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Raziskave vodno jedkanih površin s svetlobnim zaznavanjem

An Investigation of Surfaces Generated by Abrasive Waterjets Using Optical Detection

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V prispevku smo opisali načelo nove metode svetlobnih meritev vodno jedkanih površin. Definirali smo paramatre meritev in določili postopek ustvarjanja podatkovne baze izmerjenih vrednosti ter metodo statistične in analitične obdelave podatkov za optimiranje tehnologije, izboljšanje kakovosti nadzora izdelave ter proučevanje mehanizma razkroja medsebojnega vpliva jedkalnega vodnega curka z velikimi hitrostmi in obdelovanega materiala.

(Ključne besede: jedkanje površin, abrazivni vodni curek, površinska hrapavost, optične meritve, spektralne analize)

In this paper we describe the principle of a new method for the optical measurement of surfaces generated by abrasive waterjets. There measured parameters are defined and we determined the way of creating a database of the measured values, and the method for statistical and analytical processing of data for optimising the technology, improving the quality of output control, and studying the mechanism of disintegration interaction between the high-speed abrasive waterjet and the machined material.

(Keywords: abrasive waterjet, surface roughness, optical measurement, spectral analysis)

0 INTRODUCTION

In the engineering practice of machinery, recent decades have been characterized by the intense development of non-traditional technologies in the machining of materials, including many technologies for machining using high-speed jets of liquid, especially those that involve the use of highly abrasive materials. While the technology of machining using a high-speed jet has already been solved in terms of hardware and software (except for some specific cases), the method of controlling the quality of the machined surfaces has remained a technical problem. The paper deals with the problems of selecting and proposing an acceptable method for surface-quality control that is available for continuous measurement and production. Knowledge of the surface topography and classification is very important for the machining techniques and research.

1 RELATED WORKS

The scale of the basic metrology operations is defined by standards determining a required quality class. These operations lead to the correct results for surfaces created by traditional technologies. The physical basis of the formation of new surfaces by non-conventional technologies is different; therefore, the geometrical characteristics of the created surface will be different ([1] and [2]). Surfaces produced by the technology of abrasive waterjets (henceforth referred to as AWJs) are very rough in comparison with those generated by classical machining technologies. The amplitudes of irregularities in terms of height are comparable with the amplitudes of these irregularities on more roughly dressed or planed surfaces. In comparison with ground, polished and lapped surfaces, those reach values can be even two orders of magnitude higher. With reference to the flexibility of a cutting tool, which is a high-speed stream of a mixture of water, abrasive particles and air, cutting traces are intensively curved in this case, and any constant spacing is not maintained. The lagging of the cutting traces behind the nozzle causes a specific deformation in the entry initiation and also the exit zone, i.e., greater deformation of the marginal edges of the samples. The changes in the direction of the vector of the total cutting force have an oscillating character with a frequency depending upon the materials, the cut length, or cut depth. Oscillations in the total cutting force and its components manifest themselves fully in the character of the distribution of the geometrical parameters of the final surface topography. The described specifics of these surfaces require specific approaches to the measurement methodology and interpretation. That is why our work was focused on the development of a new, optical-principle-based measurement apparatus, further on a definition of and the requirements for the optical quantity measured, on the structured selection of surface parameters measured, and on the way of storing the data and processing.

2 PROBLEM DEFINITION

Fig. 1 presents a photograph of a surface produced by AWJ, including the division into individual specific zones, i.e., the initiation zone (h_I), the smooth (h_{II}), transition (h_{III}) and rough (h_{IV}) zones. Next, surfaces created like this must be controlled, and the AWJ technology parameters must be influenced to increase the quality of a cut. As can be seen in Fig. 1, this surface is very rough and, in contrast to classically formed surfaces that have a mirror-like reflection, this surface is diffusion reflecting. For this reason, it is necessary to search for a way of measuring such specific surfaces. Another problem is the selection of the characteristic geometrical parameters of the topography structure. In Fig. 1 is the photograph of, and the proposal for, geometrical parameters typical of surfaces produced by AWJ. The statistical and analytical procedure prepared by us for the processing of data measured tends, from the point of view of conception, to derive physical equations for the relationships between the individual topographic parameters and the technology quantities.

