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An Evaluation on Machining Processes for Sustainable Manufacturing

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ABSTRACT

Sustainable manufacturing consists of environmental protection, profitability and societal benefit for all industrial areas. Manufacturing practices are investigated for optimize production efficiency while minimizing environmental impact and maintaining social equity. It can be achieved through changes in products, processes and systems related to the sustainability issues. In sustainable manufacturing process, the natural resources which are key elements of sustainability must be used prudently by academic, scientific, cultural and human organizations. In this context, sustainable machining can be defined as a process which has been performed of sustainable manufacturing by using alternative machining technologies such as cryogenic machining, high pressure jet assisted machining. Sustainable machining investigates the conflict and synergy between economical and environmental considerations as well as the effect of system boundaries in determining optimum machining conditions. This paper presents a general evaluation on the importance of sustainable machining technologies in obtaining sustainable manufacturing objectives.

Keywords: Sustainable manufacturing, cooling, lubrication, cryogenic machining, high pressure jet assisted machining

1. INTRODUCTION

The compose of manufactured products that use processes which reduce environmental effects, preserve natural resources and energy is called as sustainable manufacturing [1]. Nowadays there is a remarkable need for succeeding overall sustainability in industrial activities, coming out because of several established and emerging causes, namely stricter regulations and diminishing nonrenewable resources. These causes are interested in occupational safety/health, environment and increasing consumer preference for environmentally friendly products. Especially manufacturing sector at the center of industrial economies must be made sustainable in order to conserve the high standard of living succeeded by industrialized societies and to allow for improving societies to succeed the same standard of living sustainable [2]. Moreover, at some elemental levels

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such as economic, societal and environmental, the sustainability development effort must utilize [3,4].

Because of competition, stricter environmental plannings, supply chain demand for developed environmental performance and falling skill stages within the manufacturing, metal machining companies are getting worried about their own situation in industry [5,6]. Metal machining companies of all sizes a cost effective route are offered by sustainable manufacturing practices in order to develop their economic, environmental and social performance. Cryogenic machining and high pressure jet assisted machining (HPJAM) process that offer reduction of costs, health and environmental hazarded oil-based cooling/lubrication fluid (CLF) usage is the alternatives to conventional flood machining process. That machining companies to be traditionally focused on short term financial considerations instead of the longer term view is the source of the problem. However, in order to succeed sustainable development and ultimately survival it is needed a long term business strategy. Furthermore, it is essential that companies adopt sustainable manufacturing practices to overcome the challenges facing the sector. The first way to help companies develop their economical, environmental and social performance is to increase waste reuse or recycle and less waste generated. The second way is to use material, water and energy resources efficiency. In addition to these, management of metalworking fluids, lubricating oils and hydraulics oils are improved. The other ways are to improve environmental, health and safety performance and adopt lean manufacturing and other sustainable engineering techniques, besides improving working conditions, using best practice in machining and training all employees about sustainable practices [7,8].

Machining which involves a number of sustainability factors having a big potential for environmental effect is a major manufacturing operation. Usage of coolant and lubricant, tool life, waste chip and energy consumption are included by these sustainability factors. For this reason, the analysis of machining processes and optimization of these input factors and outputs has remarkable implication for sustainable manufacturing [9]. A major manufacturing activity that helps to the development of the global economy is constituted by machining processes. On one side, machining performances through advanced tool materials, higher productivity and quality have been developed by research and improvement in machining processes. On the other side, environmentally and health friendly technologies are getting important and important for succeeding healthier, cleaner and safer machining [10,11]. In order to state the relative sustainability level, measures have to be defined by providing sustainability principles in machining processes. When the process evaluation and comparison criteria are taken into account, there are many of them in this case. The first one is the quality of machined surface integrity. The second one is the cost of the machining process and resources and energy expenditure. Waste production and the disposal cost thereof is the third one of the process evaluation and comparison criteria. The others are environmental performance, health and safety performance and required skill level [12].

This paper presents recent trends in sustainable machining technologies used as alternatives to conventional machining with an overview of the sustainability requirements for machining processes for achieving sustainability at the product, process and system levels.

