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ANALYSIS OF ACOUSTIC EMISSION RECORDED DURING MONITORING OF ABRASIVE WATERJET CUTTING OF STAINLESS STEEL AISI 309

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Original scientific paper

The paper deals with the accompanying physical phenomena that arise in the process of cutting metal materials by abrasive water jet (AWJ) technology. The text describes the causes of arising vibration and acoustic emission, course of vibration and acoustic emission by analysing their frequency spectrum. Data were collected by touch sensors within controlled experiment, in which the AWJ technology for cutting alloy steel was used. During the experiments, some input factors were changed and measured parameters were subjected to different types of analysis using specialized software LabVIEW. Obtained data provide information about vibration and acoustic emission spectrum and enable us to find a dependency between the surface topography of cut materials and the emission spectrum of the accompanying physical phenomena arising during the AWJ process.

Keywords: *abrasive water jet, acoustic emission spectrum, vibration spectrum*

Analiza akustične emisije zabilježene tijekom abrazivnog rezanja vodenim mlazom nehrđajućeg čelika AISI 309

Izvorni znanstveni članak

Tekst se bavi pratećim fizikalnim pojavama koje nastaju u procesu rezanja metalnih materijala tehnologijom abrazivnog vodenog mlaza (AWJ). Tekst opisuje uzroke nastalih vibracija i akustične emisije, tijekom vibracija i akustične emisije analizom njihova frekvencijskog spektra. Podaci su prikupljeni dodirnim senzorima u kontroliranom eksperimentu, u kojemu je korištena AWJ tehnologija za rezanje legiranog čelika. Tijekom eksperimenata, neki ulazni čimbenici su se mijenjali, a izmjereni parametri su bili podvrgnuti različitim vrstama analize pomoću specijaliziranog softvera LabVIEW. Dobiveni podaci pružaju informacije o vibracijama i spektru akustične emisije i omogućuju nam pronaći ovisnost između topografije površine rezanih materijala i spektra emisije popratnih fizikalnih pojava koje se javljaju tijekom AWJ procesa.

Ključne riječi: *abrazivni vodeni mlaz, spektar akustične emisije, spektar vibracija*

1
Introduction

Aim of the text is to clarify the interactions between the factors of hydroabrasive cutting such as: feed rate, abrasive flow rate, focusing tube diameter, etc. and surface roughness of cut surfaces and acoustic emission measured directly in the cutting of metal materials. Monitoring the process of AWJ cutting as well as working conditions is of great importance. This section of the work will summarize basic information about online monitoring of the acoustic emission (AE) dependence on the depth of cut when cutting with water jet instead of costly and time - consuming observation of the vertical cutting force. The aim of this study is to use AE techniques for prediction of machined surface roughness. It was found that square average of the energy AE increases linearly with the increase of depth of cut and can be used for online viewing. The results show that AE is the most suitable technique for monitoring AWJ, since the AE signal has a high sensitivity to changes in the depth of cut [1, 2, 3].

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Overview of current research results

