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Achievements of sustainable manufacturing by machining

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ABSTRACT

Purpose: Manufacturing industry is under increasing pressure of global competition, stricter environmental legislation and supply-chain demand for improved sustainability performance. The latter can be achieved through changes in products, processes and systems which are related to the sustainability issues. Sustainability in manufacturing is an appropriate approach; however it is still unified to a higher production rate and benefit. To encounter this problem academic, scientific, cultural and human organizations have to find the way, on a highest level of decision; maybe to rise the sustainability over production growth. This paper also presents some results from modelling and optimization of sustainable machining of Inconel 718. High temperature alloys, such as Nickel and Titanium alloys, pose significant difficulty in machining, due to their unique thermo-mechanical properties.
Design/methodology/approach: In the paper are presented and evaluated two sustainable machining alternatives: cryogenic machining and high pressure assisted machining in comparison to conventional machining. The sustainability performance measures refer to environmental impact, energy consumption, safety, personal health, waste management and costs. The sustainability evaluation is supported with machining experiments on high-temperature Ni-alloy (Inconel 718). It is shown that tooling costs are presenting the major contribution to the overall production costs, when hard-to-machine materials are machined, what is contradictory with previous analysis.
Findings: As a result, it is shown that sustainable machining alternatives offer economic, environmental and social performance improvement in comparison to conventional machining. The results of the experimental part show that appropriate cooling/lubrication application can provide improved overall machining performance while satisfying sustainable issues in terms of enhanced machined surface quality, tool-life, chip breakability, power consumption and increasing productivity.
Research limitations/implications: The Faculty of Mechanical Engineering in Ljubljana, Slovenia is implementing two new cutting strategies for the machining of a special material – Inconel. The first one is cryogenic machining and the second is material cutting by assistance of high pressure jet cooling lubrication. Both machining strategy are in rang of sustainable manufacturing. The implications of processes like those are not only nature friendly, but also modern spirit for producers and users of products.
Originality/value: Paper present the technical description of two modern machining processes, the comparison of them and benefit, advantages and disantvantages. Really new is the strategy and opinion of spirit, which can be included in product over sustainable manufacturing processes.
Keywords: Sustainable development; Sustainable manufacturing; Cryogenic machining; High pressure jet assisted machining; Near-dry machining

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1. Introduction

Metal machining companies are under increasing pressure as a result of competition, stricter environmental regulations, supply chain demand for improved environmental performance and falling skill levels within the industry. Adopting sustainable manufacturing practices offers metal machining companies of all sizes a cost effective route to improve their economic, environmental and social performance (i.e. the three pillars of sustainability) [16].

Conventional pyramid structure of production knowledge, contents three levels. Top one is an idea and design of new product. Second level is CAD, while the third presents production level with CAM and Manufacturing Engineering. The alternative sustainable production, have to put all three levels on the same equal level, while they have to synergistically define the sustainable product, based on sustainability principles. Sustainability principles are considering: manufacturing costs, energy consumption, waste management, environmental impact, operational safety and personal health (Figure 1).

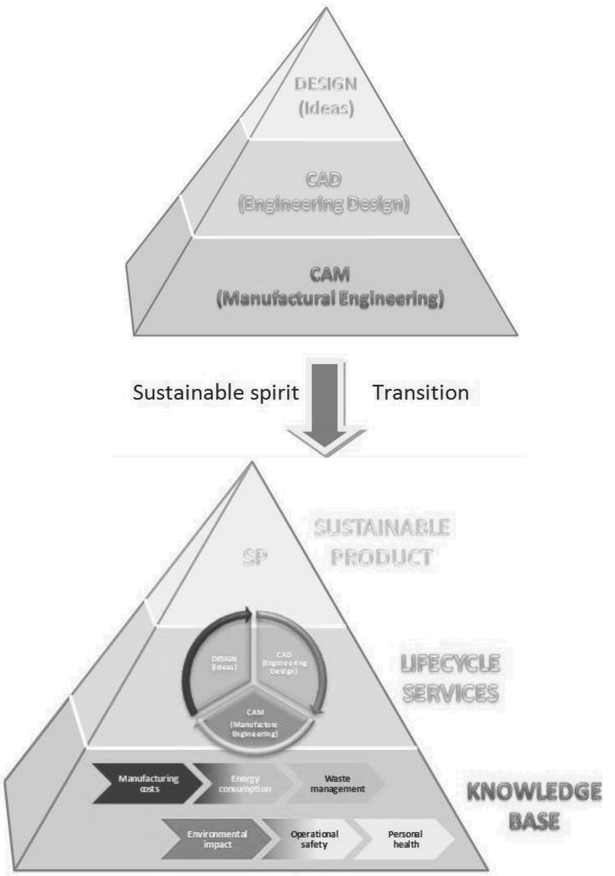

Fig. 1. Sustainability spirit transition in manufacturing processes

Sustainable production is defined as the creation of goods and services, using process and systems that are non-polluting, conserving of energy and natural resources, economically viable, communities, consumers and socially and creatively rewarding for all working people, safe and healthful for employees.

