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ORIGINAL ARTICLE

Topographical anomaly on surfaces created by abrasive waterjet

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Abstract In the present study, real topographic function and maximal depth of neglected initial zone were analytically developed to predict surface roughness on the top region of surfaces created by abrasive waterjet. An upper area of workpieces was analysed in details. Experimentally created surfaces were measured by HOMMEL TESTER T8000 and non-contact profilometer Micro Prof FRT. As an experimental material, stainless steel AISI 304, AISI 309 and aluminium with a thickness of 10 mm have been used. On the basis of analysis and interpretation of data obtained from the surface, a topography function Ra_d, which is necessary to be known for the subsequent prediction and control of abrasive waterjet cutting technology, is derived. In the framework of interpretation of measured values, relations among these parameters are systematically analysed and physico-mechanical and distributional principles governing these parameter are formulated newly. Results are very important for further estimation of analytical expression of the real topographic function for any surface created by abrasive waterjet cutting.

Keywords Abrasive waterjet · Surface topography · Initial zone

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Nomenclature

b	Material thickness (mm)
d_f	Diameter of focusing tube (mm)
d_{fopt}	Optimal diameter of focusing tube (mm)
d_o	Diameter of water orifice (mm)
E_{mat}	Young's modulus of elasticity (MPa)
h	Depth of cut (mm)
h_0	Depth level of neutral plane (mm)
h_{iz}	Depth of initial zone (mm)
h_j	Distribution function of depth of cut (mm)
K_{cut0}	Quantity of material cut ability (mm)
m_a	Abrasive mass flow rate (g min^{-1})
m_{aopt}	Optimal abrasive mass flow rate (g min^{-1})
p	Pressure of permeate (MPa)
p_{opt}	Optimal pressure of permeate (MPa)
Ra	Surface profile roughness parameter—average roughness (μm)
Ra_o	Surface roughness in neutral plane of the cut (μm)
Ra_j	Unit surface roughness (μm)
$\mathrm{Ra}_{\mathrm{rad}}$	Surface roughness in radial plane (μm)
Rq	Root mean squared (μm)
Rz	Peak to valley (μm)
v_p	Traverse speed (mm min^{-1})
$v_{p\mathrm{opt}}$	Optimal traverse speed (mm min^{-1})
Y_{ret}	Retardation of cutting traces (mm)
Y_{ret0}	Retardation in neutral plane (mm)
z	Stand-off distance (mm)
σ_{def}	Deformation tension (MPa)
σ_t/σ_p	Ratio tension and pressure deformation (MPa)

1 Introduction

On the basis of the study of historical and current developments of AWJ technology in theory, experiments and practice, we know, in accordance with the opinion of contemporary authors that the issues of physico-mechanical principle of material disintegration and generation of a new surface by abrasive waterjet cutting remain even at present unsolved and are, thus, open. Longstanding problems associated with AWJ are micro- and macro-irregularities in the form of roughness and waviness that arise from the AWJ cutting of materials. These surface defects limit the wider use of the AWJ technology in industry [1–3]. In consideration, it is surprising that there is currently no study that would bring a complex assessment of whole surface topography including neglected upper zone of the surface. AWJ is the subject of many research, their contribution is only partial. They focus on the evaluation of certain ambiguous depth defined lines and their approach is from an experimental point of view focused only on one factor, which authors consider as an important significance [4–6]. The main purpose of the experimental study is an effort of deeper, more comprehensive insight into the problem analysis to the topography of surfaces created by abrasive waterjet (AWJ), with the goal of deeper analysis of whole surface topography including neglected initial zone.

2 Related and previous works—problem definition

The cutting process in the technology using an AWJ is an abrasive waterjet disintegration process due to the force [6–8], stress and deformation action of a cutting tool of AWJ type on the material of workpiece; the tool being here a high-speed stream of a mixture of water and abrasive material [9–15]. A result of the cutting process is a cut [16]. A mechanism of antagonism between external and internal reactive physical and mechanical factors induced by the cutting tool will achieve a balance [17] that will be represented in final form by a topography function of condition of cut wall surface generated in a plane of cut. As for the AWJ technology, what is meant is a cutting, or machining tool with mechanical properties somewhat different from those of cutting, machining and drilling classical tools in machine and other industries. This cutting tool is essentially not a rigid but a considerably flexible tool, and thus the trajectory of its cut trace changes quickly in critical moments of interaction with the material [18–21]. The abrasive-deformation process of material cutting by the AWJ stream is in principle given by the elementary action of abrasive particles [20]. The essence of action of force follows from the impingement speed in contact with the surface of cutting front in the plane of contact angle. This is a case of interaction between the effective flow field of AWJ and the instantaneous geometric dimensions of surface interactive area of material in the plane of cut being subject to this AWJ flow field [22, 23]. The reverse reaction of material causes changes in the process of cutting, changes in original parameters of the material and changes in initial factors of AWJ flow field. Material cutting, utilizing the AWJ technology, is characterised by a typical curvature and a retardation of trace of the cut behind the nozzle in the course of deepening the cut [1–36]. Physico-mechanical and tensometric properties of the material of workpiece determine the intensity of reaction forces and characterise or classify each material into classes of cuttability of the material using an AWJ [13]. Up to now, generally an opinion has prevailed that the cutting process and the analytical solution for it are complicated from the physico-mechanical point of view, i.e. that the unambiguous physico-mathematical description of functions taking place in the process is complicated with regard to the complexity of the whole set of engineering, technology and material factors entering the process.

It is a fact that in the latest publications and papers at special conferences, we can find neither the quantitative solution of such analytical issues as the discussed problem of oscillations and rotation of abrasive particles and AWJ stream as a working tool, nor the solution of problem of process hydrodynamics.

The majority of theoretical works (e.g. [17–21, 24–26, 28, 33, 34]) are orientated towards the presentation of laboratory measurements of authors and/or the comparison of authors' own results with results of other laboratories but without rather deep analyses and generalization. Actually measured values are very often distorted by their idealization so that comparable results may be obtained. Thus, a so-called "trimming" of special entry region (Fig. 1) at the beginning of cut, which is called initiation zone, occurs. The shape and the geometric factors of initiation zone are of great diagnostic importance to the evaluation of technology projects [5, 6, 28, 30, 32]. In our opinion, from the point of view of objectivity and comprehensive explanation of mechanism of formation of the topography of a newly generated surface, it is not possible to neglect the initiation zone because it shows the first contact with the disintegration tool of AWJ type [5, 6, 28, 30, 32].

