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SURFACE TEXTURE ANALYSIS OF THE X5CRNI18-10 STEEL AFTER CUTTING WITH ABRASIVE WATER JET AND PHOTON BEAM (LASER)

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Abstract: The article presents an analysis of the geometric structure of the surface of X5CrNi18-10 steel sheet after cutting with a abrasive water-jet (AWJ) and a photon beam (laser). Both methods and the workpiece material were also described. Using the laser triangulation method, the cut surface texture was measured by opto-digital microscopy. Additionally, microscopic images of the cut surface were made using the Dino-Lite Edge AM7915MZT microscope by ANMO Electronics Co. The analysis of changes in the value of the *Sa* parameter for the surface after laser cutting and abrasive water-jet showed that the thickness of the cut material has the most significant influence on the obtained measurement results.

Keywords: cutting, abrasive water-jet, laser cutting, surface quality, X5CrNi18-10 steel

1. INTRODUCTION

Cutting is commonly referred to as the process of separating the material along the entire thickness of the material, along the cutting line. A variant of the cutting process is thermal cutting, where the material subjected to this process is liquid due to the supplied thermal energy, then it is blown out using the kinetic energy of the gas stream or reaches a sufficiently high temperature at which it is oxidized in a pure oxygen stream [6]. The surface of the material to be processed is shaped by means of a highly concentrated supersonic jet of water with an admixture of abrasive. The process of photon jet cutting is carried out by means of a laser beam. The laser is a device emitting electromagnetic radiation from the visible light, ultraviolet or infrared range, which uses the phenomenon of forced emission.

The above described methods are used in manufacturing companies, however, due to the condition of the surface after cutting, their use involves with quality concessions, which are generated during the process. The elimination of quality problems after cutting is often associated with a longer process time. The photon beam (laser) cutting is faster compared to water-jet cutting, but it causes quality defects of the cut surface, such as, for example, a wider heat affected zone or defects in the cut material.

The aim of the research was to assess the condition of the surface after photon beam (laser) cutting and water-jet cutting, as well as to compare their surface texture at different process parameters.

2. ABRASIVE WATER-JET CUTTING

The high-pressure water jet is perfectly suited for cutting different harnesses of materials, providing an even and extremely accurate cut, as shown in Figure 1. The scientific achievements of recent years have formed the basis for the dynamic development of new technologies. A special case in this area is the hydro-jet technology, which uses concentrated energy streams in the form of a high-pressure abrasive water-jet containing granular admixtures. The research area includes analyses of elementary phenomena occurring on the surface treated with a high-pressure abrasive water-jet doped with various solid particles such as garnet, quartz sand, silicon carbide or dry ice [1, 2].

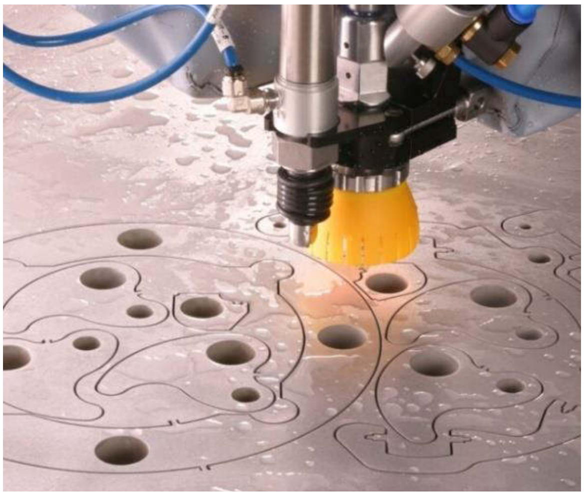

Fig. 1. View of workspace in the abrasive water-jet cutting process [12]

The basic advantages of this technology include following features [10]:

- versatility of application to various materials such as: steel, glass, ceramics, composites, stone;
- possibility to cut very thick materials (in case of aluminum alloys up to 300 mm);
- possibility to cut through multilayer material;
- possibility to shape three-dimensional elements;
- no thermal influence on the material to be cut, no warm-body influence zone;
- no material deformation in the cutting area.

An important element of treatment is the selection of the abrasive, which should not have a destructive effect on the head nozzle and at the same time should effectively remove the material. Abrasives with high density, high hardness, isometric shape and a significant number of sharp edges are most valued. The use of abrasive grains with such properties in the machining process favorably influences the machining performance depending on the kinetic energy of the grains. In the abrasive water-jet cutting process, the most commonly used abrasive is garnet [9].

Variable parameters for abrasive water-jet cutting are as follows [7]:

- working pressure 300-650 MPa;
- water output 0.07-0.11 l/s;
- abrasives output 3-5 g/s;
- nozzle diameters: water 0.3-0.4 mm; forming 0.8-1.0 mm.

