3D EVALUATION OF THE TOPOGRAPHY OF THE SURFACE BY ABRASIVE WATER JET MACHINING TECHNOLOGY

GERHARD MITAL, EMIL SPISAK, PETER MULIDRAN, LUBOS KASCAK, TOMAS JEZNY

Technical University of Kosice, Faculty of Mechanical Engineering, Department of Mechanical Engineering Technologies and Materials

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gerhard.mital@tuke.sk

The article deals with contact and non-contact evaluation of surface roughness created by water jet cutting technology (AWJ). Non-contact surface measurement was performed using an LPM laser profilometer. The values measured by the laser profilometry method were compared with the values measured by the contact method, the Mitutoyo SJ 400 roughness meter. Six samples were produced. Three in stainless steel and three in structural steel. In order to achieve a different surface topography, different feed rates of the cutting head were used on the samples, which was reflected in the quality of the resulting surface. The evaluated parameters were the average arithmetic deviation of the assessed profile and the largest height of the profile inequality.

KEYWORDS

Contactless, 3D, measure, laser, profilometry, surface

1 INTRODUCTION

Surface roughness is a parameter that often occurs in the metalworking process. It is one of many factors that speak to the quality of machining, which has the effect of increasing productivity. These roughness values are undesirable from the point of view of mechanical vibration because they cause noise and dynamic stress. These result in fatigue and failure of the construction of the machine or its functional parts and loss of energy or reduced performance [Gajdos 2015, Bozek 2021].

Experimental analysis of surface topography in the machining process is important in several aspects. Unwanted surface roughness can indicate damage to functional parts of the machine tool, wear of tools, workpiece, cutting head or other parts of the machine tool. These processes initiate damage to the machine's structure, bearing components, or other machining and parting parts [Panda 2018].

The importance of the quality of machined surfaces is constantly growing and ever higher demands are placed on it. The quality of the surface has a major impact on the functionality of the entire device. One of the main criteria in assessing the quality of the surface, but also the machinability of the material is the roughness [Dzupon 2017, Draganovska 2018, Krenicky 2015 & 2020]. Roughness represents the height of the unevenness from a perfectly and ideally smooth surface and arises as a result of the tool used during machining and finishing. With the development of science and technology and the application of their results, the issue of surface quality of components increases [Ruzbarsky 2018]. This greatly affects their service life, reliability and depends mainly on the accuracy of operation, noise, resistance to corrosion and wear, friction loss or fatigue strength of components [Murcinkova 2013, Turygin 2018, Coranic 2021]. Especially in contact surfaces, the value of roughness is often a decisive factor. It also has a significant impact on the service life and reliability of technical equipment [Izol 2014].

2 EXPERIMENTAL PART

The surface topography after AWJ beam cutting is a little explored area. Like all high-energy beam technologies, the AWJ beam leaves visible striations on the machined surface [Valicek 2016, Hlavac 2018a,b]. This significantly affects the dimensional accuracy of the workpieces and the quality of the finished surface. According to previous knowledge, the surface after cutting consists of two different areas: a smooth zone and a rough, grooved zone, which starts at a certain depth below the surface [Guzanova 2014].

The principle of hydroabrasive separation consists in blowing a hydroabrasive stream, or only water, at supersonic speed onto the divided material, which leads to its disintegration. The permeate, which carries the kinetic energy of the abrasive, washes away the products of the removal from the cutting site and ensures cooling of the cutting site. Precisely because of the cooling of the cutting point, this material cutting technology is more advantageous than conventional cutting technologies, in which undesired heat is introduced into the cut materials with a consequent change in structure, deformation and change in visual appearance [Mascenik 2014]. A device with a WJ4020 1Z-C0-PJ60 COBRA coordinate table from PTV Praha and a PTV56-60 high-pressure pump from FLOW SYSTEMS was used to separate the samples.

The parameters that affect the material removal also affect the quality of the cut, namely:

- nozzle diameter
- water pressure,
- flow rate,
- distance - stand off
- beam inclination angle,
- additives in water,
- type of abrasive.

