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THE ROLE OF CRYOGENICS IN MACHINING PROCESSES

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Original scientific paper

The purpose of this work is to present some guidelines in the sustainable machining processes, using cryogenic conditions and gaining higher performances, lower environmental and health influences, increased safety, etc. The study presents the details about cryogenic fluids and their use in machining processes as an alternative to oil-based emulsions. The details of liquid nitrogen and the ways of their application in the machining processes, known as cryogenic machining process, are given. The research is upgraded with experimental case study on high temperature alloy machining – tungsten, and so presenting an important scientific and sustainability contribution in production processes. Experimental and analytical results are proving that the cryogenic machining technology has a high potential to cut costs and improve competitiveness, by reducing resource consumption and creating less waste and have less of an environmental and social impact, fulfilling the sustainability pillars: economical, social and environmental one, over conventional machining processes.

Keywords: *cryogenics, machining, production, sustainable manufacturing, porous tungsten*

Uloga kriogenika u postupcima strojne obrade

Izvorni znanstveni članak

Cilj je ovog rada dati prikaz smjernica u ostvarenju održive proizvodnje stvaranjem kriogenih uvjeta radi postizanja viših perfomansi u obradi, manjeg utjecaja na okolinu i ljude, povećanja sigurnosti itd. Istraživanjem se prikazuju pojedinosti o kriogenim fluidima i njihovoj upotrebi u postupcima strojne obrade kao alternativno sredstvo emulzijama na bazi ulja. U radu su dane pojedinosti o tekućem dušiku i načinima njegove primjene u strojnoj obradi, poznatim kao kriogeni procesi strojne obrade. Istraživanje je provedeno eksperimentalno pri obradi legura za rad na visokim temeperama na bazi volframa i na taj način dan značajan znanstveni doprinos u postupcima održive proizvodnje. Eksperimentalni i analitički rezultati potvrđuju da kriogena tehnologija strojne obrade ima dobar potencijal za smanjenje troškova i poboljšanje konkurentnosti, smanjenje potrošnje sirovina, smanjenje otpada, manji utjecaj na okolinu i ljude, ispunjavajući uvjete održivosti: ekonomske, socijalne i okoliš u odnosu na konvencionalne postupke strojne obrade.

Keywords: *kriogenici, strojna obrada, proizvodnja, održiva proizvodnja, porozni volfram*

1
Introduction
Uvod

Sustainability – according to definition, sustainable development is the development that meets the needs of the present, without compromising the ability of future generations to meet their own needs [1]. For fulfilling this definition's aim, the ideas have to be implemented in all the fields and levels of production and in this way contribute to the idea of global sustainability.

At the moment the manufacturing industry is under increasing pressure of financial crisis, new sustainable development regulations, supply-chain and customer demands. One way to gain an advantage in this situation is to focus on competitive sustainable manufacturing (CSM) [2]. CSM has the dimension of economy, ecology, sociology and technology and calls for practices and decisions that will assure high-adding-value solutions.

The global environmental problems caused by the consumption of natural resources and the pollution resulting from the life of technical products, have led to increasing political pressure and stronger EU regulations being applied to both the manufacturers and users of such products. The industries involved in production are additionally under economic pressure, and are attempting to compensate for increasing costs and create added value for their products. The adoption of sustainable development in production offers industry a cost effective route for improving economic, environmental, and social performance (i.e. the three pillars of sustainability) [3, 4, 5].

2
Industrial needs
Potrebe u industriji

Heat resistant alloys (high-temp alloys) with high melting temperatures are nowadays important materials used in the manufacture of aero-engine components. These super-alloys can be grouped into four major categories: nickel based alloys; cobalt based alloys; iron based alloys (e.g. high chromium stainless steel), titanium alloys and tungsten. The ability to retain high mechanical and chemical properties at elevated temperatures makes super-alloys ideal materials for use in both rotating and stationary components in the hot end of jet engines [6, 7]. The components produced with super-alloys are smaller and lighter than those made from conventional steel. This results in significant fuel savings and therefore a reduction in environmental pollution.

Super-alloy materials are also used by the chemical, medical, and structural/construction industries in applications requiring extraordinarily high temperature properties and/or corrosion resistance. Power plants and the aerospace industry use higher proportions of machined components made from super-alloys, such as turbine engine components. The machining of nickel-based, tungsten, and titanium-based alloys and other high-tech materials are very expensive because of their high-temperature properties as well as their ability to retain a high strength-to-weight ratio, which are essential for the economic exploitation of aerospace engines. However, these properties, on the other hand, lead to shorter tool-life, which significantly increases tooling waste and machining costs [8, 9]. It is envisaged that the aerospace sector will witness a doubling of the aircraft fleet over the next 20 years in response to the replacement of older aircraft and growth opportunities [10]. Therefore, the same trend of development/usage is indirectly expected in innovative machining/production systems, which additionally prove the high potential for innovative sustainability-oriented machining processes.

