on virtual flat image. Standard effects of such work can be seen on the following pictures.

Basing on this prototype jet-machining tool a wide aspect of different possibilities of such material shaping method was examined. Despite mentioned above actual inaccuracy of this method, the following numerous spherical objects machined this way, are good evidences of the method possibilities. One of them, presented in Fig. 4 presents a photocopy of well known painting and includes a set of illustrations showing also important phases of its spherical reproduction made in metal plate.

Presented images shows important phases of real object (a) reproduction process into virtual 2D matrix (b) characterized with resolution reduced to the level that is possible to be realized by abrasive-water work head as well as 3D bass-relief (c), scanned that way image (d) and its perspective scan showing out depth accuracy (e).

Another example of described method may be analogical illustrations presented in Fig. 5 or on Fig. 6 showing out the Sydney Opera buildings. This object involves different parallel positioned elements of building and relatively precise elements of steel bridge construction placed just behind first stage.

Besides completely advantageous effects of worked out technology, some inaccuracy was observed as well. It can be seen especially in the form of incomplete reproduction of erosion depth for those individual and lonely placed elementary areas which characterizes with high contrast comparing to surroundings. It was observed that proper erosion depth can be achieved only when one erosion verse involves pixels located one after one characterized with close grey scale grade. Moreover, so far achieved quality effects need to be improved in the meaning of boundary levelling that occurs between individual verses. Sometimes in the deepest eroded places such boundaries may be noticed in the form of shallow and sharp edges.

Generally one can admit that despite relatively low matrix resolution, quality of reproduced image machined in metal plates is satisfactory. It should be noted positively that on all stages of that process characteristic object features are kept. Particular example of that may be seen in still recognizable subtle smile of La Gioconda presented in Fig. 4. Despite actual problems of that kind, facility of its application gives good prognosis for future. Taking above circumstances, we are now modernizing this prototype jet machining tool in the aspect of introducing much more subtle hydrojetting technique.

7. CONCLUSION

Developed method of materials spatial shaping using high-pressure abrasive-water jet confirms rightness of assumptions and accepted concept divagations as well as procedures of developed controlling-steering software. Basing on realized experiments one can generally admit that despite matrix low resolution images in the form of bitmaps were relatively well reconstructed in metal samples. Therefore developed method gives satisfactory effects.

Shortcomings of the method aren't particularly of great importance. It can be especially observed in the form of incomplete reproduction of erosion depth for those individual and lonely placed elementary areas which characterizes with high contrast comparing to surroundings. Therefore developing this method a new additional programm module should elaborated and introduced that will be responsible for erosion time correction especially in those places where set erosion depth wasn't achieved. Such module should introduce corrections basing on such characteristic places storage where suitable material erosion was done.

Presented in this paper method of automatic shaping of quasi-real objects machined in different materials using high-pressure abrasive-water jet is effective and perceptively profitable.

8. REFERENCES

[1] BORKOWSKI P.: *Creation of bas-relief basing on photography using high-pressure abrasive-water jet*. Journal of Machine Engineering, Vol. 8, No. 2, 2008, pp.43-51.
[2] BORKOWSKI P.: *Theoretical and experimental basis of hydrojetting surface treatment.* (in Polish). Monograph No 106 (ISSN 0239-7129). Publ. Koszalin University of Technology. Koszalin, 2004.
[3] BORKOWSKI P.: *High-pressure abrasive-water jet surface treatment.* (in Polish). Center of Proecological Techniques. Koszalin, 2002.

[4] BORKOWSKI P., SZPAKOWICZ A.: *Hydrojetting method of bas-relief shaping.* (in Polish). Machine Engineering. Unconventional Hydrojetting Technologies, Vol. 13, No. 1-2, 2008, s. 81-89.

[5] BORKOWSKI P., SZPAKOWICZ A.: *Spherical objects shaping with high-pressure abrasive-water jet*. (in Polish). High-pressure Hydrojetting Technologies. Publ. Koszalin University of Technology. Koszalin, 2008, s. 299-314.

[6] BORKOWSKI P., ŻUKOCIŃSKI T.: *Three dimensional method of material forming using high-pressure abrasive-water jet controlled by flat image luminance*. 18th Int. Conf. on Jetting Technology. Gdańsk, 2006, pp. 265-274.