3 PROBLEM SOLVING

3.1 Experimental Setup

A two dimensional AWJ machine Nessap 1000-V with the following specification was the main part of the experimental setup: the work table, x-axis 800 mm, y-axis 1000 mm, z-axis, discrete motion with a maximum traverse speed of 250 mm.min^{-1}. A PTV-37-60 high-pressure intensifier pump with a maximum pressure of 415 MPa and a Paser III cutting head manufactured by Flow Inc. were used. The basic technological parameters are presented in Table 1.

From the prepared metal plates of materials AISI 309, Fe 430 D2, Fe 360 BFN, GS 21 Mn5, AlMg, Zn, Al, brass and duralumin of thickness 8 mm, test samples of the dimensions (20 x 20 x 8) mm were cut out (see Fig. 2), with all the edges of the given sample being formed at different speeds (200, 150, 100 and 50 mm.min^{-1}). The height of 8 mm of each sample tested was measured by the optical shadow method

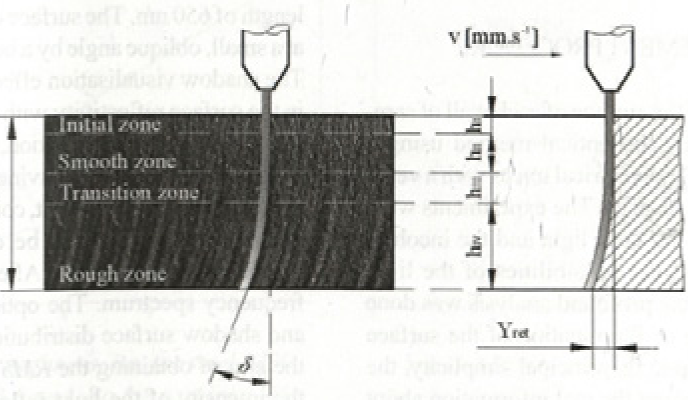

Fig. 1. *A photograph of a surface produced by AWJ with specific zones, i.e., initiation (h_I), smooth (h_{II}), transition (h_{III}) and rough (h_{IV}) zones, and the proposed main parameters of the surface profile, where δ is the angle of deviation, Y_{ret} is the retardation of the cutting trace over the height of sample h = 8 mm.*

Tabel 1. *Experimental setup*

Constant factors	Values	Constant factors	Values
Pressure p [MPa]	300	Standoff L [mm]	2 mm
Nozzle diameter d_o [mm]	0.25	Abrasive material	Barton Garnet
Focusing tube diameter d_a [mm]	0.8	Mesh [#]	80
Focusing tube length l_a [mm]	76	Cutting head	Flow Inc. Paser III.
Abrasive mass flow rate m_a [g.min^{-1}]	250	Variable factors	Values
Material thickness h [mm]	8	Traverse speed v_p [mm.min^{-1}]	50, 100, 150, 200
System characteristics of PTV-37-60 Pump			
Intensifier type	Double effect	Water pressure (max)	415 MPa
Electric input	37 kW	Water discharge (max)	3.68 l.min^{-1}

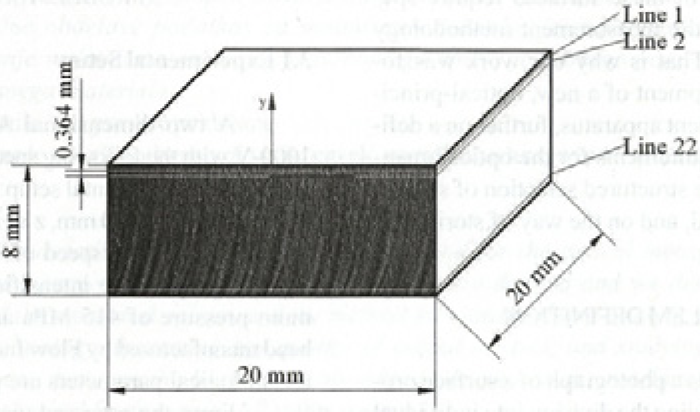

Fig. 2. *A test sample and measuring traces*

based on a CCD camera. The measurements were performed along 22 measuring lines at a vertical step of 0.364 mm on 4 walls. The soft materials, such as AlMg, pure Al and Zn, were machined at double the speed in the sequence of 400, 300, 200 and 100 mm.min^{-1} on these walls.