The fact that the volume of aerospace-alloy usage is continually increasing has resulted in huge pressure to reduce machining cost by developing efficient technologies, Ref. [8, 11, 12, 13, 14, 15]. From the initial investigations it is possible to state that innovative sustainable machining process (cryogenic machining, high pressure jet assisted machining, etc.), in combination with appropriate tool material(s) and technology, has resulted in enhanced performance when machining aerospace (hard-to-machine) alloys.

Conventional cooling lubrication fluids (CLFs) in these applications are not as effective as the proposed alternatives in terms of decreasing the cutting temperature and improving environmental sustainability. In some cases, they even cannot fulfill the machining or final part requirements related to its functionality. Additionally, one of the most fundamental concerns is the use of CLFs, which has a direct influence on the environment, performance of machined surface and machining economics. In reality there are always some losses of CLF in the production process. This occurs through vaporization, the loss with chips and parts as they leave the machine tool, the loss of machine components such as handling devices, as well as through leakage. Taking into account that up to 30 % of the annual total CLF consumption can be lost from the system by the above means, it becomes clear that technologies employing CLFs are unsustainable, and by avoiding of their usage through applying dry, near-dry, etc. machining alternatives, there would be a huge process gain from the sustainability point of view, Ref. [16, 17, 18].

Surveys indicate that few companies have accurate information regarding CLF cost. Available data in the EU automotive industry show that production costs incurred in connection with the deployment of CLFs are 15-20 %, while the percentage of tool costs is around 4 %. CLFs are made from concentrates. On average about 4 % concentrate are included in a water miscible CLF. Single machines contain up to 5 m^3 of CLFs, while large central CLF systems may have up to 100 m^3 and more. Common time intervals between replacements, range from 4 weeks (single machines) to 1 year (central CLF systems). A medium-sized automotive parts manufacturer uses 100 000 liters of oil-based CLFs, which have to be changed every year. This change can cost up to €40 000. In addition €15,000 are used for chemical treatment of oil-based CLFs, €15 000 for waste water treatment and €6 000 for cleaning pipes and installation. The market overview for CLF usage in the EU is presented in Tab. 1.

This data shows a big market on one hand, and on the other hand a frightening impact regarding environmental pollution and health hazards. Both of them have high potential regarding the proposed sustainable production systems/processes with corresponding technologies.

The question that remains is what kind of CLF and how much of the alternative CLF have to be used instead of the oil-based type, and the cost of both. This is hard to predict in advance, since the amount and cost depend on the specific application. It also has to be noted that in the case of oil-based CLF usage, the purchase cost has to be increased to take into account also the CLF disposal costs, parts cleaning and drying costs, chips cleaning and drying costs, parts protection against corrosion costs, depreciation costs, maintenance costs and costs connected with personnel and health precautions. With regard to this, cryogenic machining is proposed as alternative ahead of conventional machining processes.

3

Cryogenics

Kriogenici

Cryogenics is the field related to technology at deep freezing temperatures. Traditionally, the field of cryogenics is taken to start at temperatures below 120 K (~ −150 °C). The definition includes the more common cryogenics such as helium, hydrogen, neon, nitrogen, oxygen, argon, krypton, xenon, methane, ethane, and propane. Carbon dioxide is commonly added to the list even though a pressure over 50 kPa is required to maintain it in liquid form. Even the term "cryogenics" seem like an esoteric field, it plays a major role in modern industry and science. Some of the applications are: air separation plants for breaking it down into its components for industrial and medical uses, liquefied helium has become unavoidable cooling element of magnetic resonance imaging systems in modern hospitals, in space technology where cryogenics are through the liquefied hydrogen and oxygen used as fuels, food freezing and cooling, purging and blanketing, etc.

The beginning of cryogenic is going back in the beginning of the nineteenth century where there was a "race" in liquefying gases and reaching ever lower temperatures. This started in 1887 with the announcement of the liquefaction of oxygen (Pictet and Cailletet). In 1898, James Dewar first liquefied hydrogen. He also developed the vacuum-insulated flask for containing cryogenic liquids that are still frequently used and are called "Dewars". The last and most difficult gas to be liquefied was helium, liquefied by Kamerlingh Onnes of Lieden in 1908. As a twentieth century progress, industrial application of cryogenics increased, particularly in the area of air liquefaction and industrialization.

***Table 1** Cooling/lubrication fluid (CLF) market overview in the EU* [21]
***Tablica 1.** Pregled tržišta sredstava za hlađenje ispiranje i podmazivanje u Europi* [21]

Substance group	Germany sales (t/year)	Total sales for EU (t/year)
All lubricants	1 146 844	5,2 mil.
Of those, CLFs	78 877	360 000
Non-water miscible CLFs	48 170	220 000
Water miscible CLFs (concentrate)	30 707	140 000
Emulsions and solutions created from water-miscible CLFs	~770 000	~3,5 mil.
Total amount of CLFs used	~820 000	~3,7 mi.