[7] BORKOWSKI P., ŻUKOCIŃSKI T.: *Basis of three dimensional material forming using high-pressure abrasive-water jet controlled by virtual image luminance*. Advances in Manufacturing Science and Technology. Vol. 30, No. 1, 2006, pp. 53-62.

[8] CHUNG Y., GESKIN E.S., SINGH P.J.: *Prediction of the geometry of the kerf created in the course of abrasive waterjet machining of ductile materials*. 11th Int. Conf. on Jet Cutting Technology. St. Andrews, Scotland, 1992, pp. 525-541.

[9] FENGGANG L., GESKIN E. S., TISMENETSKIY L.: *Feasibility study of abrasive waterjet polishing*. 13th Int. Conf. on Jetting Technology. Sardinia, 1996, pp. 709-723.

[10] GROPPETTI R., GUTEMA T., DI LUCCHIO A.: *A Contribution to the analysis of some kerf quality attributes for precision abrasive water jet cutting*. 14th Int. Conf. on Jetting Technology. Brugge, 1998, pp. 253-269.

[11] HASHISH M.: *Optimization factors in abrasive-waterjet machining*. Trans. Of the ASME, Journal of engineering for Industry. 1991, Vol. 113, No. 1, pp. 29-37.

[12] HASHISH M.: *An investigation of milling with abrasive-waterjets*. Trans. Of the ASME, Journal of engineering for Industry. 1989, Vol. 111, No. 2, pp. 158-166.

[13] HASHISH M.: *Milling with abrasive-waterjets: A preliminary investigation*. 4th U.S. Water Jet Conf. Berkeley, California, 1987, pp. 1-10.

[14] HASHISH M.: *On the modeling of abrasive-waterjet cutting*. 7th Int. Symposium. on Jet Cutting Technology. Ottawa, Canada, 1984. Paper E1, pp. 249-265.

[15] HENNING A., WESTKAMPER E.: *Modeling of contour generation in abrasive waterjet cutting*. 15th Int. Conf. on Jetting Technology. Ronneby, 2000, pp. 309-320.

[16] LAUAND V.H., HENNIES W.T., STELLIN A. Jr.: *Glass and marble (Cachoeiro de Itapemirim) milling with abrasive water jetting*. 19th International Conference on Water Jetting. BHR Group. Nottingham, 2008, pp. 121-139.

[17] LAURINAT A., LOUIS H., MEIER-WIECHERT G.: *A model for milling with abrasive water jets*. 7th American Water Jet Conf. Seattle, Washinton, 1993. Paper 8, pp. 119-139.

[18] METZGER P.: *Anatomia PC*. Wydanie VII (ISBN: 83-7197-751-4). Helion. Gliwice, 2002.

[19] MOMBER A.W.: *A generalized abrasive water jet model*. 8th American Water Jet Conf. Houston, Texas, 1995. Paper 25, pp. 359-376.

[20] TAN D.K.M.: *A model for the surface finish in abrasive-waterjet cutting*. 8th Int. Symposium. on Jet Cutting Technology. Durham, England, 1986. Paper 31, pp. 309-313.

[21] YONG Z., KOVACEVIC R.: *3D simulation of macro and micro characteristics for AWJ machining*. 9th American Water Jet Conf. Dearborn, Michigan, 1997. Paper 9, pp. 133-144.

[22] YONG Z., KOVACEVIC R.: *Modeling of jetflow drilling with consideration of the chaotic erosion histories of particles*. Wear. 1997, No. 209, pp. 284-291.

[23] ZENG J., KIM T.J.: *Development of an abrasive waterjet kerf cutting model for brittle materials*. 11th Int. Conf. on Jet Cutting Technology. St. Andrews, Scotland, 1992, pp. 483-501.

[24] ZHANG S., GALECKI G., SUMMERS D.A., SWALLOW C.: *Use of pre-profiling a milled pocket as a means of improving machining and lowering energy costs*. 2007 WJTA Conference and Expo. Houston, Texas, 2007. Paper 3-H.

[25] ZHANG S., SHEPHERD J.D., SUMMERS D.A.: *Experimental investigation of rectangular pocket milling with abrasive water jet using specially designed tool*. 17th International Conference on Water Jetting. BHR Group. Mainz, Germany, 2004, pp. 435-447.