Authors were calling attention to the fact that world industrial crisis and recession are on the way, one year ago with the paper on IMSC 08 conference: "Future vision: minus 5% BGP over sustainable machining". Yesterday, the economical mass production was the key to success in the industry. However, today the crisis is spread all over the world; mass production, automotive industry, etc. are facing difficulties in finding their profit. The solution lays, in innovations and creations of attractive products with "soul", following the rules of Sustainable Manufacturing Production on all the levels and raising the sustainability over production growth (gross domestic product – GDP).

Fundamental design of new product, has to have the »spirit«, be created over the "game" and with love. Only the product with "soul", can be a long duration sustainable product. Implicating on machining process, chip mass products are without a value, if they don't assure its functionality. We simply throw them away, regardless the fact that for their production, material, energy, labour, etc. were consumed. The greatest challenges to assure sustainability in manufacturing/machining processes or products, is neither technical nor financial; it is emotional and spiritual. It is less about our ability to find solutions as it is about ability to agree on them. More than anything, the spirit of sustainability is about relating.

Described idea is planning to be presented in the paper with the application on manufacturing/machining processes through novel sustainable machining processes: Cryogenic and High Pressure Jet Assisted Machining.

Inconel 718 is a Nickel-based, high-temperature alloy containing a Columbium age-hardening addition that provides increased strength without a decrease in ductility. It is oxidation and corrosion resistant material that can be used at high temperatures. Due to its good tensile, fatigue, creep and rupture strength, this material is nowadays frequently used in aerospace and automobile applications.

In industry, various cutting oils/emulsions are still used as cutting fluids, even though they cause environmental pollution and health hazards, in addition to high costs involved. Conventional cutting fluids are considered as one of the top five health hazards in the workplace. In addition to the growing environmental/health concerns, the machining industry continues to investigate methods to enhance the machining process performance and decrease production costs.

In the paper are also presented the cooling/lubrication aspects of machining with Inconel 718; with cryogenic machining issues for achieving sustainable processes.

2. Sustainable machining

Fundamental issues mentioned above, are possible to be solved by sustainable product design and manufacturing, presented in Figure 2. The sustainability of a product or of the production can be achieved with improvements on all of the presented levels. At the economy design, it is need to examine the real market demand in dependence to cost, quality that has to be self-evident and delivery times (short to avoid storage capacities and financial investment related to this). If we want to assure such a "real" development, we have to be innovative, flexible and capable of producing high value products. Another important stage of manufacturing/machining that is connection with economy is resource utilization and/or raw materials extraction. It is necessary to improve the proportion between incoming and outgoing raw materials in the production phase, what is basically represents wastes (producing same, while using less and reduce costs).

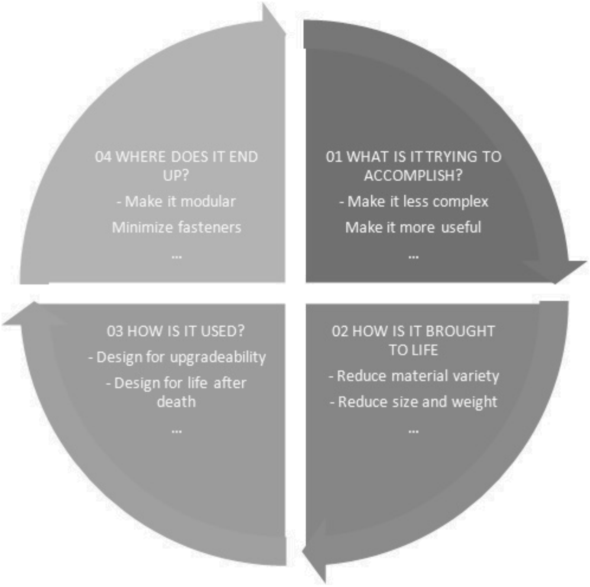

Fig. 2. Ways of design in spirit of sustainability

With the implementation of sustainability principles in machining processes, the machining companies of all sizes have potential to save money and improve their environmental performance even though the production stay on the same size or it is decreased. There is a fact that the reason for recent industrial crises is also virtually high product consumption/production, while on the other the real consumption is lower and as a consequence a lot of product is now staying in the warehouses. The source of the problem is in that, that machining companies are traditionally focused on short-term financial considerations, with little thought to the longer-term view. However, a long term business strategy is essential to achieve sustainable development and ultimately survival. To overcome the challenges facing the sector, it is vital that companies adopt sustainable manufacturing practices. The way to help companies improve their economical, environmental and social performance is by:

- minimizing waste – less waste generated and increase waste re-usage or recycle,
- using resources such as materials, water and energy efficiency,
- avoiding or at least improving management of metalworking fluids, lubricating oils and hydraulics oils,
- improved environmental, health and safety performance,
- adopting lean manufacturing and other sustainable engineering techniques,
- improve working conditions,
- using best practice in machining,
- training all employees about sustainable practices.

