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ACHIEVING AND IMPLEMENTATION OF SUSTAINABILITY PRINCIPLES IN MACHINING PROCESSES

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Abstract:
Manufacturers are striving to achieve sustainability through changes in products, processes, and systems. Sustainability at initial stage of product manufacturing in machining process is a strategy that is widely accepted in theory, but not commonly applied into real industry processes. The integration of environmental, economical, health, etc. requirements throughout the entire lifetime of a product, needs a new way of technologies to be applied. Therefore this paper describes the concept of an approach to product manufacturing, based on sustainable machining. One of such technology presents cryogenic machining, which methodologies and decision tools are discussed in this work, representing the most important sources of environmental/health impact during product manufacturing.

Key Words: Machining process, Sustainability, High machining performances

1. INTRODUCTION

Industry is becoming to feel high pressure as a response to new environmental, social and economical regulations, technologies, customer demands, etc. At the beginning of the 21st century, there are increasing sustainability concerns oriented on nation developing activities and the industrialized world. Sustainable development calls for practices and decisions that will assure future generation access to the same opportunities that we presently enjoy. This based on sustainability definition by Gro Harlem Brundtland (1987) [1] that sustainability development is (Figure 1): "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Figure 1: We do not inherit the earth from our ancestors; we borrow it from our children (Native American proverb).

More and more frequent it is appearing the question, for how long can we continue as a global society to extract natural sources, consume energy, and generate wastes with little through for the future generations? In response to growing concerns for the environment, our assistance as technologists is needed to support these ideas with the application of them on manufacturing enterprises, technologies, processes, products, etc. for achieving progress toward sustainability, not only helping to realize a sustainable future, but also Manufacture (assuring the future of manufacturing) [2].

The need for introducing environmental requirements into the manufacturing of products has already been discussed for more than a decade. Today there is general agreement on this point in principle amongst researchers and industry. However, the question remains of how important is it to apply environmental criteria to a product manufacturing, and how it is possible to compare environmental requirements with the traditional design requirements such as cost, function, quality, etc. (Figure 2).

Figure 2: Steps in the life cycle of a green product [1].

Current practices of product machining in manufacturing companies are still predominantly based on traditional cost/profit models, aiming at achieving high quality of a product at low cost and high profit. Environmental requirements are mainly considered as an unavoidable “must”, which generates additional design constraints and increases the costs. In an approach like this, environmental assessments are carried out fairly late in the product manufacturing process. They are not integrated with existing manufacturing activities, and they are likely to increase the manufacturing costs [3].

The paradigm of product manufacturing towards low cost and high profits is unlikely to change significantly in the near future, if ever. Companies will have to continue to make profits for their existence. However, the integration of environmental requirements into every single stage of product development from the very beginning is a very likely approach, leading to a new paradigm for sustainable manufacturing. Being an integrated approach, it will not purely add-on some constrains, but it will identify new environmental features of a product that have the potential to improve the overall quality of the product in the eyes of the customer and eventually decrease the overall costs, thus creating additional market potential and financial gains.

Before going into application of sustainability principles on the machining process, it has to be mentioned, what Ray Anderson in 2004 pointed out that “No one should be claiming sustainable products. There is no such thing yet in terms of zero footprint. What we can do is demonstrate reduced footprint.” Therefore, this work describes application of sustainability principles in manufacturing technologies/process for approaching to the global sustainability. One of those steps represents the cryogenic machining process described in this work.

2. SUSTAINABILITY CONCEPTS IN MACHINING

Sustainability has many definitions and various dimensions. In the field of manufacturing, sustainability is a part of optimization of the overall efficiency of company, technologies, processes and products. In this area efficiency has the dimension of economy, ecology and socials. Cost of energy or/and materials have an impact on the economic effectiveness. And nevertheless, the reduction of resources is a contribution to the economic and ecologic effectiveness.

Machining processes constitute a major manufacturing activity that contributes to the growth of global economy [1]. On one side intensive research work in machining process improve machining performances through higher machining performances [4]. Therefore, in nowadays more and more important become environmentally and health benign technologies and advanced techniques for achieving cleaner, healthier, safer and economical machining process. That view present sustainable machining, through improved information of the environmental impacts of existing manufacturing processes and explore/develop new technological/process concepts (Figure 3) [5, 6].