AWJ is the subject of scientific research, inc. examination of phenomena arising parallel with abrasive waterjet cutting process, for example research of the size and impact of the vibration and noise emissions, which are part of the supporting feature of AWJ technology. In the field of AWJ, the research area is oriented mainly to understanding of the mechanism of removal [4, 5, 6], as well as to the combination of factors, in order to optimize their effects on the quality of the newly created surfaces [7, 8, 9]. The most common causes under consideration are the pressure, traverse speed, abrasive mass flow rate [8] and [10÷13]. Even now the study and research of the mechanical cutting continues in various research laboratories and workplace research centres, contributing thus to the development of the equipment tools for the manufacturers. Mechanism of the AWJ cutting is primarily studied by analytical methods. The relationships between traverse speed and mechanical properties of the materials are mainly and usually studied by experiments. Due to the fact that material is affected by the process of erosion through the interaction of the AWJ, usage of the vibration analysis for the application and the process of monitoring is ideal [14, 15, 16]. It should be noted that vibrations register the waves generated by local deformation of the material worked on. In the past, some authors published the works in which the application of vibration or acoustic emissions were recorded for the purpose of online control and monitoring of the immediate state of created kerf and its morphology [17, 18]. Unlike the current approach, in our opinion much greater emphasis should be put on the deformation and stress-strain properties of the cut material, in relation to the mechanical stiffness of the AWJ tool, than to the basic emphasis on the study of macro and micro texture of surfaces created by AWJ. The explanatory ability of the geometric phenomena of the created surface topography is an essential analytical tool for the physical-mathematical formulation of the principle of AWJ material, as well as the principle of hydrodynamic and oscillating processes ongoing in a cut material. If the technical safeguarding of operation and appropriate AWJ technology development is considered, then the scope of research needs to be moved to the development of an automated control of technological processes that ensure cutting quality [4, 13, 18]. This progress cannot be achieved without the analytical investigation of the main principles, governing the important functions of physics and mechanics of AWJ disintegration processes in the kerf. The principal difference of the presented approach to the problem of interpretation, in comparison to the current approaches, is seen in the importance of the final state of surface and in using of AWJ mechanical flexibility to describe mechanical state of system at concrete time. Therefore, the phenomena ongoing during AWJ cutting are started to be studied by means of mechanical oscillation, vibration and acoustic emissions. In the field of researching the goals to improve the AWJ cutting performance a huge research progress has been made and tremendous works have been recorded. Great deal has been done by researches under supervision of [19÷22]. In their research reports the usage of acoustic emission (AE) models of AWJ is apparent in the place where they tried to monitor AWJ dissipated energy; this effect has been studied by [21, 23]. Kovacevic used the AE in order to monitor AWJ drilling depth of cut [1, 15, 24, 25, 26]. Identification of different removal mechanisms by AE has been studied by Momber [23, 26, 27] and finally Mohan [23, 25, 26] used AE for monitoring of AWJ depth of cut. Kovacevic [20, 21] published the research work, where the vertical force of AWJ has been measured. The goal of the experimental work was on-line monitoring of surface roughness. But a great deal of the research object created a very good base for further research, for surface roughness prediction [7, 8, 17, 28, 29, 30].

3

Research background – associated problems

During AWJ cutting material creates mechanical oscillations and acoustic emission. Despite the adverse effects of AE during the cutting of material, AE in itself bears important information about the technological process. From the perspective of mechanism of cutting, the AE also carries information which is important in monitoring of the immediate state of the technological process. This field of research is a worldwide uncovered and unsolved issue; there are few works which marginally address this issue of usage of AE in the technological process of AWJ cutting materials. Explanatory ability of physical and geometric parameters, mainly geometrical values characterizing the surface topography is an essential analytical tool for mathematical modelling and prediction of relationship AWJ - material. Using information from AE as a feedback is suitable for modelling the interaction AWJ - material for prediction of material destruction, mechanical oscillations, measurement analysis and correlation of mutual dependence. Currently known published results of research in the field testing and using on-line control systems for abrasive waterjet cutting technology did not bring relevant and clear results, reflected in a comprehensive model of AWJ process on-line control. In 2009 was described in detail the dependence of surface roughness parameters on surfaces created by AWJ by means of acoustic sound pressure level. The information referred to in the manuscript is sufficient precognition for continuation of research on the subject from off-line to on-line quality control. On-line control will be focused mainly on traverse speed regulation which directly affects the disintegration process cut by AWJ in position of technological tool. In AWJ machining, the workpiece material is removed by the action of high-speed water mixed with abrasive particles. A high-speed waterjet transfers kinetic energy to the abrasive particles and the mixture impinges on to the workpiece. The material removal rate is dependent on the abrasive attack and mechanical properties of target metal. The AWJ machining process is defined by a number of parameters, which in turn govern the material removal rate and the development of the characteristics of the surface. A considerable effort was made in understanding the influence of the system operational process parameters such as waterjet pressure, abrasive flow rate, standoff distance, number of passes on depth of cut, angle of cutting, and traverse speed. The results of the studies showed that the AWJ machining is significantly affected by the variation of process parameters [31÷44]. However, the degree of influence of parameters depends on the magnitude of parametric variation and machinability of the material. Hence those experiments are focused on deeper analysis of acoustic emission recorded during monitoring of abrasive waterjet cutting of stainless steel AISI 309.

