Journal of Machine Engineering, Vol. 13, No. 4, 2013

water jet, machining,
quality, aluminum alloy

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DEPENDENCY OF THE TECHNOLOGICAL QUALITY OF ELEMENTS MADE FROM AN ALUMINUM ALLOY ON THEIR SHAPE IN THE WATER JET MACHINING

The problem of the technological quality of elements is one of the primary problems of modern machine production. In many cases, elements are made from new construction materials with specific properties considered to have poor machinability in cases where conventional technologies are applied. Thus, there is a need to identify the capabilities of new technologies, including the technology of cutting with a high-pressure abrasive water jet for the production of elements made of Al alloys, while observing qualitative machining requirements. This paper presents the results of studies of the accuracy of production of elements with a complex shape made of a 2017A alloy (PA6) and of studies of the coarseness of obtained surfaces depending on the pressure of the water jet, cutting advance rate, and the amount of dosed abrasive for a constant thickness of the element. The measure of the accuracy of production, independent of dimensional accuracy, was assumed to be the size of chamfering on the side surface of the cut element caused by a specific mechanism of material decohesion occurring under the influence of water jet technology. In cases where Al alloys are cut, depending on assumed conditions, it is possible to shape the side surface of an element with a positive, negative, or neutral (zero) wall inclination (side of the element). In the process of cutting, specific errors in the shape of the element occur and appear on curved fragments of the object or in discontinuous areas of the profile (e.g. transition from a straight fragment to an arc fragment); this is caused by a shift in the exit of the high-pressure abrasive water jet from the object relative to the point of entry. Consequently, selection of cutting parameters for the water jet method for elements with complex shapes is, in essence, a compromise between the obtained inclination of the wall of the processed element and the required surface coarseness, and between the required (acceptable) inclination of the wall of the element or lack thereof and the obtained coarseness of the element's surface. Thus, in the outlined problem, it is not possible to simultaneously obtain two satisfactory criteria quantities of element quality, that is, accuracy of shape and requisite coarseness of the surface of the machined element, if the water jet method is applied for the purpose of machining Al alloys.

1. DECOHESION OF MATERIAL AND CUTTING GAP IN THE WATER JET

The cutting gap, the formation of which is a phenomenon of the material decohesion process when cutting by means of an abrasive water jet, has no counterpart in known mechanical processing methods. Differences in the process of decohesion of the machined material occurring under the influence of a mechanical tool, characterised by high cutting-

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edge energy, prohibit the use of known machining models to interpret problems of material destruction during the machining process using the water jet method. The result is incomplete knowledge regarding control of the course of the abrasive water cutting process in many specific problems and the need to experimentally verify the assumed indices of the technological quality of machined elements [4]. In water jet machining that uses the injective method to produce the mixture of water and abrasive, a multi-phase jet tool containing air, water, and a certain amount of abrasive dosed within the range of 3-10 g/s [3] is found in the cutting head. The listed qualities are specific to injective systems of water-abrasive mixture production which are widely used in industrial water jet system solutions (Fig. 1) [1],[5],[3].

The energy parameters of the water jet are dependent on initial conditions, i.e. water pressure and the path that the jet takes through the air from the time of its release from the water nozzle until its contact with abrasive grains in the mixing chamber. On this path, the jet is subject to expansion as a result of cavitational release of water vapour and air contained in the water into the surroundings [5]. The water jet is subject to significant aeration when travelling through the air, which contributes to the multi-phasality of the abrasive water jet [3],[5]. These qualities result in the formation of a typical cutting gap characterised by the parameters indicated in Fig. 1.

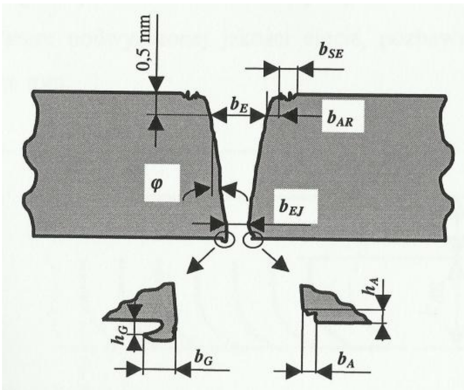

Fig. 1. Cutting gap according to VDI 2906 with positive convergence [7]

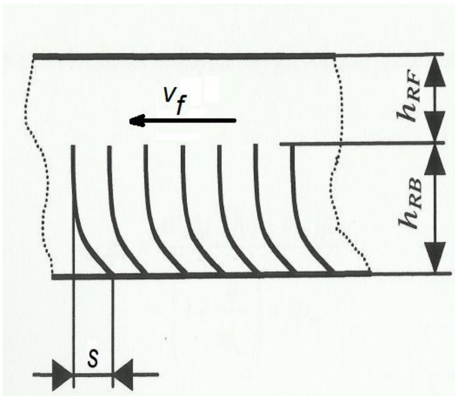

Fig. 2. Shape of the cutting gap in the feed direction [7]