2. SUSTAINABLE MANUFACTURING

Sustainable manufacturing consist of environmental protection, profitability and societal benefit by The Sustainable Manufacturing Research Group and the Center for Manufacturing and College of Engineering [13]. It is essential to move beyond the traditional 3R concept promoting green technologies (reduce, reuse, recycle) to a more recent 6R concept forming the basis for sustainable manufacturing (reduce, reuse, recover, redesign, remanufacture, recycle) to succeed this goal, product level, since this allows for transforming from an open-loop, single life-cycle paradigm to a theoretically closed-loop, multiple life-cycle paradigm [14]. It is essential to succeed optimized technological developments and process planning for decreasing resources and energy consumption's, occupational hazards, toxic wastes, etc., and for developing product life by manipulating process-induced surface integrity at the process level [15,16].

When considering physical products, designing the system and promoting sustainability in manufacturing operations must focus on a sustainable manufacturing approach by centering on a broader, innovation-based 6R methodology to recover, redesign, and remanufacture the products over multiple life-cycles as well as to reduce, reuse and recycle in Figure 1, since manufacturing is the main operation in a product's supply chain. Decreases to the first three stages of the product life-cycle and refers to the reduced use of resources in pre-manufacturing, reduced use of energy and materials during manufacturing and the reduction of waste during the use stage in the 6R methodology [17,18]. In the meantime, in order to reduce the usage of new raw materials to produce such products and components, reuse refers to the reuse of the product or its components, after its first life-cycle, for subsequent life-cycles [19,20]. Otherwise, recycle comprises the process of transforming material considered waste into new materials or products. At the end of the use stage, sorting, disassembling and cleaning for utilization in following life-cycles of the product, the process of collecting products is referred to as recover [21]. While remanufacture comprises the re-processing of still used products for restoration to their original state or a like new form through the reuse of as many parts as possible without loss of functionality, in order to make the product more sustainable, the act of redesigning products to simplificate future post-use processes through the application of techniques like design for environment is referred to as redesign.

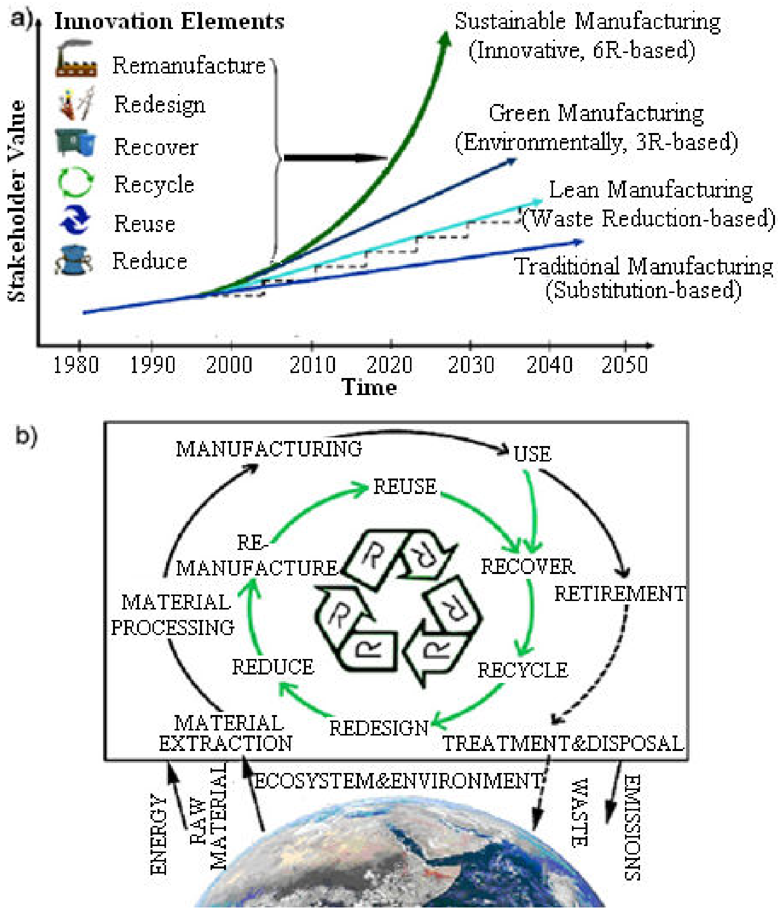

Figure 1. (a) Development of sustainable manufacturing [15],

(b) Closed-loop product life-cycle system in 6R approach [22].