9. TABLES

**Table 1.** Models of erosion for chosen metal materials realized in different conditions

| material	p [MPa]	m_a=0.90 g/s	m_a=0.56 g/s	m_a=0.28 g/s
aluminum alloy AlMg1SiMn	50	$h = 1{,}037v^{-1{,}01}$	$h = 0{,}606v^{-0{,}85}$	$h = 0{,}352v^{-0{,}76}$
	40	$h = 0{,}717v^{-0{,}93}$	$h = 0{,}425v^{-0{,}83}$	$h = 0{,}233v^{-0{,}84}$
	30	$h = 0{,}485v^{-0{,}88}$	$h = 0{,}264v^{-0{,}84}$	$h = 0{,}145v^{-0{,}83}$
	20	$h = 0{,}233v^{-0{,}86}$	$h = 0{,}125v^{-0{,}91}$	$h = 0{,}074v^{-1{,}04}$
	10	$h = 0{,}077v^{-0{,}99}$	$h = 0{,}042v^{-1{,}15}$	$h = 0{,}023v^{-0{,}87}$
brass CuZn39Pb2	50	$h = 0{,}509v^{-0{,}77}$	$h = 0{,}295v^{-0{,}79}$	$h = 0{,}164v^{-0{,}87}$
	40	$h = 0{,}390v^{-0{,}79}$	$h = 0{,}233v^{-0{,}81}$	$h = 0{,}122v^{-0{,}82}$
	30	$h = 0{,}251v^{-0{,}82}$	$h = 0{,}155v^{-0{,}83}$	$h = 0{,}082v^{-0{,}86}$
	20	$h = 0{,}138v^{-0{,}82}$	$h = 0{,}087v^{-0{,}95}$	$h = 0{,}048v^{-0{,}85}$
	10	$h = 0{,}052v^{-0{,}91}$	$h = 0{,}030v^{-0{,}90}$	$h = 0{,}016v^{-0{,}57}$
stainless steel X5CrNi18-10	50	$h = 0{,}306v^{-0{,}78}$	$h = 0{,}170v^{-0{,}81}$	$h = 0{,}083v^{-0{,}83}$
	40	$h = 0{,}227v^{-0{,}77}$	$h = 0{,}131v^{-0{,}78}$	$h = 0{,}067v^{-0{,}70}$
	30	$h = 0{,}146v^{-0{,}88}$	$h = 0{,}091v^{-0{,}95}$	$h = 0{,}046v^{-0{,}73}$
	20	$h = 0{,}080v^{-0{,}84}$	$h = 0{,}052v^{-1{,}01}$	$h = 0{,}024v^{-1{,}11}$
	10	$h = 0{,}033v^{-0{,}89}$	$h = 0{,}016v^{-0{,}85}$	$h = 0{,}009v^{-0{,}61}$

