8.09 Environmentally friendly Manufacturing Processes in the Context of Transition to Sustainable Production

D Fratila, Technical University of Cluj-Napoca, Cluj-Napoca, Romania

© 2014 Elsevier Ltd. All rights reserved.

8.09.1 Introduction

Sustainability represents a concept related to the continuity of many aspects of society, including economic, social, institutional, and environmental. The concept of sustainable development was released in the 1980s as a reaction to the destructive social and environmental effects of the approach to economic progress. One of the earliest formulations of this concept was based on the following principle: For a development model to be sustainable, it must consider the social and ecological factors as well as the economic ones, the resources, and long-/short-term advantages and disadvantages of alternative solutions (27, 28, 49).

The term sustainable production concerns the creation of products and/or services, using the nonpolluting processes and systems, besides conserving energy and natural resources. Such a development model should be economically viable, safe, and healthful for employees and attractive for consumers and communities (29, 47). Conventional production knowledge has three levels: the idea (the design of new products), CAD (Computer-Aided Design), and CAM (Computer-Aided Manufacturing). As an alternative, sustainable production puts all of these components on the same level, based on the sustainable principles. The main principles consider the following components of manufacturing processes: costs of manufacturing, consumption of energy, waste management, environmental impact, workers’ health, and work safety (16, 20, 33).

In the machine building industry, the companies are currently under increasing pressure presented by competition, environmental regulations, and the supply chain needed for improved environmental performance (23, 30, 46, 47). At metal machining, fluids (several oils and emulsions) are still added as cutting media, causing through their use environmental pollution. In addition to the high costs involved, they are one of the most important health hazards in the workplace (20, 38, 39, 41). The machining industry investigates the new methods in order to increase the process performance and to reduce production costs, in addition to responding to the growing environmental concerns (Figure 1) and to examining appropriate ways to implement the new methods (4, 4).

The fundamental issues may be solved by sustainable product design and manufacturing. The sustainability of a product and/or production can be achieved with improvements on all levels: the economy design (the real market demand correlated with the costs and the quality), and the resources utilization, by means of the balance improvement between the incoming and the outgoing raw materials in the production stage, which basically represents waste (20, 24, 47, 48).

Companies have the potential to save costs and to improve their environmental performance even if production remains the same size or if it is decreased. This is possible with implementation of the sustainability rules in the manufacturing processes (7, 12, 16) as presented in Figure 2.

8.09.2 Sustainable Technologies

Related to the production technologies are several ways to improve sustainability performance. The most important of these technologies concerns reduction of the process energy consumption, minimization of waste production through generation of less waste, and increasing recycling and reusability, high efficient usage of natural resources (materials, water, energy), usage of recyclable materials or reusability rate of product and machine-tool components, improvement of management for metal-working fluids, chips, and lubricating/hydraulic oils. The other ways are related to improved environmental, health, and safety performance, adoption of
sustainable engineering methods, training the employees about the sustainable practices, improved working conditions, and implementation of life-cycle assessment methods (14,16,17,22,25).

Taking into account the idea that the rational use of natural resources (especially of nonrenewable resources) is a key aspect of sustainability, the main resources to be considered in production technologies are materials (metals) used in the machining processes, tools, cooling/lubricating fluids, lubrication/hydraulic oils, water, and energy.

Consumption of cooling lubricating fluids (CLFs) and cleaning emulsions (CEs) is one of the critical issues related to the environmental impact of machining processes (4,7,23,33). Machining applications in the industrial area utilize conventional CLFs such as oils and aqueous emulsions in order to reduce the heat generated in the cutting zone, even though they are relatively costly, environmentally unfriendly, and hazardous to health. The pressure of the environmental regulations has led to a critical consideration of conventional cooling lubricants usage in the machining processes. The studies carried out on this issue showed that the manufacturing costs related to the cutting fluids are in a range from 10–17% of total costs and that the tooling costs can account for approximately 2–4% (13,19,20,44).
The overall part production process consists of several elements and steps: process inputs (material, energy, data), machining, cooling/lubrication, part cleaning, preparation of chips to be disposed, and their interactions, as shown in Figure 3. Compared to conventional cooling methods, environmentally friendly techniques have some potential benefits (Figure 4), including:

- Sustainability through the lower flow rates of CLF or through use of alternative methods, providing better cooling and lubrication mechanisms;
- Decrease of the cutting tool–chip contact length, resulting in lower cutting forces and lower tool wear;
- Extension of the operational range of machining parameters, resulting in increased process productivity.