*It should be noted that these statistics do not cover mineral oil-free CLFs. Such mineral oil-free lubricants have a market share of approximately 20 % of the total amount of water miscible CLFs produced.

The application of cryogenic fluid to cool the metal cutting process started as early as the 1950's. The cryogenic fluids used were CO_2, freon, or solvenlene. They were sprayed in the general cutting area or were applied to the workpiece before cutting in a prechill. This method however consumed excessive amounts of cryogenic fluid and had no lubrication effect. Additionally this reflects high costs and present high complexity in delivering of cryo fluid to the cutting zone. Therefore the process is still not applied in the industrial environment.

Today the process of liquefaction and storage system becomes more affordable, and there is a need to develop and rise the cryogenic machining on an industrial level. Due to price (in comparison to dry ice – CO_2 or helium), availability, temperature, etc. related to machining process characteristics and requirements, in this work as a cryogenic fluid liquid nitrogen (LN) is going to be used.

3.1

Nitrogen characteristics

Karakteristike dušika

Phase diagram for nitrogen is presented in Fig. 1. Its triple point occurs at an atmospheric pressure of 12,463 Pa and a temperature of 63,15 K. At lower pressures, nitrogen will sublimate. The normal melting and boiling point for nitrogen (that is, at 100 Pa) are 63,3 and 77,4 K (−210 and −196 °C) respectively (Fig. 1). Liquid nitrogen is therefore causing freezing cold environment, where delivered. Nitrogen is a safe, non-combustible, and non-corrosive gas. In fact, 78 % of the air we breathe consists of nitrogen (Fig. 2), and is therefore not problematic from health side of view. It is colorless, odorless, tasteless, and inert fluid, and therefore presents potential liquefied gas that can be used in the machining process.

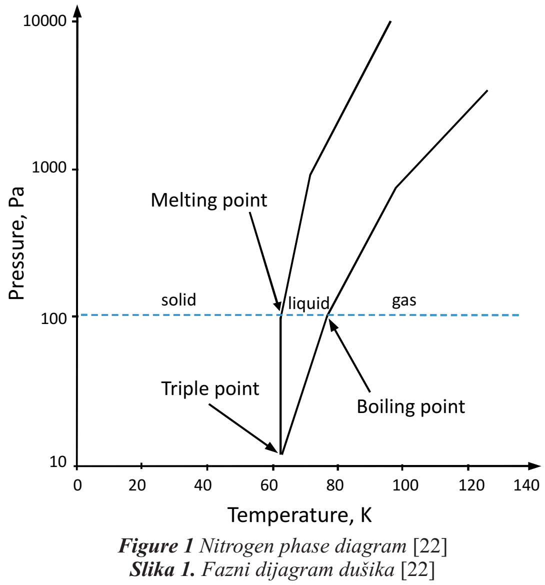

Figure 1 *Nitrogen phase diagram* [22]
Slika 1. *Fazni dijagram dušika* [22]

Nitrogen characteristics are:

- Molecular formula: N_2
- Molecular weight: 28,01
- Specific gravity: 0,967 while for air is 1
- Specific volume: 0,867 m^3/kg
- Boiling Point: −195,8 °C
- Liquid to gas expansion ratio: 1:693
- Liquid density: 808,5 kg/m^3

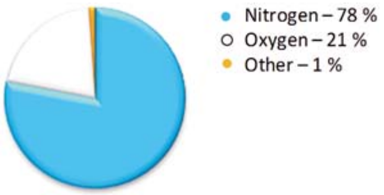

Figure 2 *Air composition*
Slika 2. *Sastav zraka*

There are three main points that we have to pay attention on when working with LN:

- Oxygen deficiency/asphyxiation; Nitrogen, if concentrated in a volume, can displace oxygen in the air, reducing the % of oxygen below the safe levels. Therefore process using nitrogen has to be installed in a well ventilated area. Recommended are 6 air changes per hour, with recommended vent to safe locations and oxygen monitoring equipment.
- Pressurized gas; Nitrogen equipment is under high pressure. Even if the operating pressures are meant to be small, there is a high expansion characteristic (1:693) of nitrogen phase transformation. Therefore, system has to be designed with adequate pressure relief to protect from over pressurization.
- Cryogenic temperatures with fog clouds; low temperatures of liquid and gas nitrogen can cause severe burns. Additionally, when liquid nitrogen is delivered rapidly it boils and vaporizes. The nitrogen vapor spreads itself out through the air picking up water vapor along the way. Because of the presence of water in the air, it smokes. The amount of water present in the atmosphere is dependent upon the temperature of the air (the warmer, the more water vapor can hold).