10. GRAPHICS
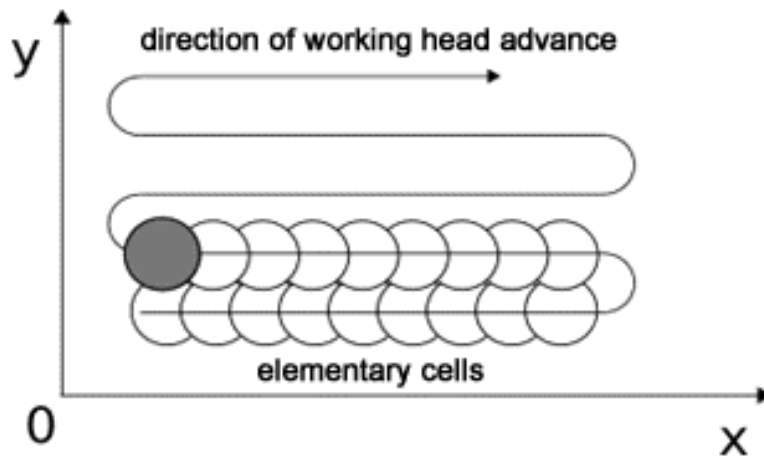

Figure 1. Concept of image creation
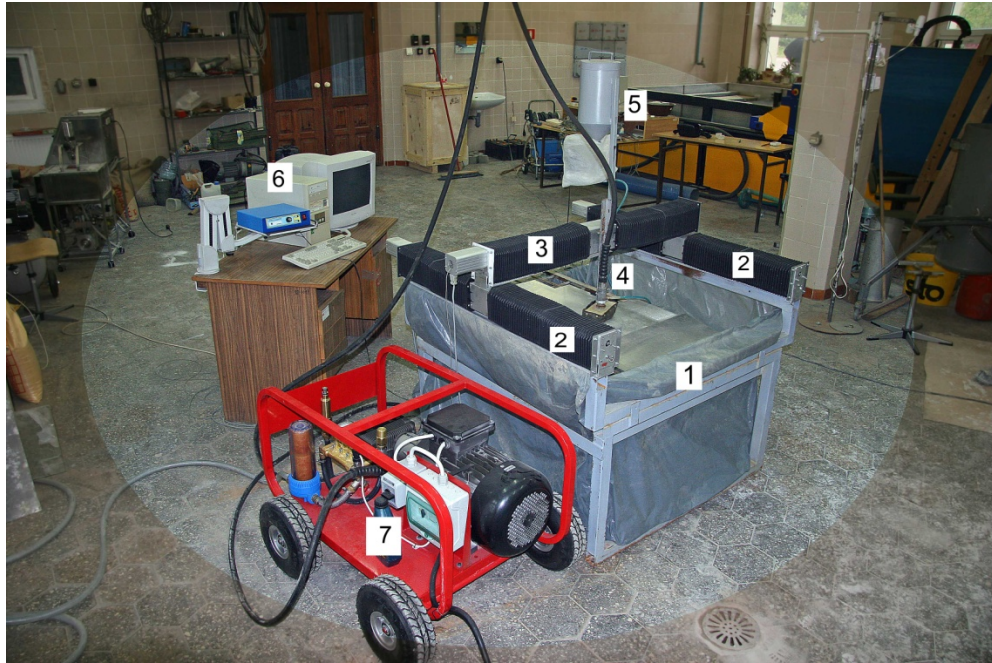
Figure 2. General view of test stand for three-dimensional material machining with high-pressure abrasive-water jet: 1 – frame, 2 – y direction slideways, 3 – x direction slideway, 4 – abrasive-water jet working head, 5 – abrasive feed container, 6 – steering PC computer, 7 - hydromonitor.