3. Sustainable machining processes

The alternatives to conventional flood machining process are cryogenic machining (Cryo) and high pressure jet assisted machining (HPJAM), offering reduction of costs and reduction/avoidance of health and environmental hazarded oil-based CLF usage.

3.1. Cryogenic machining

Cryogenic machining presents an innovative method of cooling the cutting tool or/and part during machining. More specifically, it relates to delivering the cryogenic CLF (instead of oil-based CLF) to the cutting region of the cutting tool, which experiences the highest temperature during the machining process, or to the part to change the material characteristics and improve machining performance (Figure 3).

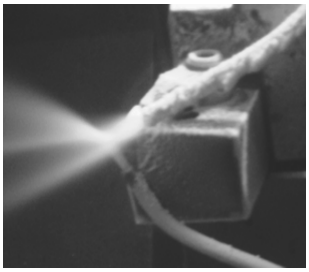

Fig. 3. Cryogenic liquid nitrogen delivery

The coolant is usually nitrogen fluid which is liquefied by cooling to –196°C (liquid nitrogen - LN). Nitrogen is a safe, non-combustible, and noncorrosive gas. In fact, 78% of the air we breathe is nitrogen. The LN in cryogenic machining system quickly evaporates and goes back into the atmosphere, leaving no residue to contaminate the part, chips, machine tool, or operator, thus eliminating disposal costs. This represents an important improvement. Additionally, cryogenic machining can help machine parts faster, with higher quality, increased machining performance, and reduced overall costs. Some potential benefits of cryogenic machining are:

- Sustainable machining (cleaner, safer, and environmental-friendly method).
- Increased material removal rate (MRR) with no increase in tool wear and with reduced cutting tool changeover costs, resulting in higher productivity.
- Increased tool-life due to lower abrasion and chemical wear.
- Improved machined part surface quality/integrity with the absence of mechanical and chemical degradation of machined surface.

Main disadvantage of this machining technology, besides additional equipment needed, is relatively high price of LN that is not reusable like in conventional CLF, since it immediately evaporates in the air. However, relevant are overall production costs that have to be lower. This is going to be shown in the continuation of this work.

3.2. High pressure jet assisted machining

HPJAM presents an innovative method of lubricating and/or cooling the cutting zone during machining. More specifically, it relates to delivering the oil-based or water-based CLF in relatively small flow rates (compared to conventional flood CLF) under extremely high pressure up to 300 MPa to the cutting tool tip. CLF under such pressure can penetrate closer to the share zone, which experiences the highest temperature during the machining process and cools it. Additional to cooling effect, HPJAM is able to control friction conditions between cutting tool rake face and chip back side. This further offers control of chip breakability through forming a physical hydraulic effect between cutting tool rake face and chip back side, leading into improved machining performances (Figure 4).

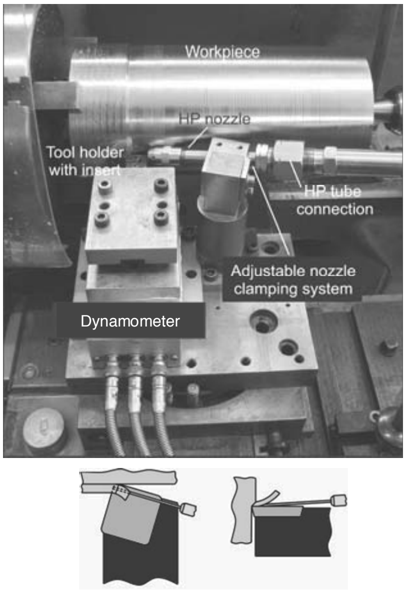

Fig. 4. HPJAM set-up with sketch of CLF jet direction

HPJAM involves high pressure pump, high pressure tubing, and outlet nozzle fixed besides tool holder. Some of potential benefits of HPJAM are:

- sustainable machining through lower flow rates of CLF in comparison to conventional machining, while providing better cooling and lubrication mechanisms,
- decreasing the cutting tool-chip contact length, resulting in lower cutting forces and longer tool-life,
- drastic improvement of chip breakability,
- extension of machining parameters operational ranges, resulting in increased process productivity through higher MRR.

Besides higher initial capital investment for additional equipment, the main disadvantage of this machining technology is the fact that still the oil-based CLF are used.