It has underlined to theme sustainability of products in the concept of sustainable manufacturing or sustainable development as stated above. On the other hand, many methodologies have been proposed for utilizing the sustainability of manufacturing systems. The sustainability chain circle is defined as the optimal process flow in terms of the sustainable development in this method [23]. The seven rings of the sustainability chain circle (Figure 2) can be declaration as: the first one is material for minimum and renewable use. The second one is economy for efficient and comparable products. Design for recycling and environment is the third one of the seven rings of the sustainability chain circle. The other are market for specific target group, equity for employee conditions, technology for quality of the products and ecology for eliminate waste [24].

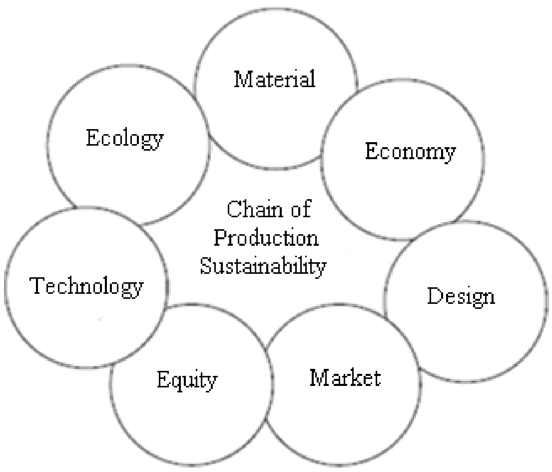

Figure 2.Chain of product sustainability [24].

It can be understood from studies in the last two decades that introducing environmental awareness to customer requirements, performing life cycle assessment during the design process, assessing environmental performance as a design objective and evaluating the product's potential for reuse and recycling is the most important stages of a product's life cycle from design through manufacture and from usage to disposal. Therefore, one of the most important sustainability criteria is described as the product design process. Three key objectives have been traditionally used for decision making in a design process, namely development cost, product cost and product performance. During the last two decades, alongside with the introduction of Concurrent Engineering, a fourth objective which is the objective of development speed was added. It is caused by the need for shortening the time-to-market. Today, a fifth objective, the environmental performance must be added in view of a sustainable development [25]. As can be seen in Figure 3, a trade-off model for sustainable development used for balancing the five key design objectives against each other is generated.

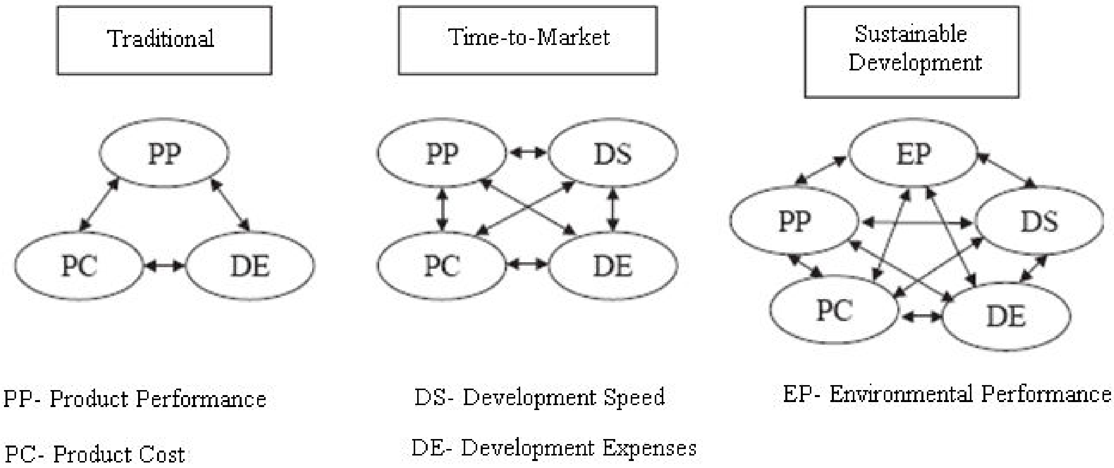

Figure 3. Trade-off model for sustainable design decision [25].