According to some authors topography of the surfaces created by AWJ of relatively thick material consists of a smooth upper zone and a striated, wavy lower zone [7–9]. The authors [9, 10] divide the surface, which is generated by AWJ of the mechanism of removal in the cutting mechanism and deformation mechanism [11–13]. Following Fig. 2, it shows development of scientist opinions on topography divisions of surfaces created by AWJ [1–17]. According to state-of-the-art analysis, most authors in their study of surfaces created by AWJ used a contact profilometer. Hence, the initial zone with a rather great roughness could not be completely detected and localized. According to our preliminary study where the contact profilometer Mitutoyo Surftest SJ 401 was used, where the first depth trace from top of workpiece was 1.45 mm, the initial zone cannot be detected and localized

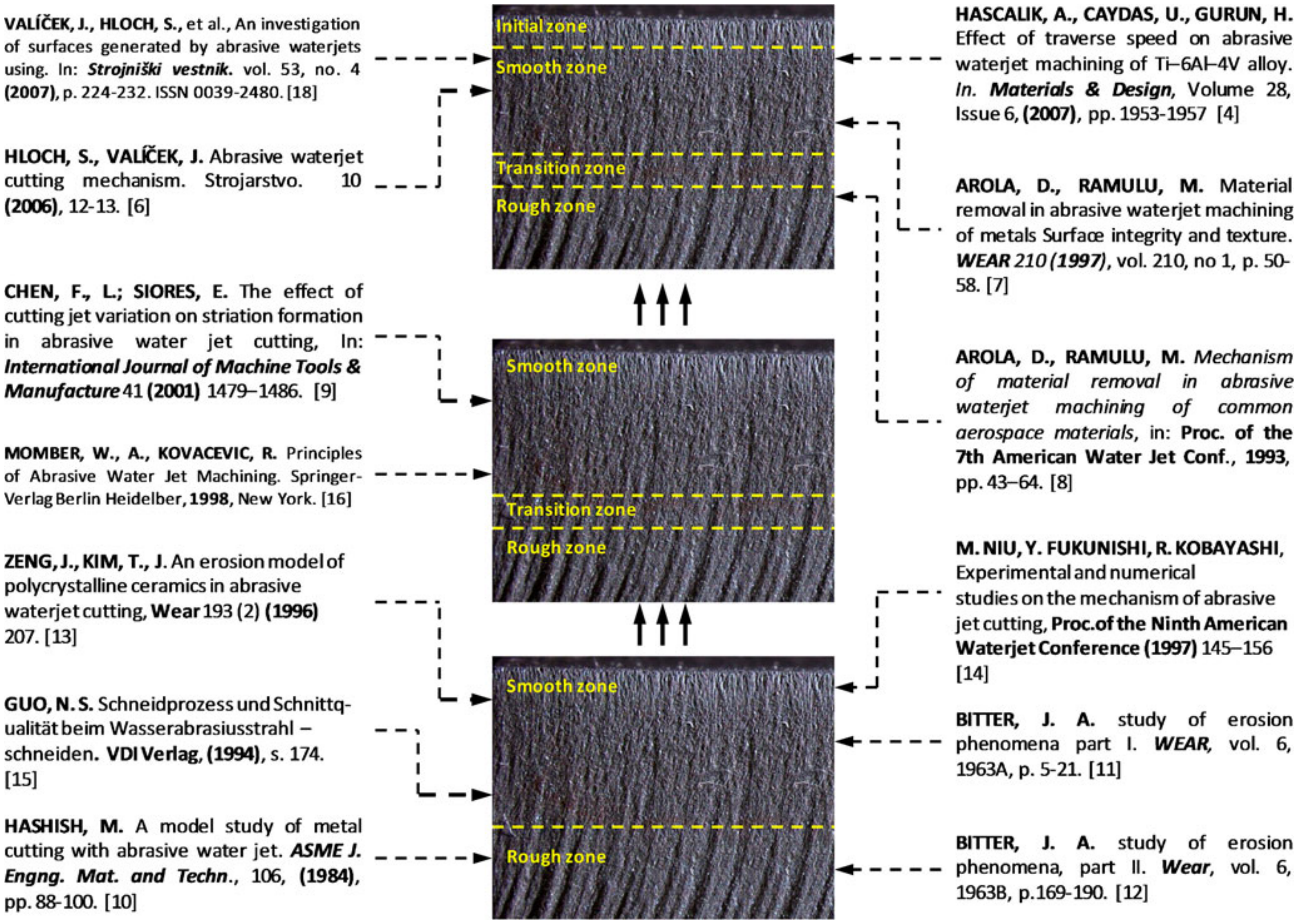

Fig. 1 Development of scientist opinions on topography divisions of surfaces created by AWJ

(Fig. 2). On the contrary, results obtained by an optical for example commercial profilometer MicroProf (FRT) show that more detailed information about the surface including the initiation zone can be provided (Fig. 2). From the theoretical point of view, this entry region is of importance to the subsequent classification of a mechanism of material removal and the explanation of AWJ–material interaction [17, 24]. From the previously made analyses and from the obtained data on surface topography, a mechanism of formation of the surface topography, which is, as a matter of fact, a memory of machining technology and also a witness to properties of the material machined, may be deduced. In our opinion, in the framework of objectivity of the explanation of mechanism of origin of newly generated surface topography, the initial zone cannot be ignored, because it evidences the first contact with an AWJ tool [14, 15].

