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Sustainable Cooling and Lubrication Strategies in Machining Processes: A Comparative Study

H. Hegab [a,*], H A. Kishawy[a], B. Darras[b]

[a]Machining Research Laboratory, UOIT, Oshawa, L1H7K4, Canada

[b]Department of Mechanical Engineering, American University of Sharjah, Sharjah, 26666, UAE

*Hussien.Hegab@uoit.net

Abstract

Applying an adequate cooling and lubrication technique during machining processes is an important issue which affects the machining system efficiency. Flood cooling offers an effective solution to reduce the effect of the high heat generated during cutting processes; however, it is not a sustainable strategy because of the health and environmental concerns associated with its utilization. Therefore, several cooling and lubrication strategies have been suggested and used as alternatives to the flood cooling. These strategies include; dry cutting, cryogenic approach, minimum quantity lubrication (MQL), nano-cutting fluids, and MQL-nano-fluids. In this work, a comparative study is presented to evaluate the sustainability effectiveness of these strategies. In order to evaluate the strategies effectiveness, five sustainability indicators are used; namely, energy consumption, personal safety and health, waste management, machining costs, and environmental impact. A weighted decision matrix is developed to assess the studied strategies in terms of the employed sustainable indicators.

Keywords: Sustainability; Machining; Dry-Cutting; Cryogenic; Nano-Fluids; Minimum Quantity Lubrication.

1. Introduction

It is a well-acknowledged fact that major environmental concerns have arisen because of the pollution and consumption of natural resources. Thus, the implementation of sustainable systems is an essential requirement in modern manufacturing to address these concerns and present effective solutions. The central aims of sustainability are focused on the environmental, economic, and social directions in order to achieve better requirements through effective utilizing of the available resources [1, 2]. The concept of sustainable manufacturing can be identified and analyzed through three main levels which are product, process, and system levels. The interaction between the three levels provides the required sustainable target. In regards to the product level, the perspective of sustainable manufacturing focuses on the new 6R approach (i.e., reduce, reuse, recover, redesign, remanufacture, recycle)

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instead of the 3R approach (i.e. reduce, reuse, recycle) of green manufacturing, as it theoretically achieves a closed loop and multiple life-cycle paradigms [3-5]. At the process level, reducing energy consumption, hazards, and toxic wastes can be accomplished through using an optimized technological process associated with an effective process planning methodology, while using an efficient supply chain system considering all life-cycle stages (i.e. pre-manufacturing, manufacturing, use and post-use) can provide a promising sustainable system level [3, 6, 7].

Providing environmentally friendly conditions and optimizing the energy consumption are two essential requirements in order to achieve sustainable machining processes. One of the major sustainable machining concerns is the implementation of cutting fluids due to its significant impact on the machining quality characteristics. In addition, several economic, environmental, and health problems are taken place due to the inappropriate application of cutting fluids; therefore, several studies have already been published in the open literature to introduce advanced cutting fluids techniques in order to optimize the cutting fluids performance during machining. The flood cooling usage revealed critical environmental problems so other alternatives are necessarily required to replace its function. Presenting new strategies is required to enhance the machining performance and accomplish a sustainable environment. Several technologies have been presented for example; dry cutting, minimum quantity lubrication (MQL), and cryogenic technology.

It can be concluded from several environmental and health concerns associated with production that the main source of environmental issues of machining processes is related to the application of cutting fluids. Also, it has been reported in the open literature that the risk of various types of cancer such as prostate and colon can be observed, especially for those whom are exposed to cutting fluids in the automotive sector. The main reasons behind these risks are airborne particles of cutting fluid and the cutting fluid aerosols effects. Thus, more studies have focused on eliminating the cutting fluids usage (e.g. dry machining), and others are focused on optimizing the use of cutting fluids to achieve environmentally-friendly cutting fluids (e.g. minimum quantity lubrication) [8, 23, 32-35].

Reducing the usage of cutting fluids has accomplished using dry cutting techniques; however, dry cutting is associated with insufficient wear behavior and poor surface roughness [8]. Another technology is MQL where the resulting mist is sprayed directly into the cutting zone with an optimal amount of oil with compressed air [9, 10]. Despite the MQL advantages, the excessive heat generation problem has not been completely solved. It should be stated that MQL technique with vegetable oil offers the best environmental solution in terms of energy consumption and environmental concerns as it provides the optimum amount of lubricant through a system consists of an air compressor, gas-based coolant lubricants (CLs) container, tunings, flow control system and spray nozzles [36-40]. Proposing new nano-cutting fluids showed a significant improvement in decreasing the severity of the induced tool wear, and it is mainly attributed to the significant enhancement in the heat transfer performance upon dispersing the nano-additives into the base oil. Also, nano-cutting fluids have superior cooling properties because of their promising heat extraction capabilities [11, 12]. Also, the MQL-nano-cutting fluid has been used to improve the MQL performance mainly when machining difficult-to-cut materials. MQL-nano-fluid technique has two main advantages; (a) improve the thermal and friction behavior, and (b) accomplish a sustainable process as using MQL approach provides effective environmental benefits [13, 14].