3.2

Liquid nitrogen production

Proizvodnja dušika

A common method for the production of liquid nitrogen is the liquefaction of air. Liquefaction is the phase change of a substance from the gas phase to the liquid phase. In liquid nitrogen compressors or generators air is compressed, expanded and cooled via the Joule-Thompson effect (Fig. 3). Since nitrogen boils at a different temperature than oxygen, the nitrogen can be distilled out of the liquid air, re-compressed and then re-liquefied. Once liquid nitrogen is removed from the distillation chamber, it is stored either in a pressurized tank or a well insulated Dewar Flask.

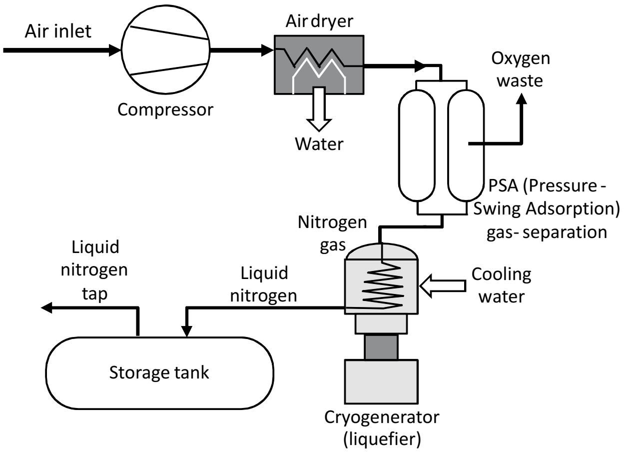

Figure 3 *Plant for the production of liquid nitrogen* [23]
Slika 3. *Postrojenje za proizvodnju dušika* [23]

Observing the nitrogen process production, there is mainly one input to the process – energy, while water is used as a cooling fluid and is returned to the environment toxicless. It has to be pointed out that there is no other waste, such as CO_2, SO_x, etc, when producing LN (Tab. 2), as a contrast to production of oil-based emulsions. Detailed Life Cycle Assessment of this is performed and presented in our recent work [23]. Having in mind that conventional emulsions in machining processes beside 1,5 % of mineral oil and approximately 97 % of water, contain also approximately 1,5 % of nonionic/anionic surfactants.

4
Cryogenic machining
Kriogena strojna obrada

Cryogenic machining presents a method of cooling the cutting tool and/or part during the machining process. More specifically, it relates to delivering of cryogenic CLF (instead of an oil-based CLF) to the local cutting region of the cutting tool, which is exposed to the highest temperature during the machining process, or to the part in order to change the material characteristics and improve machining performance.

The cryogenic coolant used in this work is nitrogen fluid. Using it in machining process, when delivered to the cutting zone, it immediately evaporates and returns back to the atmosphere, leaving no residue to contaminate the part, chips, machine tool, or operator. Thus, it is eliminating disposal costs related to CLF usage. This represents completely clean process in contrast to conventional oil-based CLFs. The set-up of cryogenic machining with LN delivery is shown in Fig. 4.

Potential benefits of cryogenic machining are [23, 24]:

- sustainable machining methods (cleaner, safer, environment friendly, more health acceptable, etc.) to eliminate numerous costs associated with conventional cutting fluids and clean-up operations,
- increase of material removal rate without increases in worn tool and tool change over costs – increase of productivity,
- increasing cutting speeds without increases in worn tool and tool change over costs,
- increasing of tool life due to lower abrasion and chemical wear,

Table 2 *Comparative Life Cycle Assessment (LCA) characterization data for the production of mineral oil with CLF surfactants and liquid nitrogen as the CLF (for 1 kg of component amount)*
Tablica 2. *Usporedba LCA podataka u proizvodnji mineralnih ulja kao SHIP s dodatcima i dušika kao SHIP (za količinu 1 kg)*

Category	Unites	Mineral oil	Anionic surfactant	Nonionic surfactant	Liquid nitrogen
Energy use	MJ	5.94	60.20	51.50	1.80
Global warming potential (GWP)	kg CO_2eq	3.56	3.00	5.60	0.00
Water use	kg	0.00	6.00	0.00	*50.00
Acidification	g SO_2eq	3.83	25.00	15.80	0.00
Solid waste	g	5.19	64.20	27.10	0.00
Land use	m^2	0.00	0.00	0.00	0.00

* cooling water at 15 °C

- machining of hard parts and hard to machine alloys, which in the past, could have been produced only via expensive grinding operations,
- surface roughness of machined workpiece improvement,
- produced parts quality improvement by preventing mechanical and chemical degradation of machined surface,
- potentially lower investment costs due to reduction in number of machine tools required,
- improvement of manufacturing flexibility due to reduced production times and high output, etc.