Six samples were made by the AWJ method (Fig.1). Three samples (SS50, SS100, SS150) were made of stainless steel marked A304 and three samples (CS050, CS100, CS150) of structural steel (S235JR). Three cutting head feed rates were used for the samples, which are shown in Figure 1. The difference in materials using the same cutting conditions is the basis for evaluating the experiment.

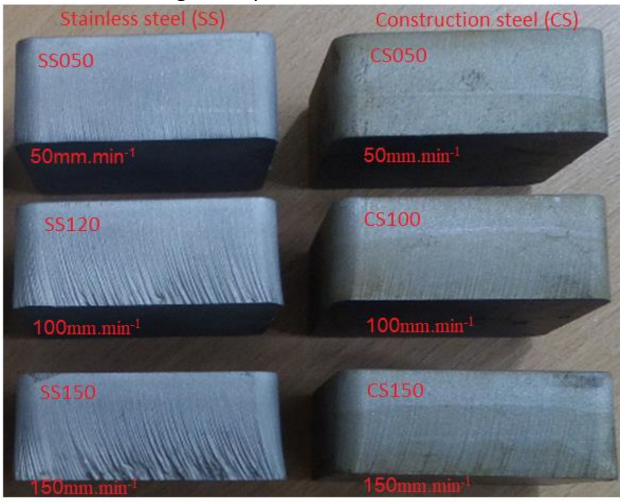

Figure 1. Materials A304 in left and S235JR in right

During water jet cutting, a certain maximum surface roughness is declared. The values of the declared surface roughness at different cutting head feed rates are shown in Table 1. Table 2 shows the parameters set when cutting with AWJ, which were constant for all samples except the cutting head speed.

Roughness		
SS050	SS100	SS150
6,3 µm	12,5 µm	25 µm
CS050	CS100	CS150
6,3 µm	12,5 µm	25 µm

Table 1. Roughness of samples processed by AWJ technology

Parameter	Value
pressure [MPa]	380
type of abrasive	Australian garnet
abrasive grain	MESH 80
water jet diameter [mm]	0,406
diameter of baffle tube [mm]	0,889
amount of abrasive [$g.min^{-1}$]	430

Table 2. Cutting parameters

2.1 Measurement of surfaces using the non - contact method

The laser profilometer assembly consists of basic and additional parts. The basic parts include a supporting frame made of components with vertical adjustment of the measuring head position and programmable sample feed in the X and Y axes, a laser radiation source, a lens and a camera with a CCD sensor. Additional parts include a PC with operating and evaluation software and an image divider [Mital 2019].

The optical part of the system consists of an AVT Marlin 131B camera and a Tamron 23FM50SP 50 mm lens with a visible area of 22 mm x 7 mm. Automated sample feed in the X and Y axes is realized by means of Standa 8MT160-300 stepper motors, in each axis with a maximum length of 300 mm. The system makes it possible to measure samples with a maximum weight of 8 kg with a positioning accuracy of 2.5 micrometers per step, each step consisting of 8 micrometers. The sensor resolution is 0.02 mm / pixel.

The samples were mounted on plasticine LPM worktop, which ensured the elimination of recesses from the machine design and ensured accurate positioning of the sample to the laser and camera.

Using an experimental system, it is possible to measure and evaluate the surface roughness parameters of samples according to the standard STN EN ISO 11562 (Rq, Rv, Rz, Ra, Rp,). The results of the evaluation of the measured profiles in the form of raw data can be exported in the .csv format, which is suitable for further processing of experiments.

The Matrox Triple Head 2 Go - Digital Edition image divider facilitates clear processing and evaluation of the measured data. This device is used to divide one graphics output from a computer into three independent graphics outputs, and in combination with the use of additional graphics output and the selection of an extended desktop, it is possible to obtain four independent images so that each monitor has a different part of the desktop.

The AVT SmartView program (Fig. 2) is used to display the image of the area captured by the system's profilometer camera. For efficient sampling, the LPM system is also equipped with an integrated light, which consists of four white LED lights. The illumination of the sample with a laser beam or LED light is selected in the software part of the system before the actual surface measurement.