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Experimental conditions of experiment

Machining tests were conducted on the adjustable precise cutting table from PTV company. The workpiece was machined tool generated by pump FLOW 9×D55 with Q = 4,7 l/min with a power P = 60 hp (40,74 kW) with an Ingersoll Rand cutting head. Cutting conditions in the experiments are shown in Tab. 1 and experimental set up in Fig. 1.

Table 1 Input factors of experiment

Factors	**Experimental runs**
Pressure p /MPa	350
Traverse speed v /mm/min	50, 75, 100, 150
Abrasive mass flow m_a /g/min	250, 400
Water nozzle d_o /mm	0,4
Focusing tube d_f /mm	0,8
Stroke z /mm	3
Leaning angle of abrasive head φ /°	90
Type of abrasive	Barton Garnet
MESH	80
Characteristics of Multiplier: Stream Line Pump SL III	
Type of multiplier	Double-acting
Power /hp	50 (37,3 kW)
Oil pressure /MPa	20
Maximum pressure /MPa	380
Amplification ratio	20:1
Volume of damper	2:1
Type of cutting head: Ingersoll Rand – AutolineTM	
Thickness of material /mm	15
Type of material	AISI 309 – (Cr – Ni steel), chemical composition: (C 0,20 %, Mn 2 %, Si 1 %, Cr 22 ÷ 24 %, Ni 12 ÷ 15 %, P 0,045 %, S 0,03 %), mechanical attributes: (HRB 95, μ = 0,27÷0,3, E = 200 GPa, R_m= 515 MPa, R_e= 205 MPa, A = 40 %, Z = 50 %)

5

The results measured during the experiment

The diagnostic measurement of acoustic emissions was performed during the experimental cutting of samples in order to assess the oscillation while cutting with water jet. The aim was to assess the influence of feed rate and type of cut material on the course and values of acoustic emissions. Measurements were taken under the given scheme and the

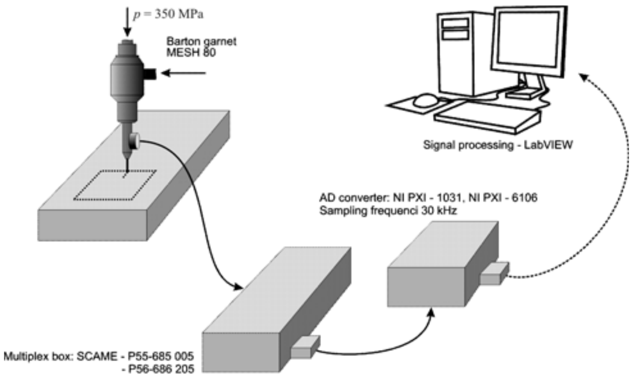

Figure 1 Experimental set up

data evaluating was performed afterwards by LabView software. The first step was to measure the data, followed by a complex and time-consuming data modification to desired formats and sizes. One of the most important tasks was graphical displaying of the work, performed using MatLab. Data collection was performed by NI PXI measurement system (type of measuring card PXI 4472B). It is used to optimize dynamic signals of AE. It is able to synchronize up to 5000 channels in the system PXi. It includes 24-bit resolution ADCS with a dynamic range of 110 dB. Output speed of this device is up to 102,4 kS/s from eight channels simultaneously. Software is configurable for AC/DC connection. The frequency analyzer Microlog GX-S was another device for collecting data. This device has high performance. It has two channels and entry as a way to collect data. It also includes an FFT analyzer. It is certified for use in ATEX Zone 2 hazardous locations. Analysis of data was performed using Lab View Professional Development System, including the Sound and Vibration Toolset and Order Analysis Toolset and Aptitude Analyst SKF Condition Monitoring. Accelerometers PCB IMI: type 607A11 with integrated cable (sensitivity of 100 mV/g, frequency range up to 10 kHz) have been used as sensors.