3. PHOTON BEAM (LASER) CUTTING

Photon beam (laser) cutting is a thermal cutting process whose main source of energy is the energy coming from the laser beam as shown in Figure 2. This beam with continuous or impulse action at the cutting point leads to melting or melting and sublimation of the material.

Fig. 2. View of workspace in the photon beam (laser) cutting process [13]

As a result of the erosion process, the kinetic energy of the jet is converted into potential energy deforming the material in the working area. Consequently, microcracks form in the work area and the material loosens, resulting in the separation of material particles from the base mass. In addition, a reactive or inert gas flowing coaxially with the laser beam is used to blow the molten material and its vapors out of the gap [6].

This method can be used for cutting metals, plastics, ceramic materials, cermets and wood, from a cross section equal to 35 mm. The laser cutting method is also used for drilling and punching holes. This operation requires an impulse or continuous supply of processed laser beam energy to the material with a much higher power density than continuous laser cutting. The value of this energy reaches 106-1011 W/mm^2 [4]. This method ensures high cutting accuracy and self-cutting edges, where the heat affected zone is very narrow [8].

The advantages of photon jet cutting include [11]:

- possibility of easy automation and robotization of the cutting process;
- high cutting speeds;
- high dimensional accuracy of the cut and smoothness of the cut surfaces, which enables cutting products that do not require further mechanic treatment as opposed to those made by oxygen or plasma cutting methods;
- lower self-tension and at the same time lower deformation of the cut material;
- narrow heat affected zone;
- possibility of conducting several operations during one cycle, e.g. piercing, cutting out holes etc.;
- minimal rounding of the upper cutting edge and no overhanging of the slag at the lower cutting edge;
- much lower emission of harmful dusts and fumes.

A comparison of both described methods is shown in Table 1.

Tab. 1. Comparison of methods of cutting with abrasive water-jet and photon beam (laser) [14]

Feature	Abrasive water-jet	Photon beam (laser)
Non-metallic materials	Yes	No
Multiple head applications	Yes	No
Multi-layer cutting	Yes	No
Combined materials	Yes	No
Hardening of material	No	Yes
Burr formation	Very minor	Yes
Additional treatment	Very minor	Yes
Material loss	Very minor	High
Tolerances	0.1-0.3 mm	0.1 mm
Poisonous vapour formation	No	Yes
Material thickness	<305 mm	<25 mm
Material deformation	No	Yes

4. RESEARCH METHODOLOGY

4.1. Workpiece characteristics

X5CrNi18-10 steel is a standard grade from the group of austenitic chromium-nickel steels. It shows good resistance to corrosion in natural environment. It is not suitable for use in saline and high chlorine environments. There is a risk of intergranular corrosion at high temperatures e.g. during welding.

Main applications: automotive industry, construction, chemical industry, food industry, oil industry. It is characterized by excellent weldability and polishing brick. The chemical composition and mechanical and physical properties achieved by the described steel are shown in Tables 2, 3 and 4.

Tab. 2. Chemical composition of steel X5CrNi18-10 according to PN-71/H-86020

	C	Si	P	S	Cr	Ni
Min.	0	0	0	0	17.5	8
Max.	0.07	1.0	0.045	0.03	19.5	10.5

Tab. 3. Mechanical properties of X5CrNi18-10 steel [15]

Yield strength	R_e ($R_{p0,2}$) min. = 230 MPa
Tensile strength	R_m = 540-750 MPa
Hardness	*HB* max. = 215 Br

Tab. 4. Physical properties of X5CrNi18-10 steel [15]

Density at 20ºC	7.9 kg/dm^3
Modulus of elasticity at 20ºC	200 GPa
Heat conductivity coefficient	15 W/m·K
Specific heat at 20ºC	500 J/kg·K
Specific resistance	0.73 (Ω·mm^2)/m

Stainless steel grade X5CrNi18-10 stands out [3]:
- good cold plastic processing;
- excellent weldability;
- excellent impact strength;
- malleability;
- very good corrosion resistance;
- sufficient strength;
- lack of magnetism.

4.2. Methodology of experimental tests

The aim of the research was to determine the most advantageous parameters of the tested samples due to the achieved dimensional and shape accuracy and surface quality after cutting sheet metal made of X5CrNi18-10 steel. To achieve the goal, 54 elements were cut out of which 27 photon beam (laser) on the Kimla FlashCUT LF 1530 6 kW machine with variable adjustable values of the cutting processes listed below:
- thickness of metal sheet in mm – it is described as the thickness of a flat or coiled metallurgical product, much smaller than its length and width, the range used for testing is 6, 8, 10 mm;
- laser power *P* in W – described as output power, standardized; it is a scalar physical quantity informing about the work done in time, the end point used in the research is 4.0; 5.0; 6.0 kW;
- axial feed rate of the cutting head $v_{f\,LASER}$ in mm/s – this is the feed rate of the cutting head relative to the workpiece in a unit of time, the range used for testing is 10, 20, 30 mm/s.