Due to:

- lower cutting temperatures in cutting zone,
- improvement of chip breakability,
- decreased BUE formation probability,
- decreased of burr appearance probability,
- inert environment assurance,
- no oil-based emulsion used,
- no additional processes needed,
- liquid nitrogen specifications,
- changes in material characteristics at lower temperatures, etc.

Figure 4 *Cryogenic machining set-up*
Slika 4. *Postavke opreme za kriogenu obradu rezanjem*

5

Case study

Primjer

There are two important case studies performed. One of them is machining of Inconel 718, while the other is related to porous tungsten machining. The first one is presented in our previous work, while tungsten machining is a part of this work.

This experimental study focuses on high performance cryogenic machining of porous tungsten, which is classified as difficult-to-machine material, where the quality of machined surface through porosity is one of the most important objectives. As the dispenser cathode matrices are the products, the resulting machined surface integrity plays the most important role in this specific application. Therefore, the surfaces were analyzed to determine their suitability for functional requirements of the dispenser cathodes.

Tungsten has high mechanical and physical properties and has the highest melting point of all the non-alloyed metals and the second highest of all the elements after carbon [25]. Tungsten is often brittle and hard to work in its raw state. It is usually used mainly in electrical applications, but its compounds and alloys are used in many applications, most notably in light bulb filaments, X-ray tubes (as both the filament and target), and super alloys. In this work porous tungsten is used for the dispenser cathodes used in Microwave Tubes, Cathode Ray Tubes, Ion Lasers, etc. Realizing the difficulty of tungsten machining, in the case of porous tungsten structure, machining is even more difficult. Therefore, tungsten in porous form is crucial for the manufacturing of products dealing with, while just the porous machined surface structure with completely open pores can assure the functionality of the final product [26].

The lag of knowledge of porous tungsten machining through the insufficient understanding of the machined process, in particular cutting parameters and cutting/tool interactions for achieving the desired machined surface quality, lead to this research work. The porosity defined by open pores, pore size, and pore distribution is the major controlling parameter in the dispenser cathodes industry, since one of the primaries in process failure modes for electron gun products is poor or low emission due to collapsed/closed cathode pores [26]. In Fig. 5, the acceptable surface with open pores and unacceptable smeared surface are shown, according to the EIA-941 standard (Engineering specification for dispenser cathodes) [27].

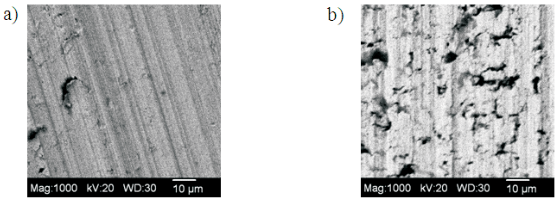

Figure 5 *Comparison of unacceptable smeared (a) and acceptable surface with uniformly distributed open pores (b)*
Slika 5 *Usporedni prikaz neprihvatljive (a) i prihvatljive (b) topografije površine s pravilno raspoređenim porama*

While with conventional machining process, the porous material is often smeared (closed pores) by the cutting tool, dispenser cathode manufacture is traditionally machined using an infiltrant. This infiltrant is usually plastic or copper, to support the pore structure and act as a lubricant in the machining process. After machining, the infiltrant has to be completely removed from the tungsten matrix without introduction of any foreign substances. The infiltration and subsequent removal processes are time consuming and a possible source of contamination, therefore the alternative is desired.

The main goal of using infiltrant in tungsten machining process is the reduction of friction, providing support and reduction of the cutting temperature. However, the advantages by using infiltrant have been questioned lately due to sustainability concerns [28]. Therefore, handling and disposal of infiltrant have to obey rigid rules of environmental and health protection. In this paper method of machining that does not require any infiltrant and is non-contaminating is discussed. Cryogenic machining which is an advanced sustainable machining process has been employed to machine porous tungsten as an alternative without using of any infiltrant material [29].

The major problem to be solved is to produce a smooth surface finish without excessive smearing of the pores of the porous tungsten material. The process may be extended to other metals commonly used in dispenser cathode manufacture.

5.1

Experiments

Eksperimenti

The experiments were conducted on a CNC lathe with added cryogenic fluid delivery system. The experimental setup is shown in Fig. 6. The sintered porous tungsten bars with a diameter of 32 mm and length of 120 mm were used in the experiments. The bars were cleaned prior to the experiments by removing approximately 0,5 mm thickness of the top surface of each bar prior to actual machining experiments in order to eliminate any surface defects and wobbling that can adversely affect the machining results. The cryogenic machining was performed by applying liquid nitrogen on the rake and flank face simultaneously under the pressure of 1,5 MPa and a flow rate of ~0,6 kg/min per nozzle.