In the recent years, it is noticed that made of extensive optimization works on the sustainable machining. The case-based optimization design process on process flow planning in terms of sustainable development should be divided into different levels. The higher level consists of machining sequence, machining processes, the optimization of the machining method and the assessment of the sustainable development characteristics of the process [26,27]. The lower level consists of the choice of machining equipment (tool, machine and cutting fluid), the process parameters (feed rate, depth of cut and cutting parameters), and estimates of energy savings and noise reduction (energy, materials and environmental impact) [28]. As can be seen in Figure 4, the levels are matched in lateral and longitudinal directions with the relationship and operation flows between these levels. Furthermore, in order to produce micro devices the use of mechanical micromachining is a flexible approach that can use any material that can be machined. The energy consumption for micromachining was compared between a micro milling facility and conventional Computer Numerical Control (CNC) and showed that the energy usage for micro milling facility is more efficient than CNC. A custom built micro milling facility is two or three times higher than CNC according to energy footprint [29].

Life Cycle Assessment (LCA) methodology used in almost all processes of sustainable manufacturing is remarkable. In order to analyze sustainability of manufacturing systems, using multiple commensurable aspects of measurable systems, based upon systems thinking, The LCA very useful methodology is preferred. LCA methods generally analyze parameters such as impact, resources, energy and outputs which are electricity, emissions, waste and total energy. The guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the supply chain are provided by the results from this analysis. For instance, the impact of producing an automobile would involve the impacts at the final assembly facility besides the impact from forming windows, mining metal ores, making electronic parts, etc. needed for parts to build the car [30].

The LCA process is iterative, systematic and phased approach and involves four components namely, goal definition and scoping, impact assessment, inventory analysis, interpretation. All inputs in terms of the material and the energy going into the machining process and outputs in terms of the emissions are covered by the system boundary.

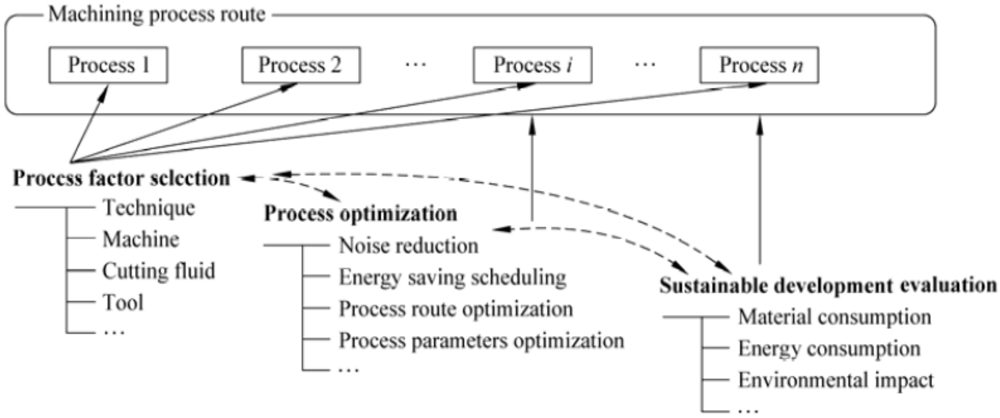

Figure 4. Optimization decisions for production process planning [28].

The process of quantifying energy, material and emissions (i.e., atmospheric, waterborne, solid) for the entire life cycle of a product are called as Life cycle inventory (LCI). All the related data is collected and organized in this phase of the LCA. Before starting any data collection, the details of collected data must be decided critically [31]. The combination of the evaluation of the potential human health and the environmental effects of the resources and the releases identified during the LCI is defined as Life cycle inventory analysis (LCIa) phase of the LCA. It refers to the resource exhaustion and the ecological and human health effects. It creates a linkage between its potential environmental impacts and the product or the process. In order to classify and characterize the types of the environmental impacts, the LCIa provides a systematic procedure [32-35]. Life cycle interpretation (LCIn) is a systematic technique for identifying, quantifying and evaluating the information by the help of the results of the LCIn and the LCIa and communicating them effectively. ISO has defined three objectives of LCIn. The first objective is to analyze the results, reach the conclusions and explain the limitations based on the findings of the preceding phases of the LCA. Second one is to report the results of the life cycle interpretation in a transparent manner. The last objective is to provide an easily understandable and complete presentation of the results of an LCA study according to the goal and scope of the study [31].