Usage of CLF can be reduced in several ways. The questions that occur are what kind of CLFs and how much of each have to be used in the manufacturing processes and their costs. In the case of conventional CLFs, their purchase costs have to be increased, taking into account CLF disposal costs, parts cleaning and drying, depreciation costs, maintenance costs, and costs connected with personnel and health issues. On the other hand, the fluid that adheres to the chips creates problems with their recycling, because the chips have to go through waste processing, which must include the cleaning, separation, and drying steps. Additionally, other losses of CLF always take place in the machining process through vaporization, loss with parts, loss related to the handling devices, as well through leakage.

It therefore becomes obvious that technologies employing CLFs are unsustainable. Thus, a huge process gain from the sustainability point of view is possible by avoiding CLFs usage through applying alternative technologies. The main issue for the sustainable machining process is to analyze the process and to understand how the cooling and lubricating mechanisms influence the process results.

8.09.2.1 CLFs in the Machining Process

Basically, the employment of cutting fluid during machining ensures tool longevity and a significant improvement in the surface quality of the workpiece. According to the desired final results, the coolants and lubricants are applied in the form of flood, as mist, or not at all in the case of dry cutting.

The mist of cutting fluids has high aerosol concentrations and can remain in a working environment for a long time since it is easily inhaled. The process parameters (depth of cut, feed, and speed) are significant factors in the formation of both metal dust and fluid mist. The mist/dust concentration increases with increasing level of the above-mentioned parameters, the greatest values being recorded at the highest material removal rate.

![Figure 3](image_url)  
**Figure 3** Overall machining process of a part.
CLFs are harmful not only to the worker’s health, but also to the environment. For this reason additional costs are needed for processing the waste before their disposal. In practice, it is not always possible to cut fluid usage by simply turning off the cooling/lubricating supply \((11,12,18,22)\). The reason lies in cutting fluid tasks such as reduction of the temperature in the cutting zone, reduction of the friction and the transport/evacuation of the chips, and cleaning of tools, workpieces, and fixtures. In the case of the cutting fluid absence, these tasks have to be taken over by other components in the machining process \((7,26,42)\).

In the cutting processes, the CLFs used are generally emulsions (oil–water mixtures) or oils, depending on the manufacturing operation, machining tasks, process parameters, cutting tool materials, and workpiece materials \((8,9)\). Both oil and water assure efficient chip transportation and evacuation. Oils are commonly used when the degree of lubrication needed is high in order to reduce the friction and the adhesion between the chip-tool and the tool-workpiece interface, while emulsions are most often used when a high degree of cooling is necessary because of their great heat transfer properties, this choice being used when the cooling is needed for improving process efficiency \((10,34–37)\).

Even if usage of pure compressed air as cooling/lubricating fluid is considered a clean machining process, most benefits of conventional fluids in machining are reduced with employment of compressed air. The main reasons for different characteristics of the cutting media are the thermal capacity and flow rate. A comparison of the effects of three different fluids usage in machining is presented in Table 1.

### 8.09.2.2 Dry Machining and Near-Dry Machining

The process carried out in the absence of CLFs is called dry machining (DM), or near-dry machining (NDM) when the process runs in the presence of a very small quantity of lubricants, in the range of \(10–150 \text{ mL h}^{-1}\), delivered in the cutting zone in a mist way. Thus, the use of NDM (called also minimal quantity lubrication or MQL) can lead to a significant cost reduction for the process.

By simply avoiding CLF usage and applying the DM alternative, using in addition new high-performance coated cutting tools, a huge progress for sustainable technologies would be possible \((1)\). A complicating factor is the use of new workpiece materials, especially in the aerospace industry (such as nickel alloys, titanium alloys, and Co–Cr alloys), which are extremely difficult to machine. In combination with high cutting speed, serious difficulties will be encountered, thus disabling the use of DM. The tasks of

<table>
<thead>
<tr>
<th>Machining medium</th>
<th>Cooling effect</th>
<th>Lubrication effect</th>
<th>Chip transport/removal effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion</td>
<td>Excellent</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Oil</td>
<td>Good</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Compressed air</td>
<td>Low</td>
<td>None</td>
<td>Low</td>
</tr>
</tbody>
</table>