Fig. 3. Cutting gap profile

As shown in the images of the cutting gap shown in Figs. 1 and 2, material particularly destruction under the influence of the high-pressure abrasive water jet is a particularly complex process. Its complexity is indicated by the cutting of layered materials with different physical and mechanical properties, such as a steel sheet with interspersed Al sheet layers (Fig. 3). In such cases, a complex transverse profile is obtained for the cutting gap, the formation of which can be explained by the effects of turbulence of the motion of water in the gap and expansion of the water jet transverse to the direction of advance motion. Deflections of abrasive grains inside the gap off steel, which is relatively harder, will also contribute somewhat to the formation of the complex cross-section of the gap and will result in a greater decrement in the softer Al.

As can be concluded from observation of the cutting surface, as the thickness of the cut material increases [1],[5], conditions for greater turbulence of flow of the multi-phase liquid in the gap occur, caused by curving in the lower zone of the gap (Fig. 2). As a result, deflection ‘s’ of the trajectory of the abrasive water jet occurs, at a magnitude opposite to the sense of the vector of feed v_f as designated in Fig. 2.

The value of deflection ‘s’, determined in the longitudinal section of the gap for a specific thickness of the cut object and material type, is dependent on the machining capacity of the abrasive water jet.

The machining capacity of the high-pressure abrasive water jet, which has an influence on the formation of the cutting gap in the longitudinal and cross-section, consequently influences the technological quality of the processed object, which is dependent on:

A. Hydraulic parameters:

1. Water jet pressure - *p*,
2. Intensity of water flow - *qw*,

B. Parameters of the abrasive:

1. Type of abrasive material,
2. Size of abrasive particles,
3. Condition of the abrasive (set of mechano-physical and stereometric properties of the grain),
4. Mass intensity of abrasive flow - *q*,

C. Designed parameters of the mixing system:

1. Diameter of the mixing nozzle – *D*,
2. Length of the mixing nozzle,
3. Diameter of the water nozzle – *d*,
4. Size of the mixing chamber and its degree of wear.

The effectiveness of machining (cutting) depends on the hydraulic efficiency of the system, expressed as the ratio of jet kinetic power to the power of the drive source. As pressure and water flow intensity increase, hydraulic efficiency decreases [3]. Factors such as compressibility of water in the applied pressure ranges and losses due to water viscosity also have an influence on hydraulic efficiency. The speeds of the water jet and of the jet of abrasive particles in the abrasive water jet are different, as expressed by formula (1). Therefore, the kinetic energy of an abrasive water jet produced by the injection method is dependent on the factors given above and on the state of wear of the mixing chamber and water nozzle and mixing nozzle.

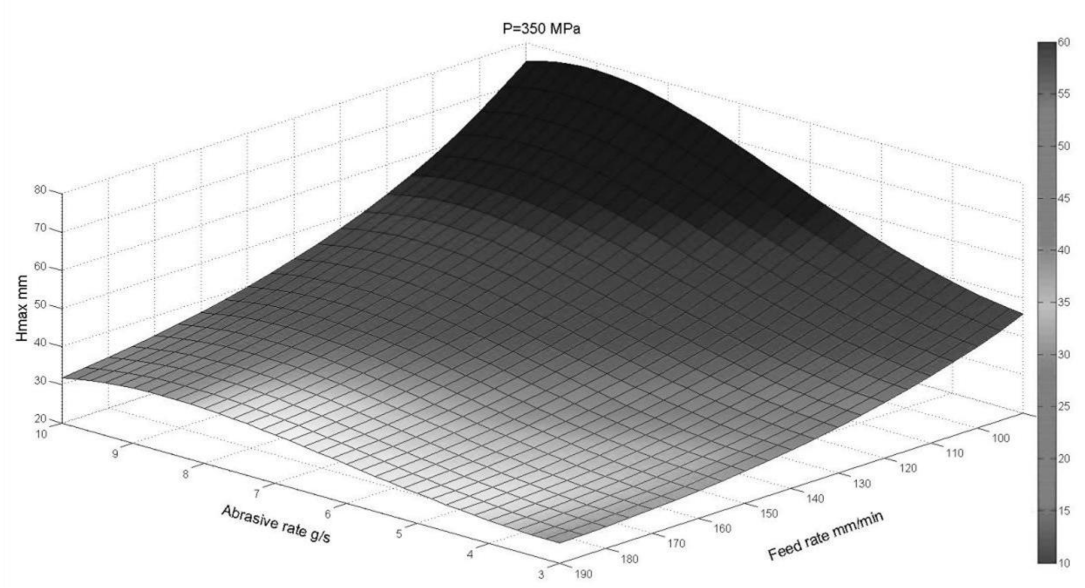

Fig. 4. Dependency of machining potential h_{max} on feed rate and abrasive flow for the water pressure established for cutting of a 2017A alloy

The maximum thickness of the cut material, determined for the entire acceptable range of variability of the listed group of parameters corresponding to the maximum machining capacity of the jet, can be defined by the concept of machining potential of the abrasive water jet.