3 Experimental set up

To secure an objective study of topography in initial zone, two designs of experiments were employed because the roughness depends on a large number of process factors such as traverse speed v_p (mm min^{-1}), abrasive mass flow rate m_a (g min^{-1}), pressure p (MPa), focusing tube diameter d_f (mm), focusing tube length l_f (mm), stand-off distance z (mm), orifice diameter d_o (mm), abrasive material grain size (MESH), abrasive material type, angle of impact φ (°). Technological and environmental conditions of experiments are shown in Table 1. For studying the influence of process factors on surface roughness in entry zone of workpiece, a precision two-axis positioning table from the company Wating, designed for planar applications of abrasive waterjet cutting technology, was used. Water pressure was generated by a pump Stream Line SL III from the company Ingersoll Rand. As a technological head, a cutting head Autoline™ from the company Ingersoll Rand was used. Furthermore, a material steel AISI 304 and 309 and aliminium of a thickness of 10 mm was used. Roughness profile parameters Ra, Rq and Rz determined by means of optical profilometer MicroProf FRT from manufacturer Fries Research & Technology GmbH, Germany, on a workplace of the Physical Engineering Institute FSI VUT in Brno [25]. Matrix value of altitude unevenness of

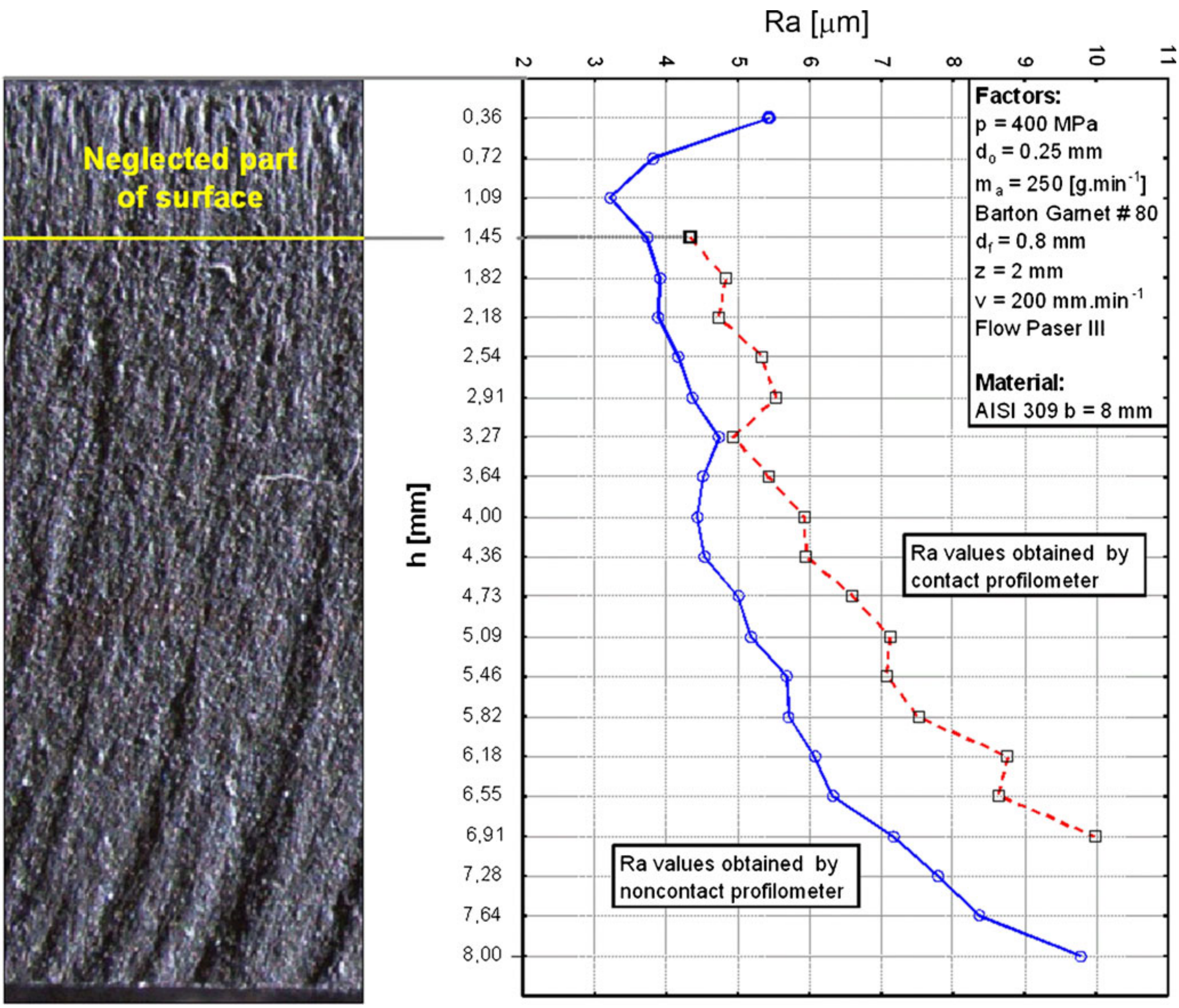

Fig. 2 Effect of measurement method of surface created by AWJ by contact and non-contact profilometer, material AISI 309, obtained real shape of surface topography function Ra = *f(h)*, including initiation zone in material steel AISI 309 at traverse speed of cutting head v_p=200 mm min^{-1}

surface, generated by composition of AWJ technology factors from the whole area of the surface was obtained by three-dimensional contactless and non-destructive measurement. In entry zone, for the purpose of identification and analysis of factors influence on topography of surface in initial zone, was the value of equidistant distances of particular depth traces in the surface from 0.1 to 2.5 mm. Measurements in entry zone were realized in 25 depth traces. Proper measurements were realized in the central zone of the sample excluding marginal areas of the sample to reach the most accurate measurements. Each measurement was repeated eight times to achieve statistically the most accurate result. Following Fig. 3a, b, display plots of surface profile parameters Ra, Rq and Rz obtained from optical profilometer MicroProf FRT were shown.

4 Results and discussion

On the samples produced by AWJ, it is possible to clearly distinguish the entrance area, the surface cut and exit the area (bottom part of the surface, Fig. 4a, b). Created surfaces and associated irregularities show the specific geometry. Technological conditions have an impact on the physico-mechanical interactions of AWJ cutting of the material, the total morphological pattern of the surface and its topography. The following pictures (Fig. 4) are given plots of impact factors on the profile of roughness parameters Ra, Rq and Rz detected in 25 lines of depth to a depth of 2.5 mm, with a focus on the study of irregularities in the initiating zone.