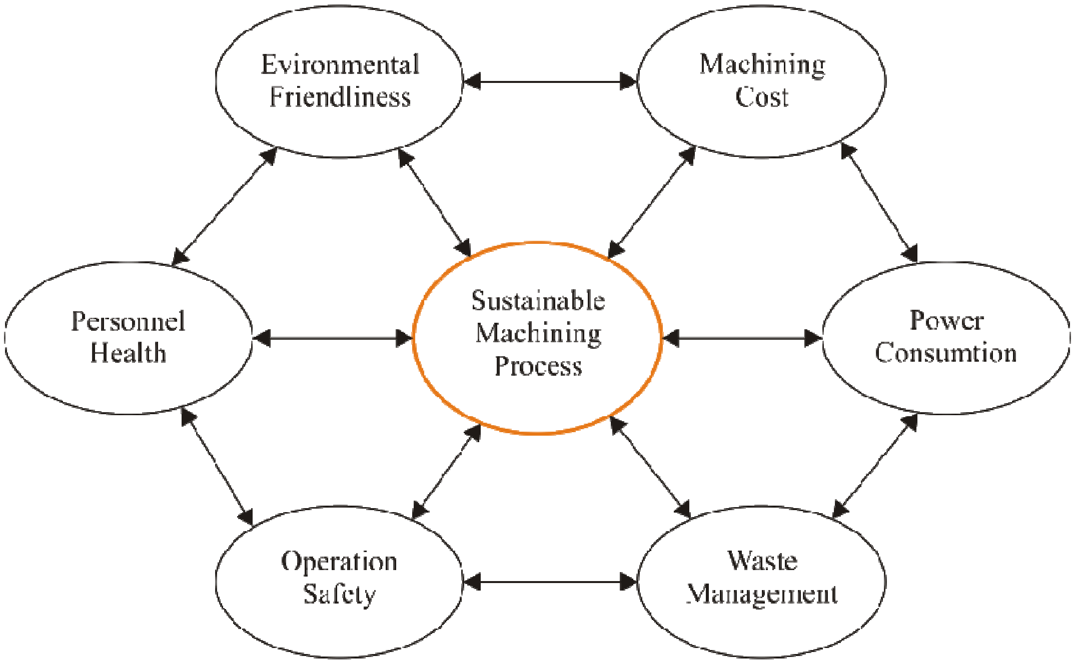

Figure 3: Basic elements of sustainable machining [5].

Research and development in the field of tool-workpiece-machine interactions have resulted in innovations that have enhanced both productivity of machining operations and part quality. The current trend towards higher productivity and high-speed-machining (HSM) inevitability leads to higher temperatures in both the cutting tool and the workpiece. Thermal management of machining operations for enhancement of both the tool-life and work quality is not new. However, the development of cooling techniques and temperature management of the process is still considered as a novel and emerging direction for study. Industrial metal cutting applications widely utilize conventional coolants (such as air, oils and aqueous emulsions) to counter the extremely high levels of heat generated at the tool-work contact zone during cutting, even their known environmental and health impacts. However, growing awareness of sustainability issues in machining, that identifies conventional coolants as a major non-sustainable element of the process, have led to research on finding alternate mechanisms of cooling. Added to this is the requirement for more efficient machining of past and newly development difficult-to-machine materials (Titanium, etc.) [7, 8, 9, 10, 11]. One such alternative to meet these growing needs is the application of cryogenic fluids. Cryogenic fluids in machining process present primary coolants. Cryogenic fluids are usually fluids that have boiling point lower than –150℃. Such fluids are for example: liquefied gasses of air, nitrogen, argon, oxygen, hydrogen and helium. While the most commonly used is nitrogen (liquid nitrogen - LN) due to its efficiency, inert behaviour and low costs.

3. CRYOGENIC MACHINING

In industry, various oils or emulsions are still used as cutting fluids, even they are environmental polluted and health hazarded as well. Beside this, in majority used machining emulsions are not biodegradable. Due to all those facts and threat to the health of workers in industry, metal working fluids have become very important part of machining process quality. In U.S. conventional fluids are considered as one of the top five health's hazarded workplaces [6]. Especially found as skin dermatitis. Approximately 4100 cases of dermatitis have been estimated yearly. Biocides, which are in coolants and are used to control coolants bacteria and microbial activity, as well as extended useful coolant life, are extremely hazardous additives. Therefore, it is difficult to assure safety with using of conventional machining fluids, what makes them even more costly.