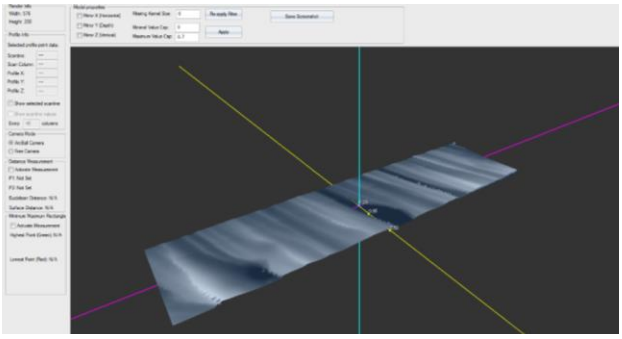

Figure 2. Created 3D profile

2.2 Measurement of surfaces using the contact method

As already mentioned in the introduction to the paper, to verify and compare the measured values, the measurement of the samples was also performed on a Mitutoyo SJ400 contact roughness meter (Fig. 3). The technical parameters of the contact roughness meter are shown in table 3.

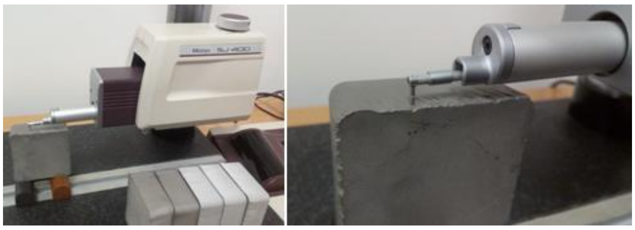

Figure 3. Measurement of samples by contact method

Measurement speed	0,05; 0,1; 0,5; 1,0 $mm.s^{-1}$
Return speed	0,5; 1,0; 2,0 $mm.s^{-1}$
Measurement direction	back
Positioning	± 1,5 ° (inclination), 10 mm (up/down)
Measurement range / resolution	800/0,01 µm; 80/0,001 µm
Power supply type	via a network adapter
Evaluated parameters	P (primary), R (roughness), W (filtered waviness)
Digital filter	2CR, PC75, Gauss
Cutoff length	0,08; 0,25; 1,8; 2,5; 8 mm

Table 3. Technical parameters of the Mitutoyo SJ400 roughness meter

On each sample, the same part of the measured surface was selected for both measurement methods. Sample materials were defined by the standard as S235JR (structural steel) and X5CrNi18-10 (A304 austenitic stainless steel).

2.3 Methodology of measuring experimental samples

Measurement by non-contact method: Workpiece surface quality values were measured on each workpiece at ten surface depths. A at depths of 0.11; 2.31; 4.51; 6.71; 8.91; 11.11; 13.31; 15.51; 17.71; 19.91 mm. Since the measurement with a contact roughness has a verification character, therefore, the measurement was performed by this method in a smaller number in each of the four mentioned surface areas.

Non-contact measurement: The values of the quality of the machined surface were measured in the contact method at four depths for each sample. And at depths of 1; 6; 12; 18 mm.

The number of measurements with this method was reduced due to the complexity and difficulty of the measurement (Tab.4).

Declared roughness	Depth/STEPS [mm]	S235JR (Construction steel)		A304 (Stainless steel)	
		Ra[µm]	Rz[µm]	Ra[µm]	Rz[µm]
6,3	1	2,61	16,4	2,38	14,3
	6	2,88	15,5	3,15	16,5
	12	3,95	17,5	4,22	17,9
	18	4,36	19,5	5,91	26
12,5	1	2,53	14,7	3,71	19,2
	6	3,32	20,5	5,57	24,6
	12	5,96	33,2	8,94	39,5
	18	9,42	42,2	9,28	41,6
25	1	3,45	19,4	6,20	20,9
	6	4,25	28,3	8,94	41,8
	12	10,89	56,4	14,79	65,2
	18	15,73	59,4	21,67	75,1

Table 4. Profile parameters measured in a contact manner

3 EVALUATION OF MEASURED VALUES

When evaluating the surface roughness, the parameters Ra - average arithmetic deviation of the profile and Rz - the largest height of the profile unevenness was observed. The surface roughness was measured in 220 steps with a step size of 0.11 mm. Gain mode was 1. Shutter time was 21.250 ms. After previous test measurements of this type of surface, these LPM parameter settings showed the clearest image preview and the least image noise.