The boundaries of this zone are typically the little rounded edges on the surface due to plastic deformation

Table 1 Technological conditions of experiments

Factors	Experiments	
	I	II
Type of intensifier (FLOW 9xD55)	Double acting	Double acting
Power of intensifier (HP)	60	60
Pressure in hydraulic circuit (MPa)	20	20
Intensification ratio	20:1	20:1
Maximal pressure (MPa)	380 MPa	380 MPa
Accumulator volume V (l)	2	2
Cutting head type	Autoline™	Autoline™
Pressure p (MPa)	200, 350	200, 350
Water orifice diameter d_o (mm)		
MESH	80	80
Abrasive mass flow rate m_a (g min^{-1})	300, 500	200, 400
Focusing tube diameter d_f (mm)	0, 8; 1, 2	0,8; 1, 2
Focusing tube length l_f (mm)	78	78
Angle of attack φ (°)	90	90
Standoff distance z (mm)	2	2
Number of passes	1	1
Traverse speed v_p (mm min^{-1})	70, 120	100, 200
Cutting direction (°)	180	180
Materials	AISI 304[a]	Aluminium[b]
Material thickness b (mm)	10	10

[a] Chemical composition—C=0.08% max; Mn=2% max; Cr=19%; Ni=9.5%. Mechanical properties—HRB=95; E_{mat}=193 GPa

[b] Chemical composition—Al, 99.99%; Cu, 0.006%; Fe, 0.006%; Ga, 0.005%. Mechanical properties—HRB=12; E_{mat}=62 GPa

of material. Deformation was caused by the initial contact of the AWJ stream with the material to the local minima of the topographic features (Figs. 3a, b and 4a, b). Figure 5 shows an example of heterogeneous surface with highlighted initial zones.

From the point of view of description of AWJ propagation and degradation towards the cut depth h and according to the measured *RMS* values, it is possible to observe the following phenomenon, namely the existence of initiation zone, which is a zone formed in the material due to the first contact with AWJ. This initiation zone is characterised by a sharp rise in RMS and Ra values (Figs. 3, 4 and 5). After overcoming the total resistance of material in the initiation zone, a steep decrease in RMS and Ra values, caused by a local decrease in material resistance to the penetrating AWJ stream, will occur (Fig. 5).

In the light of description of AWJ propagation and degradation, it is possible to observe the following facts in the material steel AISI 309 at the traverse speed of cutting head v_p=200 mm min^{-1}. What is meant is the determination of initiation zone, i.e. zone with a steep rise in RMS, Ra values to the depth h=0.8 mm. After exceeding Young's modulus and overcoming the total resistance of material in the initiation zone, there will be a sharp decline in RMS values; Ra at the depth h= 1.5 mm is connected with the fact that in the course of penetrating the input part of material the jet entrains crushed material taken from the walls. Thus, a rapid oversaturation occurs, and also the contrasting division of the jet into an inner core and an outer envelope with a high concentration of abrasive grains lagging behind the inner core appears. In the outer envelope, the kinetic component of hydraulic energy transforms at high speed to potential energy similarly to the case of incomplete hydraulic impact. By the excess potential energy, a rather deep groove with a relatively smooth trace is created, to which optics reacts by a decrease in RMS value due to a low Ra value. The next section can be characterised by the new repeated division and stabilization of hydraulic energy in the cut. The value of stress component in the direction tangential to surface generation and the value of stress component in the direction perpendicular to the deepening of cut with the formation of a so-called "tummy" are equal.

Mechanisms of material erosion can be characterised as volumetric, three axes in the entry, i.e. initiation zone, planar in the area of cut wall in the stabilized zone and deformation plastic in the exit zone of the cut. According to the geometric dimensions and shape of initiation zone at the top of the cut and at the bottom of the cut at the exit of jet from the sample, it is possible to assess back the correctness of the selection of technology parameters in relation to the physico-mechanical parameters of the cut material. At the entry to the material the AWJ stream is stable as far as