4 MEASUREMENT PROCEDURE

The quality of the surface of each wall of samples was measured by the optical method using a CCD camera along 22 geometrical traces with a vertical step of 0.364 mm (Fig. 3). The experiments were performed with both the laser light and the incoherent white light to test the possibilities of the light sources. In addition, the profound analysis was done to optimise the angle of illumination of the surface being measured. Despite its principal simplicity, the method takes into account the real information about the distribution of the surface roughness and also the elongated character of the surface defects. Thus, to all appearances, the measurement principle is appropriate for the purpose of studying the AWJ-created surfaces. At present, a CCD camera with 1090 x 1370 pixels is used for sensing and recording the intensity distribution of the light reflected off the surface. The experiments were carried out by using a laser diode with an output power of 3 mW at a wavelength of 650 nm. The surface observed is illuminated at a small, oblique angle by a beam of collimated light. The shadow visualisation effect arises from a change in the surface reflectivity with the illumination angle. Using this kind of illumination, hills, dimples and other defects and the typical waviness created by the AWJ are easily observable. Next, correct information about the surface quality can be obtained using a fast Fourier transform (FFT). After the FFT we obtain a frequency spectrum. The optical signals of the light and shadow surface distribution were analysed with the aim of obtaining the *RMS* (root mean square) of the intensity of the light reflection from the surface and transforming the equations between the *RMS* and the surface-roughness parameters, particularly the average roughness, *Ra* [µm].

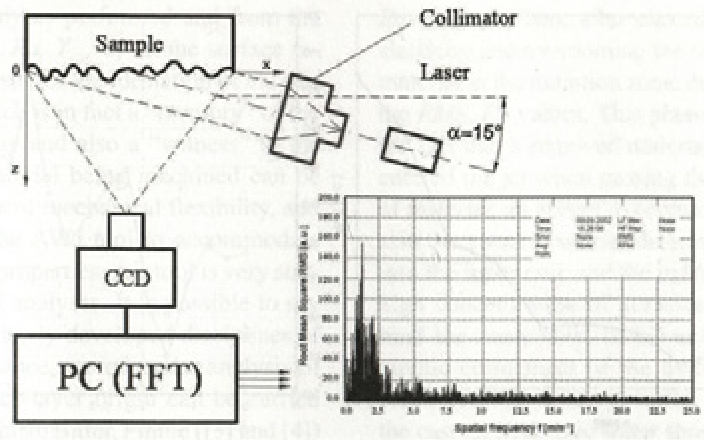

Fig. 3. *Basic setup for the optical method of shadow visualisation by CCD camera*

Along separated horizontal traces, selected geometrical parameters were measured optically as light-intensity variations. As the main surface geometrical parameters the average roughness, *Ra* [μm], the stream deflection, Y_{ret} [mm], and the deviation angle, δ[°], were proposed, see Fig. 2. The character of the distribution of the topographic elements divided the surfaces generated by the AWJ into the cutting wear zone, h_c [mm], and the deformation wear zone, h_d [mm], according to [3] and [4].

The values of the intensity distribution from the horizontal lines were projected into a CCD chip, and thus converted into the sample heights' distribution. On the basis of the statistical analyses, basic equations of the correlation with the measured optical quantity *RMS* (root mean square of the intensity of the light reflection from the surface) and to the cut depth *h*, defining the geometrical parameters of the surface were physically derived [5]. The parameters are presented in Figs. 4, 5 and 6.

The fluctuation in the *RMS* parameter depending on the topographic properties and the depth is shown in Figure 7. By the conversion of the *RMS* values to *Ra* values we obtain a characteristic view of the development of the roughness, *Ra*, the retardation, Y_{ret}, and the deviation, δ, depending on the cut depth, *h*.

5 RESULTS AND DISCUSSION

Fig. 8 presents the results achieved with a HOMMEL TESTER T8000 contact profilometer, i.e.,

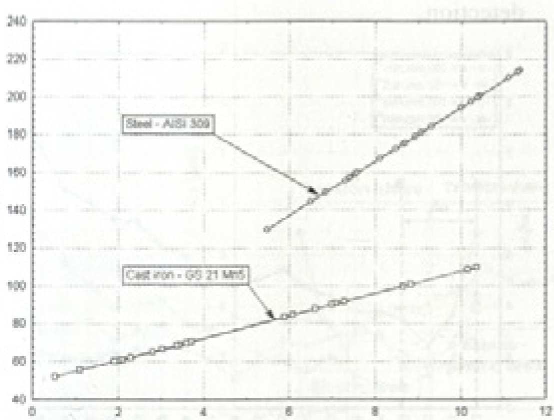

Fig. 4. *Parameter of roughness, Ra, for steel AISI 309: Ra = 0.07RMS-3.6 and Ra for cast iron GS 21 Mn5: Ra = 0.17RMS-8.3, determined by the conversion from the RMS according to the presented relations*