This article presents selected results of studies of machining potential for cutting of an Al alloy and of studies of the influence of the machining capacity of an abrasive water jet on indices of the quality of cutting of elements of the shape indicated in Fig. 5.

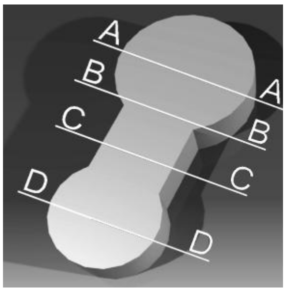

Fig. 5. Executed element made from 2017A alloy with marked zones (A,B,C,D) for investigations of out-of- squareness error

Studies of selected quality indices aimed at determining the capability of accurate machining with an abrasive water jet were aimed at determining errors in the shape of the object after machining. Because of the possible applications of this machining technology, evaluation of the error in roundness of the appropriate fragments of the object is of particular significance, with regard to both the point of entry of the abrasive water jet and its exit from the object, as well as out-of-squareness errors occurring on the walls of the machined element with respect to the plane of the base (Fig. 5).

$v_w = c_v \sqrt{\frac{2p}{\rho}}$ - *water speed*	$v_s = \frac{\eta v_w}{1+r}$ - *abrasive speed*	(1)
where: c_v – constant; ρ – water density; η – mixing efficiency; r – quotient of abrasive flow intensity to water flow intensity, p – pressure.		

2. EXPERIMENTAL STUDIES

Experimental studies of technological quality indices for cutting the PA6 alloy were performed on a water jet cutting machine from the Ridder company with an abrasive dispenser close to the head. In order to determine machining potential, studies of straight cutting of samples in the shape of a wedge, as in Fig. 6, were conducted.

The planned experiment was carried out with appropriately selected parameters of pressure *p* within the variability range of 180-380MPa, cutting feed rate v_f 1.5-3.17mm/s, and mass intensity of abrasive flow *q* 3-10 g/s. The size and grade of the abrasive particle were assumed to be constant factors. Garnet abrasive was used in the conducted studies, with a particle size of #80, a mixing nozzle diameter of 1mm, and water nozzle diameter of 0.35mm. The studied quantity was designated as h_{max}, determining the maximum thickness of the cut material identified in the cut wedge. The studies were conducted according to polysectional experiment plan PS/DS.-P:L(L) [2]. Based on statistical analysis of obtained results and function adequacy tests, the final regressive form of the machining potential function was obtained for cutting the 2017A alloy.

$$\begin{aligned} H_{max}(p,v,q) &= 1.40e-7\cdot p^3 - 0.00012\cdot p^2 - 0.00019\cdot p\cdot q \\ &+ 0.000019\cdot p\cdot v + 0.03645\cdot p - 0.00374\cdot q^3 + 0.065\cdot q^2 \\ &- 0.00038\cdot q\cdot v - 0.149\cdot q - 5.025e-9\cdot v^3 + 0.00005\cdot v^2 - \\ &- 0.026\cdot v + 1.74 \end{aligned} \qquad (2)$$

Based on the empirical function of machining potential given in formula (2), a surface plane constituting the image of machining potential was obtained, dependent on the three main studied factors, as shown in Fig. 7 for the selected water pressure.

2.1. EVALUATION OF THE ACCURACY OF EXECUTION

Based on the range of variability of machining potential for cutting the 2017A alloy and for a thickness of the machined material equal to 15mm, the maximum feed rate was determined as equal to v_f =5mm/s for a pressure of no less than p=280MPa and an abrasive flow intensity of no less than q=6.5 g/s. The data determined for the cut Al material with a thickness of 15 mm are parameters that ensure the minimum machining capacity of a high-pressure jet making it possible to produce the element. However, in order to obtain a full image of the dependency, the range of feed rate variability was expanded to v_f (0.83–5) mm/s in the second part of the study, which ensured a greater machining capacity of the jet than was required. Thus, for the implementation of the next phase of studies concerning quality indices of the machining of objects with complex shapes, the following ranges of variability of decisive parameters were assumed: v_f (0.83 – 5)mm/s, p (180–380MPa), abrasive flow intensity q (3–10)g/s. In this part of experimental studies, carried out according to plan PS/DS.-P:L(L), an object was cut out of a 2017A plate with a thickness of 15mm at the set parameters, with a shape, as indicated in Fig. 5, characterised by two fragments of a circular profile with radius of R15 and R20, respectively, connected by a straight segment. Measurements of selected errors of execution were carried out on a Global Performance CMM machine with PC DMIS software. Considering the complex path of motion of the abrasive water jet in the material (Fig. 2), characteristic areas of the object were selected (areas A, B, C, D in Fig. 7), in which the greatest errors of shape caused by the curving s of the abrasive water jet at its exit from the object could be expected.