Both alternative processes have their own pros and cons that determine when each of the processes should be used. Therefore, the basic question is: how, where, what, and in which quantity the CLF has to be applied to enhance the machining performance, satisfying constraints and product needs. In an attempt to answer this question, evaluation of sustainability measures for Cryo and HPJAM machining processes in comparison to conventional machining is done in the following section.

4. Sustainability evaluation

Talking about machining processes and application of sustainability principles, measures have to be defined for machining process sustainability level determination. Measures for the process evaluation in this study are:

- quality of machined product through machined surface integrity,
- costs of machining process and their possible reductions,
- resources and energy consumption,
- waste production and their disposal costs,
- environmental performance,
- health and safety performance,
- competitiveness, skill level and public image.

Improvement of machined part surface integrity is achieved when using presented alternative processes (Cryo or HPJAM). This has been proven in previous research. Therefore costs, wastes, energy, safety and health issues are analyzed in greater detail.

The overall part production process, consisting of machining, cooling/lubrication, part cleaning, preparation of swarf to be disposed, and their interrelations are shown in Figure 5.

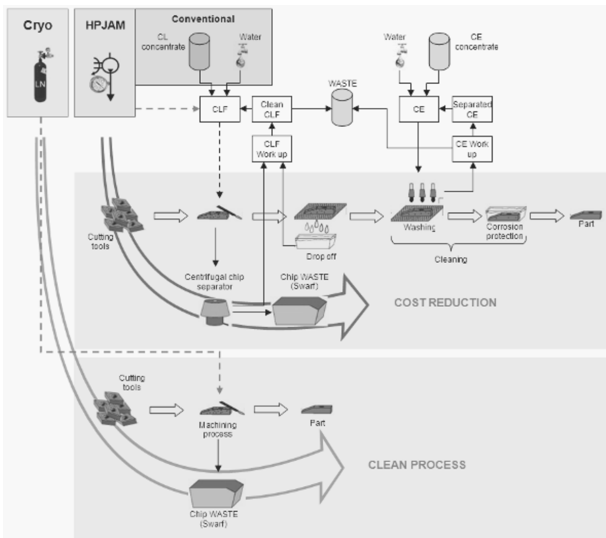

Fig. 5. Comparison of different machining technologies and relations in part production process

In conventional machining as well in HPJAM aqueous emulsions are needed (CLF and cleaning emulsion-CE). Beside health and environmental problems connected with CLF and CE usage, the processes of cooling/lubrication and cleaning are time consuming and costly processes. The same characteristics, as mentioned before, have swarf disposal preparation process, where chips have to be separated from oil and shredded if needed.

There are two machining alternatives presented and stages where they can enhance the machining process performance. In the case of HPJAM, jet CLF delivery can drastically extend tool-life and therefore lower overall machining costs. The other advantage of HPJAM, with improving of chip breakability, is swarf volume reduction and their trouble-free conveyance. On the other side, in Cryo machining technology, complete elimination of oil-based CLF is achieved, resulting in elimination of part/swarf cleaning need.

To determine the application of particular machining process, costs have to be calculated. First of all, the machine tool with belonging equipment costs have to be analyzed to determine machine tool usage rate.

It is interesting also to analyze relative composition of part production costs (Figure 6). The overall part production costs, for different machining processes, are represented with three separate pie graphs, indicating individual part percentage contributions to the final part production costs. For better representation, cutting fluid and tooling costs proportion are in exploded view. Results are highly dependent on cutting speed and are therefore presented for the optimum cases (cost criteria). The results show that costs, besides machining costs, are highly correlated with costs of cutting tools through the tool-life characteristics. In machining of such a hard-to-machine alloy, as it is Inconel 718, the percentage of cutting tool costs is in the range from 20-30% of overall machining cost. On the other side, analysis carried out in German automotive industry, carried out by, show that part related machining costs, incurred with tooling costs can account for 2-4%. The difference in those two ranges is enormous. This difference and the fact that hard-to-machine materials are in majority not used in automotive industry, is proving that tool-life in machining of hard-to-machine materials is drastically decreased and as a consequence tooling costs increased.

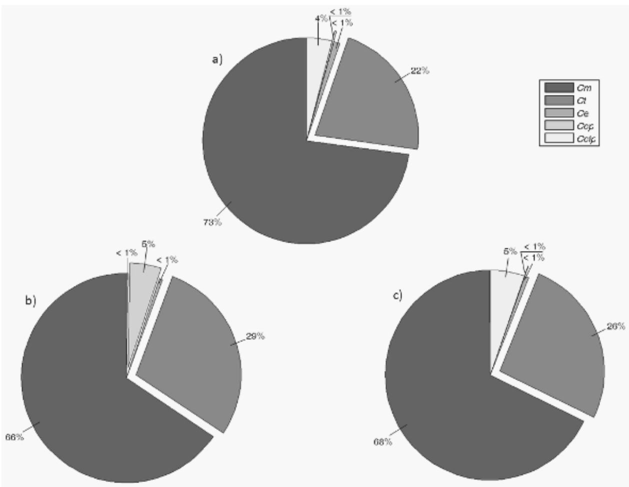

Fig. 6. Comparison of relative costs composition a) Conventional machining, b) Cryogenic machining, c) HPJAM machining

In general it is possible to point out that Cryo and HPJAM approach prove to be competitive at low cutting speeds and superior at high cutting speeds, when compared to the conventional flood machining.