Similarly, 27 workpieces were cut with an abrasive water-jet on the PTV JETS 3.8/60 Basic machine with the variable adjustable values of the cutting processes under consideration listed below:
- sheet thickness in mm, range used for testing is 6, 8, 10 mm,
- axial feed rate of the cutting head $v_{f\,AWJ}$ in mm/min, range used for testing is 0.80; 1.66; 2.50 mm/s,
- the process was controlled by adjusting the abrasives output $\dot{m}$ in kg/s, the range used for testing is 0.005; 0.0066; 0.0083 kg/s.

4.3. Measuring positions

During the tests, surface microtopographs were acquired after both types of cutting processes. Triangulation measurements were also carried out by Keyence's LK-031 non-contact laser sensor mounted in the Talysurf CLI 2000 measuring system of the British company Taylor-Hobson Ltd. shown in Figure 3. It worked with the LK-2001 controller of the same company and allowed to obtain a measurement resolution of 1 µm. The measurements were taken using Talyscan CLI 2000 version 2.6.1 supplied by the manufacturer. For the analysis and visualization of the acquired measurement data, TalyMap Platinum version 4.0 software from Digital Surf was used.

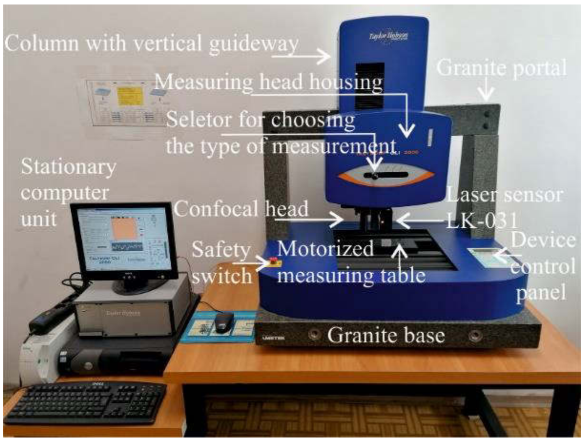

Fig. 3. Measuring position equipped with Talysurf CLI 2000 multi-headed measuring system from Taylor-Hobson Ltd.

The microscopic images of the cut edge, with a resolution of 2592×1944 pixels, were also acquired with the Dino-Lite Edge AM7915MZT microscope from ANMO Electronics Co. shown in Figure 4.

Fig. 4. Components of the position for acquisition images of the active surface and the surface treated by opto-digital microscopy equipped with the Dino-Lite Edge AM7915MZT digital measuring microscope by ANMO Electronics Co.

5. ANALYSIS OF RESEARCH RESULTS

An example of acquired microtopographs analyzed with the TalyMap Platinum 4.0 program using Digital Surf's Mountains Technology™ is shown in Figures 5 and 6. They also show the values of the determined texture parameters of the evaluated surface *Sa* (arithmetic mean deviation of the surface roughness), *St* (total height of the surface roughness) and *Sq* (square mean surface roughness deviation).

Further analysis focused on the changes in the value of the parameter *Sa*, as the most widely used parameter in practice for assessing surface roughness. In Table 5 the values of the parameter *Sa* measured on all surfaces after cutting were collected according to the adopted research methodology.

Figs. 7-12 show charts illustrating the changes in the value of the parameter *Sa* depending on the adopted parameters of the photon beam (laser) cutting process (Fig. 7-9) and abrasive water-jet (Fig. 11-12), for three examined sheet thicknesses (6 mm, 8 mm and 10 mm).

The analysis of the changes in the *Sa* parameter values for the photon beam (laser) cutting surface (Fig. 7-9) showed that the thickness of the cut material has the most significant influence on the obtained measurement results. The change of sheet thickness from 6 mm to 10 mm resulted in approximately doubling the value of the mean arithmetic deviation of surface roughness. The influence of other variable process parameters (feed rate of the $v_{f\,LASER}$ head and power of the laser source *P*) were less significant and differed with respect to particular sheet thicknesses.

Generally speaking, it can be stated that for selected combinations of technological conditions of the photon beam (laser) cutting process, increasing the power of the *P* laser source had a positive effect on the obtained surface roughness after cutting (Fig. 8). On the other hand, the observed trend of changes in *Sa* values as a function of feed rate of the cutting head $v_{f\,LASER}$ does not confirm the expected influence of this parameter on the surface quality after cutting. Increasing the feed rate removes larger volumes of material cut in a unit of time, which results in an increase in cutting marks, deformations, outflows and other defects on the analyzed surface. Presented results may therefore result from the size and selection of the area to be measured for microtopography of the surface after cutting.

