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EXPERIMENTAL EVALUATION OF WEDM MACHINED SURFACE WAVINESS

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Abstract. Wire Electrical Discharge Machining (WEDM) an unconventional machining technology which has become indispensable in many industries. The typical morphology of a surface machined using the electrical discharge technology is characterized with a large number of craters caused by electro-spark discharges produced during the machining process. The study deals with an evaluation of the machine parameter setting on the profile parameters of surface waviness on samples made of two metal materials Al 99.5 and Ti-6Al-4V. Attention was also paid to an evaluation of the surface morphology using 3D colour filtered and non-filtered images.

Keywords: WEDM; electrical discharge machining; titanium alloy Ti-6Al-4V; aluminium Al 99.5; waviness.

1. Introduction

The physical substance of stock removal in the electro-erosion process is in periodically acting electrical discharges between the tool electrode and the workpiece. The erosion process alone takes place in a dielectric medium – a liquid with high electric resistance. Microscopic particles are washed away by dielectric medium and small craters are formed on the workpiece surface. Wire electrical discharge machining (WEDM), the diagram of which is in Fig. 1, is one of the most productive electro-erosion applications. There are no limiting mechanical properties of the machined material such as toughness or high hardness and only electric conductivity is necessary. The tool is a continuously unwinding wire electrode, removing material in all directions and its geometry does not change like in conventional machining methods [1,2].

Mahapatra [3] focused on the significant machining parameters (metal removal rate, kerf and surface finish) for the performance measures in the WEDM. It was proved that every performance measure requires different combination of these factors for its optimization. For their experiment, the nonlinear regression analysis (for the study of the relationship between control factors and responses) and the genetic algorithm (for the WEDM process optimization with multiple objectives) were employed. The experiments demonstrated the ability of WEDM process parameters to be adjustable for reaching better above mentioned significant machining parameters (metal removal rate, surface finish and kerf). Sarkar [4] investigated the optimization of WEDM of gamma titanium aluminide by employing the artificial neural network modelling. According to the outcomes of the experiments done and due to the overall optimization strategy and the combination of single and multipass cutting operations, a new novel concept of critical surface roughness and effective cutting speed was obtained for the machining process selection in order to reach its maximum productivity. They focused on the influential force of four process parameters (namely, pulse on time, peak current, dielectric flow rate, and effective wire offset) on the process performance.

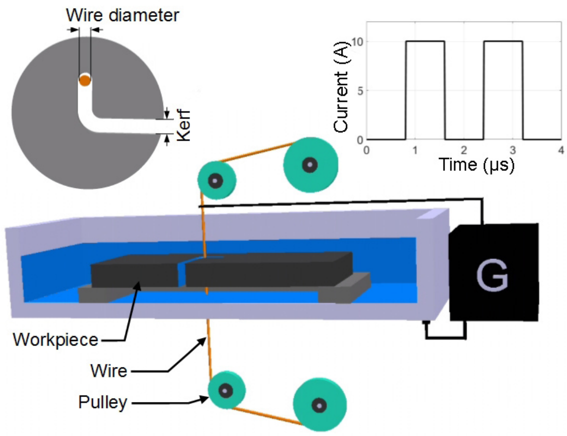

Figure 1. Diagram of wire electrical discharge machining process.

There are many factors which have a substantial influence on the quality of the machined surface and they can be found using various methods [5,6]. Although machine setting parameters are a significant factor, it is the material characteristics of the workpiece that define the final surface quality. The surface quality parameters are influenced by a set of physical and mechanical characteristics of the machined material and the type of its heat treatment [7].

Contents	Si	Fe	Cu	Zn	Ti
Max. (wt%)	0.3	0.4	0.05	0.07	0.05

TABLE 1. Chemical composition of aluminium Al 99.5 prescribed by standard.

