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ABRASIVE WATERJET CUTTING TECHNOLOGY RISK ASSESSMENT BY MEANS OF FAILURE MODES AND EFFECTS ANALYSIS METHOD

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Professional paper

Competition and scientific progress require introduction of technologies that perform challenging claims of modern production in automation field, from economy, environmental and energy efficiency point of view. Abrasive waterjet cutting represents all of these claims. For the up-to-date high requirements on quality and productivity abrasive waterjet technology is applied in fully-automated workplaces with automatic CNC control. Flexible and smart automated technique application does not exclude the human being from the manufacturing process; it only transfers his working activities from strenuous jobs and jobs in malign environment to the areas of control, maintenance and operation management. In the paper the manufacturing of AWJ technology is evaluated by means of Failure Modes and Effects Analysis Method in order to assess risks and to propose measures for its elimination.

Keywords: *abrasive waterjet technology, FMEA method, risk analysis*

Procjena rizika tehnologije abrazivnog rezanja mlazom vode metodom analize mogućnosti kvara i posljedica

Strukovni članak

Konkurencija i znanstveni napredak zahtijevaju uvođenje tehnologija koje ispunjavaju izazovne zahtjeve moderne proizvodnje u području automatizacije, glede gospodarstva, zaštite okoliša i energetske učinkovitosti. Abrazivno rezanje mlazom vode predstavlja sve ove zahtjeve. Tehnologija abrazivnog rezanja mlazom vode je za današnje visoke zahtjeve na kvalitetu i produktivnost primijenjena u potpuno automatiziranim radnim mjestima s automatskom CNC kontrolom. Primjena fleksibilne i pametne automatizirane tehnike ne isključuje čovjeka iz proizvodnog procesa; samo pomiče njegove radne aktivnosti, od napornih poslova i poslova u malignim sredinama u područje kontrole, održavanja i operativnog upravljanja. U članku se proizvodnja tehnologijom abrazivnog rezanja mlazom vode ocijenjuje pomoću metode analize mogućnosti kvara i posljedica (FMEA - Failure Modes and Effects Analysis) u svrhu procjene rizika i prijedloga mjera za uklanjanje.

Ključne riječi: *analiza rizika, FMEA metoda, tehnologija abrazivnog vodenog mlaza*

1 Introduction
Uvod

Abrasive waterjet cutting nowadays represents cold precise, computer controlled shape cutting without any strain [1, 2]. These attributes pose this technology to the position of permanent use in the future, that represents excellent perspective for expansion in volume sectors, especially there, where the materials with excellent utility properties are used [3, 4]. The AWJ technology is, under existing high requirements for manufacturing quality and productivity, applied to fully automated production workplaces with automatic CNC control [5]. However, the introduction of automated machinery and equipment with high flexibility and intelligence does not exclude the man from the production process, but it transfers human acting from laborious work and work in harmful environments into the area of control, operation, check and maintenance of automatic devices [6, 7, 8, 9]. The automation of manufacturing processes of AWJ cutting technology is a benefit having technical and economical effects above all when the existence and possibility of risks threatening this process are not omitted. Those means which were introduced into the built-up system to exclude a man from hazardous, laborious and monotonous work thus become a source of hazard to the man. These results are partly useful for all kinds of high pressure jet applications, like high pressure jet assisted machining. This hybrid technology is presented in [10].

2 Risks identification
Identifikacija rizika

In a manufacturing automated system, a worker comes into contact with various kinds of threats that are associated mainly with the technology used [11, 12, 13]. However, when making the risk analysis, it is also necessary to take into account those factors which are not directly connected with this technology but whose influence on the worker cannot be eliminated. If all risk factors affecting a man in a working environment of AWJ technology are to be assessed correctly, other influences are to be assessed as well, namely: workplace equipment, workplace size, auxiliary accessory, machines, lighting, work organization, workplace flooring, working tools used [14, 15]. Because workplaces using the technology of material cutting [16, 17] by the abrasive waterjet may have various layouts of basic and auxiliary systems, which depend only on the functional use and commercial use of this technology, it is a specific workplace with AWJ technology that is assessed from the point of view of occupational safety and health [18].