The influence of the thickness of the cut sheet made of X5CrNi18-10 steel was even more pronounced (than in the case of the surface after photon jet (laser) cutting) on the surface cut by abrasive water-jet (Fig. 10-12). In this case increasing the thickness of the sheet from 6 mm to 10 mm caused about three to five times increase of the value of parameter *Sa*. It was caused by a significant loss of energy of the abrasive water-jet in the direction of penetration into the material being cut.

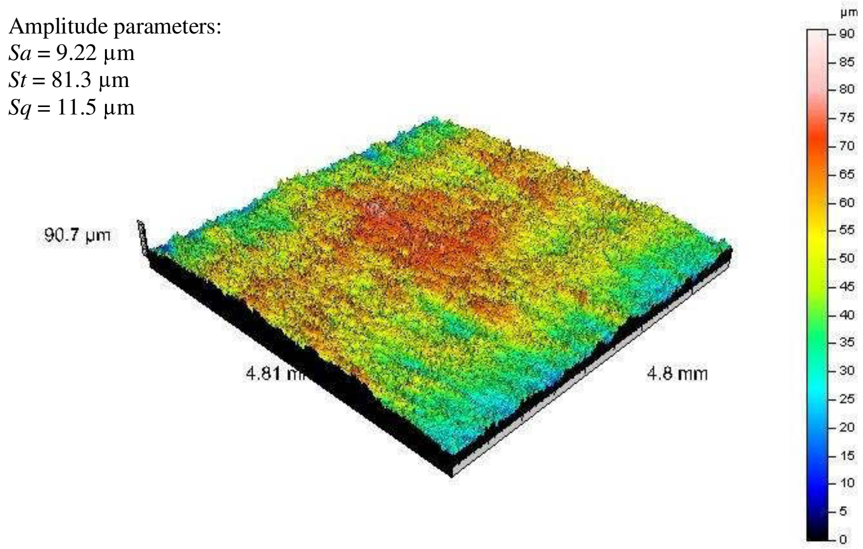

Fig. 5. Example of acquired surface microtopography after photon beam cutting

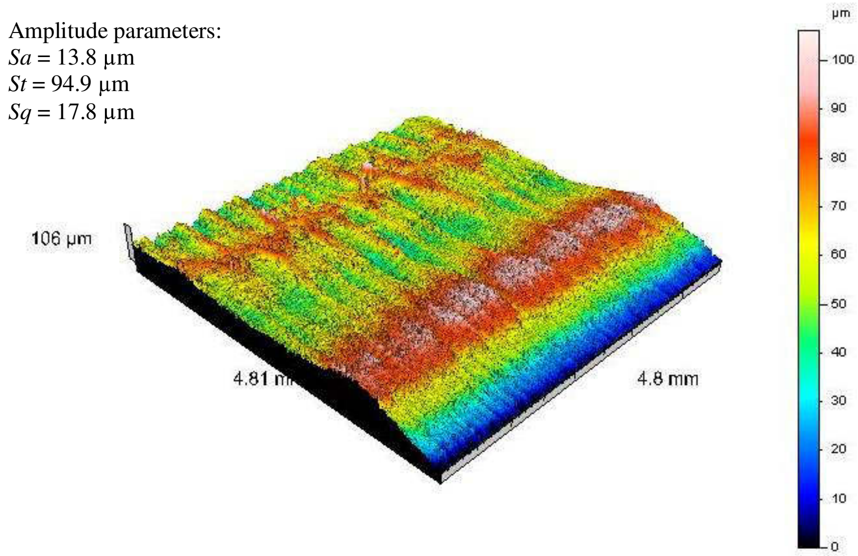

Fig. 6. Example of a acquired microtopography of a surface after abrasive water-jet cutting

Tab. 5. Measurement results of the *Sa* surface roughness parameter values

Photon beam (laser) cutting process					Abrasive water-jet cutting process				
Laser power *P* kW	Head feed rate $v_{f\ LASER}$ mm/s	*Sa* for 6 mm sheet thickness µm	*Sa* for 8 mm sheet thickness µm	*Sa* for 10 mm sheet thickness µm	Head feed rate $v_{f\ AWJ}$ mm/s	Abrasives output $\dot{m}$ kg/s	*Sa* for 6 mm sheet thickness µm	*Sa* for 8 mm sheet thickness µm	*Sa* for 10 mm sheet thickness µm
4.0	10	13.9	31.1	4.9	0.8	0.0050	9.22	23.7	28.7
4.0	20	14.7	25.5	5.1	0.8	0.0066	10.0	11.6	25.7
4.0	30	6.0	5.1	1.1	0.8	0.0083	7.49	13.8	46.3
5.0	10	14.1	25.4	19.7	1.66	0.0050	10.6	13.0	26.2
5.0	20	15.3	19.8	1.0	1.66	0.0066	6.9	8.86	19.9
5.0	30	16.7	8.9	0.9	1.66	0.0083	5.62	7.15	17.3
6.0	10	16.9	8.3	20.9	2.5	0.0050	7.9	14.0	16.5
6.0	20	14.6	8.9	0.85	2.5	0.0066	6.33	12.2	14.6
6.0	30	14.7	8.6	1.0	2.5	0.0083	5.56	12.0	15.4