In addition to environmental and health concerns, the machining industry continues to investigate methods to enhance machining process and in the same time decrease production costs lower than in case of conventional machining. Therefore, many issues remain to be investigated [12, 13, 14]. With the sustainability principles in mind nowadays, very important question appeared: "Can be conventional machining enhanced/replaced with cryogenic machining?".

Cryogenic machining presents a method how to cool down the cutting tool during machining. More particularly, it relates to providence of cryogenic cooling media to the point of the tool or/and workpiece, which experience the highest temperature during the cutting process (Figure 4).

The beginnings of cryogenic machining started with using of cryogenic fluids as CO2, freon, etc. They were sprayed in the general cutting area or were applied to the workpiece before cutting zone. This method however consumed excessive amounts of cryogenic fluid and had no lubrication effect. Practically this method cools the workpiece even before it is cut. The method was in some cases found as undesirable because with cooling of workpiece, it increase material strength and hardness, and decreases the machining performances through higher cutting forces, etc. Based on that, cryogenic machining process can be efficient just in case, where cryogenic fluid reach the point of highest temperature on the cutting tool and cool it. For satisfying this rule, it has to be found out what cooling lubrication, where, and in what quantity has to be provided to the machining process.

4. ECONOMICAL ASPECT OF CRYOGENIC MACHINING

Cryogenic machining usage was limited with cost (economical issue) and fuzziness (reliability issues) of the process. While machining process is designed to use products that generate profit, the cryogenic process is rare of use in industry. Based on those facts, cryogenic process has to be economical and practical to use. It is known that nitrogen is inexpensive, but in cryogenic machining presents consumable material/fluid what add to the machining costs. Nevertheless, the benefits of such a process have to be greater than additional costs of using such a machining technology. With those ideas, ideal cryogenic machining solution would be:

– That cryogenic fluid is applied directly on and just on the needed area.
– That is saving the energy trough adaptive control of flow and pressure depending to the heat generated in cutting process, etc.
– That cryogenic equipment is available as a commercial cutting assembly, which is economical and practice to use.

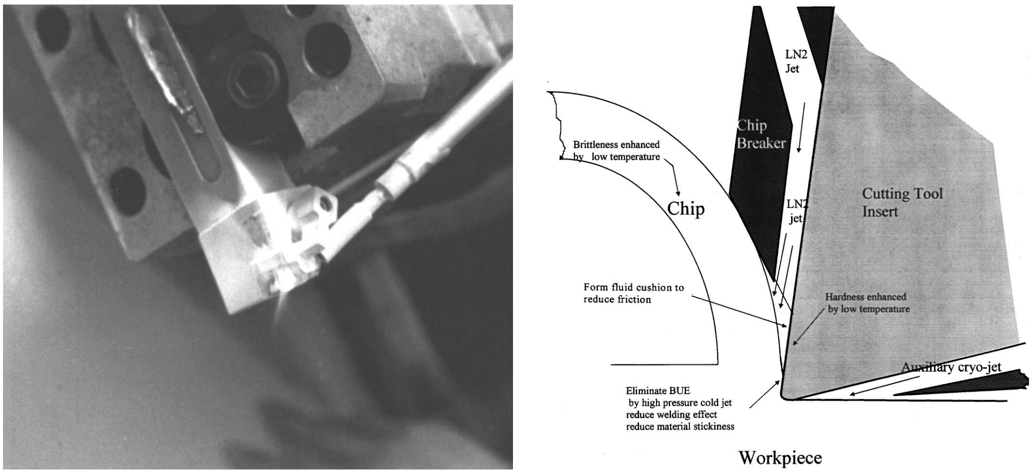

Figure 4: Principle of cryogenic cooling process [15].

However, still the productivity and production costs are the most important in real industrial production, to achieve their goal, beside nowadays goal to achieve sustainable development. The detailed economical comparison of conventional and cryogenic machining is presented in Table I.

