Eco Friendly Machining Processes for Sustainability - Review

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Abstract: Green manufacturing is a style for industrialized that minimizes dissipate and contamination. The pollution prevention resolves in manufacturing industries to expand and execute various environmentally-friendly strategies. The main purpose of green machining is to hold up future generations by attaining sustainability. Cutting fluids are discoloured with metal particles and foulness products which reduce the efficiency of cutting fluids. To minimize the unpleasant environmental effects coupled with the use of cutting fluids, the harmful components from their formulations have to be eliminated or reduced to the acceptable level. In addition, mineral based cutting fluids are going to be replaced with vegetable based cutting fluids since they are environmentally friendly. The present review primarily determined on examining different aspects of machining process from an environmental sensitivity. This paper presents the environmental green machining such as dry machining, machining with minimum quantity lubricant, Cryogenic machining, hot machining, vegetable oil-based cutting fluids and nano filled cutting fluids. The Performance of Eco-friendly machining are discussed in terms of cutting forces, tool flank wear, cutting temperatures and surface finish are also discussed.

Key words: Eco friendly machining; Cutting fluid; MQL; Cryogenics; Vegetable oil; Nano filled fluid

1. Introduction

In 1868 researchers have used water as cutting fluid in machining and observed that speeds have increased by 30–40%. The quality, productivity and cost of the product mainly depend on performance of machining operations. In machining the various properties of parameters affecting the cutting performances are cutting fluids work piece, cutting tool, machining conditions and machine tool [1]. The appropriate function of cutting fluid must not only develop the performance of machining, but also complete the needs such as non-toxic, non-harmful to health for operators, not a fire hazard, not smoke and easy disposal [2]. Veera Bhadra Rao et al [3] have concluded that flood cooling uses heavy coolant which increases cost of coolants, but has lots of health issues due to physical contact to skin and mist generated has serious effects such as respiratory disorders and other diseases. Cutting fluids have grown to be added difficult in requisites of both workers health and environmental pollution, with severe concerns ensuing from their use, behaviour and high disposal costs. Therefore, researchers have focused to minimize the use of cutting fluids and cutting energy due to important environmental links. [4]. Benedicto et al [5] have made a review on the analysis of the
applicability of cutting fluids in machining operations. They have identified main alternatives in machining like minimum quantity lubrication technique thereby meeting the industrial needs in terms of economy, environmental and technical effects.

The cutting fluids are classified into cutting oils, soluble oils, synthetic fluids and semi-synthetic fluids. Mineral based cutting fluids are even though reasonably priced the application is restricted due to the limited resource, poor biodegradability and the accessibility of mineral oil is highly dependent on political considerations. Generally, the cutting fluids are diluted with water, such that about 95 % of the cutting fluid, by volume, is water [6]. The biodegradable cutting fluids such as soybean oil, canola oil, sunflower oil, coconut oil, sesame oil, castor oil etc. as environmentally friendly lubricants as an option to mineral based cutting fluids. Modern advancement of high oleic vegetable oils as lubricants is stimulated by growing environmental and economic concerns to protect endangered species to the next generation. Vegetable oils perform better than the other oils and the reasons are illustrated in Figure 1. [7].

Researchers have proved that vegetable-based oil and nano filled oil shows superior lubricating property than conventional oil [8&9]. Cryogenic machining is a modern method of cooling the chip-tool interface, to decrease the tool wear, to modify the features of material, consequently which develop the machining performance and product excellence. This method uses non-combustible and non-corrosive gas liquefied by cooling to −196 °C as coolant [10]. The sustainable products, processes, and systems are the functional elements of sustainable manufacturing. The reduced material utilization, minimizing energy consumption and waste-free manufacturing processes are the major challenges to the industry to manufacture sustainable products [11]. The conceptual layout of sustainable machining is provided in figure 2.
Careful examination of literature review reveals that very limited review articles are available in the area of sustainability of the machining process i.e. energy-efficient manufacturing Processes. Therefore, the paper presents the various environmental cognisant machining techniques and discusses the performance of eco-friendly machining by considering cutting forces, tool wear, cutting temperatures and surface roughness.