3 Methodology of AWJ risk assessment
Metodologija procjene rizika kod abrazivnog rezanja mlazom vode

As an assessment method of AWJ technology the Failure Mode and Effects Analysis (FMEA) was employed that assess as the production processes' weaknesses and potential effects of process failure on the product being produced. FMEA emphasizes the importance of actions that can be taken to eliminate or reduce the potential causes

Table 1 *Risk analysis matrix*
Tablica 1. *Matica analize rizika*

		Effect Seriousness			
		Catastrophic	Critical	Marginal	Negligible
Occurrence Probability	Very high	1	3	7	13
	High	2	5	9	16
	Probable	4	6	11	18
	Not probable	8	10	14	19
	Very low	12	15	17	20

leading to the process failures. However, it has been observed that manufacturing engineers are too occupied with how to make things work and thus fail to consider the potential pitfalls. Thus, it is imperative that FMEA is conducted throughout the process and is revised whenever a change has been made to it. FMEA ensures that the manufactured products are met with the engineered product specifications and that the process defects do not result in product safety problems in the field. The method is semi-quantitative and evaluates the accident occurrence probability (*O*) and effects seriousness (*S*) and can be expressed as a combination of both factors as follows [7, 8, 9]:

$$R = O \times S \tag{1}$$

The total risk (*R*) is expressed in risk matrix (Tab.1) listed in [4].

Abrasive waterjet machining contributes to the manufacturing process by a number of incipient dangers, which mostly contribute to the risk origin of the AWJ technology system operation. Effects of possible personal accidents are in general considered to be most serious; therefore the assessment of the possible risk is necessary. For general assessment of the defect cause it is necessary to name the systems that can significantly influence the work safety at technology of abrasive waterjet by their operational properties and performance function. Each estimated system is assessed independently (Fig. 1). At the selection of assessed systems not only common working process, but also some exceptional activities are taken into account. Very important part of the method is estimation of assessed systems parameters.

4 Selection of assessed system
Odabir sustava za procjenu rizika

In the automatically operated AWJ machining process, many factors influence the origin of hazards and risks. To assess generally the causes of injuries objectively, it is suitable to name the systems which may significantly, via their operating properties and activities performed, influence occupational safety if using the abrasive waterjet technology. Any system identified is assessed separately (Fig.1). In the course of selection of systems assessed, not only common working processes, but also exceptional activities are considered. This step includes the determination of parameters of systems assessed as well.

In the analysis of occupational risk level in the workplace with the abrasive water jet, the basic system is the AWJ process equipment itself. The other assessed systems are auxiliary elements in a common subsystem of abrasive waterjet machining.

4.1 Water system preparation
Priprema vodenog sustava

Parts of the oil circuit fulfil functions that may, as a result of physical effects, endanger the trouble-free operation and thus the health of workers. Electromotor drives the hydraulic pump; electrical energy is supplied from the source of direct current with the voltage of 220 V. In case of not obeying safety regulations or in case of failure occurrence, the electrical energy itself is a source of risk.