Table I: Productivity and production cost comparison between conventional and cryogenic machining of Titanium alloy Ti–6–4.

Machining costs comparison									
		Vc = 60		Vc = 90		Vc = 120		Vc = 150	
		LN	emulsion	LN	emulsion	LN	emulsion	LN	emulsion
Conditions									
feed, f	mm/rev	0.254	0.254	0.254	0.254	0.254	0.254	0.254	0.254
cutting speed, Vc	m/min	60	60	90	90	120	120	150	150
tool life, T	s	1653	1050	948	290	437	158	296	56
Workpiece									
diameter, D	mm	50.8	50.8	50.8	50.8	50.8	50.8	50.8	50.8
depth of cut, ap	mm	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27
length of cut, l	mm	508	508	508	508	508	508	508	508
Machining time									
speendle speed, n	rpm	376	376	564	564	752	752	940	940
cuttimg time, Tc	s	319	319	213	213	160	160	128	128
part loading/anloading, Tl	s	24	24	24	24	24	24	24	24
number of parts per T, N	/	5.18	3.29	4.46	1.36	2.74	0.99	2.32	0.44
tool change time	s	150	150	150	150	150	150	150	150
tool change time per part, Tct	s	28.96	45.60	33.67	110.06	54.78	151.51	64.70	341.98
cycle time per part, Tp=Tc+Tl+Tct	s	372	389	270	347	238	335	216	494
production rate (products/h)		9.67	9.26	13.31	10.38	15.10	10.74	16.64	7.29
Machining costs									
machining cost per part, Cm	€	5.23	5.46	3.80	4.87	3.35	4.71	3.04	6.93
cost of tools	€	20	20	20	20	20	20	20	20
Nr of edges on tool		4	4	4	4	4	4	4	4
tool cost per part, Ct	€	0.97	1.52	1.12	3.67	1.83	5.05	2.16	11.40
coolant cost per part, Cc	€	0.73	0.01	0.49	0.01	0.36	0.01	0.29	0.01
Production costs, Cp = Cm+Ct+Cc	**€/part**	**6.92**	**7.00**	**5.41**	**8.55**	**5.54**	**9.77**	**5.49**	**18.34**
Cost reduction	**%**	**1.05**		**36.76**		**43.27**		**70.08**	

Based on quick view, one can see that the productivity of cryogenic machining is higher than in conventional machining, and productivity continues to increase as the cutting speed increases. Conventional machining productivity dramatically drops at higher cutting speeds due to rapid tool wear. The main benefit of cryogenic machining is reached by reduction of tool changing time and allowing production at higher cutting speeds, which shortens the actual cutting time. Additionally, longer tool life in cryogenic machining reduces the consumption of cutting inserts. To similar conclusions author came [16].

From the view of coolant costs (Table II), price of coolant varies from one supplier to another, from region to region, as well as by quantity. But trend of prices nowadays is increasing the prices of conventional cooling fluids and decreasing the prices of cryogenic fluids. However, if in that research cryogenic machining is known as more efficient, than nowadays situation should be even better, due to rising trends of oil prices. There is also a fact, that with higher cutting speeds, the machining time is shorter and the coolant use time is shorter. Therefore, the cryogenic coolant leads to viable alternative.

Table II: Productivity and production cost comparison between conventional and cryogenic machining of Titanium alloy Ti–6–4.

LN coolant usage & price	
Average usage (kg/min)	0.65
Price (€/kg)	0.21
Price (€/h)	**8.23**

Conventional coolant usage & price	
coolant concentrat (€/l)	9
coolant disposal (€/l)	0.2
mix ration 1:	14
coolant amount (l)	450
coolant concentrate needed	30
coolant concentrate costs	270
coolant disposal	90
coolant maintanance/preparation labor	60
overall tool coolant cost (€)	420
duration life (h)	2500
coolant cost (€/h)	**0.17**

It is possible to conclude that using low consumption cryogenic machining with low cryogenic fluid flow, directed to the local cutting point, brings process to levels at which nitrogen costs less than conventional cutting fluid. It reduces tool-wear and lengthens tool life especially in HSC. Improved productivity and reduced overall production cost can be achieved. In addition, the approach can reduce the frictional force, improve chip breaking, eliminate build-up edge, improve machined surface quality, etc. The benefits are reached also with environmental affection improvements and with reduction of employee health problems that could be highly significant. These benefits may be the main incentive for industry to select cryogenic machining.

