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CONCEPTS OF SUSTAINABLE MACHINING PROCESSES

Janez Kopac
University of Ljubljana, Faculty of Mechanical Engineering
Askerceva 6, SI 1000 Ljubljana
Slovenia

Franci Pusavec
University of Ljubljana, Faculty of Mechanical Engineering
Askerceva 6, SI 1000 Ljubljana
Slovenia

ABSTRACT
Sustainable production as a global word, content important elements on all the fields as well as machining processes. Machining can be performed either on conventional or nowadays modern CNC way. Novel machining processes are based on CNC programmable technologies containing elements as CAD, CAM, etc. To define sustainable production as the creation of goods, using processes and systems, we have to provide working conditions for all the employees, satisfying: non-pollution, energy and natural resources conservation, economical elements, safety and employees healthful communities, socially and creatively conditions, etc. This relationship, known as three pillars of sustainability: environment, earth society & people, and economic profit, have to be synergistically related [1]. After world industrial crises, started in 2007, is maybe not the first thing to do, keep reaching high economical growth (GDP – plus 5 %) from year to year. The solution lies in reaching the sustainable development strategies, even on an account off the short term negative economical result [2].
Keywords: Sustainable manufacturing, Production, Machining, Cryogenic machining, High pressure jet-assisted machining

1. INTRODUCTION
Metal machining industry is 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).
Conventional pyramid structure of production knowledge, contents level organized structure with an idea and fundamental design of new product, CAD and production level with CAM and lowest Manufacturing Engineering level. 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.
Yesterday, the economical mass production has had the key to success in the industry. However, today industrial crisis is spread all over the world; mass production, automotive industry, etc. are facing difficulties in finding their profit. The solution, to overcome this situation lays in innovations and creations of attractive products/processes with "soul", following the rules of Sustainable Manufacturing Production on all the levels and raising the sustainability view over the production growth (gross domestic product – GDP) (Fig. 1).

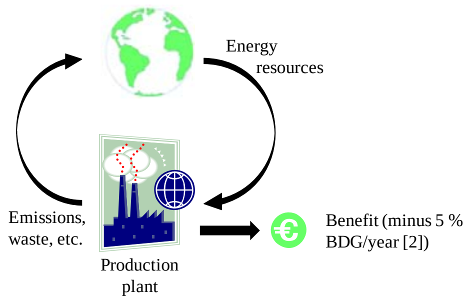

Figure 1. Sustainble development strategy even on account of negative GDP.

1.1. Socio-Technical part

Important aspect is technological and social correlation. Socio-technical part emphasizes optimization of the technical infrastructure and the human (social) processes in an organization, production, etc., promoting excellence in technical performance as well as quality in people's work lives. Organizations are designed such that relationships between socio and technical elements lead to the emergence of productivity and well being (Fig. 2).

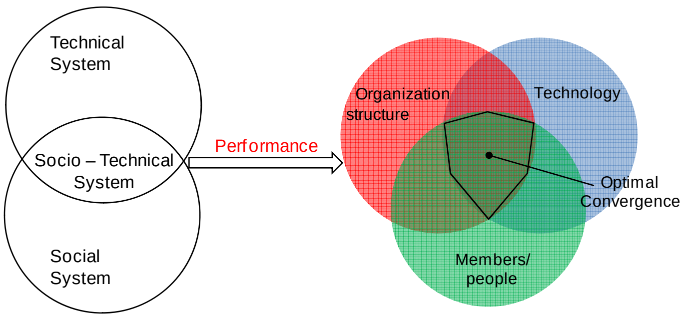

Figure 2. Overlapping best technology usage.

Described idea is planning to be presented in this paper with the application on manufacturing/machining processes through novel sustainable machining processes: Cryogenic and High Pressure Jet Assisted Machining. The outline of paper is the following. In Section 1 the idea of sustainability spirit transition in manufacturing processes, for achieving global sustainability, is discussed. The sustainable machining ideas and trends are presented in Section 2. Two sustainable machining processes, as alternatives to conventional machining, with their pros and cons are presented in Section 3. In Section 4 experimentally based economics are discussed, followed by the conclusions in Section 5.