Errors in the object's shape (profile) in the top part of the object at the point of entry of the high pressure jet are dependent on the accuracy of circular interpolation of the machine's CNC control system as well as on the degree of wear of the mixing nozzle, which has an influence on the consistency of the high-pressure abrasive water jet. The difference between the nominal (programmed) diameter of the object and the actual value can be changed by inputting the appropriate corrective value into the control system.

However, the value of the error Δ (delta) as the difference between the radius of circular fragments of the object determined at the entry and exit of the high pressure stream into and from the object (at the bottom of the object) is related to the interaction of the high-pressure jet with the material and remains in a strict relationship with its machining capacity. Errors in the object's shape defined by the out-of-squareness of the object's side surface relative to its base, and particularly profile errors in circular fragments of the profile at the exit of the jet from the object, are conditioned by the interaction of the high-pressure stream with the object in the area of the working gap.

Studies of the difference of radii Δ_{15} and Δ_{20} according to the given experimental plan made it possible to find the appropriate regression functions given by formulas (3) and (4).

$$\begin{aligned}\Delta_{15} &= 1.9e-10\cdot p^4 - 1.5e-7\cdot p^3 + 0.34e-4\cdot p^2 + 0.41e-5\cdot p\cdot q\cdot v \\ &- 0.29e-3\cdot p\cdot q - 0.33e-4\cdot p\cdot v + 0.39e-3\cdot p - 0.004\cdot q^3 + 0.095\cdot q^2 \\ &- 0.13e-2\cdot q\cdot v - 0.57\cdot q - 1.24e-8\cdot v^3 - 0.11e-4\cdot v^2 + 0.015\cdot v + 0.47\end{aligned} \tag{3}$$

$$\begin{aligned}\Delta_{20} &= 6.47e-10\cdot p^4 - 6.57e-7\cdot p^3 + 0.24e-3\cdot p^2 + 0.29e-5\cdot p\cdot q\cdot v \\ &- 0.14e-3\cdot p\cdot q - 0.27e-4\cdot p\cdot v - 0.037\cdot p - 0.0031\cdot q^3 + 0.073\cdot q^2 \\ &- 0.001\cdot q\cdot v - 0.48\cdot q - 6.58e-9\cdot v^3 - 0.42e-5\cdot v^2 + 0.012\cdot v + 2.74\end{aligned} \tag{4}$$

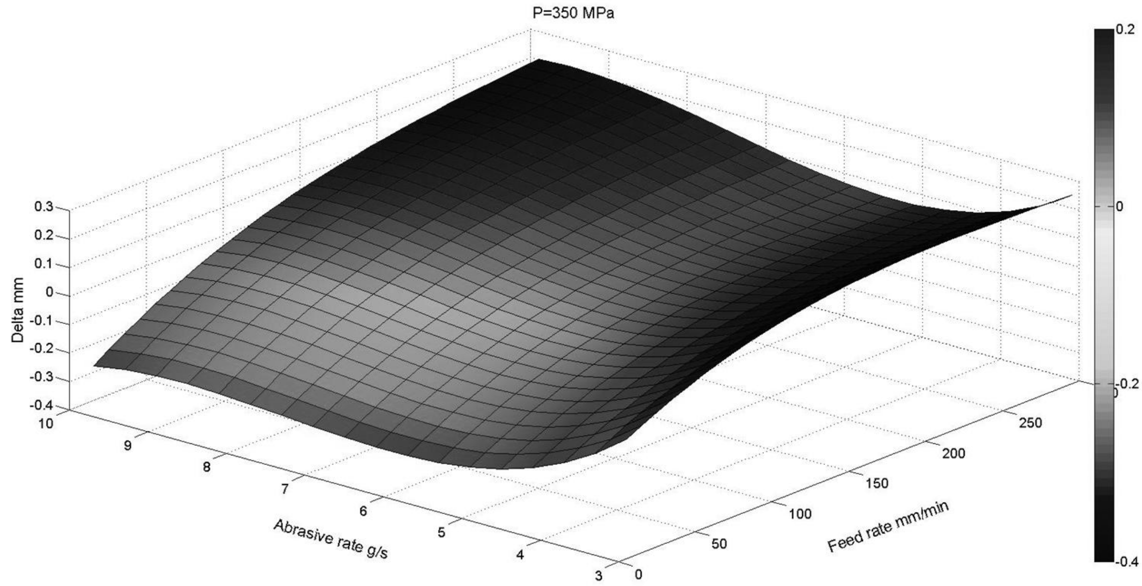

Fig. 6. Dependency of difference Δ_{15} on feed rate and abrasive flow for cutting of the 2017A alloy with a thickness of 15mm over a circular segment with a radius of R15mm. Constant water jet pressure equal to 350MPa

Examples of dependencies are presented in Fig. 6 and Fig. 7. The conducted studies show that, similarly to water pressure, the cutting feed rate has a strong influence on errors Δ_{15} and Δ_{20} in circular fragments of the object's profile, which is also illustrated by selected results of measurements for circular fragments of the object with a radius of 15mm (R15) and 20mm (R2), respectively, as presented in Table 1.