Using OriginLab 8.0 software, the data was converted into an overall file *. txt. In this form of signal, analysis can be done in several simpler programs. To work with data in this final form the program MatLab R2009a was chosen. The given signal (Fig. 2) needs to be divided into several components by detailed analysis. First, it is necessary to divide the signal into periodic and aperiodic components. In our work, we did not deal with elements that were not periodically repeated, quite the contrary. Our task was to identify the periodical parts of the signal and define their origin, their possible usage, and relations between them.

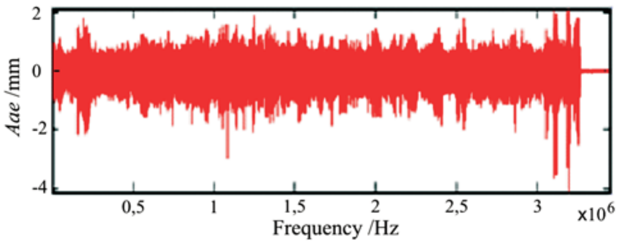

Figure 2 Signal downloaded by MatLab software

Separated by time-changing parameter - maximum read frequency f_m the lower band of the spectrum – is mainly represented by harmonic sinusoids. High band - represented either by noise components represented by sinusoids with random phase or coefficients of AR (autoregressive) filter.

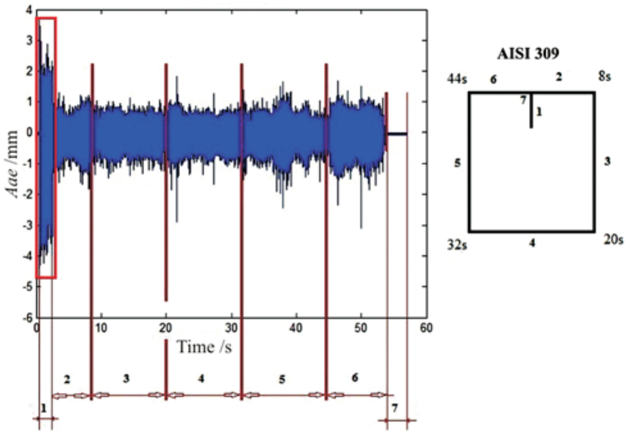

Figure 3 The course of the acoustic signal in cutting sample

One model suitable for acoustic signals is autoregressive (AR) or (all-pole), in which the current value of the signal is represented as a weighted sum P of previous values of signal. AR model is an appropriate model for many linear processes. It is available for noise-like signals and the near-harmonic signals. It can be found out from the view of out-noised signal components that the noise part of the signal reaches higher values (has higher frequency) than the actual sound caused by water flow and its impacts with the gaseous, solid and then liquid medium. Most suitable method for monitoring signals and the associated acoustic emissions in a manner appropriate for their analysis is a method of FFT - Fast Fourier Transformation. In non-mathematical terms, this means that the signal is spread over certain amplitudes adequate for the different frequency components. FFT spectrum is often used to separate periodic signal components from no periodic. In most of the analysis only periodic components are important because phenomena they describe are reasonably likely to be predicted in the future. From the above graphical displays of FFT spectra a certain periodic character in amplitude rising can be found out. It is clear from the time comparison to the