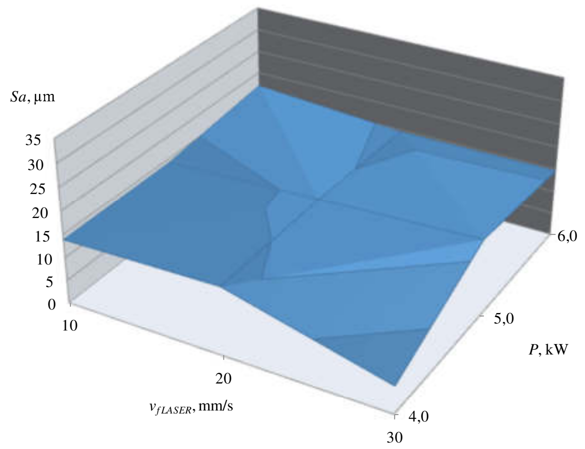

Fig. 7. Changes in the value of the *Sa* parameter of the surface after cutting 6 mm thick sheet steel depending on the variable power *P* and feed rate of the cutting head $v_{f\,LASER}$ in the process of photon beam (laser) cutting

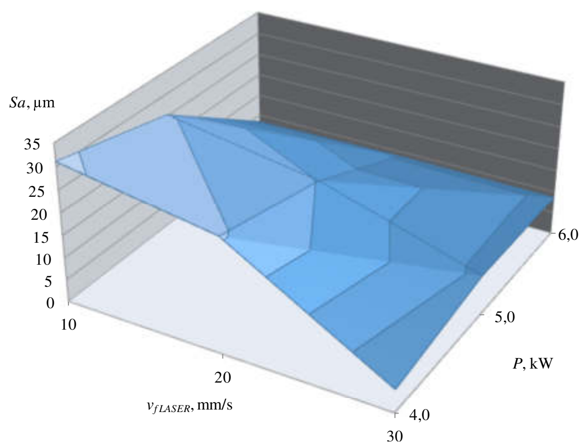

Fig. 8. Changes in the value of the parameter *Sa* of the surface after cutting 8 mm thick sheet metal depending on the variable power *P* and feed rate of the cutting head $v_{f\,LASER}$ in the process of photon beam (laser) cutting

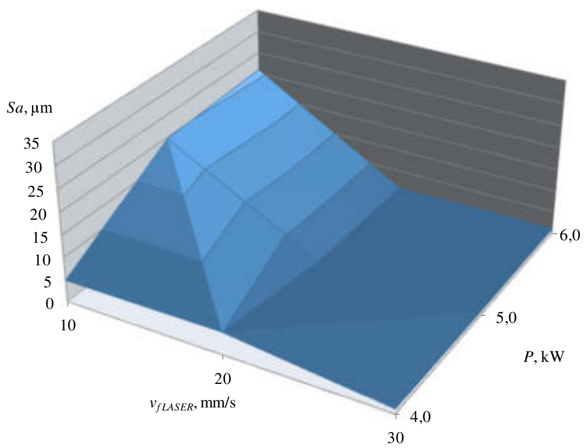

Fig. 9. Changes in the value of the *Sa* parameter of the surface after cutting 10 mm thick sheet steel depending on the variable power *P* and feed rate of the cutting head $v_{f\,LASER}$ in the process of photon beam (laser) cutting

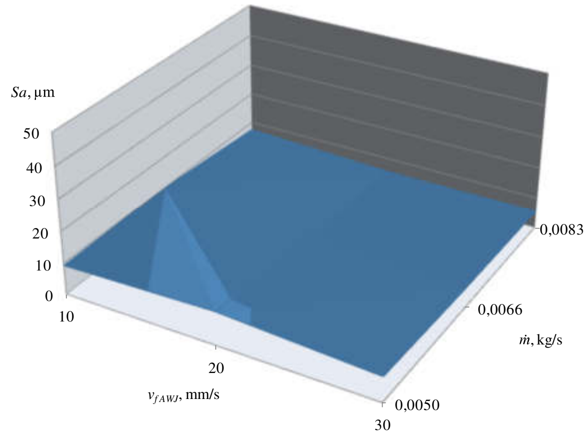

Fig. 10. Changes in the value of the parameter *Sa* of the surface after cutting sheet metal with a thickness of 6 mm depending on the variable feed speed of the $v_{f\,AWJ}$ head and on the output of the abrasives $\dot{m}$ in the process of water-abrasive jet cutting