2. SUSTAINABLE MACHINING

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 stays in the same range or it is shrinked. There is a fact that the reason for recent industrial crises is virtually high product consumption/production that is overestimating the real costumer consumption. As a consequence a lot of products is 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 [1], [2]. 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 [3],
- using resources such as materials, water and energy more efficiently,

- avoiding or at least improving management of metalworking fluids, swarf, lubricating oils and hydraulics oils – improved environmental, health and safety performance,
- adopting lean manufacturing and other sustainable engineering techniques [4],
- improve working conditions,
- using best practice in machining,
- train employees about sustainable practices, etc.

R&D in the field of machine tool-cutting tool-part interaction has resulted in innovations that have enhanced both productivity and quality of machined products. However, the current trend towards higher productivity via high-speed machining (HSM) inevitably leads to higher temperatures in both the cutting tool and the part and affecting them both. Thermal management of machining operations for enhancement of both, the tool-life and machined part quality is not new. However, the development of cooling and/or lubrication techniques and temperature management of the process, is still considered as a novel and emerging direction to study. Industrial metal cutting applications widely utilize conventional cooling lubrication fluids (CLF), such as: air, oils and aqueous emulsions, to counter the extremely high levels of heat generated in the cutting zone during the machining process, even though they are environment unfriendly, health hazardous and relatively costly. It has been reported that 15 % of the total machining costs are due to the use of CLF emulsions, while percentage of tool costs is a lot lower; around 4 % [5], [6]. With simply avoiding the CLF usage and applying dry machining alternatives, with new high performance coated cutting tools, there would be a huge process gain from sustainability point of view [7], [8], [9], [10]. However, there are new part materials used, which are extremely difficult to machine, for instance high-temperature alloys (nickel alloys, titanium alloys, etc.) that are used in aerospace industry, due to their ability of maintaining properties even at high operational temperatures (jet engines, etc.) [11], [12]. Those materials have relatively small thermal conductivity, leading to extremely high temperatures in the cutting zone. In combination with high cutting speed, serious difficulties are met, disabling the use of dry machining, even in the case of latest coating usage. These facts added to the growing awareness of sustainability issues in machining, identifying conventional oil-based CLF as a major non-sustainable element of the process, have led R&D on finding alternate cooling and/or lubrication mechanisms [13], [14], [15], [16], [17].

3. ALTERNATIVE MACHINING TECHNOLOGIES

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 (Fig. 3).

The coolant is usually nitrogen fluid which is liquefied by cooling to –196°C (liquid nitrogen - LN). Nitrogen is a safe, noncombustible, 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 [13]:

- 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, etc.

3.2. High pressure jet assisted machining (HPJAM)

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 (Fig. 3).

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,
– decrease the cutting tool-chip contact length, lower cutting forces and extend tool-life,
– drastic improvement of chip breakability,
– extension of machining parameters operational ranges, resulting in increased process productivity through higher MRR, etc.

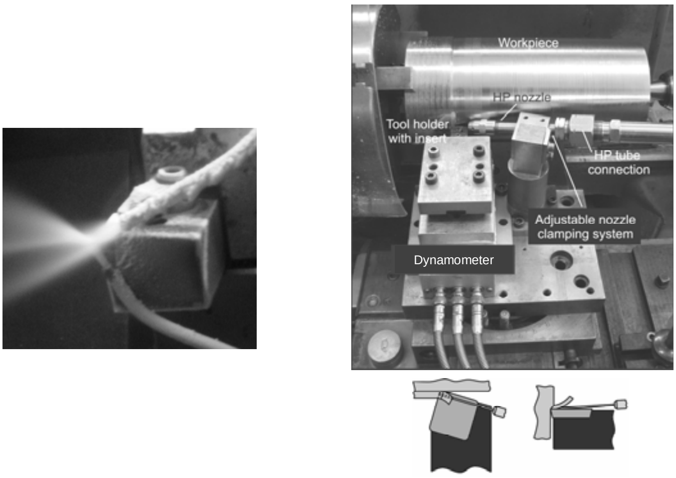

Figure 3. a) Cryogenic liquid nitrogen delivery, b) HPJAM set-up with sketch of CLF jet direction.