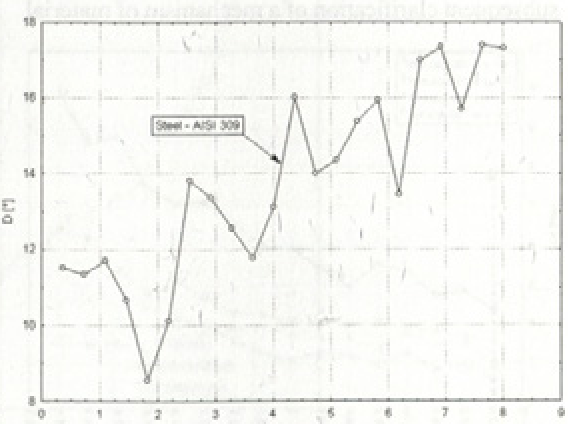

Fig. 5. *Deviation angle δ, δ= arctg(Yret/h)*

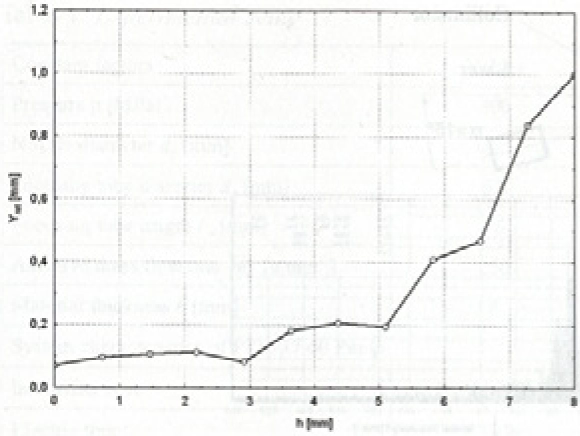

Fig. 6. *Stream deflection Y_{ret}, $Y_{ret} = 0.222.Ra.h_{rel}$, where the relative depth $h_{rel} = h_i/h$, h_i is the value of the trace depth at a cut level*

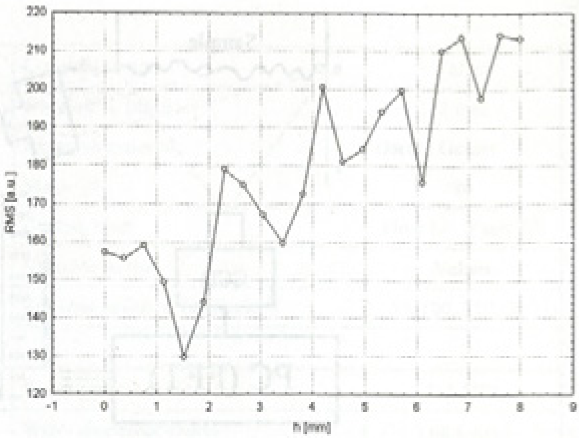

Fig. 7. *Dependence of RMS on the cut depth h for steel AISI 309*

a graph of roughness, *Ra*, versus the cut depth, *h*. These results show a good correspondence between the methods of direct measurement and those of optical measurement. Simultaneously, they draw attention to a serious fact concerning the problems of the detailed measurement of deformed sample edges in the initiation zone in a section Δh_x. This means that by using the contact profilometer the initiation zone with a higher roughness cannot be completely detected and localised. On the contrary, the results obtained with a MicroProf (FRT) optical profilometer show that more detailed information on the initiation zone can be provided. From the mechanical point of view, this entry region is of importance to the subsequent clarification of a mechanism of material removal and the explanation of AWJ-material interaction in this initiation zone (Fig. 9). From the practical point of view, it is then necessary to talk about impacts on the quality of the output control of the machined products. According to the results shown in Figure 8 and Figure 9, the initial zone is not identified by the contact profilometer, because the principle of measurement by means of a contact point does not allow any measurement in the immediate vicinity of the edge of workpiece when using the AWJ cutting technology. Improving the quality or the objectivization of the output control of the quality of the machined walls can thus be achieved by supplementing the contact measurement by optical detection.