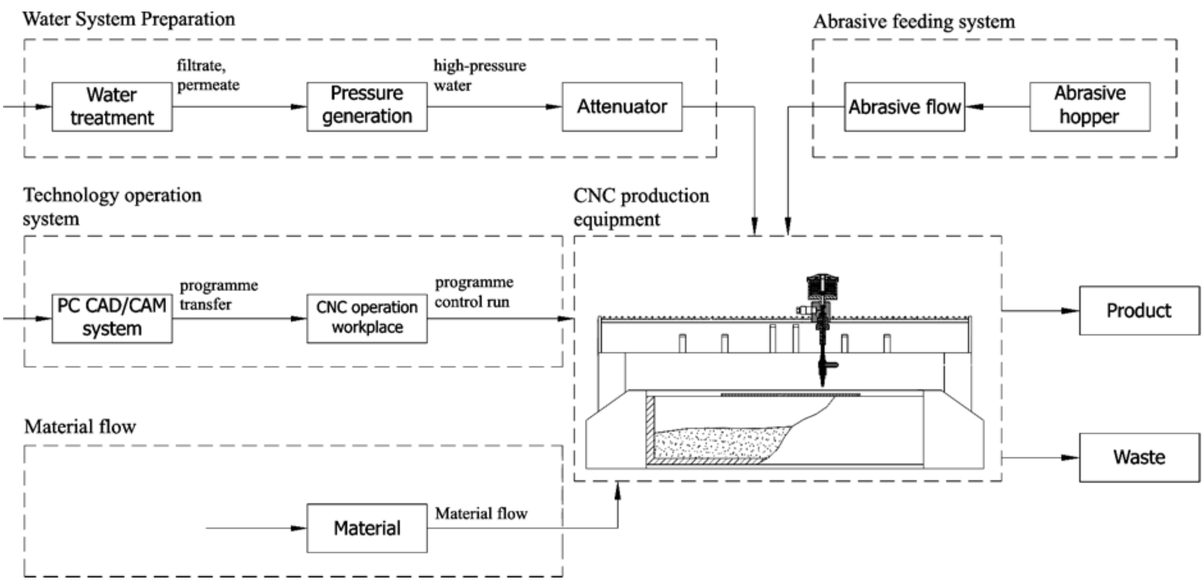

Figure 1 *Assessed subsystems of AJW production system*
Slika 1. *Procijenjeni podsustavi proizvodnog sustava abrazivnog rezanja mlazom vode*

Failures may be caused by electric insulation damage due to heat resulting from overloading or by mechanical damage of the insulation material. Insulation being damaged, a possibility of striking the human organism by electrical energy, namely directly by contact of a man in the point of injury or contact with another part of installation and subsequent distribution of electrical energy in the system, impends. In addition to direct effects of electrical energy on the human organism, injury may occur as a consequence of effects of other factors due to subsequent damage to other parts of AWJ process equipment. Damage to insulation and a threat to a man by electrical energy are in similar electrical installations very seldom. Keeping to safety regulations, the number of similar injuries is low. With regard to a possibility of occurrence of fatal accidents, sufficient attention must be paid to the above-presented sources of hazards. The working pressure of hydraulic pump moves in the range from 16 to 35 MPa. Owing to material ageing, pump structure tightness may be damaged, which causes oil leaks or damage to certain components of pressure loaded circuit. Hazards resulting from this are as follows:

- slipping and the fall of persons on the oil-polluted floor,
- stumbling over the concrete floor surface polluted by oil,
- a health hazard from the oil contaminated water ingestion,
- oil inhalation in a form of aerosole,
- injuries to operating personnel caused by a hose launched due to hose coupling leakage.

Similar cases of seal damage are rare in practice, which is also a result of the existing high level of diagnostic methods. Omitting the maintenance and diagnostics of hydraulic systems can critically endanger human health, mainly by the ingestion or inhalation of hydraulic medium [11].

The oil pipes, a part of which is also an oil reservoir, is another component of the same level of importance to the system of hydraulic oil circuit, which may cause a hazard. The oil pipes are exposed to the pressure of hydraulic medium and simultaneously, the material of pipe as well as its parts, especially sealing ones, is deteriorated. By this unfavourable influence, its integrity may be damaged and an accident may happen.

Such a condition also includes the following hazards:

- floor pollution and subsequent falls of persons,
- splashing the oil flow into the face of operating personnel and visual impediment or potential ingestion,
- damaging the floor material, formation of unevenness and subsequent stumbling,
- an injury to operating personnel by part of pipe fly-off,
- damage to the pipes or reservoir, oil leakage and contamination of water sources, which may lead to the ingestion of oil by the operator.

At the present condition of engineering facilities, with regard to materials used in the hydraulic pipe construction, similar accidents are rare. Similarly to the previous case, a hazard arisen may have critical consequences on health.

The cooling of hydraulic parts of the system is an important element which is designed for decreasing the probability of failure occurrence. The hydraulic system is, in the course of fulfilling its function, exposed to various effects that cannot be eliminated and that lead to heat generation. The heat weakens the material, of which oil circuit components are made, and thus material structure may be damaged resulting in a failure of the system. The cooling system is designed for the elimination of this affecting influence. The last element in the low-pressure system is a multiplier – double-acting generator. As with the other installations which are parts of this system, the material of the multiplier is subjected to high pressures and effects of hydraulic medium. Rising of possible hazards are analogous to the above-presented ones: slip and fall of persons, external and internal effects of medium on a staff, an injury caused by foreign particles. By these hazard factors impact, more serious consequences on human health may occur.