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 has been done [13] and is summarized in the following section.

4. EXPERIMENTAL BASED COST EVALUATION RESULTS

The overall part production process, consisting of machining, cooling/lubrication, part cleaning, preparation of swarf to be disposed, and their interrelations are shown in Fig. 4.

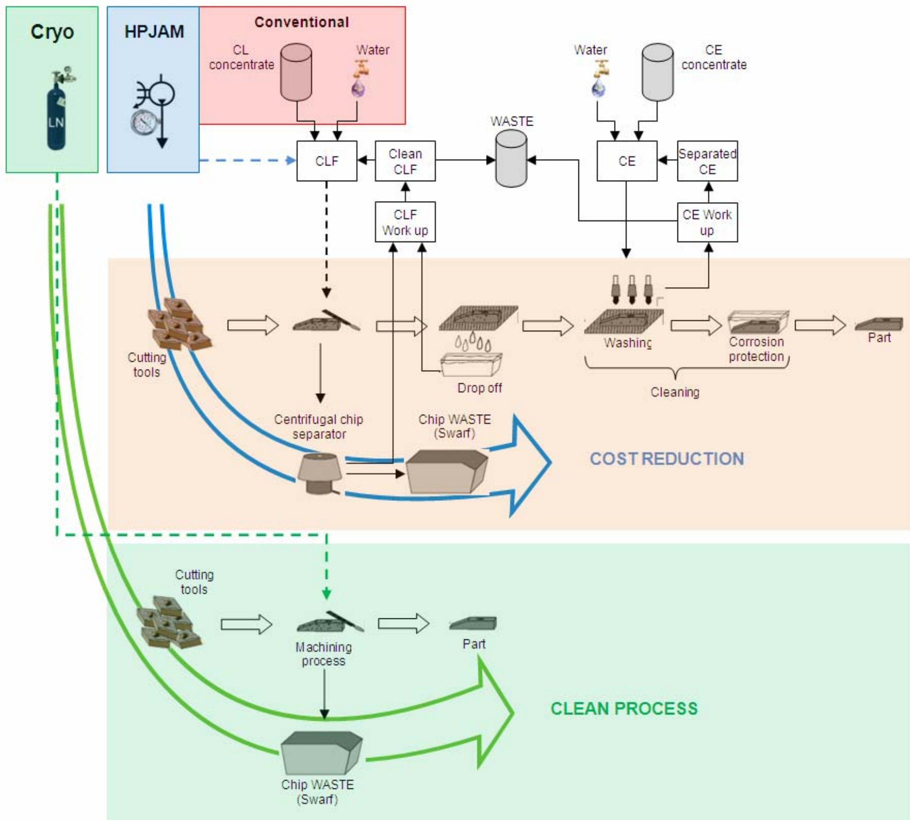

Figure 4. Comparison of different machining technologies and relations in part production process.

Comparing, 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, has swarf disposal preparation process, where chips have to be separated from oil and shredded if needed. 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. We can talk about “clean” cryogenic machining.

Accounting all machining segments, the overall production cycle time and costs are calculated when machining of high temperature nickel alloy (Inconel 718). Both results are presented in Fig. 5, while detailed calculation procedure can be seen in [13]. On the plots each of the bars is corresponding to the production time/cost of individual machining process, at the mean cutting speed, (V_c = 75 m/min). The solid line is showing the trend of production time/cost, if cutting speed is changing. To analyze the contribution of production time/cost segments, the bar plot is stacked. The height of each bar equals the sum of elements contributing to the overall production time/cost.