Contents	Al	Fe	O	V
Min. (wt%)	5.5	–	–	3.5
Max. (wt%)	6.75	0.25	0.2	4.5

Heat treatment (HT)
Quenched and tempered
940 °C / 45 min / water
500 °C / 2 h / air

TABLE 2. Chemical composition of titanium alloy Ti-6Al-4V prescribed by standard and one type of heat treatment.

2. EXPERIMENTAL SETUP AND MATERIAL

2.1. EXPERIMENTAL MATERIAL

Samples for the experiment were made of pure aluminium Al 99.5 and titanium alloy Ti-6Al-4V. Aluminium Al 99.5 is a material with low specific weight. Its indisputable advantages include excellent corrosion resistance, good weldability and suitability for anodizing with hardness 15 HB, tensile strength 65–160 MPa, and chemical composition, see Tab. 1. It is used almost in all industrial sectors for structural elements and units that are low mechanically stressed, requiring a highly ductile material with high corrosion resistance, which is very well thermally and electrically conductive [8]. Basically, it can be welded using any method [9]. The experiment used an initial rod 20 mm in diameter out of which a square-shaped material was made by the electro-erosion machining.

Titanium alloy Ti-6Al-4V with chemical composition shown in Tab. 2 was used in two sets. The first set – material without additional heat treatment, the second set – with heat treatment, see Tab. 2. This alloy has a high tensile strength of 900 MPa and an excellent corrosion resistance. It has the highest strength to specific weight ratio of all metal materials [10]. It has a high biocompatibility and capacity to resist thermal loads up to a temperature of 315 °C. It is used for manufacturing constructional parts of weapons and aircraft, turbine blades, fasteners, medical and dental implants, and sport equipment [11]. The experiment used an initial square-shaped material 18 mm in thickness. For the purpose of increasing the hardness, heat treatment was carried out.

ZHR 4150AK hardness tester, series Rockwell by Zwick Roell was used for the measurement of hardness of sample material. For titanium alloy, a hardness of 46 HRC (432 HB) was measured.

Sample number	**GV** (V)	T_{on} (μs)	T_{off} (μs)	**WOT** (m/min)	**DC** (A)
1	70	8	40	12	30
2	60	8	30	12	30
3	60	8	40	12	25
4	60	10	40	12	30
5	50	8	40	12	30
6	60	8	50	12	30
7	60	6	40	12	30
8	60	8	40	12	35
9	60	8	40	10	30
10	60	8	40	14	30
11	60	8	40	12	30
12	50	6	30	10	35
13	70	10	50	10	25
14	70	10	30	10	35
15	60	8	40	12	30
16	70	6	50	10	35
17	70	10	50	14	35
18	60	8	40	12	30
19	60	8	40	12	30
20	70	6	50	14	25
21	50	6	30	14	25
22	60	8	40	12	30
23	70	10	30	14	25
24	50	6	50	10	25
25	60	8	40	12	30
26	50	10	50	14	25
27	50	10	30	10	25
28	50	6	50	14	35
29	50	10	50	10	35
30	70	6	30	14	35
31	50	10	30	14	35
32	60	8	40	12	30
33	70	6	30	10	25

TABLE 3. Machining parameters used in the experiments. GV – gap voltage; WOT – wire off time; DC – discharge current.

2.2. WEDM MACHINE SETUP

The WEDM machine used in this study was high precision five axis CNC machine MAKINO EU64. As electrode, a brass wire (60 % Cu and 40 % Zn) PENTA CUT E with a diameter of 0.25 mm was used. Samples were immersed in the deionized water which served as dielectric media and also removed debris in the gap between the wire electrode and the workpiece during the process. To find out the effects of parameters of gap voltage, pulse on (T_{on}) and off time (T_{off}), wire feed and discharge current on the machined surface, their different setting (Tab. 3.) was used for each of 33 samples made of individual materials. The values of individual parameter settings were determined on the basis of previous tests [12].