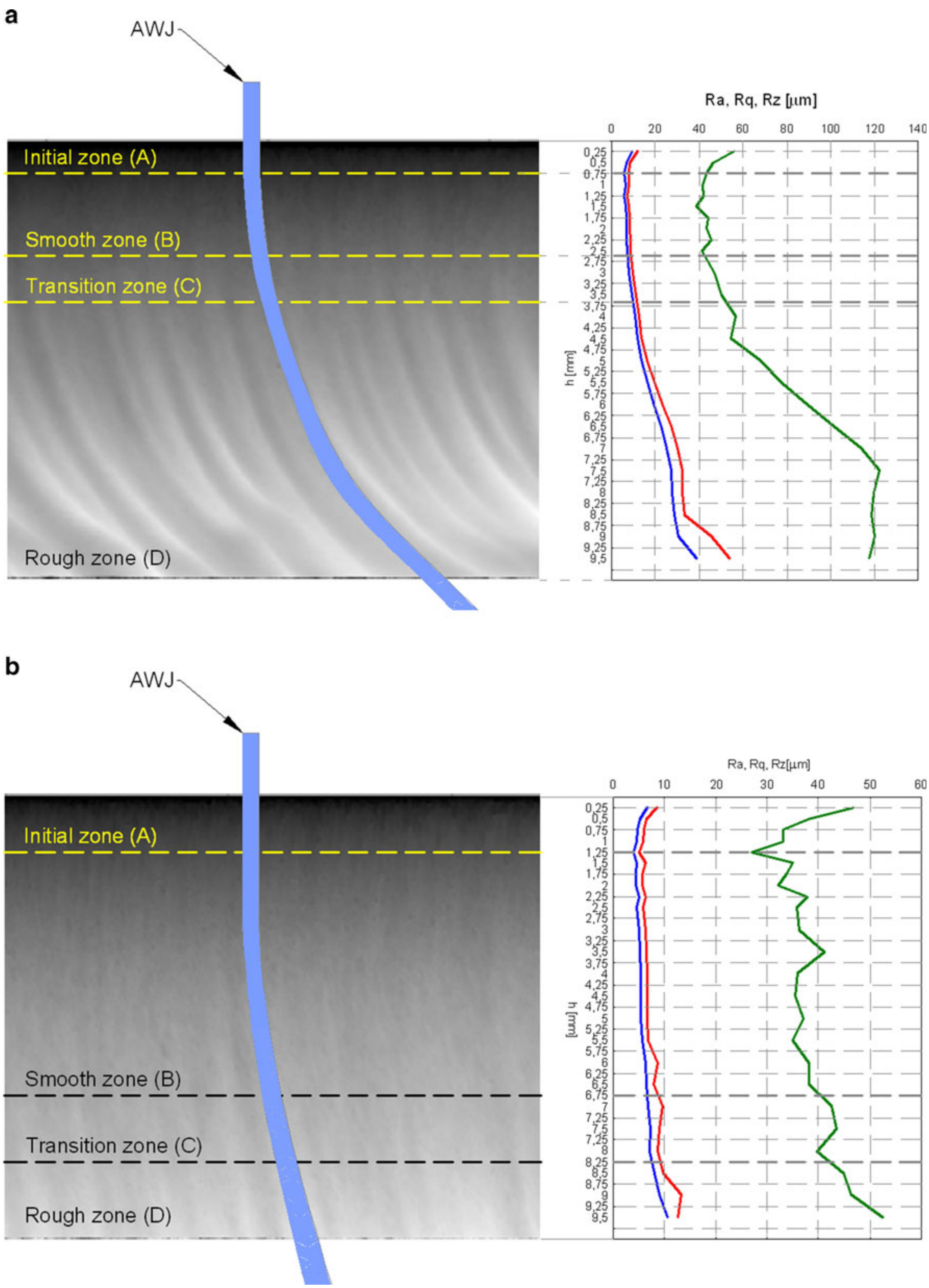

Fig. 3 Factors influence on surface roughness profile parameters Ra (μm), Rq (μm) and Rz (μm), where surfaces were made under the following conditions **a** v_p=70 mm min^{-1}, p=200 MPa, m_a=300 g min^{-1} and d_f=1.2 mm; **b** v_p=70 mm min^{-1}, p=350 MPa, m_a=300 g min^{-1} and d_f=1.2 mm

volume and direction are concerned, concentrated, and the orientation of cutting front corresponds in the transverse and longitudinal directions to the position of the nozzle; it occurs in the plane of the nozzle. The trace of the cut does

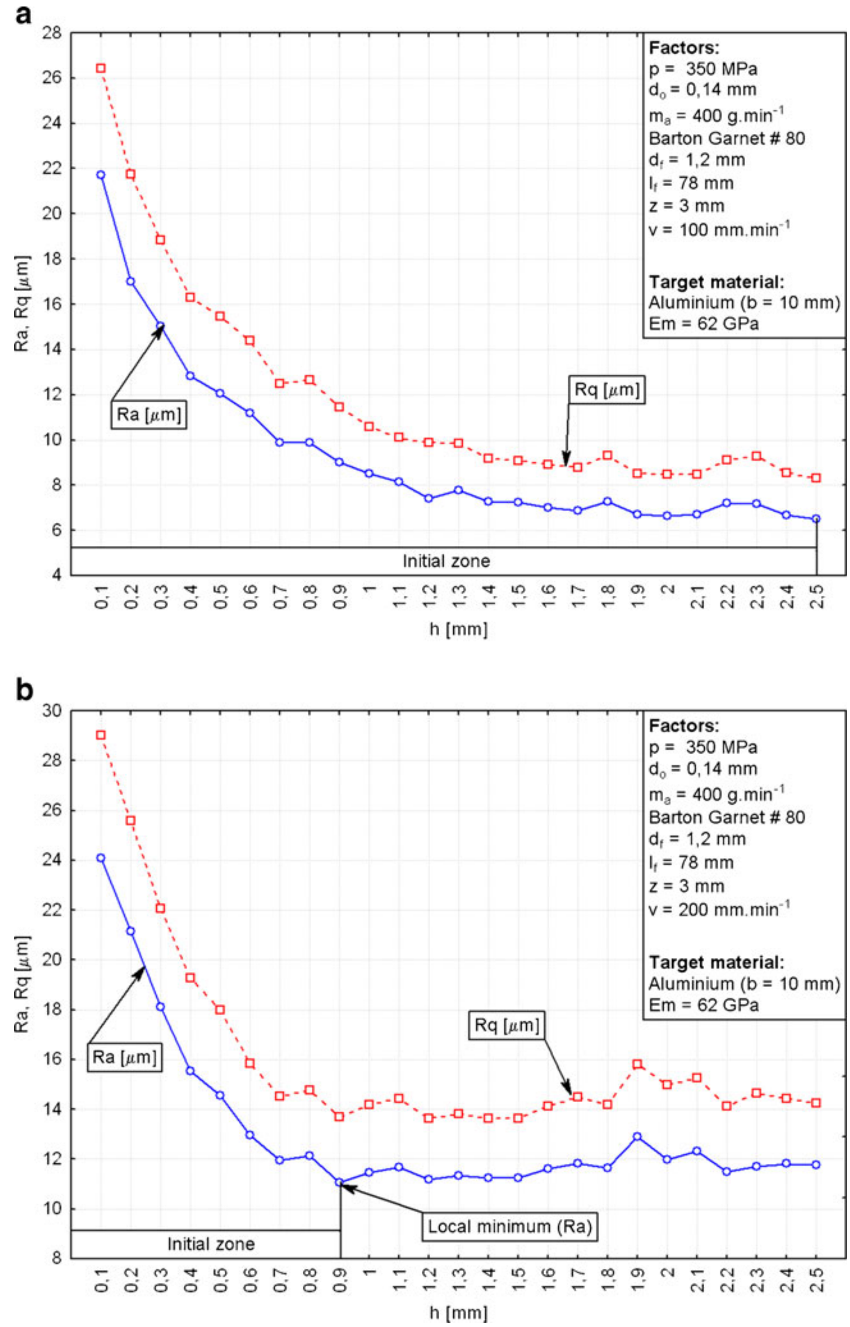

Fig. 4 Detailed view of plots of surface profile parameters Ra and Rq in entry area of sample (initial zone is highlighted) dependence at different traverse speed: **a** 100 and **b** 200 mm min^{-1}

not yet curve intensively due to lagging in relation to the traverse speed of cutting head. At first, there is an initiation zone, which is heavily dependent on the material and, as far as the technology parameters are concerned, especially on the selection of traverse speed of cutting head.