2. Sustainable Machining Techniques

2.1 DRY Machining (DM)

The machining process conceded in the nonexistence of cutting fluid is termed as dry machining (DM). High performance cutting tools enables dry machining for sustainable expertise [12]. Wu et al (2018) have proved that the feasibility of dry machining of the high-throughput drilling of compacted graphite iron for 3150 holes [13]. Thomas et al. have stated that dry machining cause high temperature in the machining zone which results in tool life reduction and inaccurate dimensions of the work piece. [14] Goindi and Sarkar have performed a comprehensive review of dry machining based on sustainability aspects meeting major research objectives. They have concluded that dry machining is environmentally friendly which eliminates hazardous cutting fluids during machining operations resulting in sustainable machining [15]. The extremely difficult to machine metals such as nickel alloys, titanium alloys, Co-Cr alloys have machined by cemented carbide (WC/Co) tools filled with solid lubricant. The performance of dry machining is enhanced by self-lubricating tool with the employ of conservative tools [16].

2.2 Minimum Quantity Lubrication (MQL)

The machining process sprints in the presence of an extremely small amount of cutting fluid, in the assortment of 10–150 ml/h, distributed in the cutting zone in a vapour technique is called MQL [17]. Inconel was machined under MQL and found that machinability is improved for MQL as compared to dry or wet machining [18]. Liu et al. attempted to prove that dry machining and MQL could be the most appropriate processes for machining titanium. Tool coating was one key factor to realize high speed machining and green manufacturing [19]. Khan et al showed that an improved surface roughness of concerning 31.6% was achieved for MQL over wet cutting and about 18% was obtained for dry cutting [20]. Boubekri and Shaikh has concluded that MQL serves as an alternate to flood cooling but without significant health concerns. Dry and MQL gave comparable results for turning, milling, drilling and grinding for all materials. [21]. Nandakumar et al. has employed MQL machining condition and has developed superior surface finish at lower wear of tool in grinding Al-SiC composites [22]. Most of the authors have demonstrated perceptible enhancement in performance with MQL machining compared to dry machining, more significant results could have been obtained. Table 1 explored the difficulties in machining of materials under dry conditions [23-33].

| SI.NO. | MATERIAL USED | CUTTING TOOL USED | REMARKS |
|--------|---------------|-------------------|---------|
| 1      | Inconel 718   | Carbide CVD coated insert | During the investigation no major signs of tool damages are observed while machining Inconel 718 at low speeds i.e. at 60 and 90m/min. Comparatively at high cutting speeds tool gets worn out at faster rate with major tool failure patterns like heavy notching. |
2. Inconel 825
Uncoated cemented carbide insert and CVD multilayer coated tool

CVD multilayer coating has synergistic influence on the improvement of the machined surface integrity-based super alloy.

3. Inconel 718
PVD coated tungsten carbide cutting insert

As cutting speed increased from 30m/min to 70m/min, the predominant tool wear mechanisms are abrasion, oxidation and edge chipping due to the friction and thermal softening.

4. Inconel 825
Uncoated and PVD multilayer coated cemented carbide inserts

The average flank wear increased with both cutting speed as well as with machining duration. However, use of PVD multilayer coated improved the resistance to flank wear.

5. EN25 Steel
CVD and PVD coated carbide tools

The results of ANOM shows that a combination of machining parameters for this investigation are cutting speed of 244m/min, feed rate of 0.10mm/rev and depth of cut of 1.0mm with CVD coated tool. The result of ANOVA shows that the coated tool is the most significant parameter followed by cutting speed.

6. Super Duplex Stainless Steel
CVD and PVD coated tungsten carbide cutting inserts

MT-TiCN-Al2O3 coating provides relatively better performance in terms of tool wear, cutting force, cutting temperature and surface integrity.

7. AISI 304L austenitic stainless steel
PVD advanced tools

The best coatings for turning of difficult to machine materials as austenitic stainless steels are nACo and AlTiN coatings.

8. Inconel 825
Uncoated and CVD coated cemented carbide tool

Micro hardness increased with increase in cutting speed. Coated tool resulted in reduction in micro hardness in the surface and sub-surface region.

9. Cold rolled steel C62D
SNMM coated tungsten carbide inserts

The results revealed that feed rate seems to influence surface roughness more significantly than nose radius and cutting time.

10. 2030-T4 aluminium alloy
Inserts of hard metal with a coating of titanium nitride

The most significant factor was the interaction effect between the depth of cut and the feed rate.