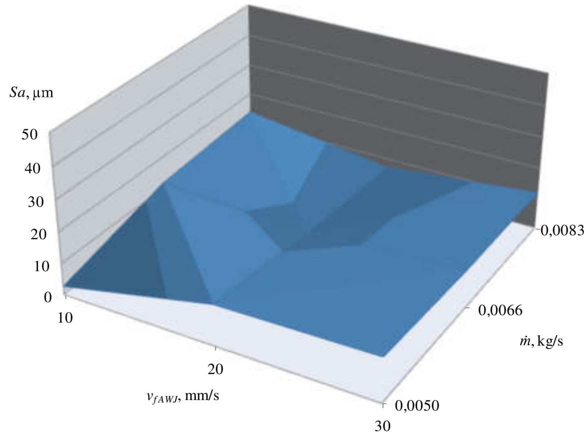

Fig. 11. Changes in the value of the parameter *Sa* of the surface after cutting sheet metal with a thickness of 8 mm depending on the variable feed speed of the $v_{f\,AWJ}$ head and on the output of the abrasives $\dot{m}$ in the process of water-abrasive jet cutting

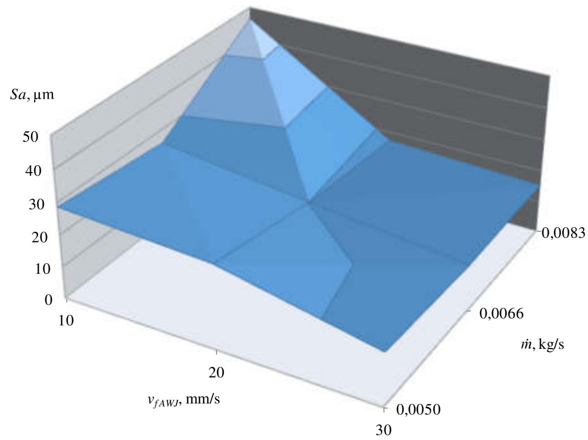

Fig. 12. Changes in the value of the parameter *Sa* of the surface after cutting sheet metal with a thickness of 10 mm depending on the variable feed speed of the $v_{f\,AWJ}$ head and on the output of the abrasives $\dot{m}$ in the process of water-abrasive jet cutting