4.2 A high-pressure circuit
Sustav pod visokim tlakom

A high-pressure water generator, high-pressure tubes, a high-pressure atteunator and an abrasive cutting head are subjected to high pressures, and that is why high requirements for quality, reliability and safety are put on them. In the system of generation of high-pressure water, failures may occur in the course of fulfilling functions required for the implementation of pressure generation of up to 450 MPa. Those failures are due to damage to the materials, especially sealing components. Simultaneously, the following hazards to workers arise: falls on the slippery floor after being polluted by the medium, injury to health by the medium flow spurted from the damaged part. An overview of all hazards shows the severity of possible injuries to health in the course of operating the system of high-pressure water generation. Therefore, it is necessary to pay attention above all to the equipment controll from the point of view of technical level, automation and diagnostics. Damage to some parts of the system may have unfavourable effects on the level of services performed.

4.3 Supply of high-pressure water
Dovod vode pod visokim tlakom

Water as a working medium comes to contact with materials of which equipment of high-pressure circuits is made. Water occurring in the sources of common use (drinking water, industrial water) contains particles of various origins; they may affect unfavourably this material, and by their acting, the material structure may be damaged, which is connected with failure and risk occurrence. Simultaneously, it contains mineral substances which settle inside equipment of high-pressure circuit and cause thus the reduction of water orifice cross-section. The reduction of water orifice cross-section also causes an increase in pressure in the system, and the coherency of connecting nodes may be disturbed. This process causes the hazardous condition as well. To prevent or at least to reduce these unfavourable influences, water must be treated before the entry to the system – impurities must be removed from the water. For this purpose, a filtration system is used. Thus filtration can be ranked among the elements for the elimination of danger in the system. The filtration system itself employs methods and means which do not threaten the safety of people, and thus there is no need to analyse it from this point of view. Purified water is supplied to the system by means of an auxiliary pump under pressure of 0.6 MPa. It is not subjected to high pressure and thus the probability of failure origin is very low. In the case of occurrence of such state, consequences are negligible.

4.4 Abrasive feeding system
Abrazivni sustav napajanja

The abrasive is supplied by the system of feeding to the abrasive head, in which it is mixed with high-speed water. The preparation of abrasive is required only for recycled abrasives to prevent impurities from penetrating into the abrasive system, which could cause its failure. A risk following from the situation arisen like that does not endanger a man by any direct health injury, but it has adverse effects due to associated factors (delayed work, inadequate acceleration of work).

5 The technological process risks analysis
Tehnološki postupak i analiza rizika

The process of abrasive waterjet machining contributes to the manufacturing process by many emerging hazards which in a considerable degree contribute to the origin of risks of AWJ equipment operation. Generally, consequences of possible injuries occurred are regarded as very serious; therefore, in this case the risk management is unavoidable. In the cutting process (Fig. 2), two main elements participate – AWJ and a workpiece.

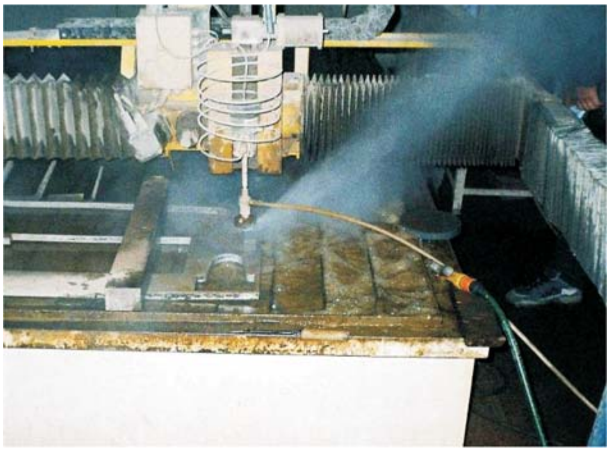

Figure 2 *The process of material cutting and rebound of abrasive waterjet from stainless steel AISI 304*
Slika 2. *Postupak rezanja materijala i odbijanje abrazivnog vodenog mlaza od nehrđajućeg čelika AISI 304*

AWJ flow at the speed of up to 900 m/s and dispose of very high kinetic energy, from whose acting the greatest hazard follows. In the course of machining, the particles of water and also abrasive impinge upon the surface of target material, and thus material particles separate from the workpiece. After cutting the material machined across the whole width, the residual kinetic energy of AWJ is retained in the space filled with a fluid of the same kind, where the stream flowing from the workpiece gradually broadens and after a certain distance will disperse and fade out (Fig. 3) [19]. Simultaneously, the particles of abrasive waterjet and also particles separated from the workpiece rebound into the free working space (Fig. 2). Interference between them and a man may happen and human health may be endangered. The abrasive water jet can cause, when incorrectly handled by operating personnel, a very serious injury, mainly when approximating the danger zone.