This phenomenon is related to the fact that a removed material from the workpiece entered the jet when passing through the entry part of material an abrupt oversaturation took place and also a contrast division of jet structure into the inner core and the external envelope with a high concentration of abrasive grains lagging behind the inner core. Peripheral part of AWJ at this stage contains a high concentration of grains, which accumulate in the depth due to the slowdown. In the depth the rate of pressure component is increasing, which has deformation character on material being cut. In AWJ stream, volume and weight ratio of removed material with zero kinetic energy increases. Because of local congestion is to create a relatively smooth trail surface where we detect low values of surface profile roughness parameters Ra, Rq and Rz (Fig. 4a, b). Factor analysis from experiments and subsequent analysis showed the impact of several factors, therefore we consider these assumptions to be inaccurate. As seen in Figs. 3, 4 and 5, width of initial zone depends on

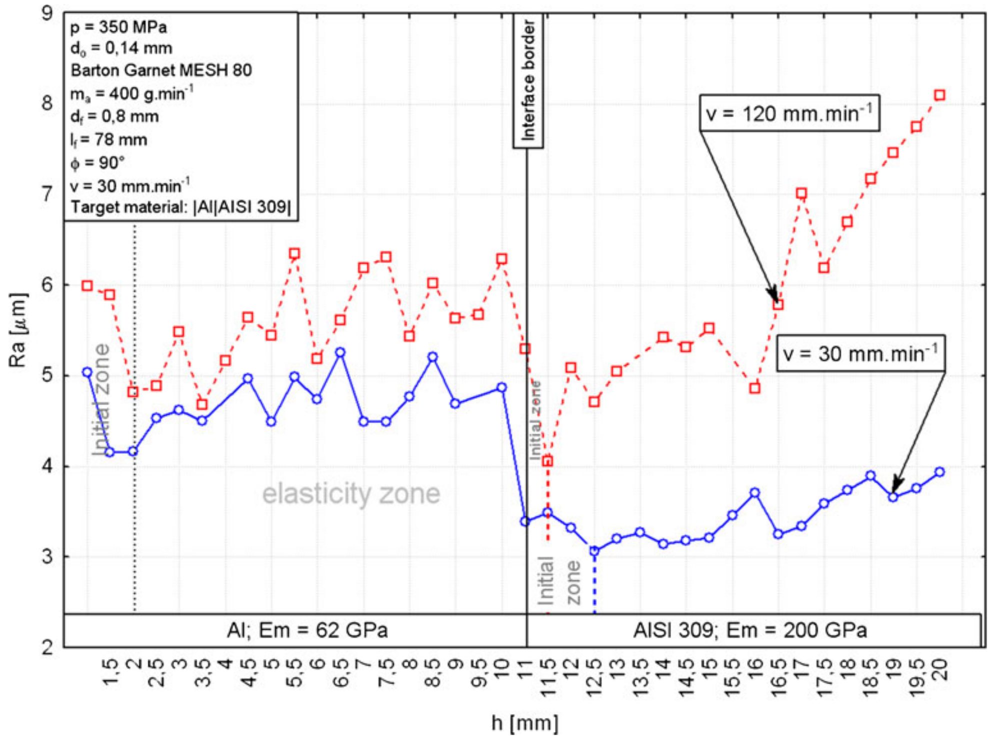

Fig. 5 An example of heterogeneous surface with highlighted initial zones (material composition, |Al|AISI 309|)

specific combination of affecting AWJ factors. Figure 5 shows that surface roughness and the topography of the whole surface also depends on physical properties of material. This means that the occurrence of initial zone depends on the hydrodynamic properties of the AWJ, technological factors and material properties. One of the most important factors in AWJ cutting is the traverse speed of a cutting head.

5 Prediction depth of initial zone and surface roughness

On the basis of measurement by the optical profilometer MicroProf FRT, further by the contact profilometer HOMMEL TESTER T8000 and by the shadow method, data were analysed and interpreted to describe theoretically the surface topography. The analytical solving of surface topography function is complicated, and that was why the influence of initiation zone was neglected and the dependence of really detected roughness $Ra_d = f(h)$ was replaced according to various authors by more easily definable functions. Idealization and principal distortion, thus, occurred. For this reason, a more realistic approximation for the calculation of really detected surface roughness Ra_d (μm) was derived in the works of the authors according to Eq. 1 using an auxiliary function Ra_{rad} (μm) dependent on deformation stress. To Ra_{rad}, the following relation applies:

$$Ra_{rad} = f(\sigma_{def}),\ \text{where},\ \sigma_{def} = f(Y_{ret}, E_{mat})$$

The derivation of the distribution function of roughness Ra_d, including the approximation expression of onset of roughness in the initiation zone is semi-empirical. From the analytical point of view, it is based on the assumption that the construction of it on the real surface is given by the geometric sum of instantaneous stress-deformation components of disintegration.