3.1 Evaluation of measured values by non-contact method

In this part of the paper, the measured data of the surface of the samples by the LPM system are presented. From the measured data, 4 graphical dependences were created for the quality parameters Ra and Rz depending on the measured area of the material at the given feed rates. The measured surfaces are examined at ten depths on three samples of stainless steel and three samples of structural steel. Each material contains two graphs for individual dependences of roughness parameters depending on the depth of the material at the specified speeds of the technological head. These are addictions:

- the dependence of the average arithmetic deviation of the profile Ra and the dependence of the largest height of the irregularities of the profile Rz on the depth of the material h for the feed rate 50 mm.min^{-1}, 100 mm.min^{-1} and 120 mm.min^{-1} (SS),
- the dependence of the average arithmetic deviation of the profile Ra and the dependence of the largest height of the irregularities of the profile Rz on the depth of the material h for the feed rate 50 mm.min^{-1}, 100 mm.min^{-1} and 150 mm.min^{-1} (CS).

Stainless steel samples (SS050, SS100, SS150)

Figure 4 shows 3D models of the scanned surface of stainless steel samples, which was created by assembling a series of measured profiles using the LPM system.

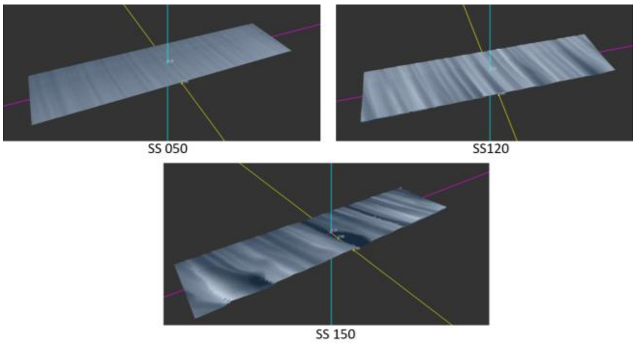

Figure 4. 3D model of scanned samples made of A304 steel

For the material stainless steel X5CrNi18-10 (A304), the roughness parameters of the machined surface Ra and Rz shown in Figures 5, 6 are evaluated. The curves for all samples have an increasing tendency of Ra and Rz values depending on the increasing measured depth of cut h.

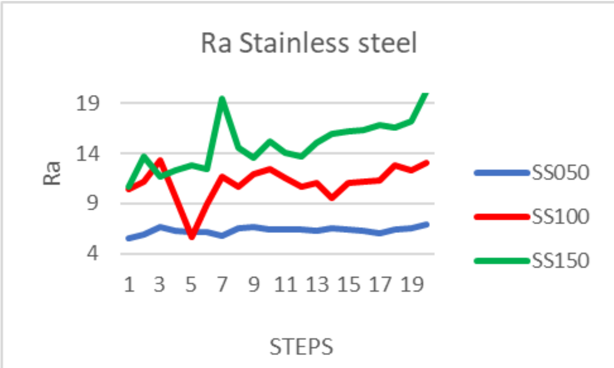

Figure 5. Graphical dependence of the parameter Ra depending on the measured depth of cut (A304)

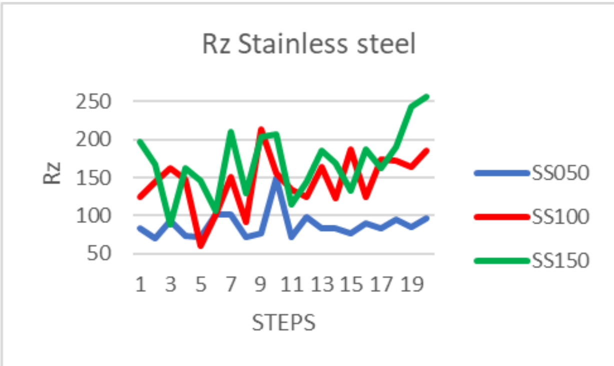

Figure 6. Graphical dependence of the parameter Rz depending on the measured depth of cut (A304)

Construction steel samples (CS 050, CS100, CS150)

Figure 7 shows 3D models of scanned samples of structural steel, which was created by stacking a series of measured profiles using the LPM system.