From plot, it can be seen that conventional machining yields the longest production time. With usage of Cryo or HPJAM the production time can be decreased up to 63 %, depend on which cutting speed are we going to use. From the individual segment contribution, one can see that machining time contribution in all three cases is the same. Only the tool changing time has a much higher contribution in conventional machining than in the other two alternatives. The actual cutting tool changing time is not longer, but the number of changes is higher, due to increased tool-wear rate in case of conventional machining.

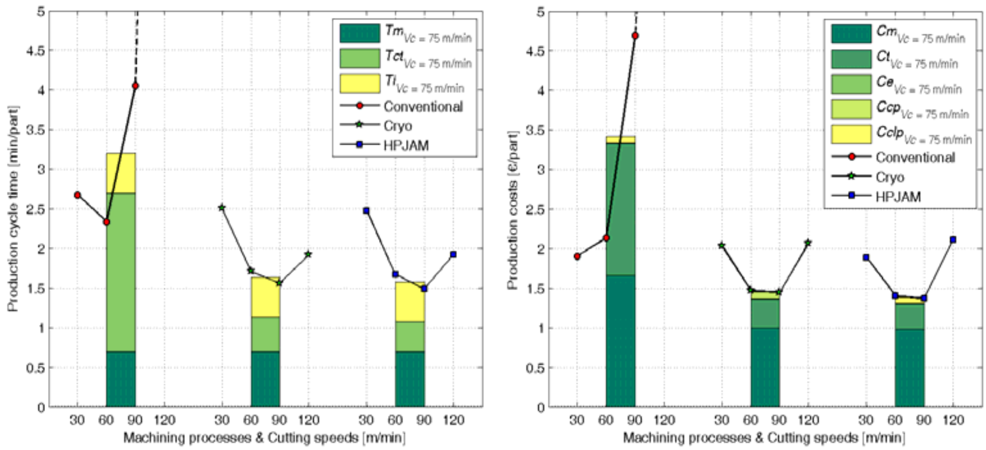

Figure 5. Product cycle time and production costs comparison (machining parameters f = 0.25 mm/rev, a_p=1.2 mm, left plot: T_m – machining time, T_{ct} – time needed for changing worn cutting tools, T_l – time for changing of part, when the machining process is finished; right plot: C_m – pure machining costs, C_t – tool costs per part, C_{cp} – CLF usage costs (per part), and C_{clp} – costs connected with cleaning of CLF from part, etc.).

From the cost results, it is possible to assert that conventional machining is significantly more expensive than Cryo or HPJAM. This trend is even more dominant if employing high cutting speeds. What is really interesting from those plots is that at lower cutting speed conventional machining can be the cheapest. However, this cutting speed is not the optimal one. Therefore, sustainable alternative machining processes, like Cryo or HPJAM, should be used, when high efficiency and high productivity are required. Regarding the contribution to the overall production costs, it can be seen that machining costs and costs due to cutting tool changing are the highest in case of conventional machining. Energy consumption costs are almost negligible in all three cases, while coolant costs are almost negligible in conventional and HPJAM, however not in Cryo, since the price of LN is much higher. Due to part cleaning, if the finished part does not have any regulation about cleaning, HPJAM is preferable. In the opposite case, if environmental concerns are of major importance or worse if CLF is affecting the functionality of machined part, then Cryo machining is preferable.

5. CONCLUSION

This paper presents the production sustainability principles, especially from very important side of their application on manufacturing or more detailed – machining process. Focus is oriented on technologies that are showing the direction in sustainable development, with the use of cryogenic machining or high pressure jet-assisted 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. As a case study, overall economical analyses of machining processes are performed. For this an experimental based Inconel 718 machining cases were carried out with turning process. Based on the results, it is concluded that sustainable machining through alternative machining processes (cryo or HPJAM) 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.

As a conclusion of this work, it can be stated that with the increasing worldwide trends in achieving sustainable machining, cryogenic or high pressure jet assisted machining option are indubitably emerging as viable sustainable alternatives to flood cooling in machining processes.

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