By means of an analytical solution, the assumption that the construction of the function of real surface is given by the sum of tensile and pressure component of deformation tension in initial zone till h_{iz} depth (mm). A new equation (Eq. 7) is derived for the initial zone range. The real topographic function can be express by the equation derived in Ref. [37] (Eq. 1):

$$Ra_d = Ra_j \cdot \left(\sqrt{\left(\frac{v_p}{v_{popt}} \cdot \frac{m_a}{m_{a\,opt}} \cdot \frac{p}{p_{opt}} \cdot \frac{d_f}{d_{f\,opt}} \right)} \cdot e^{\ln\left(\sqrt{(\log h)^2} + \sqrt{\left(\log \frac{1}{Y_{ret}}\right)^2 + Ra_{rad}^2} \right)} \right) \qquad [\mu m] \qquad (1)$$

Where v_p is the traverse speed of cutting head (mm min^{-1}), v_{popt} is the optimal traverse, m_a is the abrasive mass flow rate (g min^{-1}), m_{aopt} is the optimal abrasive mass flow rate, p is pressure, p_{opt} is optimal pressure, d_f is the focusing tube diameter and d_{fopt} is the optimal focusing tube diameter speed of the cutting head (mm min^{-1}), h is depth (mm), Ra_j is unit surface roughness (μm), Y_{ret} is the retardation of cut trace (mm). Auxiliary topography function is expressed by relation (2) Ra_{rad} (μm):

$$\mathrm{Ra}_{rad} = \mathrm{Ra}_j \cdot e^{\ln\left(10^3 \cdot \mathrm{Ra}_o Y_{ret}^{0,25} \cdot E_{mat}{}^{-0,5}\right)} \qquad [\mu m] \qquad (2)$$

where E_{mat} is Young's modulus of elasticity (MPa), Y_{ret} (mm) in Eq. 2 is retardation of abrasive waterjet and can be expressed by following term (Eq. 3):

$$Y_{ret} = \mathrm{Ra} \cdot \frac{h}{K_{cut}} \qquad [mm] \qquad (3)$$

where is variable K_{cut} (mm) is ability of abrasive waterjet to cut material and can be expressed by following Eq. 4:

$$K_{cut} = \mathrm{Ra}_o \cdot \frac{h_o}{Y_{ret_o}} \qquad [\mu m] \qquad (4)$$

where Y_{ret_o} (mm) is retardation of AWJ trace on the level of the neutral plane. From theory $Y_{ret_o} = Y_{ret_j}\, \sigma_t/\sigma_p = 1$ where σ_t/σ_p is ratio of tension and pressure deformation, h_0 (mm) is depth level of neutral plane. Equation for expression of h_0 (mm) is Eq. 5:

$$h_o = h_j \cdot \frac{K_{cut}}{\mathrm{Ra}_o} \qquad [mm] \qquad (5)$$

where h_j unit depth of cut (mm), Ra_0 (μm) is surface roughness in neutral plane of the cut. Value of the constant K_{cut} (μm) determines a technological property—cuttability of material by AWJ. Figure 6 graphically expressed the typical behaviour of topographical function Ra_d. Prediction of theoretic behaviour represents in Fig. 6 a smooth curve derived according to Eq. 1.

Additional benefit of the research is an opportunity to derive a technologically optimal traverse speed v_{popt} (mm min^{-1}) for material, which is expressed by material mechanical property E_{mat} (Eq. 6):

$$v_{p_{opt}} = v_{pj} \cdot e^{\ln \sqrt{\left(10^{-3} \cdot \mathrm{Ra}_o\right)}} \cdot \frac{10^6}{\sqrt{E_{mat}}} \qquad (mm\ min^{-1}) \qquad (6)$$

The depth of initiation zone h_{iz} is there, where the topographical function Ra_d by Eq. 1 reaches a local minimum (Figs. 2 and 3). The initiation zone varies according to the used materials and technologies and it does not depend on the thickness of material. The smaller the strength of the material is, the higher a cutting depth is, and thus up to 2.5–3 mm. This is also evidenced by the attached dependency graph in Fig. 7 generated by Eq. 7. This also means that in smaller thickness of about 10 mm, the topographic anomaly reaches up to 30% of thickness and markedly decreases the quality of the cut wall, functionality and usability of the workpiece or it requires a subsequent processing. To prevent the creation of the initiation zone is very problematic because this is inevitably related to the mechanism of disintegration of the material in the area of the flexible tool penetration. Several methods were tested, e.g. the method of rotation a cutting head in the

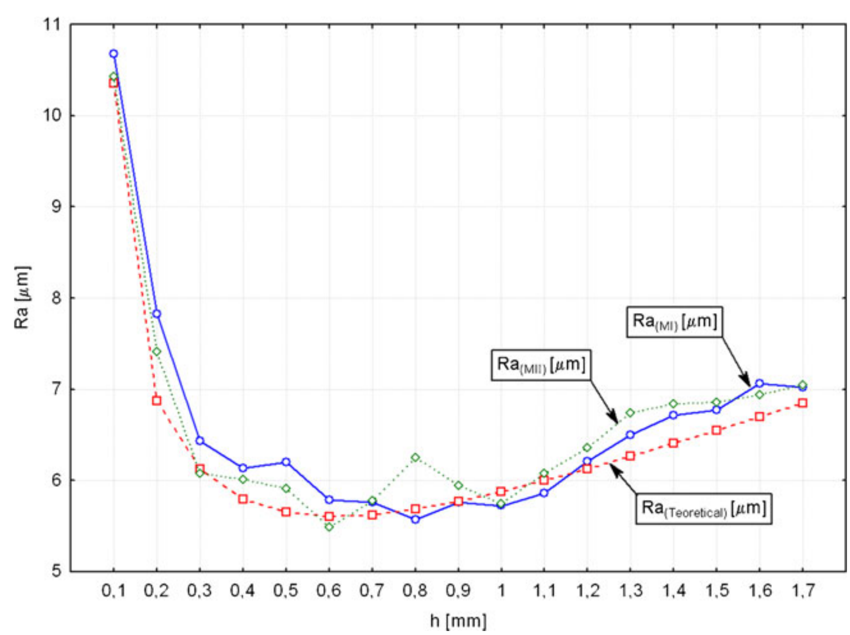

Fig. 6 Detail of the plot of experimentally observed surface roughness in initial zone $Ra_{(MI)}$ and $Ra_{(MII)}$ versus predicted values $Ra_{(Teoretical)}$ (AISI 304, E_{mat}=193 GPa and v_p=100 mm min^{-1}