5. BENEFITS OF CRYOGENIC MACHINING

The cryogenic coolant usually used is nitrogen that is a safe, non-combustible, and noncorrosive gas, with 79% presence in the air that we breathe. Colourless, odourless, and tasteless, nitrogen is often used as an “inert” gas due to its nonreactive nature with many materials. The liquid nitrogen used in cryogenic machining systems quickly evaporates leaving no residue to contaminate the workpiece, chips, machine tool, or the operator, and thus, eliminating disposal costs, which represents significant improvement over conventional cooling fluids as coolants/lubricants. Some other benefits mentioned in the literature are: sustainable operations, higher productivity, increased cutting tool-life, improved product quality with improved surface integrity, improved chip breakability, decreased BUE and burr formation, etc. [17, 18, 19, 20].

5.1 Cooling / lubrication effect of cryogenic machining

Effectiveness of cryogenic machining in machining of different materials could be evaluated via the cooling efficiency as well as lubrication effectiveness. While cooling approach is not so different for different materials, the most important role is influence of cryogenic fluid on friction coefficient in workpiece-tool contact [15, 18].

In metal cutting process right after chip is formatted it slides along cutting tool rake face. Because of the nature of sliding mechanism there is presence of friction effect which additionally consumes huge part of energy. Thus, higher the friction is, higher the cutting force is, due to increased difficulty of chip sliding along the cutting tool rake face. Consequently, chip becomes thicker, and the shear angle is lowered. With decreasing of friction due to effective lubrication, chip becomes thinner with lower cutting force and energy consumption and furthermore improved cutting tool life. The friction and wear behaviour of materials is greatly dependent on material and material surface conditions. Various material properties like shear, tensile, hardness, etc. are strongly connected with friction behaviour, while all of these properties are strongly dependent on temperature. Therefore, does and under what circumstances cryogenic machining have lubrication ability?

In machining process the major lubrication mechanisms that appear are: hydrodynamic lubrication, boundary lubrication and extreme pressure lubrication. In hydrodynamic case contact surfaces are fully separated with lubrication film. That kind of lubrication mechanism is very difficult to cause in machining because of extremely high stresses at the cutting tool interface contact area. In boundary lubrication, lubrication fluid chemically bond to the interacting metal surfaces of the cutting tool and the workpiece. These kinds of films are extremely thin, but still have a very low friction coefficient. But the problem in that kind of mechanism is that it is possible to appear just in light-duty cutting operation of easy to machine steels, cooper alloys, etc. where the cutting zone temperatures do not exceed 200°C. In most real cases the cutting temperatures are much higher than 200°C, therefore it should be used such a lubrication fluid additives which form the bonding film and have higher melting point. In the last mechanism, extreme pressure lubrication, chlorinated or sulphurized additives are used to chemically react with the metal surfaces and prevent drastic wear and welding.

Nevertheless, lubrication effect of cryogenic fluid is very hard to compare with conventional fluids. In conventional machining main lubrication mechanism present boundary lubrication, but in the cryogenic cutting fluid cryogenic fluid evaporates quickly, has a very low viscosity and is very chemically stable. This makes it almost impossible to remain between the tool and the chip for the purpose of forming a film. Therefore, it is hard to expect the same lubrication mechanisms. Thus, possible mechanisms of cryogenic fluid lubrication are mainly focused on friction (friction coefficient) and wear behaviour by material properties at the low temperature and cryogenic fluid hydraulic effect. Lubrication mechanisms in cryogenic are:

- Cryogenic cooling fluid reduces friction force and wear according to the following mechanisms: change in material properties, hydrodynamic effect, and a surface integrity.
- Change of cutting tool material properties, such as module of elastic, hardness, etc. may decrease friction coefficient by reduction of the adhesion at low temperatures even for heavy–duty cutting.
- Hydraulic lubrication effect may reduce the friction by generating a lubrication layer. Even it is hard to expect that fluid film will complete separate contact bodies by external pressure; a thin lubrication between contact shapes in micro scale may slightly decrease friction force.
- The surface integrity affects friction force in the case of cutting tool wear. Due to significant reduced interface temperature, chemical and physical reactions can be minimized and the tool face maintains its surface finish with slower material loss and a decrease in friction coefficient.