Figure 4  Comparison of conventional and environmentally friendly machining processes.
coolants/lubricants, in the case of its absence, have to be taken over by other machining process components. In this respect, the latest technique concerns demonstrating the application of modified tools for DM use (2). A solid lubricant (molybdenum disulfide) was filled into the microholes on the rake and rake and flank face of the cemented carbide (WC/Co) tools in order to create self-lubricated tools. Using such a tool, the cutting forces, the tool wear, and the friction coefficient at the tool-chip interface are significantly lower during DM of hardened steel, compared with the use of a conventional WC/Co tools. This effect is caused by the self-lubrication action of the modified tool.

For both economically and technologically optimal results, the NDM must be considered as a system with the following components: CLF feed technology, NDM media, parameter settings, tools and machine tools. The principle of this technique is schematically presented in Figure 5.

In NDM the most commonly used media are synthetic esters and fatty alcohols, but some applications are still using emulsions or water. Such high-performance oils have excellent lubricity and biodegradability properties (Table 2), and they are environmentally friendly (41,44).

These fluid media are fed in very small quantities (usually 10–20 ml h⁻¹) to the machining area with or without the assistance of a transport medium. In the case of airless systems, a pump delivers the CLF in the form of a rapid succession of precision-metered droplets. In the case of high-pressure systems, the medium is atomized to form extremely fine droplets delivered to the machining point in the form of an aerosol spray using compressed air at 4–6 bar pressure. The CLF delivery system can be an external or internal supply device. The external equipment can have one or more nozzles fitted separately in the cutting area. Number, direction, and emplacement of nozzles play an important role in the quality of the process results. The internal system supplies the media through the channels built into the tool body.

A distinction should be made between MQL and MQC (minimal quantity cooling), depending on the type and main functions of CLF used. When good lubrication properties are needed, then oils are used as cutting fluids, their function being to reduce friction and adhesion between workpiece, chips, and tool and thus the amount of friction heat generated. This is regarded as the MQL.

---

**Figure 5** Near-dry machining principle.

**Table 2** MQL fluids characteristics

<table>
<thead>
<tr>
<th>Synthetic esters (chemically modified vegetable oils)</th>
<th>Fatty alcohols (alcohols made from natural raw materials or from mineral oils)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Toxicologically harmless</td>
<td>• Poor lubrication properties</td>
</tr>
<tr>
<td>• Low level of hazard</td>
<td>• Better heat removal due to evaporation heat</td>
</tr>
<tr>
<td>• Good biodegradability</td>
<td>• Little residuals</td>
</tr>
<tr>
<td>• Very good lubrication properties</td>
<td>• Low flash and boiling point, comparatively high viscosity</td>
</tr>
<tr>
<td>• Good corrosion resistance</td>
<td></td>
</tr>
<tr>
<td>• Inferior cooling properties</td>
<td></td>
</tr>
<tr>
<td>• Vaporizes with residuals</td>
<td></td>
</tr>
<tr>
<td>• High flash and boiling point with low viscosity</td>
<td></td>
</tr>
</tbody>
</table>

Source: Fuchs Petrolub AG.
Table 3  DM and MQL application areas

<table>
<thead>
<tr>
<th>Material process</th>
<th>Aluminum</th>
<th>Steel</th>
<th>Cast iron</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cast alloys</td>
<td>Wrought alloys</td>
<td>High alloyed bearing steel</td>
</tr>
<tr>
<td>Drilling</td>
<td>MQL</td>
<td>MQL</td>
<td>MQL</td>
</tr>
<tr>
<td>Reaming</td>
<td>MQL</td>
<td>MQL</td>
<td>MQL</td>
</tr>
<tr>
<td>Taping</td>
<td>MQL</td>
<td>MQL</td>
<td>MQL</td>
</tr>
<tr>
<td>Thread forming</td>
<td>MQL</td>
<td>MQL</td>
<td>MQL</td>
</tr>
<tr>
<td>Deep hole drilling</td>
<td>MQL</td>
<td>MQL</td>
<td>–</td>
</tr>
<tr>
<td>Milling</td>
<td>MQL</td>
<td>MQL</td>
<td>DM</td>
</tr>
<tr>
<td>Turning</td>
<td>MQL, DM</td>
<td>MQL, DM</td>
<td>DM</td>
</tr>
<tr>
<td>Gear milling</td>
<td>–</td>
<td>–</td>
<td>MQL</td>
</tr>
<tr>
<td>Sawing</td>
<td>MQL</td>
<td>MQL</td>
<td>MQL</td>
</tr>
<tr>
<td>Broaching</td>
<td>–</td>
<td>–</td>
<td>MQL</td>
</tr>
<tr>
<td>Grinding</td>
<td>–</td>
<td>–</td>
<td>MQL</td>
</tr>
</tbody>
</table>