5. Cooling/lubrication in machining process

The environmental awareness, which increases cost pressure in industry, has led to a critical consideration of conventional cooling lubricants usage in machining processes. Analysis carried out by German Automotive industry show that workpiece related manufacturing costs, incurred with the deployment of cutting fluids, range from 7-17% of the total machined workpiece cost. In comparison to this, the tooling costs can account for approximately 2-4%. Therefore, there is obvious that with using of dry or near-dry machining, the cost reductions can be significant. There is not just cost efficiency; with using dry, near-dry or cryogenic machining, the machined surface integrity characteristics can be improved. These facts are stressing the further need for understanding the whole process parameters such as machining fluid, material, cutting tool, etc. Nevertheless, the key issue for sustainable machining process is, to analyze and understand the machining process with cooling/lubricating mechanisms dealt within.

To reach the aim of cooling/lubricating fluids usage reduction, it is not possible just to turn off the cooling/lubricating fluid supply. The reason lies in several important tasks of C/L fluids, like: reduction of friction, reduction of temperature in cutting zone, transport/evacuation of chips, cleaning of tools, workpieces and fixtures, etc. These tasks, in the case of its absence, have to be taken over by other components in machining process. As a rule, emulsions (oil-water mixture) or straight oils are generally used in machining, depending on the manufacturing operations, machining tasks, cutting tool material, etc. The comparison of three C/L fluids is presented in Table 1. Both media (emulsion or oil), with relatively high density, guarantee efficient chip transport/evacuation. Emulsion is commonly used because of excellent heat transfer characteristics due to high water content. In addition, straight oils are usually used when a high degree of lubrication is needed. Oil and emulsion C/L media are superior to compressed air from the view of lubrication benefits, the cooling effects and chip transportation/evacuation. Therefore, most of the benefits of conventional cutting fluids in machining processes are decreased with using of pure compressed air. However, machining with pure compressed air, as a C/L fluid, is presenting clean machining process.

Table 1.
Comparison of lubrication/cooling media characteristics

Medium	Cooling	Lubrication	Chip removal
Emulsion	Excellent	Good	Excellent
Oil	Good	Excellent	Good
Compressed air	Little	No	Little

5.1. Near-dry machining

In MQL machining, the media used is generally straight oil, but in some applications even emulsion or water are used. Those media are feed into cutting zone during machining in small quantities. Normal consumption of cooling/lubricating fluid in near-dry machining per machine hour is 10-120 ml. The transportation medium is usually air, or if there is airless system the droplets are formed and feed to the cutting zone in the way of aerosol spray. The term “near-dry machining”, generally presents machining with small amount of cooling lubricant. Therefore, depending of the main media supplied, a distinction can be drawn between minimum quantity lubrication (MQL) and minimum quantity cooling (MQC).

Oils are used when good lubrication properties are needed, to reduce friction and adhesion between the chip-tool and tool-workpiece interfaces. Consequently, the heat generated is lower than in completely dry machining case. Using emulsions or pure water in near-dry machining is less frequent than using of oils as a media. They are used just in cases where the cooling is needed to be more efficient than it is possible to get when using oils. The reason for this fact is the thermal capacity value of each media. The thermal capacities of oil, water and air are: $c_{p,oil}$ = 1.92 kJ/kgK, $c_{p,water}$ = 4.18 kJ/kgK, and $c_{p,air}$ = 1.04 kJ/kgK. Base on these numbers, one can conclude that oil give very slight cooling effect in comparison to water and it is therefore usually used in MQL machining and vice versa.

With these thoughts, nowadays requirements are directly related to the need of alternative cooling/lubrication methods in machining processes. One of those alternatives presents cryogenic machining.

6. Experimental setup and procedure

The experiments were conducted on a Mazak CNC lathe. The experimental set-up is shown in Figure 7. The centerless-ground Inconel 718 round bars with a diameter of 32 mm and length of 150 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 the actual machining experiment, in order to eliminate any surface defects and wobbling that can adversely affect the machining results. Four different cooling/lubrication conditions were investigated and analyzed: dry, near-dry, cryogenic and cryogenic-lubrication combination. A commercially available UNIST Coolube 2210EP metalworking lubricant was used with a flow rate of 60 ml/h for MQL machining. The cryogenic machining was performed by applying liquid nitrogen under 1.5 MPa pressure and a flow rate of ~0.6 kg/min per nozzle. The machining process with cryo-lubrication was also investigated by applying liquid nitrogen and Coolube 2210EP lubricant simultaneously. Experiments were conducted with uncoated 890 grade carbide tool inserts (SECO) with ISO tool designation CNMG120404. The tool inserts have MF1 chip breaking geometry.