In this work, a comparative study is presented to evaluate the sustainability effectiveness of five cooling and lubrication strategies (i.e., cryogenic approach, minimum quantity lubrication (MQL), nano-cutting fluids, and MQL-nano-fluids). In order to evaluate the strategies effectiveness, five sustainability indicators [15] are used; namely, power consumption, personal safety and health, waste management, machining costs, and environmental impact.

2. Assessment Methodology

As mentioned earlier, five sustainability indicators are used to evaluate the studied cooling and lubrication strategies. A weighted decision matrix is used to evaluate each strategy. A schematic of the used decision matrix is provided as shown in Table 1. It should be stated that equally-weighted factors are assumed for all indicators throughout this study. In this work, each strategy is discussed and then evaluated for each indicator. The effectiveness is measured by three-levels in this work; high-level (3 points), medium-level (2 points), and low-level (1 point). The second step is to determine the total points score for each strategy based on the previous evaluation of all indicators. Finally, the studied strategies are ranked based on their effectiveness score (i.e. higher-the-better).

Table 1. A schematic of the used decision matrix for evaluating the studied cooling and lubrication techniques

		Cooling and Lubrication Strategies				
		Dry Cutting	Cryogenic Approach	MQL	Nano-Fluids	MQL-Nano-Fluid
Sustainable Indicators	Energy Consumption	———	———	———	———	———
	Personal Health and Safety	———			———	
	Waste Management	———				
	Machining Costs		———			
	Environmental Impact					
Total Points						

Furthermore, it should be stated that this work presents a first attempt (i.e., comparative study) to generally assess the sustainability effectiveness of various cooling and lubrication technologies from different aspects.

3. The Evaluation of Cooling and Lubrication Strategies

3.1. Dry Cutting

Eliminating the cutting fluids usage completely has been presented under using dry cutting techniques, and it results in a reduction of the machining costs and ecological hazards [8, 14]. In spite of the previous advantages, dry cutting has some problems which associated with excessive tool wear and poor surface quality [16]. For example, during end milling of titanium alloy [17], localized flank wear was observed because of the excessive heat generated. It is mainly due to the high power consumption associated with dry machining technqiue beacuse of the excessive heat generated during the cutting process [18, 19]. Also, more expenses are required for introducing better tool materials, coatings or tool geometries to compensate for the effects of the cutting fluids elimination [16]. Based on the previous discussion and current assessment methodology, low-levels of energy consumption and machining costs are considered while using the dry cutting technique. Regarding the personal and health safety, waste management, and environmental impact, high-effectiveness-levels are considered. This is mainly due to eliminating the cutting fluids usage (i.e. less enivromental and health issues). Moreover, it has been reported in the open literature that the risk of various types of cancer such as prostate and colon can be observed, especially for those whom are exposed to cutting fluids in the automotive sector. The main reasons behind these risks are airborne particles of cutting fluid and the cutting fluid aerosols effects. Thus, dry cutting represents an environment-friendly cooling and lubrication strategy during machining processes.

3.2. Cryogenic Approach

The cryogenic cutting is mainly based on reducing the cutting zone temperature using a super cold medium with liquefied gasses (i.e., lower than 120ºK) into the cutting zone [16]. As a result of lowering the temperature, an increase of strength and hardness for workpiece or tool can be noticed. Also, applying the cryogenic technique showed a significant reduction in the chip-tool interface temperature, chemical reactivity, and diffusion wear [20-22]. However, the cryogenic cutting improves the cutting processes performance in terms of reducing the process power consumption, it associates with heavy installation and equipment. Thus, the medium-effectiveness level is considered for the energy consumption element. Since the cryogenic cutting enhances the cutting processes performance, fewer expenses are required for cutting tools. However, the high-intial cost is required because of the heavy installation and equipment associated with the cryogenic cutting. Thus, similarly to the energy consumption element, a medium-effectiveness level is considered for the machining cost. Usage of non-hazardous gasses (e.g., nitrogen, helium) provides an environmentally sustainable system [23, 24] ;however, usage of liquid carbon dioxide could reduce the workplace safety as it could cause oxygen deficiency problems because of CO_2 accumulation. Thus, a medium-effectiveness level is considered for the personal and health safety, waste management, and environmental impact elements.