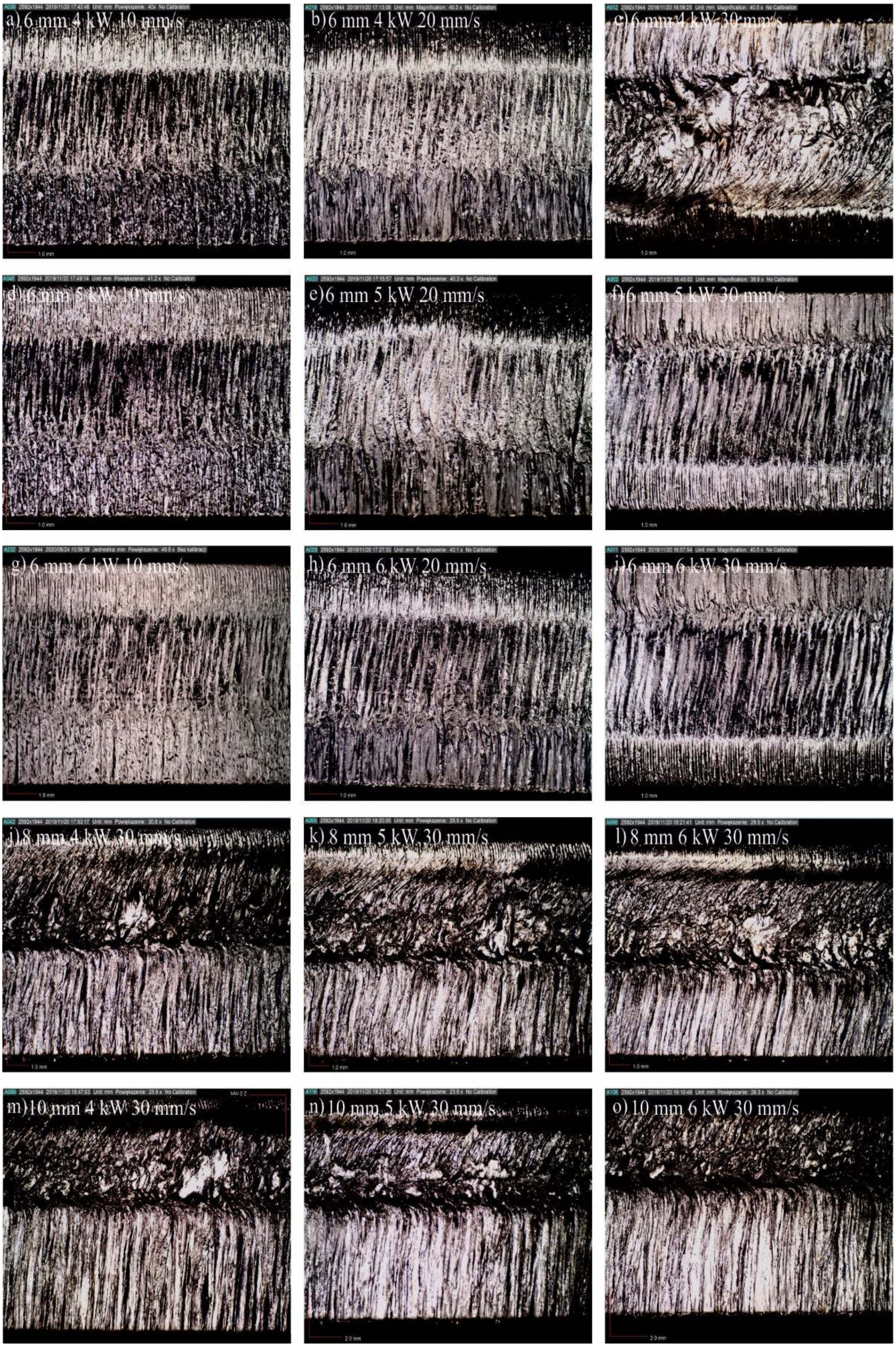

Fig. 13. Example of microscopic images of elements with thicknesses of 6 mm (a-i) with variable parameters P = 4, 5, 6 kW and $v_{f\,LASER}$ = 10, 20, 30 mm/s feed rate; with thickness of 8 mm (j-l) with variable parameter P = 4, 5, 6 kW and constant feed rate $v_{f\,LASER}$ = 30 mm/s; with thickness of 10 mm (ł-n) with variable parameter P = 4, 5, 6 kW and constant feed rate $v_{f\,LASER}$ = 30 mm/s with visible plastic deformations cut out by photon beam (laser)