5.2 Chip formation improvement

With increasing of cutting speeds, the possible (depend on workpiece material) long continuous chips can appear. Those chips produced in metal cutting present serious problems from the view of process productivity and safety. Moreover, cutting speeds have increased to such an extent that chip control is necessary. The chips have long grain structure inverse to the direction of cutting. When the chip rubs the cutting tool rake surface, the grain structure on the lower surface bends to form "long tail" due to the secondary deformation zone. This lower surface then recrystallizes due to the grain structure. The recrystallized area is highly undesirable since it is much more difficult to get smaller broken chips.

In above presented cryogenic machining [15], improvement of chip breakage was successfully reached. The success was reached through:

– increasing of brittleness of the chip material,
– reducing the secondary deformation zone, that occurs at the bottom surface of the chip which rubs on the cutting rake face,
– reducing the long tail in the grain structure of the chip, which is the major cause for difficulty in breaking ductile chipping,
– avoiding of welding or recrystallizing of the chip bottom layer (to avoid of strong bending of the chip structure which adds to the difficulty in chip breaking) by a coldness and reduction of the secondary zone deformation, and
– pushing chip into bending and curling to reached breaking by use of both a mechanical chip breaker and the pressure from the cryogenic fluid (this may occur when the fluid expands into gas).

Furthermore, a chip breaker is used to slightly lift up the cut chip, that coolant can easier penetrate to the highest temperature area and reduce the contact length of the chip and the cutting tool rake face. This improvement lead to reduction in cutting forces and therefore, heat due to the frictional deformation zone is greatly reduced. The cooling effect is evident, but more surprising is lubrication effect. This effect comes from fluid nitrogen heat absorption, which quickly evaporates and forms a fluid/gas cushion.

5.3 Decrease of BUE formation probability

The problem in HSC is high friction between the chip and cutting tool especially when material is highly ductile. It can become so huge, that workpiece material in combination with high cutting force, itself welds to the cutting tool. Welded material additionally increases friction and build up layer on cutting tool appears which presents the beginning of BUE formation. It is known that BUE continuously grow to the stage where it becomes unstable and breaks down. Beside vibrations, it results also in high cutting tool wear and low machined surface quality.

The invention [15], also prevent BUE formation by injecting cryogenic fluid to the cutting zone (edge) area. This reduce the adhesion of the chip material to the cutting tool and results in lower cutting zone temperature as a consequence of lower friction. It is possible to conclude, that also from that aspect of view, cryogenic machining should offer improvement in cutting tool life and machined surface quality.

6. CONCLUSIONS

This paper presents the sustainability principles especially from very important side of their application on manufacturing or more detailed on machining process. Focus is oriented in technologies that are showing the direction in sustainable development with the use of cryogenic machining as a viable alternative to conventional, oil based emulsions used in machining processes. It involves a study of major sustainability elements such as power reduction, increased tool-life and enhanced functional performance in terms of surface integrity improvement, etc. in machining. It is presented that sustainable machining can essentially provide: (i) improved environmental friendliness, (ii) reduced cost, (iii) reduced power consumption, (iv) reduced wastes and more effective waste management, (v) enhanced operational safety, and (vi) improved personnel health. With the increasing worldwide trends in achieving sustainable machining, cryogenic machining option is emerging as viable sustainable alternatives to flood cooling in machining.

It is known that with all the natural disasters and trends of environment changes, we are entering a sustainable revolution, and this revolution will present us with many issues to be addressed. The manufacturing research community needs to recognize that sustainability principles need to be addresses and critically examine all elements of the processes, technologies and systems for which we are responsible – what should we do to help achieve sustainable development.

Therefore this paper presents beside the core idea of sustainability, also one of the solutions/alternatives (cryogenic machining) used in the machining processes to avoid using health and environmental hazarded oil based emulsions. This is of course just one the solutions of machining process. However, additional solutions for other problems in machining, manufacturing, etc. are needed and viable. Unless appropriate actions are taken, we run the risk of determining our future.

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