At the orifice of AWJ from the focusing nozzle on the boundary of elastic medium, the jet impinges against molecules of external environment, which causes the oscillation of particles and as a consequence of energy conversion forms a sound field (Fig. 3) [20]. This manifests itself in the origin of mainly high-frequency noise which affects negatively the central nervous system. In the course of measurement of the level of acoustic pressure, exceeded limit values were found. At the noise evaluation of AWJ technological node, they exceed them by 7 dB and up to 26 dB in the case of audible sound and high-frequency sound, respectively. Ways of threatening are as follows: high levels of acoustic pressure, the bounce of abrasive particles off the material, the bounce of AWJ, high air humidity.

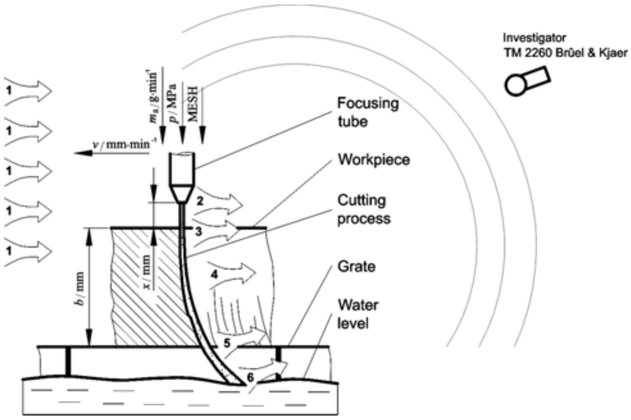

Figure 3 *Noise emissions sources at technological node in AWJ (1 - background noise, 2 - focusing tube outlet, 3 and 4 - cutting process, 5 - residual flow outlet from workpiece, 6 - residual flow contact with water surface in catcher tank)*
Slika 3. *Izvori buke u tehnološkom čvoru kod abrazivnog rezanja mlazom vode (1 - pozadinska buka, 2 - izlaz fokusirajuće cijevi, 3 i 4 - postupak rezanja, 5 - izlazni smjer otpadaka od obradnog komada, 6 - dodir otpadaka s vodenom površinom u hvataču)*

The machined material participates in hazards generated in several ways. They are for example the weight of material, its size, material composition, workpiece position, its mounting [21, 22]. A hazard may already appear in the course of handling the workpiece before or after performed manufacturing operations. Other hazards arise during the machining process in case of wrong workpiece position. Strong attention must be paid to the material from which the workpiece is produced. The acting of dispersed particles on the human organism depends of the kind of them; the case of allergens being different to the case of inert elements. As well, the effects of a separated particle on the skin of a man are different in the case of brittle material (sharp edges) and the case of relatively soft material. Possible ways of threatening are as follows: the fall of workpiece and subsequent tumbling of the operator, cutting due to the handling of a sharp edged item, a hazard following from inhalation if the material of workpiece is composed of elements which can affect adversely the human organism (toxic, allergenous materials) and their distribution in the air.

Table 2 *An overview of possible hazards and their consequences*
Tablica 2. *Pregled mogućih opasnosti i njihove posljedice*