3. COOLING/LUBRICATION IN MACHINING PROCESS

Type of machining processes, type of machined workpiece material and type of cutting tool material in machining processes are the factors that the cutting fluids are applied depending on them. Cooling effect, lubrication effect, taking away formed chip from the cutting zone are the three fundamental characteristics of them [36,37].

In order to succeed specific results in machining processes, cooling/lubrication (C/L) fluids namely, air, oils and aqueous emulsions assist. In terms of tool life, surface quality and accuracy, cooling/lubrication fluids are recognized as undesired factors [38]. Instead of cutting fluid generally, nitrogen, oxygen and carbon dioxide gases have been used and compared to wet and dry machining processes. Finer surface quality in lower feed and reduced cutting force in high feed in gas application instead of wet machining would be provided by increasing gas pressure and flow rate [39]. Gas application would produce positive results instead of direct gas application (by directing gas into cutting zone by using a holed tool holder) in high speeds machining such as temperature in cutting zone and reduction of cutting forces [40]. Although the disadvantages of cooling lubricants have such as disposal problems, health problems and economical reasons, completing avoidance of cooling lubrication in metalworking will not be possible without deductions in tool life or surface quality. On the one hand, the C/L is necessary for technological reasons such as chip transport or machine tool cooling [41], on the other hand, the environmental awareness, which increases cost pressure in industry, has led to a critical consideration of conventional C/L usage in machining processes [42,43]. It is not possible just to turn off the cooling/lubricating fluid supply in order to reach the aim of C/L fluids usage reduction. Transport/evacuation of chips, cleaning of tools, reduction of friction, reduction of temperature in cutting zone, workpieces and fixtures are some important tasks of C/L fluids which the reason lies in. These tasks, in the case of its absence, have to be taken over by other components in machining process. Workpiece relating manufacturing costs, incurring with the deployment of cutting fluids, ranging from 7-17% of the total machined workpiece cost is shown from analysis carried out by German Automotive industry. However, compared to this, tooling costs can account for approximately 2-4%. For this reason, it is obvious that the cost reductions can be important with using of dry or near-dry machining [44]. It is also known that one of the most unsustainable elements of machining processes is oil-based cooling/lubrication fluids (CLF). Mineral oils obtained from non-sustainable crude oil extracts can formulate many CLFs and other industrial lubricants. Due to alternative naturally derived CLFs'(vegetable oils) higher cost and reduced performance there has been limited use of them although they are sufficiently available. Vegetable-based CLF benefit biodegradable raw materials considered less toxic than mineral oil-based formulations and may offer developed working conditions for operators [45].

In addition, it has been reported that while percentage of tool costs is around 4 %, 15 % of the total machining costs are due to the use of CLF emulsions [46]. There would be a huge process gain from sustainability point of view with simply avoiding the CLF usage, applying dry machining alternatives and new high performance coated cutting tools [10,15,47]. Though, while reducing machining costs, decreasing the cutting temperature and improving environmental sustainability conventional CLF in machining of the aerospace alloys (hard to-machine) are not effective. The problem is that conventional CLF do not contact the tool-part and tool-chip interfaces, under high contact pressure. Moreover, in the machining processes there are always losses of CLF. This occurs through vaporization, the loss with chips and parts leaving the machine tool, the loss by way of handling devices, as well as through leakage. When this point is considered, it is obvious that technologies employing CLF are unsustainable, and there would be a huge process acquisition in terms of the sustainability by avoiding of their usage through applying alternative machining technologies [11, 47,48].

The alternatives cooling and/or lubrication mechanisms improved with increasing awareness of sustainability issues in machining and defining conventional oil-based CLF as a main non-sustainable element of machining processes, by means of the research and improvement in the processes [49-51]. These mechanisms are called as near-dry machining (NDM) which is also defined as minimum quantity lubrication (MQL). In the machining processes, not only straight oil is used, but also even emulsion or water is used. During machining in small quantities, these tools are feed into cutting zone [54]. MQL contrary to flood lubrication uses only a few drops of lubrication (approx. 5 ml to 120 ml per hour) in machining [31, 55]. If there is airless system the droplets are formed and feed to the cutting zone in the way of aerosol spray, but generally the transportation tool is air [56]. Discrimination can be made between minimum quantity lubrication (MQL) and minimum quantity cooling (MQC) due to the fact that the term near-dry machining (NDM), generally presents machining with small amount of cooling lubricant [57]. The minimization of cutting fluid also leads to economic benefits by way of reducing lubricant costs and workpiece/tool/machine cleaning cycle time.