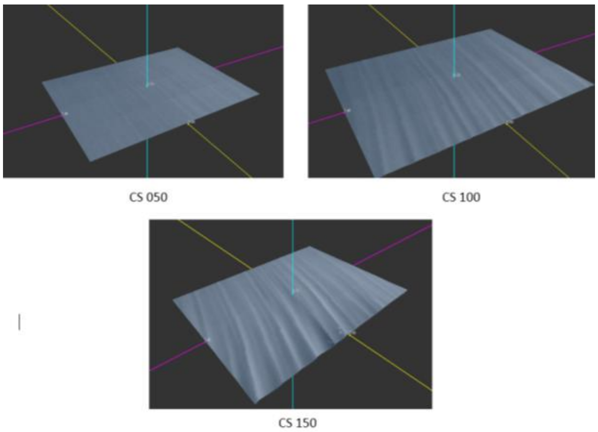

Figure 7. 3D model of scanned samples made of S235JR steel

For the material structural steel STN11 373 (S235JR), the roughness parameters of the machined surface Ra and Rz shown in Figure 8, 9 are evaluated. The curves for all samples have an equally increasing tendency of Ra and Rz values depending on the increasing measured depth of cut h.

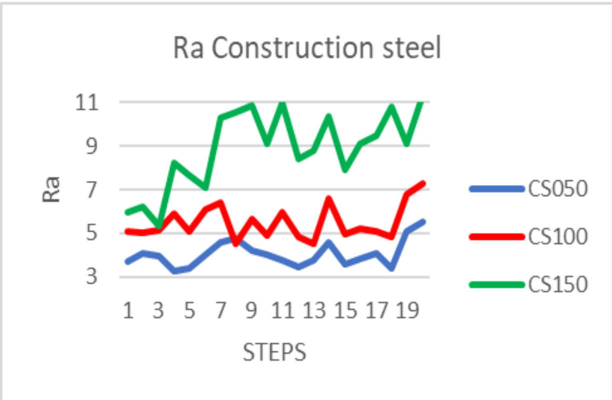

Figure 8. Graphical dependence of the parameter Ra depending on the measured depth of cut (S235JR)

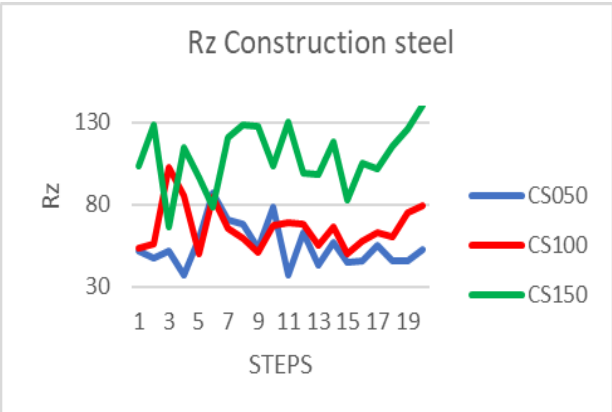

Figure 9. Graphical dependence of the parameter Rz depending on the measured depth of cut (S235JR)

4 DISCUSSION

The high-speed stream creates a relief in the sample, which can be divided into several sections according to the texture nature. Smooth, medium smooth, medium rough and rough zone. The task of our experiment was to compare and evaluate the surface of samples produced according to AWJ technology by DRC s.r.o. (Ltd). The company declares that the surface roughness of each manufactured sample is not greater than that one given in Table 1 for each sample. According to values measured on the contact roughness meter Mitutoyo SJ 400 its first disadvantage compared to the LPM device is clear. The contact roughness meter gives an incomplete picture of the examined surface in individual surface sections due to the fact that measuring the surface on the section 800 µm which passes the tip of the instrument over the measured surface is the result of a single average value of the roughness parameters Ra and Rz. When measuring with LPM, the measurement result is a set of values that shows a part of the surface in each measurement step. LPM also evaluates the largest depression and the largest protrusion of the examined surface, i.e. evaluates several parameters in individual measurement steps. Another advantage is the creation of a 3D image of the examined surface, where it shows the character of measured object surface better.