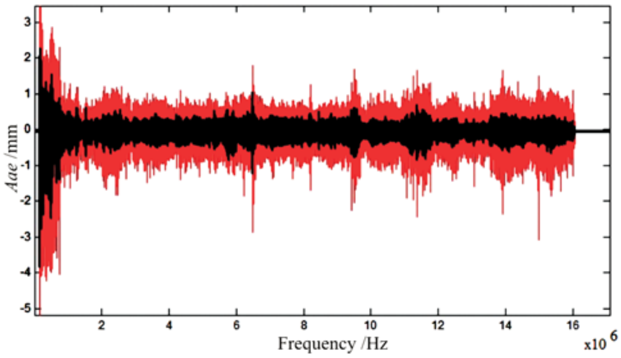

Figure 4 The course of the signal with designated noise component

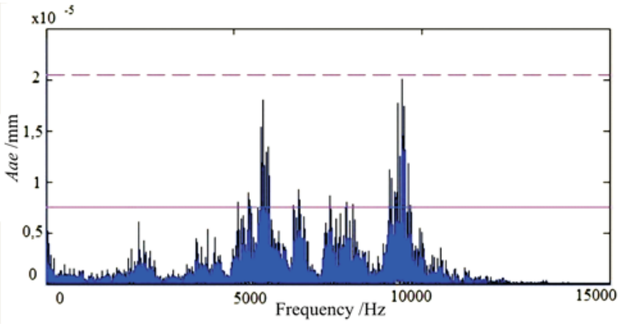

Figure 5 FFT spectrum of acoustic signal with highlighted amplitude (Sample A)

cut trajectory that the increases in amplitudes are associated with a change of direction of cut in 90°. Length of the cut on each side is roughly the same and this confirms our claim.

6
Use of results for prediction of quality process

It is possible to solve practical problems with the use of acoustic emission which most of the engineers and users face in the process of AWJ technology. Results also serve to maximize the performance of AWJ production and to set values of process parameters, which will bring the desired product quality. With the use of sound emission, which is related to the surface roughness, the system of production previously run and adjusted only by the experience of workers can be improved. Amplitude component of acoustic emission signal was selected as the most suitable for on-line control. The following picture shows the amplitude correlation $A_{ae}(t)$ to the surface roughness for $Ra = 0$ to 30 μm for the purpose of deriving the function for controlling traverse speed AISI 309. For AISI 309 were derived polynomial equations of dependence to implicit function $A_{ae}(t) = f(Ra, t, h, v)$. Graphical courses of these functions are shown in Fig. 6. Linear regress equation 1:

$$A_{ae}(t) = -0{,}02767 + 0{,}11216 * Ra(t)$$

It represents the correlation of amplitude $A_{ae}(t)$ to the cross-sectional roughness $Ra = f(t, h, v)$ with the linear regression equation, which can be used for online control in automated process of cutting as control function for regulating traverse speed v_R m/min. Fig. 6 shows example course of dependency, which demonstrates the suitability of using acoustic emission for on-line control of cutting head´s feed rate and thus ensuring the control of the whole process and final inspection of roughness. Derived equations and their graphic illustrations show the suitability of amplitude component of acoustic emission for the on-line control of cutting speed of the head and final control of surface roughness, leading to the possibility of fully automated system. These equations can be derived in a similar procedure for the frequency components of acoustic signal. Because both components of the signal can be measured simultaneously, they can be also used simultaneously to control and manage the process as well as for mutual control

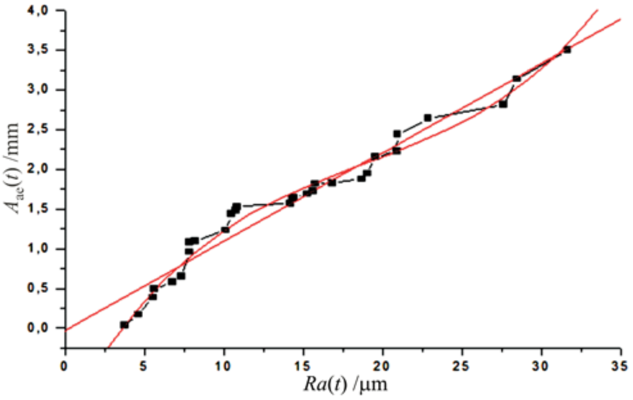

Figure 6 Graphic display of dependence $A_{ae}(t)$ to the surface roughness Ra by v= 150 mm/min, AISI 309

7
Conclusion

Technology of abrasive waterjet cutting is one of the leading manufacturing technologies. At present, higher demands of the technology are placed mainly to create quality surfaces. The quality of machined surfaces is greatly affected by the cutting conditions and the accompanying phenomena arising in the process of cutting. From AWJ factors those are mainly feed rate, abrasive mass flow, cutting surface roughness, depth of cut, and to the effects of these conditions are included mainly the acoustic emissions, vibrations, deformation force etc. Despite the rapid advancement of the technology, many relationships among these AWJ factors have not been clarified, yet.

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