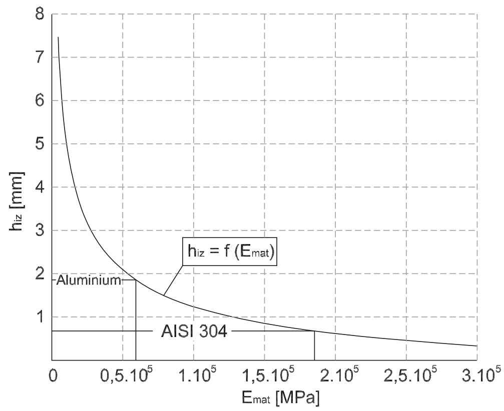

Fig. 7 Influence of the modulus of elasticity in tension E_{mat} of cut material by AWJ on initial zone depth h_{iz} ($v_p = v_{p\mathrm{opt}}$ = const)

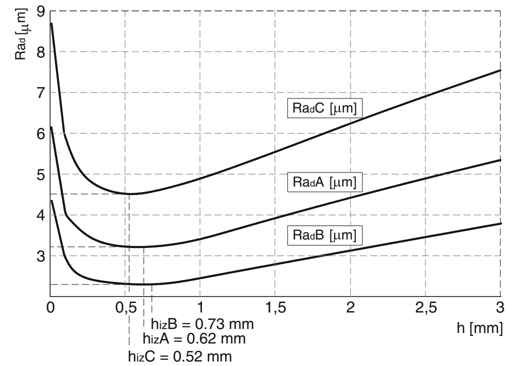

Fig. 8 Prediction of maximal depth of initial zone for AISI 309, E_{mat}=200 GPa and v_p=$v_{p\mathrm{opt}}$=136 mm min^{-1}

direction, respectively in the opposite direction, in the direction of the general curvature of the cut and so on, but with a lack of effect. By means of Eq.7 and in practice, there is an online control of ratios in members $m_a/m_{a\mathrm{opt}}$, p/p_{opt}, $d_{f\mathrm{opt}}/d_f$ $v_{p\mathrm{opt}}/v_p$ and $\mathrm{Ra}_{do}/\mathrm{Ra}_o$. The online detection of the instantaneous roughness can be in automated service implemented by acoustic and vibration measurement, where there is a close functional link of the signal to the roughness. A used regulator should come into action which will respectively change the ratio $v_{p\mathrm{opt}}/v_p$ in the order of 10–2 at a normal traverse speed of 50–300 mm min^{-1}.

For the prediction of maximal depth of the initial zone h_{iz} (mm), a newly derived and validated semi-empirical relationship from the previous equations (Eqs. 1–6), Eq. 7, can be used:

$$h_{iz} = h_j\, 0.5 \left(\frac{v_{p\mathrm{opt}}}{v_p} \cdot \frac{m_a}{m_{a\mathrm{opt}}} \cdot \frac{p}{p_{\mathrm{opt}}} \cdot \frac{d_{f\,\mathrm{opt}}}{d_f} \right)^{0.25} 10^{\log\left(\log\left(\frac{0.1\mathrm{Ra}_o K_{\mathrm{cut}}}{0.1 R_o + 1}\right) \cdot \left(\frac{\mathrm{Ra}_{do}}{\mathrm{Ra}_o}\right)^{0.5}\right)} \quad (\mathrm{mm}) \tag{7}$$

where v_p is generally the controlled traverse speed, $\mathrm{Ra}_{do}/\mathrm{Ra}_o$ is ratio of roughness in trace and roughness in the radial plane of the cut estimated on the level of neutral plane—depth horizon h_o. In Eq. 7, E_{mat} is implicitly included in all variables $v_{p\mathrm{opt}}$, Ra and K_{cut}. The depth of cut is also included in the previous variables. Therefore, Eq. 7 can be transformed into Eq. 2 or discrete for h_o (Eq. 3), where a variable material value E_{mat} and optimal traverse speed $v_{p\mathrm{opt}}$ (mm min^{-1}) can be found. Continuous curve/function is achieved by changing of traverse speed v_p (mm min^{-1}). Figure 7 is the depth of initiating zones according to different materials; $h_{iz} = f(E_{\mathrm{mat}})$ is the curve given the choice E_{matx}=5,000:5,000:300,000. Therefore, the *x*-axis in Fig. 8 may be E_{matx} instead of E_{mat} and also the implicit function $h_{iz} = f\,(E_{\mathrm{matx}})$

6 Conclusions

According to the character of topography irregularities within the height or depth of cut, four zones can be conventionally introduced, namely the initiation, smooth, transition and deformation zones. These regions show specific geometries as if being generated by different machining technologies.

This paper highlights the lack of deeper analysis of the surface topography in the upper area of the initial zone. For that reason, a systematic state-of-the-art overview is given in the paper, which was precisely in terms of technological heredity analysed in details. According to empirical works, we focused the attention on the influence of several factors simultaneously in order to obtain as much information about AWJ factors in relation to surface topography as we could. Experimental samples were measured by optical non-contact method. Confirming the existence of initial zone, which has not been the subject of intensive research, the authors bring arguments that the topography of the surface is divided into four qualitatively different parts. Based on the observed regularity of development and related areas of numerical values of roughness profile parameters Ra, Rq and Rz, the authors provide a new way to specify the horizontal division of the surface topography based on the identification and analysis of factors in relation to the topography of the surface through the factors. Occurrence of the initial zone on surfaces for most engineering materials is in the range from the top of the workpiece to a depth from 0.5 to 3 mm according to Young's modulus of elasticity; E_{mat} from breaking strength is lawful characteristic anomaly on the surfaces created by AWJ. Concentration of large roughness in the initial area of the cut degrades a lot the quality of products in terms of their use and disadvantage of the AWJ technology versus traditional technologies of machining. Hence, a new equation needed in engineering practice for the prediction of depth range of an anomalous zone has been derived. Follow-up experimental and analytical works should bring further results aimed at deriving a technology solution of that problem with the main purpose of paving the way of surface roughness regulation on the whole surfaces created by AWJ, including that very problematic section of the AWJ tool penetration into the material. The formation of the topographical anomaly in the initiation zone that is inevitably related to the mechanism of disintegration of the material in the area of the flexible tool penetration must be shown. The presented results should serve to supplement the analytical documents for control and especially for automation of management operations. Ra_d in entry zone is extremely high and causes, together with material thickness, problems regarding surface functionality evaluation.

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