Subsystem	Hazard source	Hazard	Consequence
Low-pressure circuit	• electric installation • pressure accessories • medium	• damaged insulation and electric shock • oil leak, floor polluted and damage • leak of oil in the form of mist, its inhaling • breaking of a part off, action of operating personnel	• slip • fall • death • contusion • respiratory tract injury • poisoning
High-pressure circuit	• high-pressure accessories • medium - permeate	• pipe damage, medium leak, floor dirtying and subsequent falls of persons • leak of medium and squirting of medium into face • knocking personnel in case of breaking a part of equipment off	• death • visual impediment • contusion • cutting • amputation
Water preparation and supply	• filtration system	• bad insufficient water treatment, impurity deposition, damage to equipment of WJM technology, mechanical hazard	• death • contusion • cutting
Abrasive supply	• recycling system	• impurity penetration into abrasive head, damage, production line slugging	• production losses
Machining	• abrasive jet • workpiece	• rebounce of particles of water, abrasive, machined material, and hitting a man • noise • dispersion of particles in the air and their inhalation • injury due to contact with water jet • workpiece fall, covering with a fallen workpiece, sharp edges • properties of workpiece material and its adverse effects on organism	• limb removal • impaired hearing • lung impairment • cutting • contusion • poisoning
Abrasive waterjet controll	• control system • handling unit • abrasive	• electric shock • collision between a man and a moving part of robot, covering with objects, fall • stream deflection, effects of the stream on a human organism • dispersion of particles in the air and inhaling them	• death • contusion • limb removal • cutting • lung impairment

Table 3 *Qualitative expression evaluated*
Tablica 3. *Verbalni izraz procjene veličine rizika*

Hazard	Accident probability	Effect seriousness	Risk size	Verbal expression of risk size
Electric shock	D	I	8	undesirable
Fall of person	A	III	7	undesirable
Pollution of water resources	E	II	15	acceptable with inspections
Oil mist inhaling	D	II	10	acceptable with inspections
Hitting by an object	C	II	6	undesirable
Hitting by a stream of liquid	C	II	6	undesirable
Inhaling microscopic particles	B	II	5	unacceptable
Noise	A	III	7	undesirable
Tumbling with falling materials	B	II	5	unacceptable
Injury due to sharp edges	A	III	7	undesirable
Effects of allergens	D	III	14	acceptable with inspections
Injury due to microscopic particles	A	III	7	undesirable
Ingestion of hazardous material	E	II	15	acceptable with inspections

6 Risk assessment
Procjena rizika

In the following table, risks of particular subsystems of AWJ cutting technology are assessed (Tab. 2). On the basis of properties of systems evaluated according to the FMEA method risk levels were determined (Tab. 3).

7 Assessment of safety level
Procjena stupnja sigurnosti

The AWJ technology, including equipment is in the system of working a bearer of more multiple sources of risks to the health of workers and operational safety. Especially the risks resulting from electric shocks, falls of persons, hitting by the stream of liquid, injury due to sharp edges, the effects of noise seem to be undesirable. As for electric shocks, manufacturers of electrical equipment make efforts to eliminate them by measures and safety regulations that are already introduced and maintained in the system of working in the framework of AWJ technology. For this reason, the risk of electric shock is already eliminated in the workplace and the system of electrical equipment is considered to be safe. In the case of AWJ technology, a serious hazard which may cause even occupational diseases, such as serious hearing impairment or deafness, is noise. According to the results of measurements taken, the resultant values of noise exceed the allowable values of normalized level of noise exposure. That is why it is unavoidable to deal with the protection of workers against noise. The other risks taken as undesirable are bearers of high occurrence probability, or serious consequence, or the combination of them. Therefore, the AWJ technology, including equipment cannot be regarded as safe, and measures to eliminate these dangers must be implemented.

In the work environment, above all those risks which follow from covering with fallen objects, injury due to sharp edges and decreased attention causing delayed reactions to hazards arisen are assessed as undesirable. With regard to these risk factors, relevant measures to prevent injuries and diseases from occurring are to be implemented.

In the system of work organization in the workplace, the risk following from disusing personal protective equipment at work is assessed to be unacceptable. Possibilities of elimination are included in the system of occupational safety and health management. An undesirable risk due to accident of AWJ equipment should be eliminated by the system of maintenance and timely diagnostics.

8 Possibilities of eliminating hazards and risks

Mogućnosti eliminiranja opasnosti i rizika

Because the analysis of risks of the assessed system of AWJ technology has shown more risks exceeding the level of acceptability, it is necessary to take steps to eliminate these risks primarily, and if it is not possible to eliminate them completely, to propose steps leading to their alleviation. A risk can be eliminated fully only if a hazard rom which it follows can be removed. It follows from Table 4 that the working system of AWJ technology does not contain the risks which can be eliminated in the given way.