Porosity through number of pores N and pore size D_p, were the performance measures measured and analyzed. The porosity is defined based on using the images of the machined surface, from a scanning electron microscope (SEM).

The experiments were conducted using the Design of Experiments (DOE) method, varying cutting conditions on ranges: cutting speed v_c = 30, 60, 90, 120 m/min, cutting feed f = 0,05; 0,12; 0,18; 0,25 mm/rev, and depth of cut a_p = 0,04; 0,06; 0,08; 0,1 mm. The cutting inserts used were PCD tools with a sharp cutting edge, while just a sharp cutting edge can provide benefits out of the process. Part of the experiments was presented in [30] where the detailed description and explanation of experimental procedure is given, and therefore won't be repeated here.

5.2

Results

Rezultati

For smearing evaluation, porosity of the machined surface has to be observed and analyzed [31]. For this purpose image software was developed, which is capable of individual analysis of all the pores based on the SEM pictures. After performing of all the experiments, each machined surface roughness is measured through SEM picture with area 0,075 × 0,125 mm under the 1000× magnification. Fig. 7 presents a machined porous tungsten surface with detailed individual pore analysis. The number, size and the distribution of open pores are analyzed, while it has to be mentioned that the pore size is interpreted with Waddel Disk Diameter (D_p) that represents the diameter of the circle with the same area that has the individual pore.

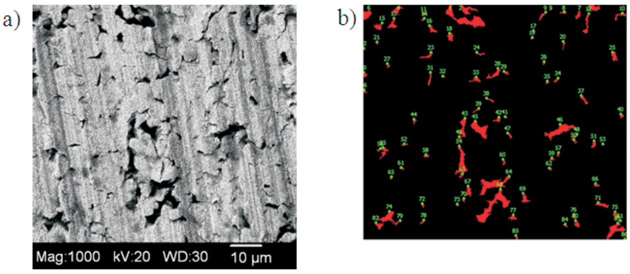

***Figure** 7 SEM picture of porous tungsten machined surface (a), and corresponding pore analysis (b)*
***Slika 7.** SEM slike porozne površine volframa (a) i odgovarajuće analize pora (b)*

The comparison of the pore size and the number of pores under cryogenically machined and conventionally machined samples is presented in Fig. 8. Comparisons are made for two cryogenic machining samples and two with infiltrant machining samples. Based on that, it is possible to see that the machining process technique (cryo or infiltrant) is not significantly affecting the size of the pores, but is significantly affecting the number of pores. The typical pore size range is 3-7 µm, while the average pore size is approximately 1,5 µm (Fig. 8). While high significance for defining the porosity is related to the number of open pores, this parameter is used as an estimator of machined surface porosity.

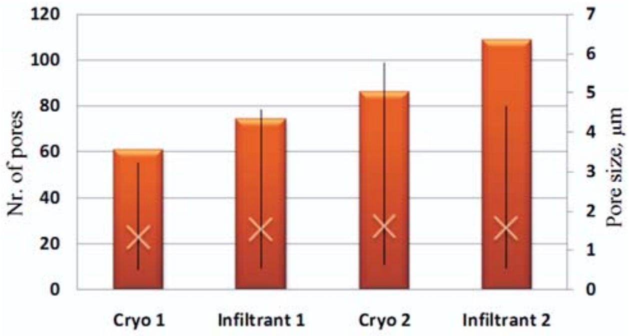

***Figure 8** Pore size and number of pores corresponding to different machining techniques (two examples of cryogenic and two examples of machining with infiltrant)*
***Slika 8.** Dimenzije i broj pora za različite tehnike obrade (na primjeru dva kriogenika i dvije obrade infiltrantima)*

Additionally it is interesting to compare pore size distribution on the machined surface (Fig. 9). The distribution curve for the cryogenically machined sample shows a wider pore size distribution and fewer pores than the conventional plastic infiltrated sample. However, both samples would be useable for a dispenser cathode, while the plastic infiltrated sample is considered slightly superior to the cryogenic sample due to less smearing. On the other side, essential advantages of the cryogenic process (no possibility of contamination, greatly reduced cycle time, and environmentally sustainable process) put ahead cryogenic machining process. Moreover, while these were initial experiments, cryogenic machining has the potential to be improved over conventional machining of porous tungsten for dispenser cathodes.

6
Conclusion
Zaključak

The work is pointing out the reasons and needs for practices in the field of sustainable development on all the levels and fields, even machining process, for assuring our common goal of global sustainability. The focus is on novel machining technologies that are meeting environmental and social regulation, while still being competitive. In this work as alternative to conventional machining processes, "clean" cryogenic machining is presented and analyzed.

Additionally the main pillars of sustainability are under the scope, i.e. reduced energy consumption, prolongation of tool-life, improved final product functionalities through improved machined surface integrity, etc.