strategy. When it is essential to cool the tool or the part more efficiently, emulsions and water are used much less frequently than oils. These operations are regarded as MQC (44).

There are several application areas for DM and MQL. They involve a wide range of material–process combinations, as presented in Table 3.

The processes associated with interrupted cuts ensure short breaking chips, a cooling of cutting edges, and good chip transportation. The turning operations are also suited for a CLF reduction, due to the good accessibility to the cutting zone. Other processes with geometrically defined cutting edges (drilling, tapping, reaming) are hard to accomplish without at least a small quantity of lubricant. In these cases, high process heat may be generated, and the chip removal is difficult. Even though the DM and MQL are very difficult to apply in the machining processes with geometrically undefined cutting edge because of high energy density and the high-quality demands concerning the parts quality, some promising results have been obtained for the grinding process.

The CLF avoidance requires alternative solutions that can be achieved through appropriate design of machine tools. The primary functions of the cooling lubricants from the flood cooling process should be overtaken from other system components or solved by other technical solutions. In order to be suitable for DM, the constructional changes of the existing equipment may require a lot of effort and high costs. When the machine tool rebuilding is not economically feasible, then the application of the MQL supply system and the housing of the working area are reasonable and necessary changes (21,44). For the newly developed machine tools, the possibility of making substantial design modifications is easier, since requirements are known from the beginning. There is not only a single practical solution concerning the boundary conditions, since the manufacturing equipment is so different (individual machine tools, transfer lines, machining centers, etc.). In mass production and flexible manufacturing systems, the demands concerning the changes of manufacturing structures can be divided into several categories: chip removal from the working area, temperature compensation, MQL system integration, and safety measures (43,44).

With the increasing trends in achieving sustainable machining, DM and NDM are emerging as viable and sustainable alternatives to flood cooling in the machining processes. Even NDM is slowly being accepted as an alternative to flood cooling and provides up to 80% longer tool life. Further studies are needed to find the best design of external nozzles and get the right amount of fluid to the cutting point.

The use of these two machining methods could result in increased efficiency, due to lubricant elimination in the form of conditioned waste, process chain optimization, and improvement of the work environment. The procedure is strongly dependent on the concrete process characteristics and the material properties of the workpieces and tools.

8.09.2.3 Cryogenic Machining

Another innovative method of cooling the cutting area (cutting tool and/or workpiece) during the cutting process is cryogenic machining (CM). This is a very effective machining technique that utilizes a cryogenic CLF as a coolant to bring down the temperature at the chip-tool interface, reducing the tool wear or changing the characteristics of material and thus improving machining performance and product quality (2,15). Researchers have attempted four cryogenic approaches: workpiece precooling, indirect cryogenic cooling, cryogenic jet spraying, and direct cryogenic treatment of cutting tools.

It is not usual to employ the air as coolant since all gases have relatively poor cooling properties compared with liquids. Better cooling performances have been achieved by refrigerating the gases; high pressure of gases has been considered an additional help. In the case of CM, the coolant used is a safe, noncombustible, and noncorrosive gas (nitrogen), liquefied by cooling to −196 °C.

The basic principle of this process and that of the liquid nitrogen (LN) production process are schematically presented in Figure 6. LN returns to the atmosphere by evaporating quickly in the CM system; it leaves no residue to contaminate the parts, chips, machine tool and operator. Thus the coolant disposal costs are eliminated.
CM can be successfully used in the machining of difficult-to-machine materials, hard materials, high-abrasive materials, or superalloys. The method, first introduced in industry in 2003, was specially developed for turning and some milling applications. Today, it is implemented for high-speed machining for hard and superalloys in aerospace and automobile industries. The tool manufacturers produce new machine tools that utilize CM technology.