3.3. Minimum Quantity Lubrication (MQL)

When applying the MQL technique, an induced mist is sprayed into the cutting zone using an optimal amount of cutting fluid with compressed air. MQL technique has shown a good potential in enhancing the machining processes performance; for example, a cutting forces reduction has been observed during machining AISI 1045 in comparison with the dry cutting [16]. However, the excessive heat generation problem hasn't been completely solved under using MQL approach. In addition, MQL has limitations in machining of difficult-to-machine materials such as titanium and composite materials where excessive heat generation exists. The reason behind that is the insufficient cooling capability of MQL system as it is considered as a lubricating method rather than cooling [16;]. Based on the above points, a medium-effectiveness level is considered for energy consumption under-employing MQL. Regarding the machining cost element, MQL utilizes an optimal amount of cutting fluid; however, other expenses are required to accommodate the problems associated with the excessive heat generation (e.g., short tool life). Consequently, a medium-effectiveness level is considered for the machining cost elements. It should be stated that MQL is an environment-friend approach since it applies an optimal amount of cutting oils which decreases several environmental and health problems associated with machining operations. However, the resultant mist still has a slight effect on the environmental impact element, especially when using toxic cutting fluids. Thus, a medium-effectiveness level is considered for personal health and safety, and environmental impact elements, while a high-effectiveness level is assigned to the waste management element.

3.4. Nano-Cutting Fluids

The Nano-cutting fluids have shown promising results in enhancing the base fluid characteristics. Such improvements are mainly focused on the thermal, tribological, and rheological properties. The nano-cutting fluids have revealed promising results in terms of machining quality characteristics improvements such as reducing the generated cutting forces, improving the friction behavior and tool wear, and decreasing the induced cutting temperature [25]. Despite the previous improvements, a number of challenges [26] still face its implementation; for example, the long-term stability for nano-fluid dispersion, difficulties associated with the turbulent flow cases, the high cost of nano-fluids, and challenges associated with the nano-fluids/nano-additives production process. However, the nano-fluid application reduced the consumed energy during machining processes, the nano-fluid preparation (i.e., dispersion step) still requires high-energy. Thus, a medium-effectiveness level is considered for the energy consumption element. As previously mentioned, one of the challenges facing the nano-fluid implementation is the high processing cost (e.g., nano-additives, dispersion, characterization, chemical agents, disposal). Consequently, a low-effectiveness level is considered for the machining cost element. Also, it should be stated that the nano-fluids usage under flood cooling is an environmental concern because of the harmful effects of the used nano-additives and their disposal techniques. During the experimentation with applying nano-cutting fluids, specific safety procedures [27] should be used to achieve a standard health and safety level in the workplace to prevent any harmful impacts for the machine operator. Regarding the disposal method, the nano-fluids should be carefully filtered before being released to the sewer according to a standard material safety data sheet as similarly discussed in a previous work [28]. Based on the previous consideration when using nano-cutting fluids, a low-effectiveness level is considered for personal health and safety, waste management, and environmental impact elements.

3.5. MQL-Nano-Cutting Fluids

One of the best techniques to enhance MQL heat capacity is the application of nano-cutting fluids as they offer significant enhancement in the tribological and heat transfer characteristics. Also, the MQL-nano-cutting fluid has been used to improve the MQL performance mainly when machining difficult-to-cut materials [29-30]. MQL-nano-fluid technique offers two main advantages; (a) improve the thermal and friction behavior, and (b) accomplish a sustainable process as using MQL approach provides effective environmental benefits. As mentioned earlier, the nano-fluids usage when employing flood coolant has harmful environmental effects; however, when using MQL technique, an optimal amount of oil is used and it results in a fine mist where fewer procedures (i.e., compared to classical nano-cutting fluid approach) are required to reduce any concern of using the nano-additives. Based on the previous considerations, a medium-effectiveness level is considered for the energy consumption element since all activities associated with nano-fluids preparation (e.g., dispersion) are still same as those conducted in the nano-cutting fluid approach. Using an optimal amount of nano-fluid with compressed air decreases the severity of the health and environmental problems associated with employing nano-cutting fluids approach; however, these problems aren't completely eliminated. Thus, a medium-effectiveness level is considered for the personal health and safety, waste management, and environmental impact elements. In addition, employing MQL-nano-fluid technique shows a noticeable reduction in the total machining costs since it decreases the used amount of nano-additives. Accordingly, a medium-effectiveness level is considered for the machining costs when machining with MQL-nano-fluid.