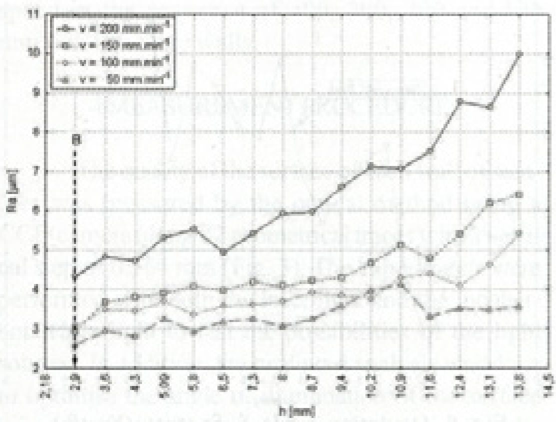

Fig. 8. *Results of the Ra measurement achieved with the contact profilometer, where B is the potential measurement beginning*

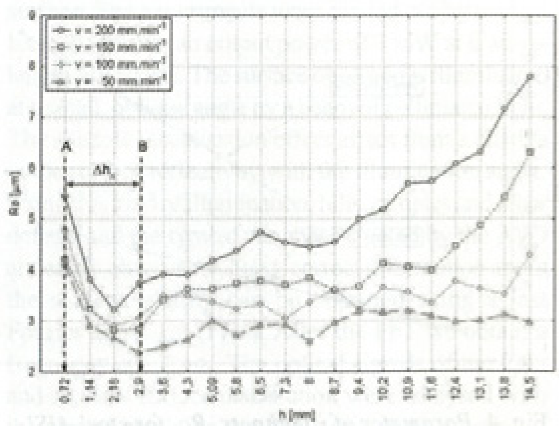

Fig. 9. *Results of the Ra measurement achieved with the optical method, where Δh_x is the difference between the points A and points B, representing an additionally measured surface*

From the analyses performed and from the obtained data (*RMS*, *Ra*, Y_{ref}, δ) on the surface topography, a mechanism for the formation of the surface topography, which is in fact a "memory" of the machining technology and also a "witness" to the properties of the material being machined can be deduced. For reasons of mechanical flexibility, and thus the ability of the AWJ tool to accommodate itself to the material properties, this tool is very suitable for a theoretical analyses. It is possible to say that in terms of the newly developed disciplines of technological inheritance, a profounder analysis of the process of surface-layer origin can be carried out. The authors Hashish, Bitter, Finnie ([3] and [4]) divide generated surfaces from the point of view of the removal mechanism into those with the removal mechanism of a cutting character and those with the removal mechanism of a deformation character. According to the literature [5], the topography formed is divided into the initiation zone (which is, however, neglected by the majority of authors), the smooth zone, and the rough zone. In our opinion, in the mechanism of the origin of a newly generated surface topography, the initiation zone cannot be ignored. This is the first contact with a disintegration tool, which here is a high-energy jet of a mixture of water, air and abrasive. In terms of a description of the AWJ's spread and degradation, it is possible to observe some phenomena (Figs. 10 and 11), i.e., the initiation zone, with a steep increase in the *RMS*, *Ra* values. Then, after exceeding the modulus of elasticity and overcoming the total resistance of the material in the initiation zone, there is a sharp drop in the *RMS*, *Ra* values. This phenomenon is related to the fact that a removed material from the sidewalls entered the jet when passing through the entry part of material, an abrupt oversaturation took place and also there was a contrast division of the jet structure into the inner core and the external envelope with a high concentration of abrasive grains lagging behind the inner core. In the external envelope, the kinetic component of the hydraulic energy transforms quickly to the potential energy, similarly to the case of hydraulic water shock. Using the potential energy excess, a deeper groove with a rather smooth trace will be formed, to which the optical device will respond with a decrease in the *RMS* value due to a low *Ra* value.