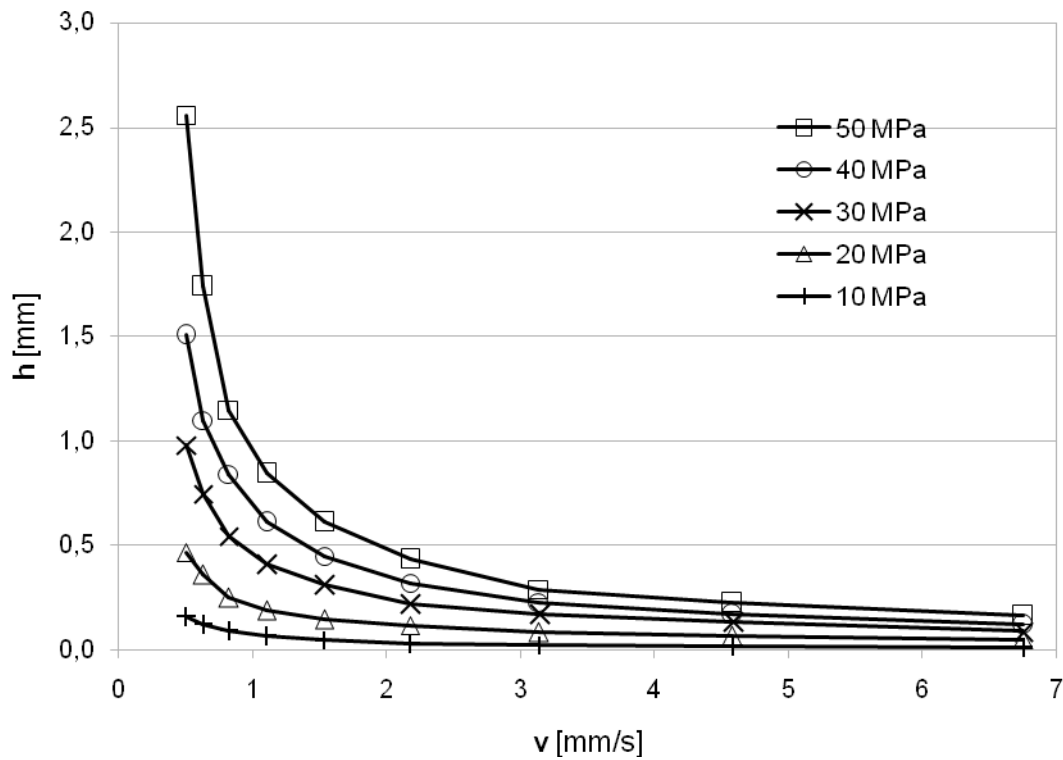
Figure 3. Aluminum alloy AlMg1SiMn type erosion realized with abrasive-water jet technology (m_a=0.90 g/s).
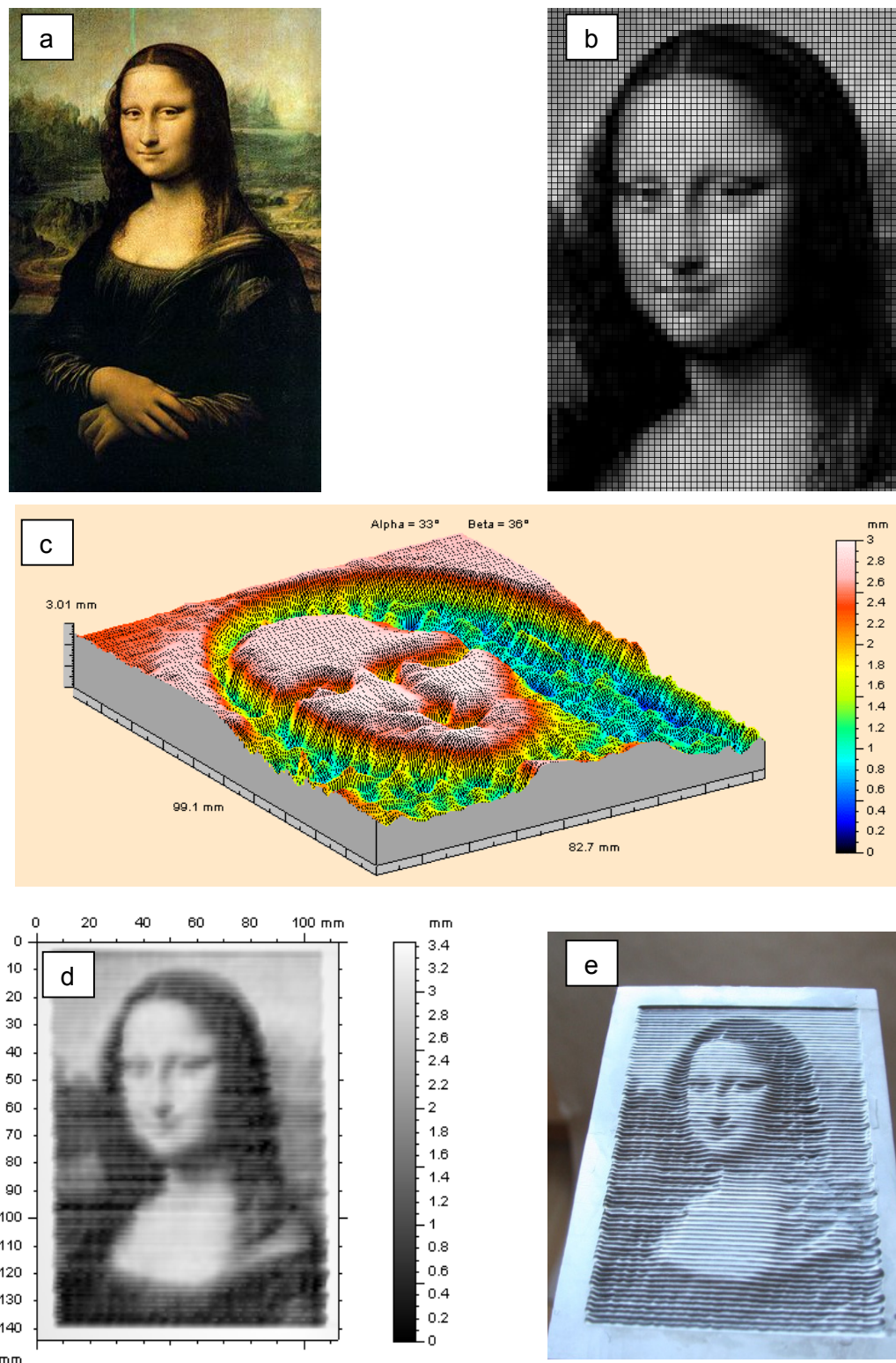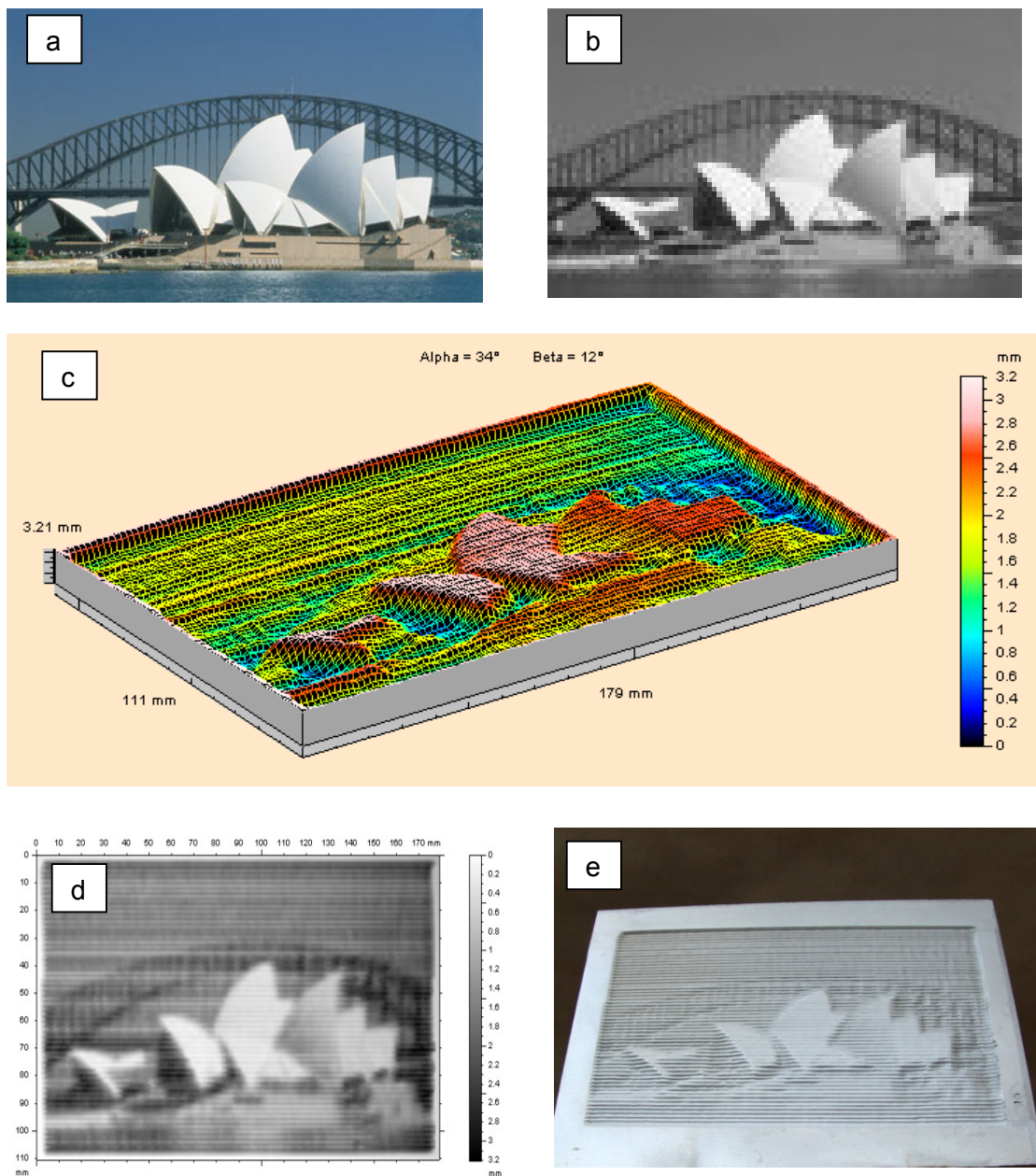
Figure 4. Images showing important phases of 3D quasi-spatial object (Mona Lisa) sculpture basing on its photo: a- picture, b – virtual 