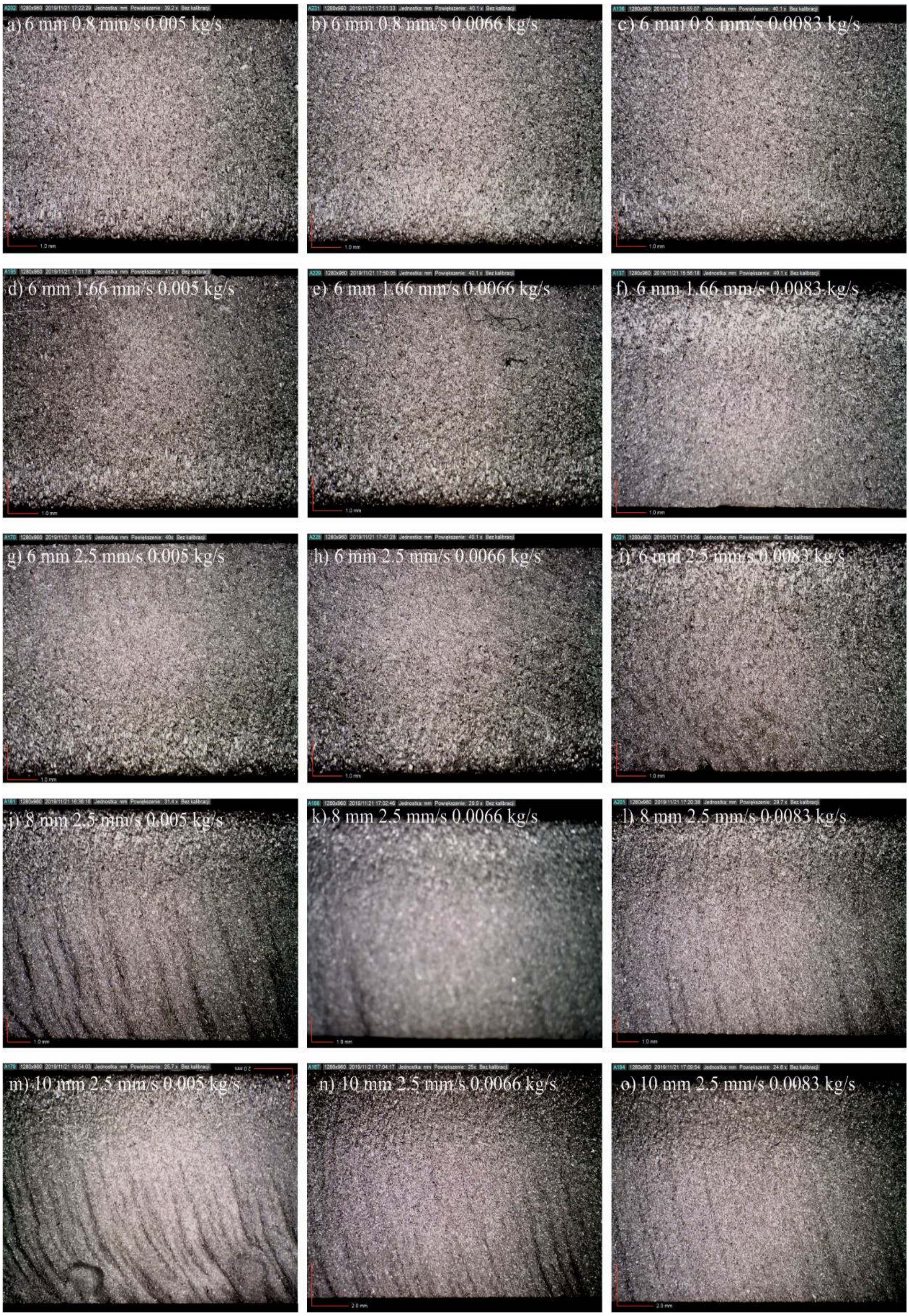

Fig. 14. Example of microscopic images of elements 6 mm (a-i) thick with variable parameters v_{fAWJ} = 0.8, 1.66, 2.5 mm/s and $\dot{m}$ = 0.005, 0.0066, 0.0083 kg/s; 8 mm (j-l) thick with variable parameter $\dot{m}$ = 0.005, 0.0066, 0.0083 kg/s and constant head feed rate v_{fAWJ} = 2.5 mm/s; 10 mm (ł-n) thick) with variable parameter $\dot{m}$ = 0.005, 0.0066, 0.0083 kg/s and constant head feed rate v_{fAWJ} = 2.5 mm/s with visible plastic deformations cut out by a water-abrasive jet

The influence of the remaining variable parameters of the cutting process (feed rate of the v_{fAWJ} head and the abrasives output $\dot{m}$) was much smaller.

The results of the analysis of the surface texture after cutting were additionally supplemented by the acquisition and evaluation of microscopic images. The analysis of the surface condition of the elements after cutting using photon beam (laser) showed that there were numerous defects such as plastic deformations that were not present on the surface cut with an abrasive water-jet, which can be seen in Fig. 13 (laser) and 14 (abrasive water-jet). On the surface of the elements cut with an abrasive water-jet, on the other hand, fewer defects can be observed for each thickness of X5CrNi18-10 steel sheet. As the thickness of the sheet being cut increases, semi-circular machining marks, characteristic for abrasive water-jet cutting, resulting from the decreasing energy of the jet deep into the material being cut, are clearly visible.

6. CONCLUSIONS

Cutting with both methods is beneficial depending on the quality parameters of the surfaces after cutting. The obtained roughness of the surface after cutting allows to formulate the following conclusions:

1. The analysis of the changes in the value of the parameter *Sa* for the surface after photon beam (laser) cutting showed that the thickness of the cut material has the most significant influence on the obtained measurement results.
2. Increasing the power of laser source *P* when cutting with photon beam (laser) had a positive effect on the obtained surface roughness after cutting, while the feed rate of the cutting head v_{fLASER} does not significantly affect the quality of the surface after cutting.
3. The influence of increasing the thickness of X5CrNi18-10 steel sheet from 6 mm to 10 mm cut by the abrasive water-jet resulted in about three- to five-fold increase of the value of the parameter *Sa*, which was caused by nullification of the jet penetrating force into the cutting gap.
4. When cutting with a photon beam (laser), it can be observed that there were numerous defects, such as plastic deformations, which were not present on the surface of the samples cut with an abrasive water-jet J.

Nomenclature

Symbols

$\dot{m}$ – abrasives output during AWJ cutting, kg/s
P – laser power, W
Sa – arithmetic mean deviation of the surface roughness, µm
Sq – square mean surface roughness deviation, µm
St – total height of the surface roughness, µm
v_{fAWJ} – axial feed rate of the cutting head during abrasive water-jet cutting, mm/s
v_{fLASER} – axial feed rate of the cutting head during laser cutting, mm/s

Acronyms

AWJ – abrasive water-jet

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Biographical notes

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