Table 1. Examples of object roundness errors after cutting with a high-pressure abrasive water jet

Column 1	Column 2	Column 3	Column 4
Sample no. 2 Δμm Pressure 339.5MPa Feed rate 64mm/min Abrasive flow 4.42g/s	Sample no. 13Δ μm Pressure 280MPa Feed rate 152.5mm/min Abrasive flow 3g/s	Sample no. 12 Δμm Pressure 280MPa Feed rate 300mm/min Abrasive flow 4.42g/s	Sample no. 11 Δμm Pressure 280MPa Feed rate 5mm/min Abrasive flow 6.5g/s
Top R20 = 0.017 Bottom R20 = 0.014 Top R15 = 0.010 Bottom R15 = 0.019	Top R20 = 0.003 Bottom R20 = 0.053 Top R15 = 0.007 Bottom R15 = 0.039	Top R20 = 0.016 Bottom R20 = 0.042 Top R15 = 0.013 Bottom R15 = 0.045	Top R20 = 0.014 Bottom R20 = 0.005 Top R15 = 0.009 Bottom R15 = 0.006

The obtained results indicated that within certain ranges of cutting parameters the diameter of the circular fragment of the object at its base is greater than the diameter of the object in the top part (at the point of the jet's entry), and this difference is on the order of tenths of a millimeter. In such cases, it can be concluded that during the cutting of the 2017A alloy under certain conditions, particularly at higher cutting rates, a classic cutting gap with positive convergence is formed, as shown in Fig. 1.

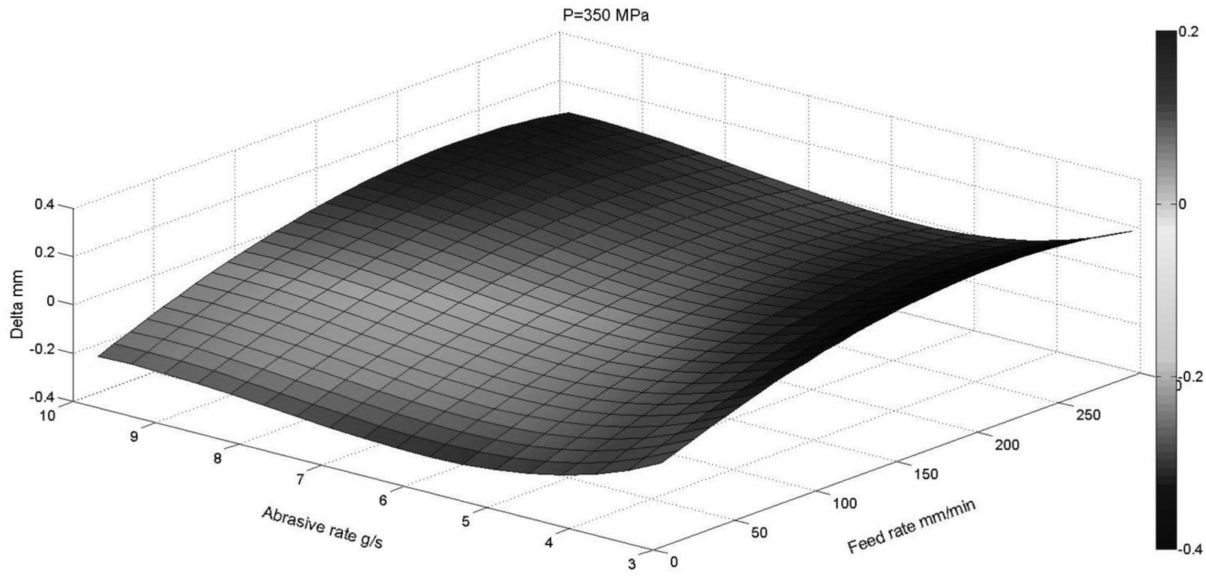

Fig .7. Dependency of difference Δ_{20} on advance rate and abrasive consumption for cutting of a PA6 alloy with a thickness of 15mm over a circular segment with a radius of R20mm. Constant water jet pressure equal to 350 MPa