2D matrix, c- perspective scanned view showing depth analysis, d- image scanned from the relief, e- photo of 3D bas-relief cut in AlMg1SiMn alloy plate.
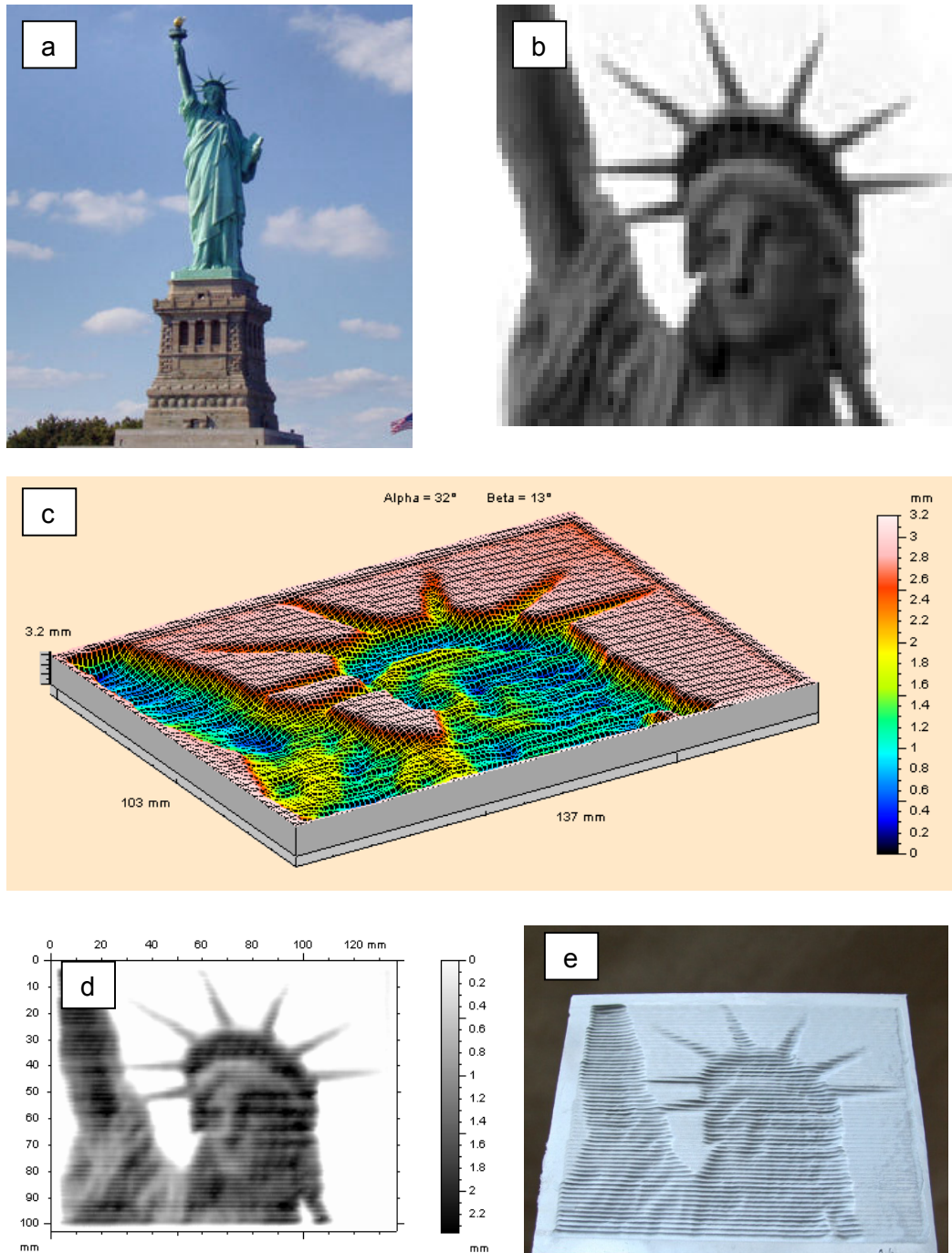
Figure 5. Images showing important phases of 3D quasi-spatial object (Statue of Liberty) sculpture basing on its photo: a- picture, b – virtual 2D matrix, c- perspective scanned view showing depth analysis, d- image scanned from the relief, e- photo of 3D bas-relief cut in AlMg1SiMn alloy plate.

Figure 6. Images showing important phases of 3D quasi-spatial object (Opera-House in Sydney) sculpture basing on its photo: a- picture, b – virtual 2D matrix, c- perspective scanned view showing depth analysis, d- image scanned from the relief, e- photo of 3D bas-relief cut in AlMg1SiMn alloy plate.