Nearly a decade ago, the concept of minimum quantity lubrication (MQL) was suggested as a means of addressing the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting fluid particles on factory shop floors. Flooding of cutting fluid leads to various drawbacks like increase in overall cost of cutting, problem of disposal of the fluid, etc. So MQL seems to be a good alternative for effective cooling during machining. [58,59]. Depending on the accessibility to the cutting edge, different requirements apply to the devices in use. For this reason, a distinction is made between external and internal feed of the lubrication tool, which makes a noticeable difference to the cost of the device technology. In the case of external feed (Figure 5a), the lubricant is applied by means of spray nozzles around the circumference of the tool. This system is especially suitable for entrance-level implementation for conventional processes such as turning, milling, drilling. With internal feed (Figure 5b), the lubricant is transported through the spindle system of the machine and through the channels in the tool to the machining point. This system is used primarily when flexible processing centers and new machinery are in use as well as with high speed machining [55,60].

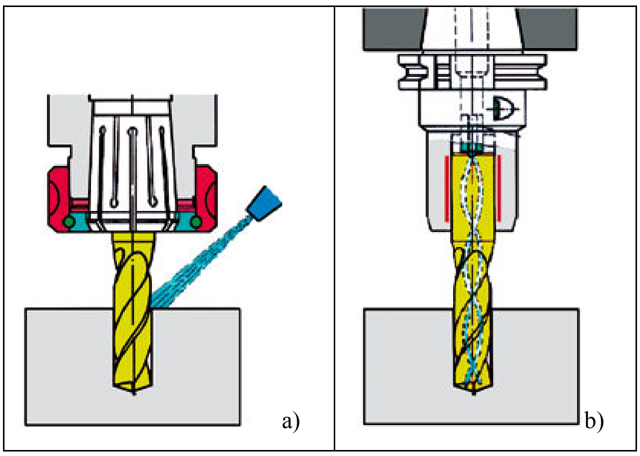

Figure 5. External and internal lubrication feed in MQL systems [55]

The advantages of MQL application on machining operations can be explained as follows: the first one is provides lubrication on machines set up for flood or high-pressure, high-volume coolant delivery and recovery. The second one is reduces mist and spray, therefore, offering an attractive alternative on unenclosed machines like a typical tool room mill or lathe. Reduces or eliminates problems associated with thermal shocking of the cutting tool is the third one of the advantages of MQL application on machining operations. The other are MQL technique produces a significant role in terms of reducing cutting temperature between tool-work piece interfaces, particularly well suited for tools and operations either generated heat or abrasion to the flank of the tool is the major players to tool failure, MQL can reduce the corner and flank wear more effectively than a solution type of cutting fluid, reduces or eliminates problems associated with thermal shocking of the cutting tool and reduces both cost of buying and disposing of conventional cutting fluid if all operations can be run with MQL [61].

4. SUSTAINABLE MACHINING PROCESSES

Machining is one of the most important and major manufacturing processes, and it is estimated that machining processes contribute about 5% of the gross domestic product (GDP) in the developed world. The indirect impact of machining is greater due to its effect on surface integrity, and hence on product life time. Moreover, as economic factors induce shorter product cycles, and more flexible manufacturing systems, the importance of machining is expected to increase even further [3]. Despite the above mentioned, the sustainable machining research was performed piecemeal manner without methodology to systematically consider available model and data and guide decision making to optimize machining operations for minimal environmental impact in a virtual environment [23]. The alternatives to conventional flood machining process are cryogenic machining and high pressure jet assisted machining (HPJAM), offering reduction of costs and reduction/avoidance of health and environmental hazarded oil-based CLF usage.

4.1. Cryogenic Machining

Cryogenic cooling approaches in machining are classified into four groups according to applications of the researchers. These includes cryogenic precooling the workpiece by repulsing or an enclosed bath and cryogenic chip cooling, indirect cryogenic cooling or cryogenic tool back cooling or conductive remote cooling, cryogenic jet cooling by injection of cryogen to the cutting zone by general flooding or to the cutting tool edges or faces, tool–chip and tool–work interfaces by micro nozzles, cryogenic treatment of cutting tools to enhance their performance [62]. Cryogenic machining presents an innovative method of cooling the cutting tool and/or part during machining (Figure 6a). More specifically, it relates to delivering the cryogenic 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 6b).