2.3 Cryogenic Machining

High abrasive materials, super alloys and novel machine tools have utilised cryogenic machining for safe and environmentally-friendly method [34]. In machining of AISI 304 stainless steel by oblique cryogenic cooling, tool life was improved more than four times [35]. Joshi et al have made an experimental study to assess the effects of dry, MQL and cryo-MQL on grinding force, temperature, surface roughness and chip morphology on Inconel 751. The experimental results indicate that liquid nitrogen and MQL has improved the machining characteristics as compared with MQL and dry grinding [36]. Pereira et al [2015] have presented a new cooling system which consists of CO2 cryogenic and MQL technique. The new system provides an environmental and economic efficient alternative. The results indicate that CO2 + MQL system is more effective in improving the machining characteristics of Inconel 718 during milling operation when compared to conventional machining techniques [37]. Gholap and Mohod had stated that cryogenic fluids such as liquid nitrogen are not reusable, sometimes may not be feasible [38]. Kaynak and Gharibi have made an experimental study on the progression of tool wear in the turning operation of AISI 4140 steel under CO2 assisted MQL, CO2 assisted and LN2 assisted cryogenic machining conditions. The experimental results indicate that CO2 assisted machining is not performed better in turning of AISI 4140 steel and is not recommended [39]. Tapoglou et al [2017] have investigated the performance of CO2 cryogenic coolant...
in milling of titanium alloy Ti-6Al-4V to analyse tool life under different coolant delivery options. They have performed machining under cryogenic CO$_2$, flood cooling, dry machining and cryogenic CO$_2$ combined with MQL environments. The results indicate that cryogenic CO$_2$ plus MQL has achieved a tool life of 18.5 minutes better than other machining conditions [40].

Jerold and Pradeep Kumar have investigated to study the influence of cryogenic coolants in machining of titanium alloy Ti-6Al-4V and its effects on cutting temperature, cutting forces, surface roughness, chip morphology and tool wear. They have compared the results of cryogenic machining with dry and wet machining. The results indicate that the use of CO$_2$ coolant has improved the machinability characteristics of titanium alloy when compared to other cryogenic coolants [41]. Fengbiao Wang et al. [2017] have investigated the performance of Nickel-based super alloy on tool wear during milling operation under cryogenic machining conditions. They have found that the application of liquid nitrogen coolant has reduced the tool wear [42]. Chetan et al have done an experimental study to analyse the performance of liquid nitrogen in cryogenic machining of Nimonic 90 alloy by using uncoated tungsten carbide inserts. The experimental results indicate that the liquid nitrogen has suppressed the notch wear and edge fracture for the uncoated tools during the machining [43]. Shokrani et al have investigated the role of cryogenic cooling in enhancing the machinability characteristics of Ti-6Al-4V titanium alloy during CNC end-milling operation. The experimental results indicated that the cryogenic cooling improved the machinability by reducing surface roughness by 40% when compared to conventional machining conditions [44]. The table 2 shows the machining of materials under cryogenic cooling and it is determined that substantial improvement in tool life and surface finish-dimensional accuracy [45-49].

**Table 2. Machining of Hard materials under Cryogenic cooling [Sunil Magadum et al., 2014; Alborz Shokrani, 2016; Iturbe et al., 2016; Ibrahim Sadik et al., 2016; Aramcharoen and Shaw, 2014]**

| SLNO. | MATERIALS USED | CUTTING TOOL | CUTTING FLUID USED | CRYOGENIC PARAMETERS | REMARKS |
|-------|----------------|--------------|--------------------|----------------------|---------|
| 1     | EN-24 hardened steel | TiAlNi coated carbide tool inserts | Liquid nitrogen | Liquid nitrogen at -185°C was used as a cryogenic coolant. | There is an improvement in tool life by 22.46%, 35.74% and 38.60% in cryogenic machining over flood coolant machining at cutting speed 125m/min, 160m/min and 200m/min respectively. The influence of cryogenic cooling reduces the cutting force by 15.42%, 8.22% and 7.58% at 125, 160 and 200m/min respectively. |
| 2     | Cobalt chromium (CoCr) alloy | Solid carbide cutting tool | Neat oil is used for MQL system. Liquid nitrogen is used for cryogenic cooling system. | Liquid nitrogen at 1.5bar pressure and 20kg/h flow rate was sprayed along the cutting tool into the cutting zone. | Results indicated that 71% reduction in surface roughness and 96% reduction in flank wear can be achieved using cryogenic cooling when compared to conventional machining practice. |
Titanium alloy coated carbide inserts