The next part can be characterised by a new redistribution of hydraulic energy in the cut and the compensation of the values for tension components in the tangential direction to the formation of the surface and in the axial direction to the deepening of the cut with the creation of a so-called "belly" with rather low values of *RMS*, *Ra* until striations occur. These are a feature of the endurance fractures of metals and alloys, and thus the beginning of a zone of steady plasticity of deformation with a marked periodicity beginning to be formed. The striations usually form shapes of shallow, parallel rows. The

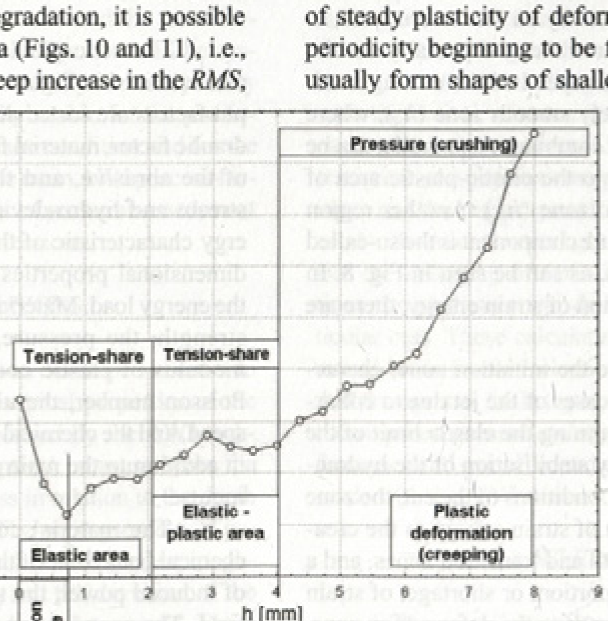

Fig. 10. *Dependence of the surface roughness, Ra, on the cut depth, h, geometrical and stress-deformation curve of topography zones*

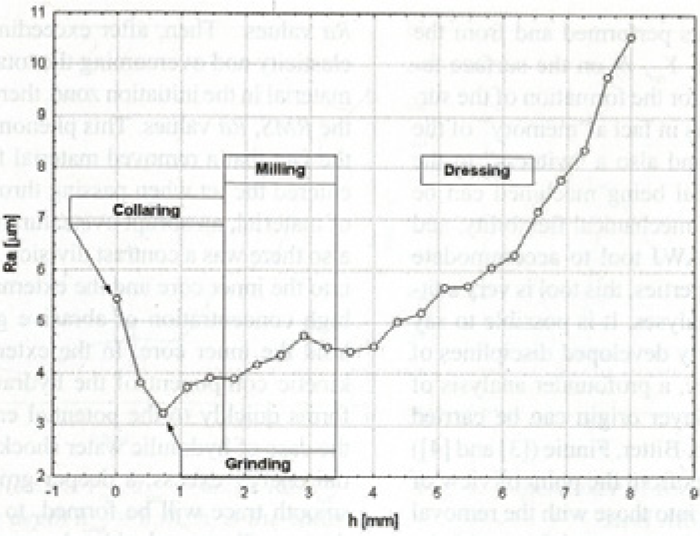

Fig. 11. *Dependence of the surface roughness Ra on the cut depth h and the expression of analogy concerning the proportions of the various technologies in the cut formation*

layout of the striations provides information about the local direction of the endurance fracture's propagation. From the standpoint of stress-deformation conditions, at the beginning the high stress and a rather smooth cut occur, and towards high values of *RMS*, *Ra* the stress diminishes proportionally to the increase in these values. We can say that the division of the cut into the initiation zone (h_I) can be used, which depends heavily on the material and, as for the technology parameters, especially on the selection of the traverse speed of the cutting head. Furthermore, a relatively smooth zone (h_{II}), where mainly a tension-shear combination prevails, can be determined, passing into the elastic-plastic area of the so-called transition zone (h_{III}). Another region with a prevailing pressure component is the so-called deformation zone (h_{IV}), as can be seen in Fig. 8. In terms of the consumption of strain energy, there are in principle three zones.

These zones are the initiation zone, characterised by the energy losses of the jet due to collaring the material, overcoming the elastic limit of the material and the energy stabilisation of the hydraulic and hydrodynamic conditions of the cut, the zone with a high proportion of strain energy in the creation of so-called smooth and transition zones, and a zone with a lower proportion, or shortage, of strain energy, which corresponds to the deformation zone. What is a specific feature of the surfaces generated by means of the AWJ is the fact that they are rough. Thus they may be regarded as surfaces produced by various classical technologies, such as collaring into the material in the initiation zone, grinding (high-energy area-zone) and machining in the medium part of the cut, across the area of rather rough turning, planing and rough dressing at the end of the cut (Fig. 11).