Cutting forces, F_c, F_f, F_r, surface roughness, R_a, tool wear (flank wear, VB_{max} and rake wear, KW_{max}), and chip breakability, C_{in}, were the major performance measures considered in the analysis. The initial tool cutting edge radius of the cutting tools was measured/checked to ensure consistency of the tool edge geometry for all the experiments. Cutting forces generated during machining were measured using a three-component piezoelectric dynamometer (KISTLER 9121). Tool-wear was measured using an optical microscope. Surface roughness and tool edge radius were measured with a non-contact, three-dimensional, interferometry profiler ZYGO 3D - New View 5000.

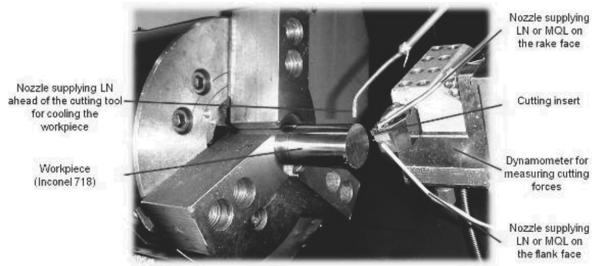

Fig. 7. Cryogenic and near-dry machining delivery system set-up on turning centre

6.1. Experimental matrix

The experiments were carried out for four sets of cooling/lubrication application, as shown on Figure 8: *Dry machining, Near-dry machining (MQL)* - where oil mist is applied with one nozzle on rake face in the direction of cutting zone shown by arrow B, *Cryogenic machining* - where liquid nitrogen (LN) is applied with two nozzles; One nozzle delivers LN onto the rake face in the direction of cutting zone (arrow B), while the second nozzle delivers LN onto the workpiece to cool it just before the actual cut (arrow A), and *Cryogenic-lubrication* combination where liquid nitrogen is applied on the flank face of the cutting tool (arrow C) and oil mist on the rake face (arrow B) as it is shown in Figure 8.

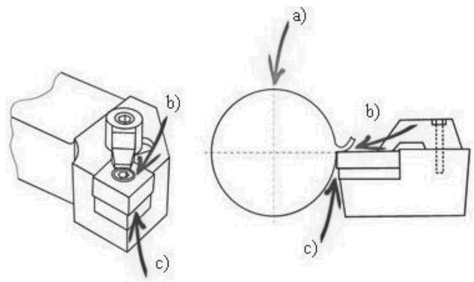

Fig. 8. Direction of cooling/lubrication application (3D view and its cross-section)

7. Comparison of tool wears mechanisms

Beside trends, additional information of the cutting tool performance can be gained through tool wear mechanisms analysis. Comparisons of tool wear for different cooling/lubrication (C/L) conditions are shown in Figure 9. From this comparison, it can be seen that in the case of dry machining, the tool did not stand mechanical and thermal loads and did fracture. When applying oil mist (MQL) on the rake face, oil did provide some lubrication and prevent tool from fracturing. In the case of cryogenic, the tool again fractured, while it has to be mentioned that beside on the tool rake face, cryogenic fluid was delivered also on the workpiece before being actual cut, what has negatively affected the machining performance. Most probably the reason is in increasing workpiece machine surface hardness and more extensive hardening effect. In the last case, where cryo-lubrication C/L condition is used, slight improvement is shown on rake face and drastic one on the flank face, even from the case of near-dry machining. Therefore, combination of cryogenic fluid on the flank face and oil mist on the rake face provides best C/L condition, from those that were presented.

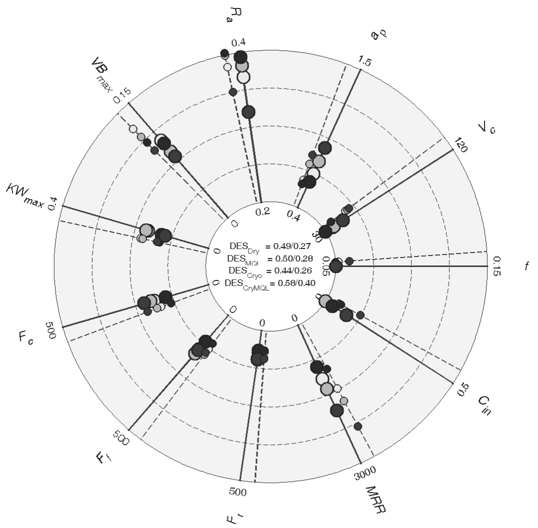

Fig. 9. Comparison of optimum machining conditions and desirability function for each C/L conditions (big markers – no chip breakability included in optimization, small markers – chip breakability included in the optimization procedure)