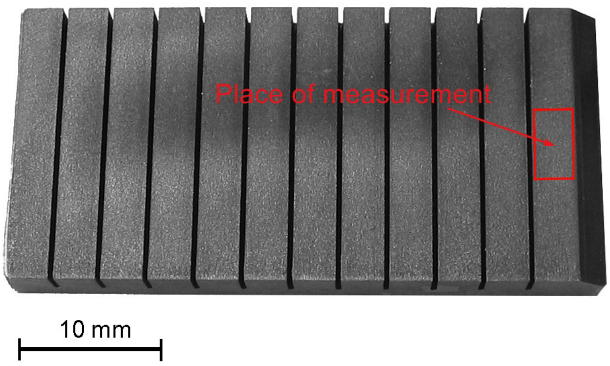

Figure 2. Waviness measurement area on each sample (sample of titanium alloy).

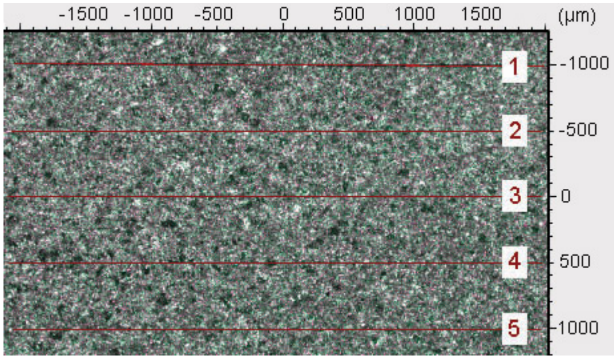

Figure 3. Position of distribution of areas for waviness measurement.

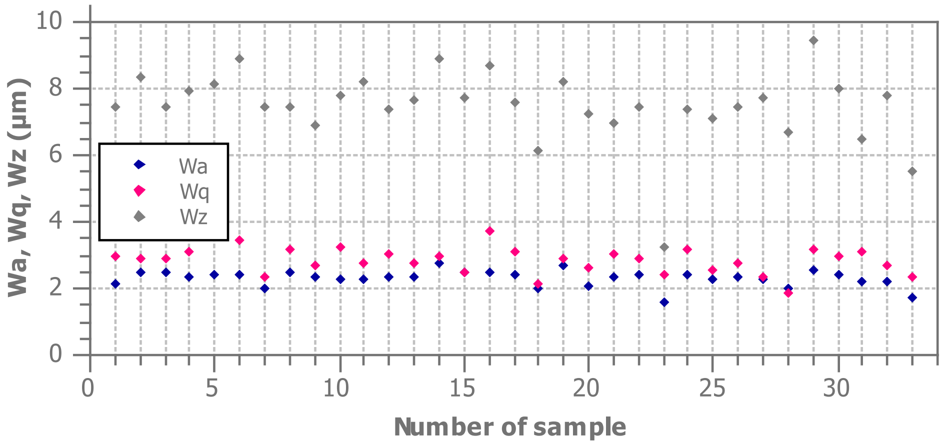

Figure 4. Average values Wa, Wq and Wz of samples made of Al 99.5.

For the experiment, a "half response surface design" containing 33 runs grouped in two blocks (Tab. 3) was chosen. In order to reduce the possibility of systematic errors, the individual runs are randomised; besides that, 7 central points were added to the experiment to ensure a better measure of error. This plan of data collection has been described in detail, for example, by Montgomery [13].

3. Results of experiment

The morphology and parameters of waviness of the machined surface were studied using the contactless measuring instrument from IFM G4 from Alicona. The measured data were analyzed using the software IF-Laboratory Measurement supplied by Alicona. The term profile waviness is defined by a curvature that shows a certain periodicity – waving.

The area of waviness measurement on each sample is shown in Fig. 2. In this area, waviness measurement was carried out according to ISO 4287 [14] on straight lines 4.2 mm long, always at exactly defined distances from one another as shown in Fig. 3. The waviness parameters evaluated by profile method were maximum height of the waviness profile Wz, arithmetic average of waviness Wa and root mean square deviation of the waviness profile Wq.