***Table 4** Hazards inducing undesirable risks*
***Tablica 4.** Opasnosti koje dovode do neželjenog rizika*

Undesirable risks	Sources of hazard
Fall of persons	Floor
Hitting by the stream of liquid	Process of cutting by AWJ technology
Injury due to sharp edges of workpiece	AWJ technology, including equipment, workplace equipment, workpiece material
Impaired hearing	Noise produced by AWJ technology in the course of machining process
Delayed reactions to hazard arisen	Noisy environment
Disuse of personal protective equipment at work	Worker
Equipment accident	Work organisation
Covering with falling objects	AWJ equipment, workpiece material

8.1 Technical measures to reduce the risk

Tehničke mjere za smanjenje rizika

The following Table 5 presents technical measures for risks elimination of cutting by the AWJ technology.

***Table 5** Technical measures for risks elimination*
***Tablica 5.** Tehničke mjere za eliminiranje rizika*

Exhausting plant	Inhaling particles of solid substances	Exhaustion of microscopic particles produced in the course of machining from the material of workpiece and used abrasive, whose trajectory of motion does not the collecting grooves of table tank.
Guard of metal material	Hitting by a stream of liquid	To prevent access to the vicinity of abrasive stream in the course of machine operation. The guard should be located on the circumference of positioning table on all accessible sides.

Therefore, an alternative of measure to reduce noise, preventing abrasive particles jet off the material and the stream from bouncing exists - by underwater cutting of the target material. However, many pieces of equipment do not enable this possibility, and in addition, it is not possible to control visually the process of material cutting (Fig. 4c).

8.2 Organizational measures

Organizacijske mjere

Many undesirable and unacceptable risks can be eliminated by a set of organizational measures. These can concern the workplace layout, the management of occupational safety and health, the use of personal protective equipment at work, and finally the management of technical equipment maintenance.

- Risk reduction by the delimitation of safety zones is one of alternatives of injury prevention. Such measure reduces the risk of injury especially in the case of visiting and unauthorized persons to the place of operation. Safety zones are marked by yellow stripes on the floor; the stripes must be used in the zone with the minimum probability of injury minimally 3 m from the positioning table owing to the bounce of abrasive particles off the target material.
- The use of personal protective equipment at work in the course of cutting and handling of materials. Above all the use of hearing protection equipment is in this case, with reference to the values exceeding the acceptable high-frequency sound (8-12,5 kHz), unavoidable. During material cutting, workers are obliged to use protective goggles preventing sharp microscopic particles from penetrating into the sight organs. They are obliged to use protective gloves to avoid injury due to sharp edges when material handling.

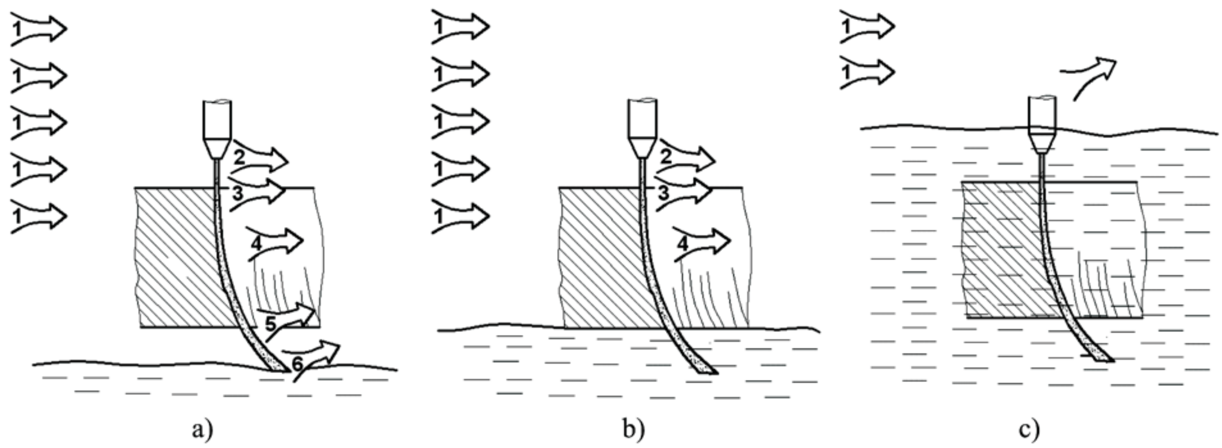

Figure 4 *Reduction of the sources of acoustic sound pressure level in order to eliminate the noise at AWJ technological node*
Slika 4. *Reduciranje izvora akustičke razine zvučnog tlaka kako bi se eliminirala buka u tehničkom čvoru kod abrazivnog rezanja mlazom vode*