- **3** Ti-6Al-4V
- **4** Inconel 718
- **5** Ti-6Al-4V
- **6** Inconel 718

### 2.4 Hot Machining

Hot Machining is a novel technique in which the temperature of the workpiece is elevated to several hundred Celsius over ambient, which sources reduction in the shear strength of the material. Tigham first innovated the process of hot machining in 1889, since then it has fashioned much interest among various investigators. Researchers observed that at an optimum temperature the tool life increases to a highest value and after that it reduces in hot machining of stainless steel, S-816alloy, X-alloy and Inconel-X [51-52]. Many researchers have proved that hot machining is a very useful method for machining of hard-to-cut materials and to reduce tool wear; power consumed and increase surface finish. [53-54] The effect of temperature of work-piece is found to be the most significant on tool life [55]. Authors have simulated the hot machining of Inconel 718 using finite element analysis. They concluded that use of heat in secure immediacy to the surface of the workpiece can considerably reduce the force. The increase of process zone temperature reduces heat...
generation which reduce flow stress and cutting force in hot machining. The previous studies confirm that the performance of hot machining is improved by extended tool life. Improved surface finish and higher metal removal rate [56].

2.5 Machining using nano filled cutting fluid

In recent times scientists engaged nano particles in conventional lubricants since its extraordinary development in thermo-physical, and heat transfer capabilities, decrease the coefficient of friction and wear effect to develop the efficiency and consistency of machine tools [57]. Kalyan Chakaravarthy et al. have employed Nano CuO filled rapeseed oil in the drilling of Al- SiC composites. The experimental results have shown that the surface finish of the machined specimen is found to be superior which is majorly due to the nano particles in the vegetable oil [50]. Sahu et al have evaluated the machining performance of MWCNT filled Nano fluid in turning of Ti-6Al-4V alloys and found that nano fluids are effective in overcoming the problems faced by the conventional machining conditions [58]. Venkatesan et al have made an experimental study to improve the machinability characteristics of Nimonic 90A alloy during machining operation by using Nano fluid MQL technique. They have prepared Nano fluids by dispersing copper oxide Nano particle with groundnut oil through ultra-sonication process. They have obtained optimum response values at 40m/min cutting speed, 0.14rev/min and concentration 0.25 by Taguchi methodology [59]. Ahsan Ul Haq et al have done an investigation to analyse the effects of feed, depth of cut and flow rate on the temperature in face milling of D2 tool steel. They have done machining by MQL and Nano fluid MQL conditions. RSM based central composite design was used to design the experiments. The results indicate that 25% temperature reduction is observed during NFMQL technique as compared to MQL [60].

Conclusions

Sustainable manufacturing turns out to be a global concept, substance important elements on all the fields as well as machining processes. The technique to sustainable manufacturing through environmentally-friendly machining begins from the steps that must be taken to implement ecological machining methods in order to make these technologies consistent, environmentally friendly and cost efficient. The review focuses on the performance and environmental blow of environmentally-friendly machining for various materials and machining conditions. The salient features are as follows:

- High performance cutting tools enables dry machining for sustainable expertise. The dry machining lessen costs associated with cutting fluid which is approximately 7–17% of total manufacturing costs, dry machining technique will unavoidably be considered
- MQL gave comparable results for turning, milling, drilling and grinding for all materials.
- MQL based nano fluid lubrication has clearly demonstrated significant decrease in consumption of cutting fluid as well as the cutting energy or cutting power while improving surface quality, this technique has been established as a environmentally friendly green manufacturing
- The cryogenic cooling application in machining operations could be firm as enabling considerable progress in tool life and surface finish-dimensional accuracy through reduction in tool wear through control of machining temperature desirably at the cutting zone.
- Cryogenic LN2 coolant reduced the cutting temperature to an extent about 9–34% and 3–17% when compared to wet and CO2 machining conditions respectively. Cryogenic CO2 cooling reduced the cutting forces efficiently than wet and cryogenic LN2 machining to a range of about 17–38% and 2–12% respectively (Dilip Jerold and Pradeep Kumar 2012)
- The economical machining can be carried out using low costly cutting tools by implementing hot machining technique to machine difficult to cut materials.
The introduction of vegetable oil-based metalworking fluids in machining applications has made it possible to achieve better performance as reported by all researchers. Researchers proved that vegetable oil assisted machining made it credible to increase assembly volume by 10% and also reducing tool cost by 40 to 50%

Nano fluids assisted machining exhibits the energy-efficient heat transfer due to superior thermal conductivity and heat transfer coefficient.

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