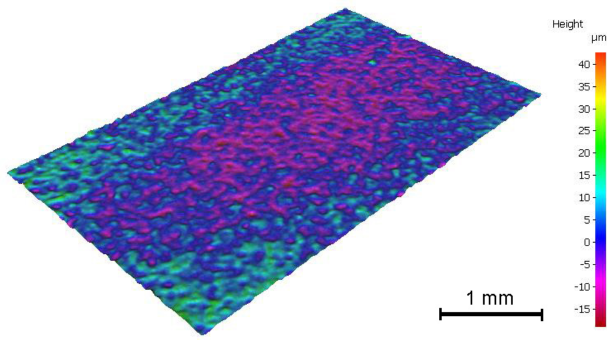

Figure 5. Colour filtered image of the surface of sample 23, 2.5 × magnified (voltage 70 V, $T_{on} = 10\,\mu s$, $T_{off} = 30\,\mu s$, wire feed 14 m/min, current 25 A).

3.1. The results of the profile waviness measurements on samples made of Al 99.5

The measured values of the waviness parameters Wa, Wz and Wq were processed into Fig. 4. Each of the parameters was measured in 5 points on each sample and then the average value was calculated.

The measured values of the waviness parameter Wa range in an interval from 1.56 µm (sample 23) to 2.75 µm (sample 14). The average value Wq in

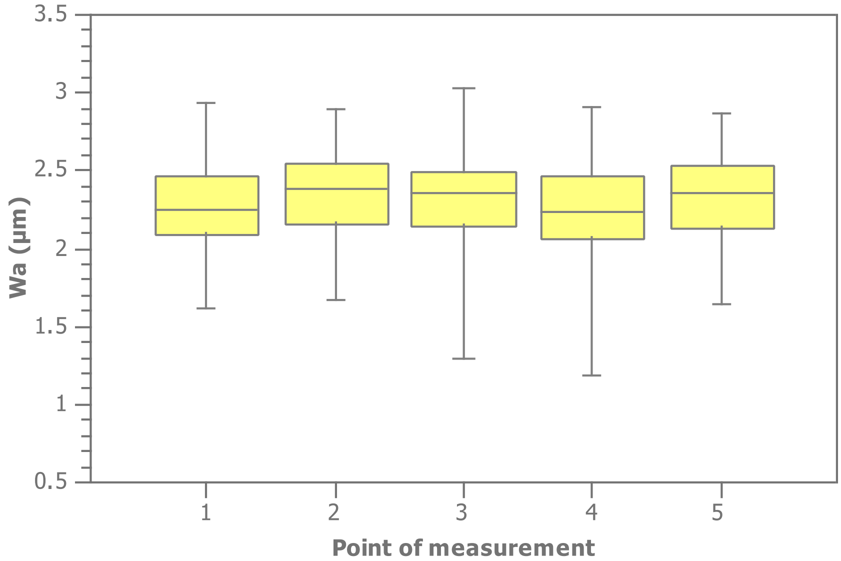

Figure 6. Values Wa in individual points of measurement on all samples made of Al 99.5.