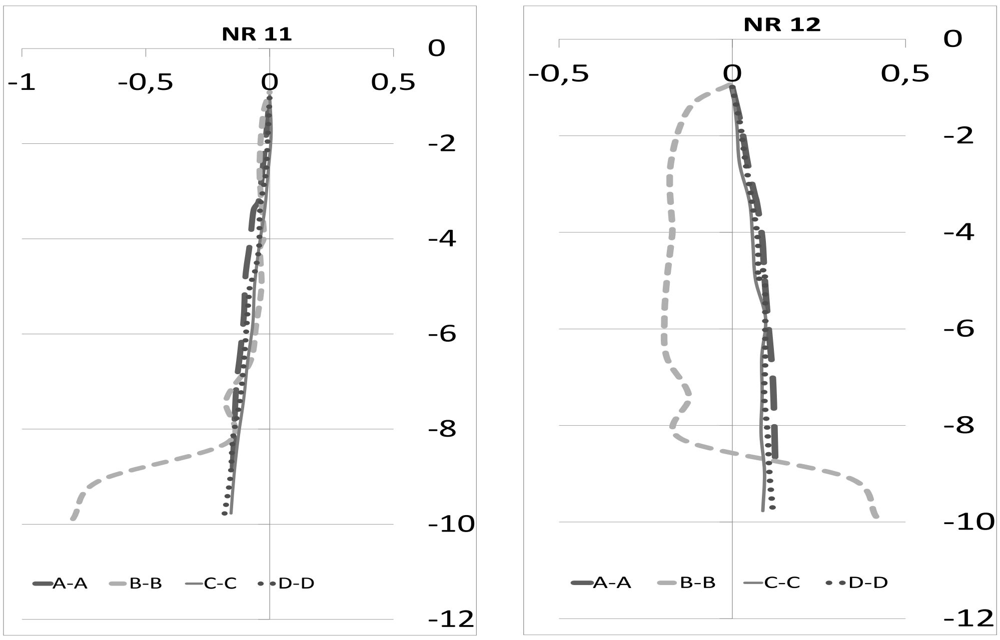

Fig. 8. Errors in shape of the side surface of selected samples in marked areas A, B, C, D for research samples no. 11 and no. 12

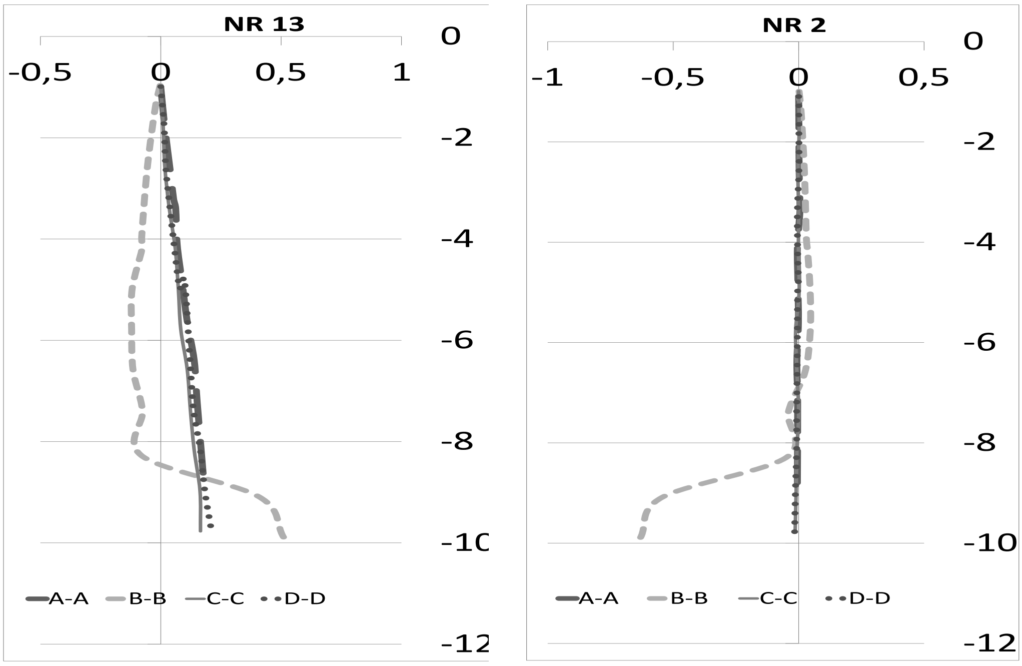

Fig. 9. Errors of shape of the side surface of selected samples in marked areas A, B, C, D for research samples no. 13 and no. 2

However, analysis of the full range of variability of the studied factors (Figs. 6 and 7, Table 1, column 4) indicates the possibility of formation of a cutting gap with negative convergence, and in this case, the respective diameters of circular fragments of the object at its base become smaller than the diameter at the point of entry of the jet into the material.

The results presented in Figs. 6 and 7 as well as in Table 1 indicate that under conditions of high jet machining capacity, which is related to a low feed rate, a large abrasive flow at high water pressure, or as a result of incorrect selection of all three parameters, a cutting gap with negative convergence may be formed.