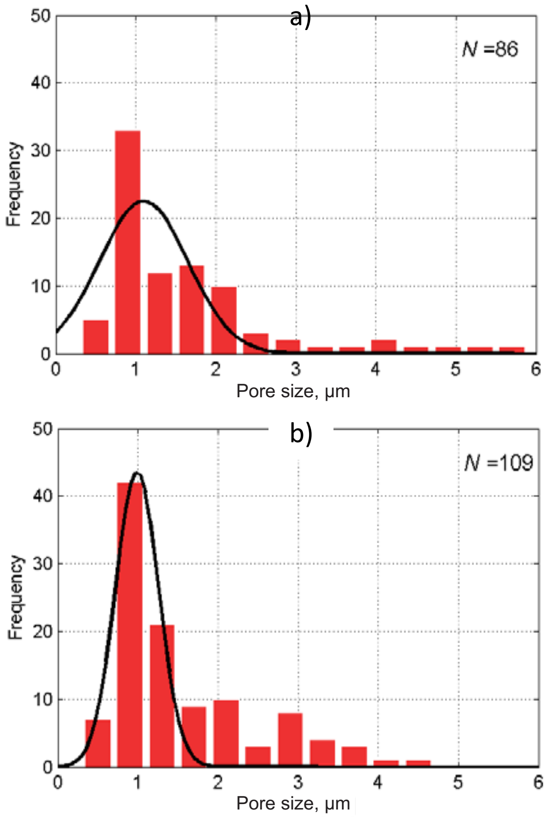

***Figure 9** Distribution of pores on the machined surface (a – cryogenic machining, b – machining with plastic infiltrant)*
***Slika 9.** Razdioba pora na obrađenoj površini (a – kriogena obrada, b-obrada s infiltrantom)*

Experimentally, this study is focusing on sustainable machining of hard to machine porous tungsten material and is presenting the investigation of combined effects of machining process technique (cryogenic machining vs. machining with plastic infiltrant), on the porosity of machined surface in turning process. Analysis shows that as an alternative to cost infectivity, health and environmental problems of plastic infiltrant machining procedure, cryogenic machining can be used for machining of porous tungsten for dispenser cathodes. Cryogenic machining is able to keep unsmeared surface - keeps open pore structure that satisfies the industry standard. This accomplishment has never been achieved with using of any other cooling/lubrication techniques.

Sustained machine performance and acceptable surface quality are among the major accomplishments of this work. Through experiments, the directions for improved overall machining performances in the case of porous tungsten machining with surface porosity characterization are achievements and contributions of this work. As a result, it can be claimed that cryogenic machining as sustainable machining alternative can essentially provide: (i) improved environmental friendliness, (ii) reduced cost, (iii) reduced energy consumption, (iv) reduced waste and more effective waste management, (v) enhanced operational safety, and (vi) improved personnel health.

7
References
Literatura

[1] World Commission on Environment and Development (Author). Our Common Future. Oxford University Press, New York, 1987.

[2] Towards Competitive Sustainable Manufacturing. // The ManuFuture Road / Jovane, F.; Westkämper, E. Springer-Verlag, Berlin, Heidelberg, 2009, pp. 31-52.

[3] Kopac, J. Odrezavanje – teoretične osnove in tehnološki napotki. University of Ljubljana, 2008.

[4] Sutherland, J. W.; Riviera, J. L.; Brown, K. L.; Law, M.; Hutchins, M.J.; Jenkins, T. L.; Haapala, K.R. Challenges for the manufacturing enterprise to achieve sustainable development. // CIRP Conference on Manufacturing Systems, Japan, 2008.

[5] Westkamper, E. Manufuture and sustainable manufacturing. // CIRP Conference on Manufacturing Systems, Japan, 2008.

[6] Ezugwu EO. Key improvements in the machining of difficult-to-cut aerospace superalloys. // International Journal of Machine Tools & Manufacture. 45 (2005), pp. 1353-1367.

[7] Pusavec, F.; Deshpande, A.; M'Saoubi, R.; Kopac, J.; Dillon, O. W.; Jawahir, I.S. The modeling and optimization of machining of high temperature Nickel alloy for improved machining performance and enhanced sustainability. // 11th CIRP Conference on Modeling of Machining Operations. Gaithersburg, USA, 2008, pp. 21-28.

[8] Kramar, D.; Kopac, J. The high performance manufacturing aspect of hard-to-machine materials. // Journal of Advances in Production Engineering & Management (APEM). 1-2 (2009), pp. 3-14.

[9] Stoic, A.; Lucic, M.; Kopac, J. Evaluation of the stability during hard turning. // Journal of Mechanical Engineering. 52/11 (2006), pp. 723-737.

[10] Surface Engineering Committee. Foresight in Surface Engineering. Institute of Materials, London, October, 2000.