- The right maintenance strategy may prevent occurrence of serious risk situations, of which a system accident is the greatest threat to operational safety. The system of maintenance includes activities to increase the level of preventive maintenance, to increase the qualification of maintenance workers and to find the wear of AWJ equipment. Improvement in these areas can be achieved by a system approach in the area by the determination of weak points in the system, the observation of equipment life, the data collection and analysis of failures.

9 The evaluation of proposed measures
Ocjena predloženih mjera

The proposed measures lead to the elimination or reduction of risk at the workplace using the AWJ technology. They are aimed at decreasing the level of risk which is unacceptable or undesirable. Technical measures in the form of exhausting plant is designed, thanks to its favourable effects on improving the condition of air humidity, dustiness and spattering of liquid in the surroundings, especially for reducing the risk of slip and subsequent fall of persons. The plant does not make it possible to eliminate the risk completely, but it mitigates the consequences of the risk. Simultaneously, it helps to mitigate the residual risks induced by low-level hazards, namely by the inhalation of microscopic particles, injuries to the face and sight organs by abrasive particles. The disadvantage of the plant is the purchase price and operating costs of maintenance. The measure in the form of guard is designed for the risk elimination resulting from hitting by the stream of liquid, which may cause a serious injury up to limb amputation. If the guard is fully functional, no person can come into contact with the water jet. As well, the spattering of particles causing injuries is the most conspicuous in the region close to the machining process, which means that preventing access to this space, the risk of hitting by abrasive particles is reduced. The disadvantage of this device is a need of handling when replacing and positioning the material. The organizational measure in the form of marking safety zones is aimed at reducing the risk of fall of persons as a result of collision with objects, the covering with fallen objects and the injuries due to sharp edges. These risks are undesirable in operation. It also helps reduce the residual risks of being hit by the stream of liquid and injury due to microparticles. It is necessary to use personal protective equipment at work intended for risk reduction. This can be ensured merely by consistent and adequately frequent inspection controls in the workplace. By a systematic approach to performing controls, the hazard level of permanently impaired hearing can be significantly decreased. By removing noise effects on the worker's organism, stress and consequences of stress on the operator´s state of mind, which manifest themselves in inattention and delayed reactions even to the hazard arisen, are removed as well. Personal protective equipment at work mitigates also the residual risk of injury due to sharp edges, abrasive particles, slip and fall of persons. The correct creation of maintenance systems mitigates the probability of state of disrepair of process equipment. Thus, benefits are increasing the safety of the system and increasing the productivity of labour, decreasing operational costs and extending the lives of individual nodes of the system. As follows from the evaluated measures to increase the safety level of the system, it can be stated that by their implementation in practice, the degree of hazard of individual risks may be decreased so that they may be taken as moderate or acceptable.

10 Conclusions
Zaključci

The analysis of risks of abrasive waterjet cutting technology has revealed many dangers, to which operational personnel are exposed. In addition to the acceptable risk, it confirmed the division of hazards into the classes of probability of hazard occurrence and classes of possible consequences, and the occurrence of undesirable and unacceptable risks. According to the FMEA, risks associated with the disuse of personal protective equipment at work, noise in the workplace, risks of being hit by the stream of liquid and bounced abrasive particles seem to be the most significant. The proposed measures to remove undesirable risks in particular show possibilities of directing towards ever-improving occupational safety and health by means of technical and organisational measures. New trends in the organisation of work show prospective possibilities of permanent and continuous increasing the safety level of manufacturing systems by increasing the qualification of workers and by educational measures. In the given work system, it is necessary to eliminate undesirable and unacceptable residual risks or to mitigate them to acceptable levels and to create acceptable working conditions for operating personnel, and thus to increase the efficiency of process equipment, equipment reliability, occupational safety and last but not least, to improve the image of the company.

11
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