Other improvements consist of a faster machining process, higher parts quality, better machining performance, and overall cost reduction. In summary, some advantages of CM are reduced chip-tool interface temperature, reduced tool wear, higher production rates, greater product quality, power saving, no mist collection, no filtration, no wet chips, and no contaminated workpiece or disposal costs. The main disadvantages of this technique are the additional equipment costs and the high price of LN, which is not reusable.

This technique can be considered a sustainable machining, being a clean, safe, and environmentally friendly method. It allows increasing process productivity by a higher material removal rate without an increase in tool wear and with reduced cutting tool changeover costs.

8.09.2.4 High-Pressure Jet-Assisted Machining

Even the trend in machining is the large-scale implementation of DM and NDM (combined with the most advanced tool materials and coatings) in order to reduce the consumption of cutting fluids; there are cases when the lubricants cannot be completely avoided. One of the techniques developed to replace the conventional process, keeping or even increasing the machining performance, is high-pressure jet assisted machining (HPJAM).

HPJAM is another innovative method of lubricating/cooling the tool-chip interface during the cutting process, using the thermal and mechanical properties of a high-pressure jet of water or emulsion directed into the cutting zone. This technique is related to delivering the oil-based or water-based CLF under extremely high pressure in the range 80–360 MPa to the cutting tool tip through small-diameter nozzles (0.15–0.25 mm). The basic principle of HPJAM is shown in Figure 7.

Compared to conventional flood, the CLF flow rate is, in this case, relatively small. Due to their higher flexibility, external nozzles are widely utilized compared to internal channels. Having a high pressure, the CLF jet can penetrate closer to the shear zone and cool it. The fluid jet is directed to the cutting edge at a low angle directly in between the rake face and the chip.
Besides the cooling effect, this method allows control of friction conditions between the tool rake face and the chip backside, leading to an improved machining performance. The initial goal of HPJAM was a substantial increase of removal rate and productivity in the machining of advanced materials, such as hardened steels used for molds, Cr–Co alloys used for prostheses, and Ti-based and Ni-based alloys used in gas turbines and in the aerospace industry.

Some of the method’s disadvantages include higher initial capital investment for equipment and the fact that the oil-based CLFs are still used. The machine tool should be fitted with high-pressure equipment. The system components involve a high-pressure pump supplied with filtered water or emulsion, high-pressure pipes or tubes, a nozzle fixed beside a tool holder clamped with adjustable system, and a filtering system.

By implementing this method in the practice, the relatively larger energy consumption (which is compensated for by higher removal rates and longer tool life), the noise, and emulsion aerosols have to be considered.

With regard to the potential benefits of HPJAM, they refer to the sustainability through lower flow rate of CLF in comparison to conventional machining and the lower cutting forces and longer tool life. This technique allows an extension of the operational area up to a 35% increase in both the maximum achievable feed rate and the cutting speed. Other advantages are the significant improvement of chips’ breakability and the increased process productivity by the extension of the machining parameters’ operational ranges. Unfortunately, a technological gap remains concerning the poor investigations of the relationships between the HPJAM process parameters (that act and interact in a complex manner) and the machining performance responses.

**8.09.3 Evaluation of Technologies’ Sustainability**

The most important alternatives to conventional machining (characterized by flood lubrication and cooling) have been briefly presented in Section 8.09.2. Although these new techniques (NDM, HPJAM, CM) offer low costs and reduce or avoid the environmentally hazardous CLF usage, their performance from the sustainability point of view should be analyzed in order to assess if and where they are applicable. The relative environmental emissions and the quantitative and qualitative assessment of environmental impacts have to be evaluated. Therefore, a balance should be sought between their advantages and disadvantages in comparison to conventional methods.

Concerning the application of sustainability principles and measures in the field of machining processes and the assessment of the relative sustainability level, some criteria have to be established. Usually, the process evaluation and comparison criteria concern the following aspects:

- machined part quality and integrity;
- machining process costs;
- consumption of resources and energy;
- environmental performance;
- health and safety performance;
- waste production and waste disposal costs.

With regard to the overall machining cost rate, the main differences are caused by the higher initial cost in the case of alternative methods, due to the additional equipment needed for the CLF delivery systems. A machine tool equipped for DM, MQL, CM, or HPJAM, including installation, tooling, maintenance, materials, and labor, increases the usage cost rates.
Usage of the CLFs is one of the most fundamental concerns when considering machining environmental issues, having a direct ecological influence. CLFs must be analyzed in terms of ecological and economical performance. There are also losses of CLFs from the machining system, beside their usage. Additionally, there are the disposal costs of conventional CLFs, when they reach their lifetime and they have to be treated/recycled/disposed.