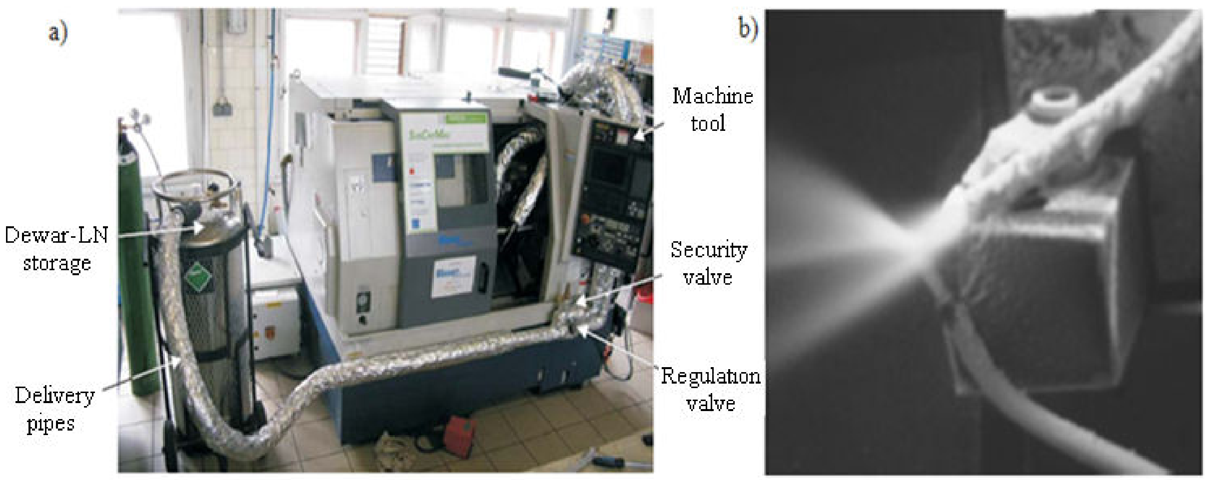

Figure 6.(a) Cryogenic machining set-up [48], (b) Cryogenic liquid nitrogen delivery [7].

Liquid nitrogen (LN) is a gas environmentally-friendly used the most commonly in machining medium. Other cryogenic fluids are Helium, Hydrogen, Neon, Air and Oxygen [63].The coolant is usually nitrogen fluid which is liquefied by cooling to –196°C. 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 benefits of cryogenic machining as follow [7]: the first benefit is sustainable machining. The second benefit is increased material removal rate (MRR) with no increase in tool wear and with reduced cutting tool changeover costs, resulting in higher productivity. The third benefit is increased tool life due to lower abrasion and chemical wear and the last one is improved machined part surface quality/integrity with the absence of mechanical and chemical degradation of machined surface.

When compared with dry cutting and conventional cooling, the most considerable characteristics of the cryogenic cooling application in machining operations could be determined as enabling substantial improvement in tool life and surface finish-dimensional accuracy through reduction in tool wear through control of machining temperature desirably at the cutting zone [62]. 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 [7].

4.2. High Pressure Jet Assisted Machining

The aerospace superalloys such as titanium, nickel-based alloys are widely used in aerospace industry also in other industry sectors such as biomedical and chemical applications because of high temperature resistant alloys. Main problem associated with conventional machining of superalloys is the accelerated tool wear, resulting from generated high temperature in the cutting zone due to the poor thermal conductivity of these alloys [51, 52].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. 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 7). The HPJAM supports the sustainability directions in manufacturing, especially hard-to-cut materials, by increasing tool life and reducing the cutting forces resulting in higher productivity and lower energy consumption [53].

HPJAM involves high pressure pump, high pressure tubing, and outlet nozzle fixed besides tool holder. Some of potential benefits of HPJAM as follow: the first one is sustainable machining through lower flow rates of CLF in comparison to conventional machining, while providing better cooling and lubrication mechanisms. The second one is decreasing the cutting tool-chip contact length, resulting in lower cutting forces and longer tool life. Drastic improvement of chip breakability is the third one of potential benefits of HPJAM. The last one is 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 cryogenic and HPJAM processes in comparison to conventional machining is done in the following.