Relating the obtained results to machining of Al alloys, it can be concluded that these cases occur when the high-pressure abrasive water jet has an excessive machining capacity relative to the required capacity. This dependency is confirmed by the results of studies of out-of-squareness relative to the base of the side surfaces of the produced object, as shown in Figs. 8 and 9. The presented results show that inaccuracy of an object with a complex shape determined by the out-of-squareness of its side surface is dependent not only on the curve of the processed profile itself, but also on the type of transition between different curves. The greatest errors of this type occur in the lower part of the object when the curved path makes the transition to a straight cutting path (area B-B, Figs. 8 and 9). The cutting gap formed during the machining of Al alloys is a rarity of sorts, because it can have a positive or negative convergence, which exerts a significant influence on the errors in the machined object. A significant conclusion arising from these studies is the affirmation of the possibility of obtaining a cutting gap with parallel walls (omitting the undercutting of the element in area B-B), which results in the most accurate machining of an element made from an Al alloy (Fig. 9, sample no. 2).

2.2. EVALUATION OF THE COARSENESS OF THE MACHINED SURFACE

In evaluating the quality of execution of elements characterised by a complex contour with the water jet method, the characteristics of the topography of the cutting plane play an important role as a supplement to the basic set of attributes comprising the technological quality of an object. Surface roughness R_a, determined on a straight fragment of the contour of the element that was cut out, was assumed as a measure of evaluation of the object's surface topography.

The large dispersion of surface roughness after machining with a high-pressure water jet is known [3], and it can be significant enough that the quotient of the length of the unevenness wave to its height assumes a value greater than 1000, which corresponds to the category of shape errors. However, if the appropriate machining capacity of the high-pressure abrasive water jet is selected, the unevennesses of the machined surface become homogeneous and can be qualified as surface roughness. In the conducted studies, machining capacity was selected based on studies of machining potential presented in Fig. 4 [6].

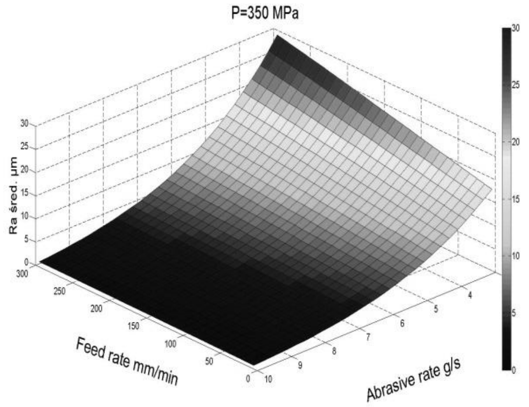

Fig. 10. Dependency of the roughness of a machined surface on cutting feed rate and abrasive flow at a water pressure of 350MPa

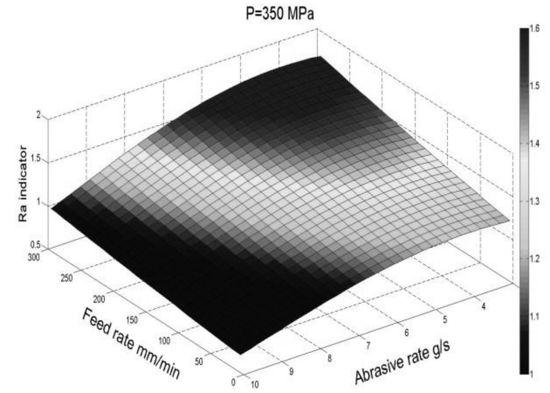

Fig. 11. Dependency of the roughness dispersion index R_a of a machined surface on cutting feed rate and abrasive flow at a water pressure of 350MPa

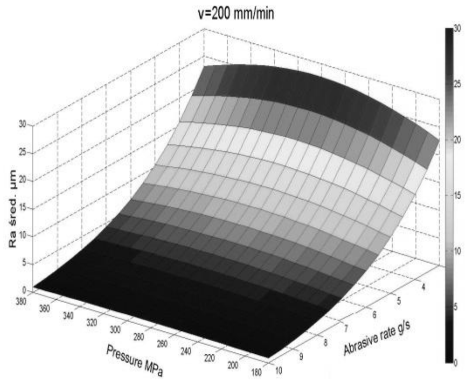

Fig. 12. Dependency of the coarseness of a machined surface on water pressure and abrasive flow at a cutting feed rate of 200mm/min

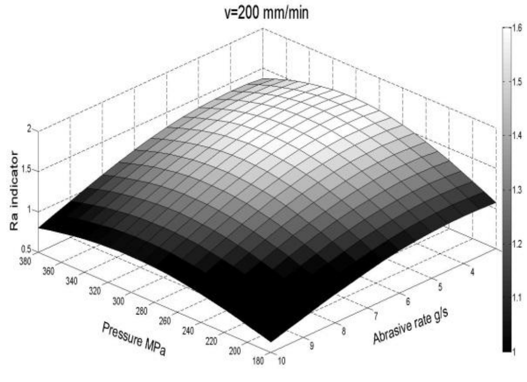

Fig. 13. Dependency of the coarseness dispersion index R_a of a machined surface on water pressure and abrasive flow at a cutting feed rate of 200mm/min