Another way to improve process sustainability performance is through reduction of energy consumption. This is included in the overall machining cost by the electrical energy consumption when the process is being carried out and when the machining is in standby. The electric energy consumption arising from control of the CLF's delivery devices is small, and it can be discounted.

Waste management is another important sustainability measure that has to be considered. In the case of machining processes, the waste products are connected with CLFs, worn-out cutting tools, and chips. When the alternative environmentally friendly machining techniques are compared with conventional machining, the only variable that needs to be evaluated is CLF usage. The mass of chips is the same for all machining methods, but the main approach to increasing the chips' sustainability value is to minimize their contamination with CLFs and to compact them for easy transportation. The cleaning, centrifugal separation, and drying of chips represent additional costly processes. Moreover, in the case of conventional machining, the costs are increased by the separation process of CLFs water and oil phases, before their disposal.

8.09.4 Ecodesign Focused on Life-Cycle Assessment (LCA)

8.09.4.1 LCA Thinking

The products’ consumption and their production processes are the cause of most of the pollution and resource depletion. To achieve successful implementation of the sustainable business models, it is necessary to promote a change in the economic values by the life-cycle thinking and to consider the raw materials scarcity, the environment’s limitation to assimilate wastes and emissions, and the growing consumption needs (14,27).

As an instrument of sustainable development, sustainable design conceives of products, processes, and services that meet society's needs while striking a balance between economic and environmental interests (24,49). In order to evaluate the environmental consequences of a system, process, or product, it is necessary to consider the impact of each stage of its life cycle. Practically there are some concepts to consider, when discussing sustainability and the ways to achieve it, based on understanding the entire life cycle, from raw materials to final disposition.

Implementation of life-cycle thinking is associated with the efforts related to increasing efficiency through the product, process, or service life cycle (14,25,27). Life-cycle thinking consists of the integration of life-cycle perspectives into the overall strategy, planning, and decision-making process of a company, considering economical, social, and ecological aspects.

While the traditional manufacturing systems focus on obtaining profits by selling to the final customers as many products as possible, the present paradigm implies considering life-cycle aspects of products and their optimization through engineering, assembly, service, maintenance, disassembly, and disposal.

Figure 8 presents a typical material product life cycle and shows some alternative at the end-of-life phase. The main flow has many phases: raw material extraction, primary processing, manufacturing, assembly, transport and distribution, usage, and scenario for product disposal at the end of the life cycle.

The end-of-life strategies describe the approach or treatment method employed when recovering value from products, including the activities associated not only with planning and implementation of the collection and processing of used products, but also with the possible impacts to society and the environment (48). There are three main end-of-life disposal strategies related to the secondary flows: reuse, recycling, and remanufacturing (both of the products and their components) (27).

The reuse process consists of collecting used materials, products, or products’ components and distributing or selling them in this state as used. Thus, the identity and functionality of the original product are retained. Reuse of products could be an ideal solution for the product end-of-life approach in order to minimize the environmental impact, but it cannot be considered a primary strategy because it does not consider user needs or product quality.

Recycling is the process of collecting used products, products’ parts, or materials to disassemble, separating them into categories, and then processing them as recycled products, components, or/and materials (27). Being focused on material recovery, recycling should only be considered when all alternatives are found to be economically nonviable. The processing of materials (both from manufacturing process residues and from processes used in customer products) often alters their basic properties such as material resistance, density, and elasticity. The quality of the resulting materials is determined by achieving the recycling process with or without prior disassembly. These imply the use of recycled materials for less important purposes after being processed. The cost of disassembly can increase the cost of recovered products and materials, so that such products end up by mechanical material separation. The disassembly process of products previous to end-of-life alternative destinations can lead to an increase in the recovered materials' purity, a safe disposal of hazardous wastes, and recovery of subassemblies for reuse or remanufacturing. Recycling helps to reduce pollution, extend the landfill's usefulness, and conserve natural resources, but it cannot be a company's main disposal strategy.