[11] Su, Y.; He, N.; Li, L.; Iqbal, A.; Xiao, M.H.; Xu, S.; Qiu, B.G. Refrigerated cooling air cutting of difficult-to-cut materials. // International Journal of Machine Tools & Manufacture. 47 (2007), pp. 927-933.

[12] Dubzinski, D.; Devillez, A.; Moufki, A.; Larrouquere, D.; Zerrouki, V.; Vigneau, J. A review of developments towards dry and high speed machining of Inconel 718 alloy. // International Journal of Machine Tools & Manufacture. 44 (2004), pp. 439-456.

[13] Ezugwu, E. O.; Bonney, J. The effect of high-pressure coolant supply when machining nickel-base, Inconel 718, alloy with coated carbide tools. // Journal of Materials Processing Technology. 153-154/10 (2004), pp. 1045-1050.

[14] Balic, J.; Cus, F. Intelligent modeling in manufacturing. // Journal of Achievements in Materials and Manufacturing Engineering. 24/1 (2007), pp. 340-348.

[15] Zuperl, U.; Cus, F. Machining process optimization by colony based cooperative search technique. // Journal of Mechanical Engineering. 54/11 (2008), pp. 751-758.

[16] Westkamper, E. Manufuture and sustainable manufacturing. // 41st CIRP Conference on Manufacturing Systems. Japan, 2008, pp. 11-14.

[17] Sutherland, J. W.; Riviera, J. L.; Brown, K. L.; Law, M.; Hutchins, M. J.; Jenkins, T. L.; Haapala, K.R. Challenges for the manufacturing enterprise to achieve sustainable development. // 41st CIRP Conference on Manufacturing Systems. Japan, 2008, pp. 15-18.

[18] Skerlos, S. J.; Hayes, K. F.; Clarens, A. F.; Zhao, F. Current advances in sustainable metalworking fluids research. // International Journal of Sustainable Manufacturing (IJSM). 1/2 (2008), pp. 180-202.

[19] Weinert, K.; Inasaki, I.; Sutherland, J. W.; Wakabayashi, T. Dry machining and minimum quantity lubrication. // CIRP Annals - Manufacturing Technology. 52/2 (2004), pp. 511-537.

[20] Klocke, F.; Eisenblätter, G. Dry cutting. // Annals of CIRP – Manufacturing Technology. 46/2 (1997), pp. 519-526.

[21] Baumann, W.; Grafen, M.; Pollklasner, D. Assessment of the environmental release of chemicals used in metal- cutting and forming fluids. // Emission scenario document - Metal extraction industry, refining and processing industry, IC8. Dortmund, Germany, 1999.

[22] Larson, A. M. Planetary Surfaces Fundamentals: Reflectance, Density, and Phases. http://www.astro.washington.edu/users/larson/Astro150b/Lectures/Fundamentals/fundamentals.html [visited 21/05/2009].

[23] Pusavec, F.; Krajnik, P.; Kopac, J. Transition to sustainable production – part I: Application on Machining Technologies, // Journal of Cleaner Production. In Press (2009).

[24] Pusavec, F.; Kopac, J. Achieving and implementation of sustainability principles in machining Processes. // Journal of Advances in Production Engineering & Management (APEM), 3/3-4 (2009), pp. 58-69.

[25] Daintith, J. Facts on File Dictionary of Chemistry. 4th ed. New York, New York: Checkmark Books, 2005.

[26] Chen, S.; Head, D.; Effgen, M.; Jawahir, I. S. An Investigation of Sustained Machining Performance for Controlled Surface Quality Requirements in Porous Tungsten. // IEEE Transactions on Electron Devices. 52/5 (2005), pp. 903-908.

[27] EIA-941: Engineering specification for dispenser cathodes. Electronic components, Assemblies, & Materials Association, Nov. 2002.

[28] Jawahir, I.S.; Dillon, O.W. Sustainable manufacturing process: new challenges for developing predictive models and optimization techniques. // International Conference on Sustainable Manufacturing. Montreal, Canada, 2007.

[29] Tarter, J. O.; Effgen, M.; Pusavec, F.; Jawahir, I.S. Cryogenic Machining of Porous Tungsten for Dispenser Cathode Applications. // IVEC (2008), CA, USA.

[30] Pusavec, F.; Deshpande, A.; Tarter, J. O.; Effgen, M.; Dillon, O. W.; Kopac, J.; Jawahir, I. S. Optimization of machining performance in finish turning of porous tungsten under cryogenic conditions. // 2nd International Conference Innovative Cutting Processes & Smart machining, Intercut, Cluny, France, (2008).

[31] Wijangco, M.; Grant, T. Application of modern image analysis to quantify dispenser cathode surface condition. // IEEE Int. Vacuum Electronics Conference, Monterey, CA, (2004), pp. 146-147.

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