3.6. Discussions

Based on the previous evaluation, the total points are calculated for each strategy. Also, the studied strategies are ranked based on their effectiveness score (i.e. higher-the-better) as shown in Table 2. As can be seen in Table 2, both dry cutting and MQL show the best sustainable cooling and lubrication strategies. Furthermore, the cryogenic and MQL-nano-fluid techniques showed the same sustainability performance based on their effects on the studied sustainability aspects. The worst performance has been observed when using nano-fluid approach. It should be stated that the current evaluation does not consider the machinability efficiency (e.g., tool life, surface quality). However, the nano-fluid showed the worst performance among the studied strategies, it usually showed a significant performance in terms of the machinability efficiency as has been presented and discussed in previous studies [25, 28-30]. In addition, cryogenic and MQL-nano-fluid techniques usually show better cutting performance than dry and MQL techniques in terms of tool wear, surface roughness, and cutting forces as has been discussed in a previous research work [16]. Thus, a modified decision matrix has been developed in order to provide an effective assessment of the studied cooling and lubrication strategy. The modified matrix includes a new element representing the machinability efficiency. The added element is measured by four-levels because of its importance in enhancing the machining process. As previously discussed and based on previous studies [16-22, 24-31], a high-effectiveness level

(4-points) is considered for this element when machining with MQL-nano-fluid, cryogenic, and classical nano-fluid; however, a medium-effectiveness level (2-points) is assigned for MQL strategy, and low-effectiveness level (1-point) is assigned for dry cutting. The total effectiveness points for each studied strategy are listed in the modified matrix (see Table 3). It can be found that MQL-nano-fluid and cryogenic machining are the best sustainable strategies which offer a balance between achieving a sustainable environment and accomplishing higher machinability efficiency. Also, it should be stated that both MQL and dry cutting offer promising sustainable cooling and lubrication strategies; however, the excessive heat generated during their implementation is still a significant problem affecting the machining performance.

Table 2. The proposed decision matrix including all sustainable indicators

		Cooling and Lubrication Strategies				
		Dry Cutting	MQL	Cryogenic Approach	MQL-Nano-Fluid	Nano-Fluids
Sustainable Indicators	Energy Consumption	1	2	2	2	2
	Personal Health and Safety	3	2	2	2	1
	Waste Management	3	3	2	2	1
	Machining Costs	1	2	2	2	1
	Environmental Impact	3	2	2	2	1
Total Points		11	11	10	10	6

Table 3. The modified decision matrix

		Cooling and Lubrication Strategies				
		Dry Cutting	Cryogenic Approach	MQL	Nano-Fluids	MQL-Nano-Fluid
Sustainable Indicators	Energy Consumption	1	2	2	2	2
	Personal Health and Safety	3	2	2	2	2
	Waste Management	3	2	3	2	2
	Machining Costs	1	2	2	2	2
	Environmental Impact	3	2	2	2	2
Machinability Efficiency		1	4	2	4	4
Total Points		12	14	13	10	14

4. Conclusions

In this work, a comparative study is presented to evaluate the sustainability effectiveness of different cooling and lubrication strategies namely; dry cutting, cryogenic approach, minimum quantity lubrication (MQL), nano-cutting fluids, and MQL-nano-fluids. In order to evaluate the strategies effectiveness, five sustainable indicators are used; namely, energy consumption, personal safety and health, waste management, machining costs, and environmental impact. A weighted decision matrix is developed to assess the studied strategies in terms of the employed sustainable indicators. Both dry cutting and MQL showed the best sustainable cooling and lubrication strategies. Furthermore, the cryogenic and MQL-nano-fluid techniques showed the same sustainability performance based on their effects on the studied sustainable elements. The worst performance has been observed when using nano-fluid approach. In addition, a modified decision matrix has been developed in order to provide an effective assessment of the studied cooling and lubrication strategy. The modified matrix includes a new element representing the machinability efficiency. Based on the modified matrix, MQL-nano-fluid and cryogenic machining showed the best sustainable strategies which offer a balance between achieving a sustainable environment and accomplishing higher machinability efficiency. In terms of the future work, a detailed discussion for each sustainable indicator should be considered in order to offer a comprehensive comparative study for the studied cooling and lubrication techniques.

Also, along with including a detailed discussion for each sustainable indicator, a clear sensitivity analysis can be performed to assign different weighting factors rather than equally weighted factors. Addressing these points would clearly affect the evaluation outcomes.

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