While recycling implies material recovery without conserving any production structure, remanufacturing conserves the product identity by bringing it back into a condition through carrying out the necessary disassembly, check, and replacement operations. Among all possible end-of-life scenarios, the remanufacturing process currently faces an increasing importance and recognition. The remanufacturing strategy reduces the use of raw materials and energy consumption necessary to fabricate new products, and at the
same time it preserves the product value gained during the design and manufacturing processes. Through remanufacturing, the products' components are resorted and reconditioned in order to rebuild them according to their original design. Thus, the product runs in several stages, until it meets the standard of a new one.

The process is divided into many steps: disassembly, testing, repairing, cleaning, component inspection, updating, parts replacements, and reassembly (14). Successful implementation of remanufacturable products requires that they have been previously designed for this purpose. That means the products should be easily disassembled, cleaned, controlled, replaced, and reassembled; they should also be wear resistant.

8.09.4.2 LCA of Machining Processes

LCA of alternative machining processes should be focused on the production and delivery of CLF into the cutting zone, while the machining process performance can be assumed to be the same (29,33,38). Looking at the machining technology schemes (Figure 9, Figure 10, Figure 11, Figure 12), it could be observed that CLFs are still used in the conventional as well as HPJAM and vegetable oils to NDM.

In CM, the lubricating and cooling effects are provided by liquid-phase nitrogen. This is stable, while the oil-based cutting fluids are not, or they need additives for stabilization. But LN production is an energy-intensive process that can be directed toward sustainable production by powering the cooler in LN production with renewably generated electricity.

The cost and emissions generated may be reduced by additional sale of the liquid oxygen that is a by-product of the liquefaction process. This LN production method can lead to clean process production in comparison with conventional CLF production. These usually contain water, oil, surfactants, and about 10 other specific additives.

Besides the CLF composition and the environmental impact of CLF production, information needed is CLF usage amounts (consumption rate for a considered period of time). A major difference exists between oil-based flood systems (conventional and HPJAM), NDM, and cryogenic-based systems.

![Conventional Machining Diagram](image1)


![Cryogenic Machining Diagram](image2)


![Near-Dry Machining Diagram](image3)
The conventional cooling systems recirculate CLFs, and NDM completely consumes the cutting fluids, while the cryogenic fluid is delivered once due to nitrogen evaporation after delivery. In this case, consumption is determined by the nozzle mass flow rate. In flooding systems, the consumption rate is determined by CLF volume at the machine tool and disposal time interval.

In contrast with oil-based CLF usage systems, in the case of CM the only energy need is that for CLF production and process cooling water.

In addition to the machining process, the CLFs have to be delivered to the cutting area (by a pump or by pressure) from a reservoir attached to the machine tool. The production of CLF delivery equipment (compressors, tanks, reservoirs, pumps, devices) can be neglected since their impacts are small compared with the use stage and their long working life.

8.09.5 Conclusions

Whereas in the past the manufacturing industry played a minor role, drawing on a large quantity of resources and contributing with a relatively small amount of waste, nowadays, due to its rapid growth, it has a major effect on the environment.

At present, many manufacturing processes and products are produced by applying modern cutting tools and coatings, adapting tools design, and manufacturing strategies. By renouncing conventional cooling lubricants and using the new innovative machining methods, the companies can improve the efficiency of their production process and work conditions, and at the same time improve their image in the market. But practically the implementation of these processes also involves construction or adaption of machine tools and their peripheral equipment.

In recent years, the response of industry to environmental issues has been engagement in order to reduce the ecological impact of manufacturing processes. This is being achieved through development of alternative improved processes such as dry cutting, NDM, CM, and high-pressure jet-assisted machining.

Their successful implementation in the factories will result in considerable environmental and economical advantages, even if the application of all these new methods in high-volume and large-scale industry still requires special solutions. It is expected that the increasing number of industrial applications and the research activities in the field will ultimately lead to the expansion of these modern environmentally friendly technologies to small and medium-sized manufacturers.

The fundamental compromises as regards the environmental impacts, in terms of using alternative methods instead of conventional manufacturing processes, demonstrates that the transition to more sustainable processing technologies could lead to benefits such as reduced environmental pollution.

See also: Assessment of Impacts to Health, Safety, and Environment in the Context of Materials Processing and Related Public Policy; Health and Safety in Today’s Manufacturing Industry; Economic Implications of Impact of Manufacturing on Environment and Health.

References