A fast surface profiling algorithm based on white light interferometry was designed using the sampling theory that was installed in the commercial system to reach the world's highest scanning speed of 80 microns per second. The resolution of the system height is in the order of 10 nm, for a measuring range is greater than 100 microns.

The surface character was measured in Gain 1 mode in 220 steps with a step size of 0.11 µm. The entire sample surface was examined at ten measurement sites when measured with LPM, and four measurement sites when measured with Mitutoyo SJ400. For comparison and verification of measured values, samples made of construction steel and stainless steel were measured on a Mitutoyo SJ400 contact roughness tester (Tab. 4). This comparison shows that the Ra values measured on the laser profilometer are within the range of values measured on the Mitutoyo SJ 400. The values of Rz measured by the contact method are on average three times lower than the values measured on LPM. This is partly due to the fact that the measuring contact in the contact method cannot go into small cracks formed on the surface depending on the rounding of the tip radius. In the non-contact method, the increase in unmeasured values is caused by the reflection of laser light from the workpiece surface into the CCD camera. This measurement error can be partially eliminated by deleting bias values from the exported tables.

5 CONCLUSION

The feed speed of the cutting head is one of the most important and technologically most easily adjustable technological parameter which affects the quality parameters Ra and Rz. Figures 5, 6 and 8, 9 show plotted dependencies of surface roughness Ra, Rz versus depth of material at the given cutting head feed rates depending of separating the respective materials. The measured and evaluated surface area of 0.11–19.91 µm gradually passed from smooth to rough surface section.

Therefore, the measurement results can be summarized as follows:

- The plotted dependencies show that surface roughness varies linearly the deeper the AWJ cut.
- All plotted dependencies show a growing trend for roughness values.
- As the feed rate decreases, the smooth zone size (characterized by lower roughness values) increases.
- It occurs primarily in the first cut zone of the machined surface. This can also be seen in the plotted dependencies where the smallest initial surface roughness is (Figures 5, 6 and 8, 9).

- The values of the Ra and Rz parameters of the smooth zone are closest to each other, but even at these values, a difference in surface roughness is apparent, depending on the speed of the cutting head.
- The Ra and Rz parameter values of the CS050, CS100 and SS050, SS120 samples show a linear increase. The CS150 and SS150 samples exhibit a rather exponential increase in the Ra and Rz parameter values and their value is jump-like.
- Linearly increasing roughness is true for both the smooth and medium smooth zones (from 0.11 µm to 8.91 µm). An exponential increase in value occurs in the medium rough and rough (end) zone of the surface from 11.11 µm to 19.91 µm.
- It follows from the cuts and the measured values compared that the AWJ material separation technology shows equally manifesting increases. Occurrence of reliefs on the sectioned surfaces in both soft (CS) and hard metal materials (SS) was less frequent for the samples made of construction steel than for the samples made of stainless steel.
- This means that a different cutting head speed must be used to achieve the same surface roughness in different materials.

We can say that the roughness of the sample surfaces produced by the DRC Company did not exceed the declared roughness of any of the samples used. The task of the experiment was to compare and evaluate the surface of samples produced by the AWJ technology at the DRC Company and to evaluate the measurement methods. The company declares that the surface roughness of each sample produced is not greater than that shown in Table 1 for each of the samples. The values measured with the contact roughness meter Mitutoyo SJ 400 show its first obvious disadvantage compared to the LPM device. The contact roughness meter does not provide a complete picture of the surface under evaluation or the roughness of its individual parts. This is because in measuring the 800 µm section of the surface (radius of curvature of the tool tip), the result is a single average value of the roughness parameters Ra and Rz. When measured with LPM, the measurement result is a set of values that describe the surface areas at each measurement step. The LPM also evaluates the largest depression and the largest protrusion of the surface under evaluation, i.e., it evaluates several parameters in the individual measurement steps. Another advantage is the creation of the examined surface 3D image where the surface nature of the object being measured is better seen and then can be analysed more thoroughly.

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CONTACTS:

Ing. Gerhard Mital, PhD.
Faculty of mechanical engineering, Technical university of Kosice, Department of mechanical engineering technologies and materials, Mäsiarska 74, Kosice, 040 01, Slovakia