6 PROPOSAL FOR A DATABANK OF AWJ TECHNOLOGY CONTROL

The conceptual structure of the databank is characterized in Figure 12. The main input and output factors are sorted according to [6] so that a hydraulic factor, material factors, the shape and MESH of the abrasive, and the technical factors of the stream and hydro-devices create an output of energy characteristic of the stream. The material and dimensional properties of the samples depend on the energy load. Material parameters, like the tensile strength, the pressure, the torsion strength, the modulus of elastic compression, the weight, the Poisson number, the ultrasonic wave propagation speed, and the chemical composition, will represent, in addition to the main technology factor, the basic inputs.

The material constants determine the mechanical behaviour of the material and the character of induced power, the tension and the deformation field. The examination of a mathematical function between the input, i.e., the material and technology, and the output, i.e., the geometrical surface parameter, is the basis for their mutual influencing in the control system. The machining done by AWJ is a

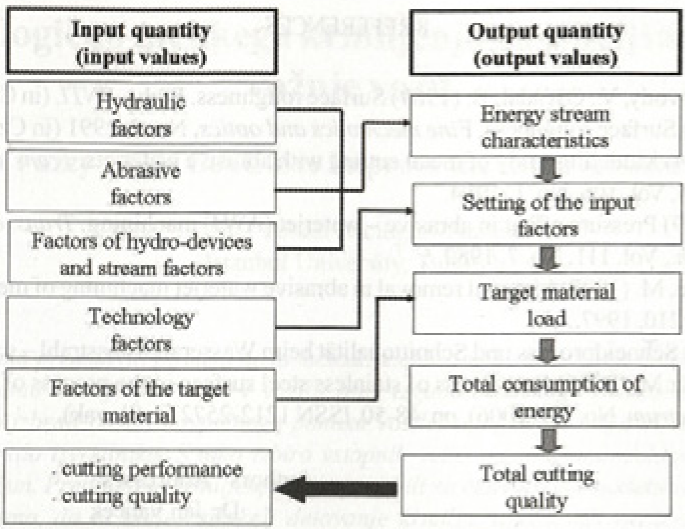

Fig. 12. *Conceptual structure of the databank*

process that is difficult in terms of technology. The project preparation, optimisation and the overall result of the AWJ machining are influenced by a number of factors. Partial influences of the factors are interconnected; some statistical-mathematical methods, such as factor analysis, which is presented, for example, in [7], have been applied to their optimisation and selection. Besides the cut surface topography parameters, the total energy consumption, the performance parameters and the manufacturing costs will be observed. The data will be systematically updated and statistically and analytically evaluated in order to be fully usable for the prediction of the geometrical surface condition and for the project of optimisation of the main AWJ process factors, which covers all kinds of materials used most frequently in technical professions.

7 CONCLUSIONS

An optical method was developed in order to characterize the basic geometrical properties of the topography of surfaces produced by the AWJ technology. On the basis of optical measurements the values of the *RMS* roughness in relation to the depth of cut *h*, can be evaluated. The main geometrical parameters of AWJ traces, such as the surface roughness *Ra*, the retardation Y_{ret} and the deviation of the cutting trace δ_t were defined and determined. These are the properties that are considered to be very important for many reasons, known well in both theory and practice. This is especially the case for the surface roughness *Ra*. A databank for the systematic holding and processing of the measured data in relation to the technology and material parameters was drafted. In the framework of verification it was found that optical methods, with regard to many specific advantages over the classical surface measurements, also represent the substantial objectives of the output control in the AWJ technology. For the development of the theory and practice of AWJ technology, a basis was defined in the above-presented way for solving other complicated issues connected with the theoretical handling of the mechanism of interaction between the flexible cutting tool and the material, and with theoretical relations to the regime technology parameters of the process. From the evaluation of statistical and physical-analytical rules between the input and the output quantities, it is possible to proceed to the mathematical generalisation of these rules and the deducing of statistical and physical equations for predictive and design calculations of particular cuts. These calculations should form a theoretical basis for the selection of cutting parameters that are optimal for the given material as well as for the required parameters regarding the quality, performance and overall economics of machining works made with the AWJ stream.

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