The dominant tool wear mechanisms in all the cases are crater wear and later catastrophic fracture. When machining Nickel based alloys, the contact length between tool and chip is short, while the loads and temperatures are high. Therefore the chip is rubbing the surface at extreme conditions close to the cutting edge and forming the crater on the rake face. When this crater becomes big enough, the cutting edge become so weak that it catastrophically fracture and represent the end of tool-life. This trend of tool wear mechanisms is evident from the tool wear Figures (Figure 10). More evident improvement of cryo-lubrication C/L condition, over other used C/L in this work, can be seen from the flank wear figures. From the results it is possible to conclude that cryogenic fluid delivered on the flank face provide the protection of tool flank face; while oil mist delivered on the rake face improve the friction conditions between chip and cutting tool rake face.

Before going to the overall process evaluation, following by optimization, the extension of machining process measures is performed. Besides, cutting forces, surface roughness and tool wear, the chip breakability is going to be analyzed and models for it are going to be developed. The incorporation of chip breakability index (Cin), provides a referable numerical value, which would benefit the optimization of machining operations by taking chip breakability as a quantifiable variable.

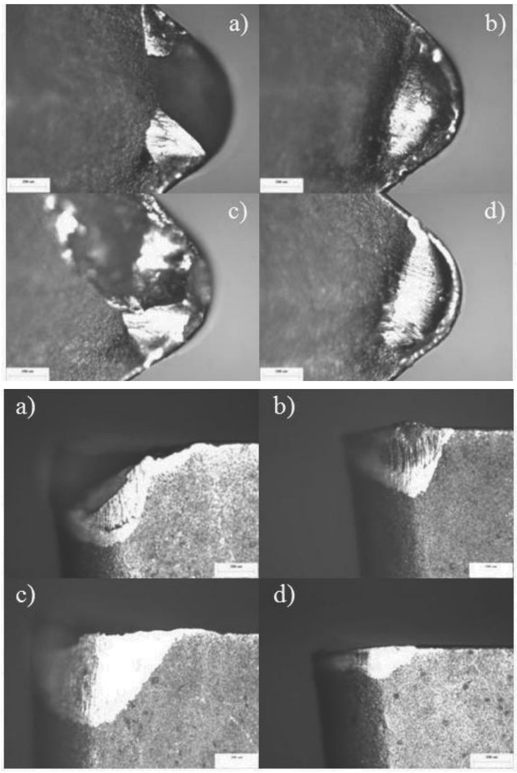

Fig. 10. Comparison of tool wear mechanisms on flank and rake face for different C/L conditions (a) Dry, (b) Near-dry, (c) Cryo, (d) Cryo-lubrication

Another interesting phenomenon that can be seen from the optimum plot (Figure 9) is that when including the maximum chip breakability as an objective in optimization procedure, the optimum is shifting the feed rate and cutting speed a bit up, and contrary slightly decreasing the depth of cut. The output parameters in this case are truly increasing the chip breakability. Besides chip breakability, the proposed optimum is offering also higher productivity (MRR) on account of higher tool wear.

Based on these optimization results, it can be concluded that in the case of Inconel 718 alloy machining, both low temperatures and lubrication play an important role in being able to improve machining performance. This is especially important for precision finish machining operations. Therefore, for improved performance in machining of Inconel 718, the nickel based alloy, both sufficient cooling as well as good lubrication have to be provided in the process.

8. Description of achieved results of own researches

Achieved results of own researches are models and measuring chains for the experiments we made by machining with cutting. Machine tool, cutting tools and measuring equipments helped us made many experiments, statistical analyses and comparisons, which differences between machining processes. In every case the circle optimum diagrams are some very unique results of this researching.

9. Conclusions

This study focuses on sustainable machining of hard-to-machine Nickel-based alloy (Inconel 718) with uncoated carbide tools at various cutting conditions, and involves a study of major sustainability elements such as power reduction, increased tool-life and enhanced functional performance in terms of surface roughness improvement by investigating dry, near-dry, cryogenic and cryo-lubrication cooling/lubricating machining processes and comparing the effectiveness of these methods through their optimal cutting parameters.

Taguchi DOE technique was used and repeated for each of cooling/lubrication conditions: dry, near-dry, cryogenic and cryo-lubrication machining, which were compared under the range of different cutting parameters (f, a_p, V_c). Cutting forces, surface roughness, chip breakability and tool wear (flank and rake) were measured, modelled, analyzed and used as an input into the optimization procedure for obtaining the optimum machining parameters. The optimization procedure was performed with using genetic algorithms.