The sustainable machining processes in manufacturing are comprehensively evaluated in respect of sustainable machining basic elements which is environmental friendliness, machining cost, personnel health, power consumption, operation safety, waste management, and their interrelations [3,7,12,31,45]. In conventional machining, as well in HPJAM, aqueous emulsions are needed as a CLF and a cleaning emulsion (CE) that absorbs abrasion and temperature, but leaves a residue on the part surface. Therefore, the CLF supply also has to ensure the cleaning of the parts after machining, drying them, and protecting them from corrosion. The central supply systems include separators to remove chips and a unit for fine purification. The life time of the CLF is also not unlimited. The content of foreign matter gradually increases and microbial decomposition process may occur, causing disagreeable smells or the sedimentation of sludge in pipes. Beside health and environmental problems connected with CLF and CE usage, the cooling/lubrication and cleaning processes are time consuming and costly. The same applies to the chip waste disposal preparation process, where chips have to be separated from the oil and shredded if needed. In the case of HPJAM, the CLF jet improves chip breakability, which reduces chip waste volume and enables their trouble-free conveyance. However, in cryogenic machining, complete elimination of oil-based CLFs is achieved, resulting in the elimination of the need for part and chip waste cleaning.

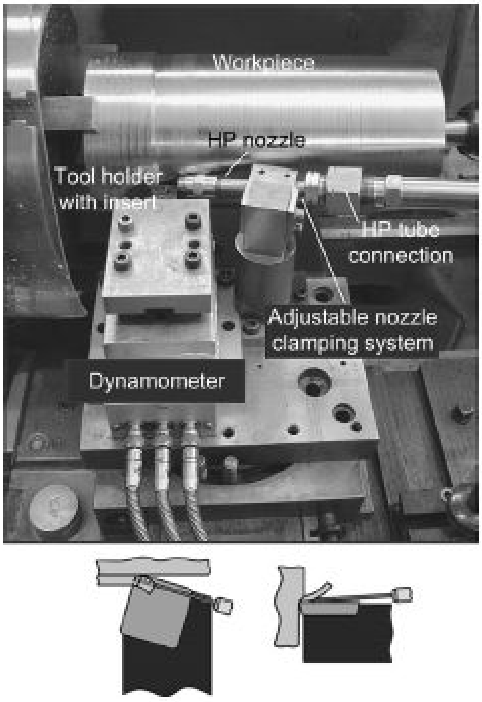

Figure 7. HPJAM set-up with sketch of CLF jet direction [7].

In order to maximize sustainability performance, the materials that are both in abundant supply and have the potential for recycling/reuse with no significant environmental impact should be used. In machining processes saving money and sustainability performance can be improved by reducing energy consumption. Energy is an essential resource for production [64]. For example, about 10% of industrial energy consumption is attributed to the use of compressed air. Another factor is electrical drives. A share energy consumption of approximately 50% may be attributed to electrical drives [45]. Cryogenic machining and HPJAM result in a drastic decrease in overall production costs in comparison to conventional machining, up to 30% [12].

5. CONCLUSIONS

In worldwide, machining continues to be used as one of the most important material removal methods in manufacturing. This paper presents an overview on recent trends and new concepts that are emerging for evaluating the sustainability contents at the product, process and system levels for enabling sustainable manufacturing.

With the increasing worldwide trends in achieving sustainable machining, dry, NDM/MQL, cryogenic machining, high pressure jet assisted machining and their options are emerging as viable and more sustainable alternatives to flood cooling in machining processes. It can be concluded from that improved environmental friendliness, reduced cost, reduced energy consumption, reduced waste and more effective waste management, enhanced operational safety and improved personnel health can effectively provide through cryogenic machining. Even though the initial cost and effort involved with cryogenic machining or HPJAM are higher, they can obviously offer significant sustainability benefits through: the first one is shorter production cycles and the lower cost needed to machine a part, the second one is enhanced productivity due to higher output, the third one is potentially lower investment due to reduction in the number of machine-tools required and the last one is improved manufacturing flexibility due to shorter production times and high output.

Based on the results the following can concluded, with regard to HPJAM and cryogenic machining, HPJAM can be the most cost efficient, however cryogenic machining is completely clean and has the highest sustainability potential.

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