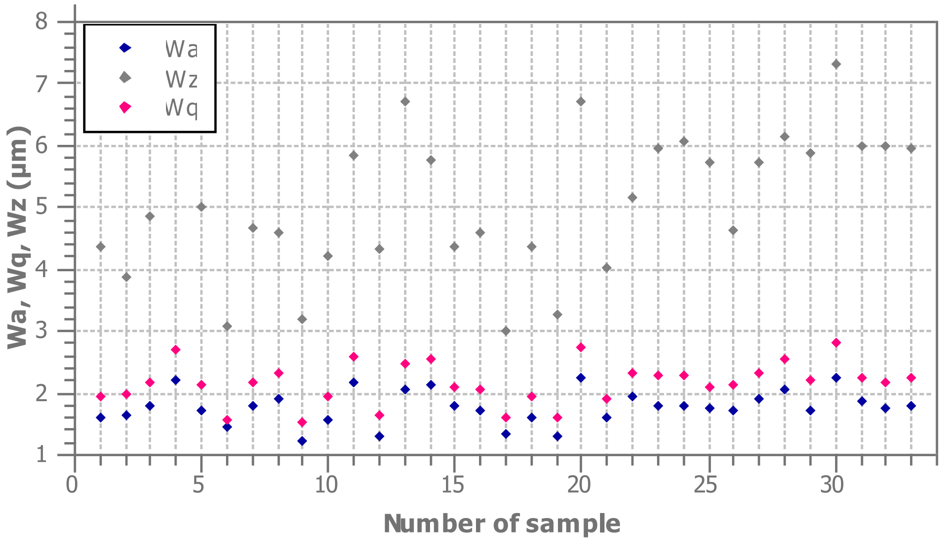

Figure 7. Average values Wa, Wq and Wz of samples made of titanium alloy Ti-6Al-4V.

measured samples was 2.85 µm and for Wz it was 7.48 µm. Overall, sample 23 has the lowest values of all measured parameters Wa = 1.56 µm, Wq = 1.88 µm and Wz = 3.23 µm and its surface is shown in Fig. 5.

A box graph (Fig. 6) was compiled of all measured values Wa in individual points on samples according to Fig. 3. The average measured value Wa does not differ significantly in individual points of measurement. Only the maximum and minimum values measured in individual points are different. The lowest values were measured in the middle of the sample in points 3 and 4.

3.2. The results of the profile waviness measurements on samples made of titanium alloy Ti-6Al-4V

The average values of waviness parameters in 5 points on the surfaces of samples made of titanium alloy were processed into Fig. 7. The minimum measured value of the waviness parameter Wa was in sample 9, specifically 1.21 µm, and the maximum in sample 20,

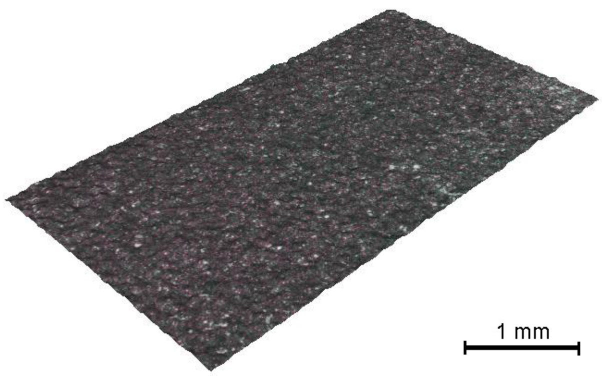

Figure 8. Non-filtered image of the surface of sample 30, 2.5 × magnified (voltage 70 V, $T_{\text{on}} = 6$ µs, $T_{\text{off}} = 30$ µs, wire feed 14 m/min, current 35 A).