Based on the results it can be concluded that cryo-lubrication machining process shows the best performance among the three cooling/ lubrication conditions in machining of Inconel 718. Results are demonstrating that Inconel machining is influenced by both high temperature and lubrication issues. To counter against this problem, efficient cooling with good lubrication has to be provided.

What is more important is the quality of machined part. In this work part of surface integrity was analyzed through surface roughness. Results show that even improving sustainability issues with using of cryogenic machining, the productivity as well as quality of machined surface can be improved. It is shown that C/L conditions in machining of Nickel-based alloy (Inconel 718) significantly affect the quality of machined surface (surface roughness). The contribution of feed rate and speed in determining the pitch and the amplitude of the surface profile generated in machining is known from the fundamentals of metal cutting. However, in the finishing machining of Inconel 718, the third factor, the C/L condition, also highly influences the surface roughness.

Additional improvement that can be gained is chip breakability. In work it was shown that if selecting the right machining parameters and cooling/lubrication condition, even chip breakability can be improved and importantly contribute to the idea of overall machining process performance improvement.

In general, it has been shown that sustainable machining essentially provides:

- enhanced environmental friendliness,
- reduced cost,
- reduced power consumption,
- reduced wastes and more effective waste management,
- enhanced operational safety,
- improved personnel health.

With the increasing worldwide trends in achieving sustainable machining, dry, near-dry and cryogenic machining C/L options are emerging as viable and more sustainable alternatives to flood cooling in machining processes.

Therefore, this study shows a good potential for the cryo-lubrication machining, and it calls for a need for further research using this approach on other hard-to-machine materials that are frequently used in industrial applications. The overall process modelling and optimization results show that appropriate combination of cooling and lubrication can provide improved machining performance of Inconel 718.

References

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

[2] E. Westkamper, Manufuture and Sustainable Manufacturing, Proceedings of the 41st CIRP Conference “Manufacturing Systems”, Tokyo, 2008, 11-14.

[3] F. Pusavec, J. Kopac, Achieving and Implementation of Sustainability Principles in Machining Processes, Journal of Advances in Production Engineering and Management 3 (2009) (in press).

[4] J. Kopac, F. Pusavec, S. Ekinovic, High performance manufacturing – definition and aims, Proceedings of the 10th International Research/Expert Conference “Trends in the Development of Machinery and Associated Technology” TMT 2006, Barcelona, 2006, 11-24.

[5] S.Y. Hong, Cryogenic Machining, U. S. Patent 5,901,623, 1999.

[6] S.Y. Hong, Y. Ding, Cooling Approaches and Cutting Temperatures in Cryogenic Machining of Ti-6Al-4V, International Journal of Machine Tools and Manufacture 41 (2001) 1417-1437.

[7] S.Y. Hong, Economical and Ecological Cryogenic Machining, Journal of Manufacturing Science Technology 123 (2001) 331-338.

[8] I.S. Jawahir, O.W. Dillon Jr., Sustainable Manufacturing Processes: New Challenges for Developing Predictive Models and Optimization Techniques, Proceedings of the 1st International Conference “Sustainable Manufacturing” SM1, Montreal, 2007.

[9] R. Ghosh, Z. Zurecki, J.H. Frey, Cryogenic Machining with Brittle Tools and Effects on Tool Life, Proceedings of the ASME International Mechanical Engineering Congress, Washington, 2003, 422-432.

[10] F.J. Da Silva, S.D. Franco, A.R. Machado, E.O. Ezugwu, A.M. Souta Jr., Performance of Cryogenically Treated HSS Tools, Wear 261 (2006) 674-685.

[11] K.M.C. Öjmertz, H.-B. Oskarson, Wear on SiC - whiskers reinforced ceramic inserts when cutting inconel with waterjet assistance, Tribology Transactions 42/3 (1999) 471-478.

[12] F. Pusavec, A. Deshpande, R. M’Saoubi, J. Kopac, O.W. Dillon, I.S. Jawahir, Predictive Performance Models and Optimization for Sustainable Machining of a High Temperature Nickel Alloy, Proceedings of the 3rd CIRP International Conference “High Performance Cutting” HPC, Dublin, 2008, 355-364.

[13] K. Weinert, I. Inasaki, J.W. Sutherland, T. Wakabayashi, Dry Machining and Minimum Quantity Lubrication, CIRP Annals – Manufacturing Technology 53/2 (2004) 511-537.

[14] G. Byrne, B. Dornfeld, B. Denkena, Advancing Cutting Technology, CIRP Annals – Manufacturing Technology 52/2 (2003) 483-507.

[15] F. Cus, M. Sokovic, J. Kopac, J. Balic, Model of complex optimization of cutting conditions, Journal of Materials Processing Technology 64/1 (1997) 41-52.

[16] F. Cus, U. Zuperl, Model reference-based machining force and surface roughness control, Journal of Achievements in Materials and Manufacturing Engineering 29/2 (2008) 115-122.