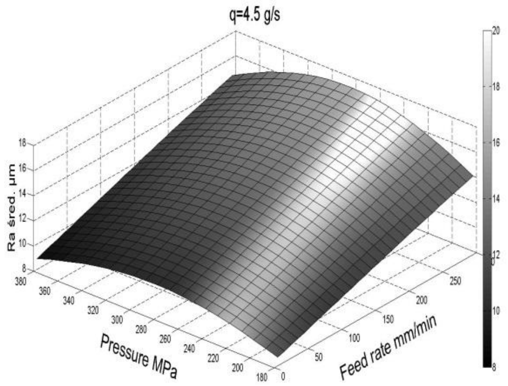

Fig. 14. Dependency of the coarseness of a machined surface on water pressure and feed rate at abrasive flow of 4.5g/s

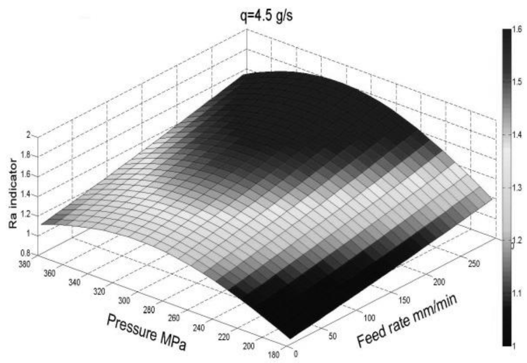

Fig .15. Dependency of the coarseness dispersion index R_a of a machined surface on water pressure and feed rate at abrasive flow of 4.5g/s

According to the principles of a passive experiment, an analogous programme of studies, PS/DS.-P:L(L), was assumed for the purpose of identifying the form of the approximation function based on the results obtained from studies of surface roughness. Average surface roughness, which is a more conclusive evaluation of a surface than roughness evaluation at points, was selected as the studied quantity. The index of roughness dispersion, given as the quotient of roughness measured at the jet's exit from the material to roughness at its point of entry, was selected as the supplementary quantity indicating the dispersion of roughness.

The appropriate regression equations are presented in formulas (5) and (6), and the planes of surfaces corresponding to them are given in Figs. 10-15.

$$\begin{aligned} R_{a\_sred} = \exp(&0.010730931248 * p - 0.0000189551308 * p\text{^}2 - \\ &- 0.01223665325 * q\text{^}2 - 0.3021907745 * q - \\ &- 0.0000018031376655 * v\text{^}2 + 0.0022592283711 * v + 2.437386013575) \end{aligned} \tag{5}$$

$$\begin{aligned} W_{Ra} = \exp(&0.0166\ 12481568\ * p - 0.00002744\ 25028\ * p\text{^}2 - 0.01569985\ 7 * q\text{^}2 + \\ &+ 0.12723447\ 8 * q - 1.13138049\ 6e - 7 * v\text{^}2 + 0.00124514\ 821152\ * v - \\ &- 2.51705781\ 1576) \end{aligned} \tag{6}$$

Based on the obtained results, it can be concluded that selected parameters of cutting with a high-pressure abrasive water jet make it possible to machine an object with a relatively low surface roughness variability index that does not exceed 1.8. The lowest average roughness of a machined surface is obtained for a relatively large range of feed rate variability from 10 to 300mm/min, with maximisation of abrasive flow. However, the roughness dispersion index increases along with the increase of cutting feed rate, achieving a value that is nearly twice as great at an advance rate of 300mm/min in comparison with the lowest rate.

3. CONCLUSION

Machining of Al alloys with a high-pressure abrasive water jet in terms of shape complexity and accuracy of the machined object is characterised by significant variation in such accuracy indices as: inclination of the walls of the machined object, non-roundness errors of arc fragments (if present), and also by the occurrence of characteristic shape errors in the object caused by the path of motion of the high-pressure jet in the area of its exit from the object. Errors of this type are particularly great in areas of non-continuity of the object's contour, and thus at places of transition of straight fragments into curved fragments. A characteristic quality of cutting of elements made from light alloys (2017A) with a high-pressure abrasive water jet is the possibility of formation of a cutting gap with a positive or negative convergence, which is dependent on the selection of the jet's machining capacity.

Appropriately selected parameters (machining capacity) enable cutting with a gap with zero convergence. In this situation, evaluation of the object's technological quality after machining using the water jet method is particularly complex due to the simultaneous variability and co-dependency of accuracy of execution and surface coarseness. The conducted studies indicate that it is within the ranges of cutting parameter variability for which the lowest levels of surface roughness and shape errors are obtained that chamferring of the machined surface reaches its maximum value. If the opposite (assumption of an acceptable value of surface chamferring or the lack thereof) is assumed, the value of the obtained surface roughness will be related to the assumed cutting parameters. The presented dependencies clearly indicate a dependency of errors on an object's shape and of the roughness of a machined surface on an object's shape, cutting conditions, and type of material. In the case of soft materials such as Al alloys, this dependency is particularly apparent.

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