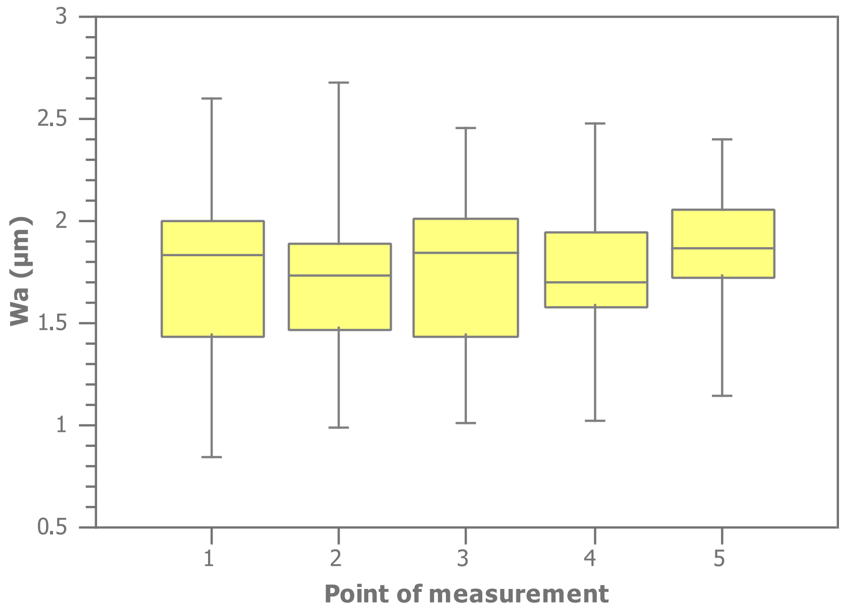

Figure 9. Values Wa in individual points of measurement on all samples made of titanium alloy Ti-6Al-4V.

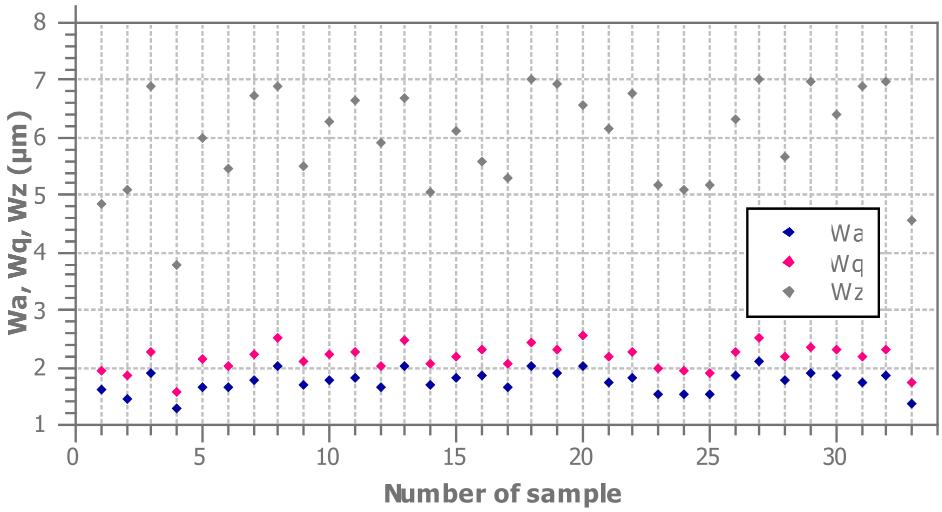

Figure 10. Average values Wa, Wq and Wz of samples made of titanium alloy Ti-6Al-4V with heat treatment.

specifically 2.26 μm. The average value Wq in the measured samples was 2.16 μm and for Wz it was 5.08 μm.

The maximum values of all of the three waviness parameters were for sample 30; its surface morphology is shown in Fig. 8.

The parameter Wa was measured in 5 points on each sample and its values did not differ significantly in these different points, which is apparent from Fig. 9. Nor in the parameters Wq and Wz was a significant deviation in individual points of measurement.

3.3. The results of the waviness profile measurements on samples made of titanium alloy Ti-6Al-4V with heat treatment

The profile measurements of the surface waviness parameters of samples made of titanium alloy with heat treatment were processed into Fig. 10. The average value Wq of the measured samples was 2.17 μm and for Wz it was 6.01 μm. The minimum measured value of the waviness parameter Wa was 1.3 μm for sample 4 and the maximum was 2.08 μm for sample 27.

No significant deviation was found in any of the three examined waviness parameters in individual points of measurement. The values of parameter Wa in 5 points of measurement were compiled into Fig. 11.

4. Conclusions and discussion

The morphology of sample surfaces is made up of a large number of craters which were formed by erosion process [15,16]. The profile parameters of the machined surface are dependent not only on the machine setting parameters [17], but also on the mechanical and physical properties of the machined material

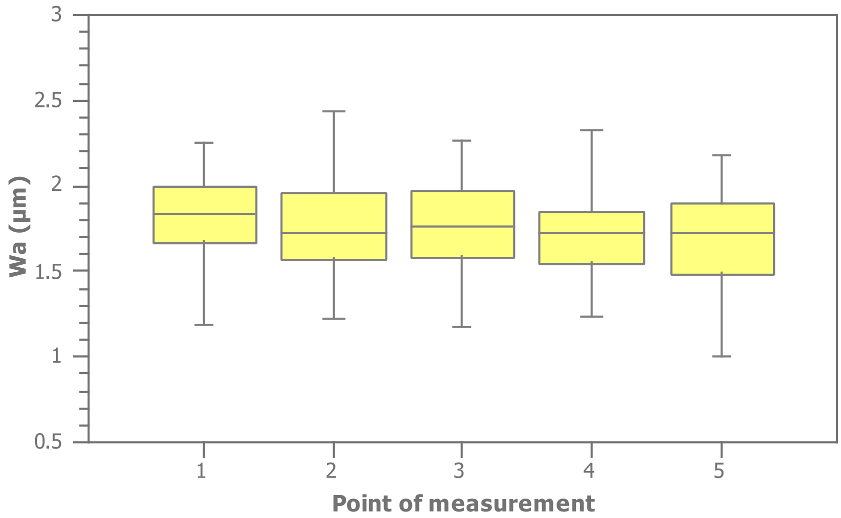

Figure 11. Values Wa in individual points of measurement on all samples made of titanium alloy Ti-6Al-4V with heat treatment.

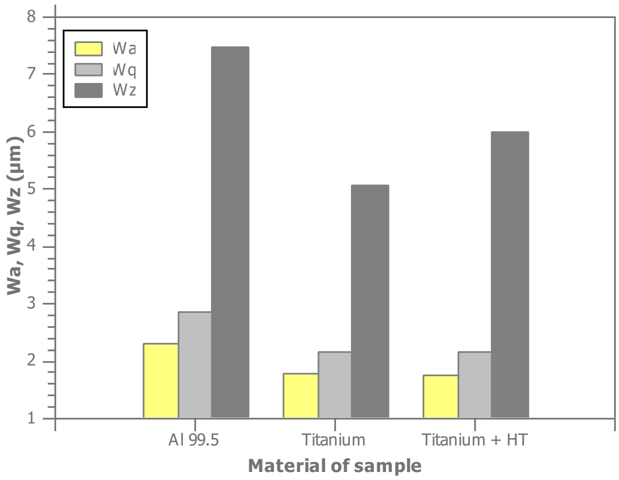

Figure 12. Average values of waviness parameters of individual sample sets of tested materials.

which are a direct consequence of the microstructure parameters of the studies materials [18].

The measured values of the surface waviness parameters are in accordance with literature [19,20,21]. It is evident from Fig. 12 that the maximum values Wa were measured in samples made of Al 99.5. The high values of Wa unequivocally relate to the low melting temperature of the material, low strength and with a relatively large grain size of the machined Al stock [22]. The surface of samples made of titanium alloys with and without heat treatment had almost the same average waviness value Wa, specifically 1.77 and 1.75 µm.

The average value of parameter Wz was highest in the set of samples made of Al 99.5, specifically 7.48 µm. The average value of Wz of samples made of titanium alloy without heat treatment was lower by 1 µm than of the samples made of the same material with additional heat treatment (quenched and tempered). This fact is quite in accordance with the rougher microstructure of the titanium sample after heat treatment.

The above-mentioned experiments quite clearly show that the profile parameters of surface waviness depend quite significantly not only on the setting of technological parameters during machining, but particularly on the chemical composition of the machined material and its mechanical properties after heat treatment. Effects of machining parameters are subject to a further research.

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