This review paper discusses some of the aforementioned developments for sustainability in conventional machining processes. It also provides review of some important past work conducted based upon the use and effectiveness of sustainable techniques in conventional machining. The scope of this paper is limited to the discussion on dry cutting, minimum quantity lubrication and cryogenic cooling based near dry machining.

2. Dry Cutting

Machining without cutting fluid (dry cutting/machining) is a prime most requirement to decouple environmentally-unfriendly factors from manufacturing of engineered products. Globally, it is being adopted by manufacturers due to strict environmental regulations. The significant benefits of dray machining are manifolds, such as, no atmospheric pollution in terms of gases, mist and particulates from machining; no danger of health; significant reduction in the resource (no lubricant) and energy (no pump for lubricant supply) consumption; and machinability at par with other machining techniques (Goindi and Sarkar, 2017). Lubricants and lubrication-free machining (i.e. dry cutting) significantly reduces manufacturing costs.

There has been significant past research conducted on dry cutting of a range of engineering materials and their machinability analysis. Moreover, dry cutting was also done in combination with other techniques such as heat-assisted machining, textured tool based machining, and with coated tools etc. Some of the important past attempts on dry cutting are discussed here as under.

In a recent investigation, Sharma and Gupta (2019) conducted coated tool based dry machining of SS304. A comparative study with wet and green lubricant based machining revealed that dry machining of difficult-to-machine materials certainly need the assistance of some secondary technique where coated tool helped to attain machinability at par with wet cooling. Devilez et al. (2011) reported successful machining of Inconel 718 using coated carbide tool under dry machining environment. Acceptable surface quality was obtained. An interesting work conducted by Thakur et al. (2012) on high speed dry turning of Inconel 718 superalloy found TiN/Al_2O_3/TiCN (CVD) coating best suitable for the improved machinability. This coating outperformed TiN/TiAlN (PVD) coating for minimizing cutting temperature and forces. Machinability of Waspalloy was investigated by Deepu et al. (2016). They also recommended the use of coated tools with optimum parameter combination for the improved machinability. Use of Polycrystalline cubic boron nitride (PCBN) and polycrystalline diamond (PCD) cutting tools was also investigated in dry machining of grade 5 titanium alloy (Sun et al., 2015). PCD tools were identified superior to PCBN tools with lower surface roughness and longer tool life. Heat sources have also been used to conduct thermal assisted machining of difficult-to-machine materials in dry environment. Assistance of heat greatly helped to overcome the machining challenges and significantly reduced cutting forces and improved surface conditions (Venkatesh and Chakradhar, 2017).

Literature review concludes that dry cutting has potential to generate machinability at par with wet cooling based machining with comparatively lower environmental footprints. Its more effective when used in combination with treated and coated tools.

3. Minimum Quantity Lubrication based Machining

In traditional wet cooling based machining, hydrocarbon based cutting fluids are used to carry away the heat generated during machining. It works for the cooling of machining zone rather than lubricating it (Astakhov, 2008; Gupta and Laubscher, 2016). As discussed earlier, conventional cutting fluids suffer from many inherent limitations most of them are related to the health, safety and environment. It compelled to develop alternate techniques of cooling and lubrication in conventional machining. One of such sustainable lubrication techniques is minimum quantity lubrication (MQL) where a small quantity of the fluid is supplied to the cutting zone for effective lubrication between tool-work interface in order to manage the heat generated and gain the desired machinability. The lubricants used in MQL technique are generally green in nature and made by synthetic esters, fatty acids and vegetable oils. MQL facilitates near-dry machining. As shown in Fig. 2, a typical MQL system consists of many subsystems such as nozzle spray and supply system (valves, nozzle, and pipes), fluid control system (micro-pumps and mechanisms), storage system (fluid container), and air compressor. In MQL, micro-droplets of cutting fluid/lubricant are mixed with air by atomization (then the mixture is called aerosol) is sprinkled to the machining zone. This mist form or aerosol particles make cushion like arrangement over the tool face and work surface and facilitate smooth removal of chips. The uniformly distributed aerosol particles reduce friction, prevent the heat to generate and spread, protect the tool and work surface, and hence help to obtain better machinability. Some of the important past studies on MQL based sustainable machining of engineering materials are discussed here as under.

Balan et al. (2013) investigated MQL grinding of Inconel 751 alloy. They sustainably grind Inconel without any grinding burn, and considerable reduction in grinding force and temperature, and high surface quality. The effectiveness of a combination of MQL environment and coated carbide tools was studied by Haron et al. (2011) for turning of Inconel 718. Excellent surface quality with average roughness value of 0.243 µm was achieved. Tamang et al. (2019) performed optimization of MQL assisted turning of Inconel-825 by Genetic Algorithm and claimed to obtain the machinability (average roughness- 0.39 µm, tool flank wear- 15.37 µm, and cutting temperature- 56.47^0 C) better than reported in previous literature. Nano fluid based MQL was also used for machinability enhancement of difficult-to-machine materials. In a recent study, Inconel-625 was machined by Singh et al. (2018) using carbon nanotube CNT in vegetable oil as cutting fluid. Nanofluid based machining was found superior to dry cutting and equal to wet cooling based machining of Inconel 625. Another important investigation conducted by Ali et al. (2017) where Al_2O_3 mixed nanolubricant MQL fluid assisted to achieve optimum surface quality with average roughness 0.188 µm when turning Inconel-718 alloy. Vasu and Reddy (2011) also used Al_2O_3 integrated cutting fluid for green machining of Inconel 600 alloy. Different volume fractions of nanoparticles significantly affected surface finish and machining temperature. Moreover, a comparative study found the performance of nanofluid based MQL machining much better than dry cutting and plain MQL machining of Inconel 600.

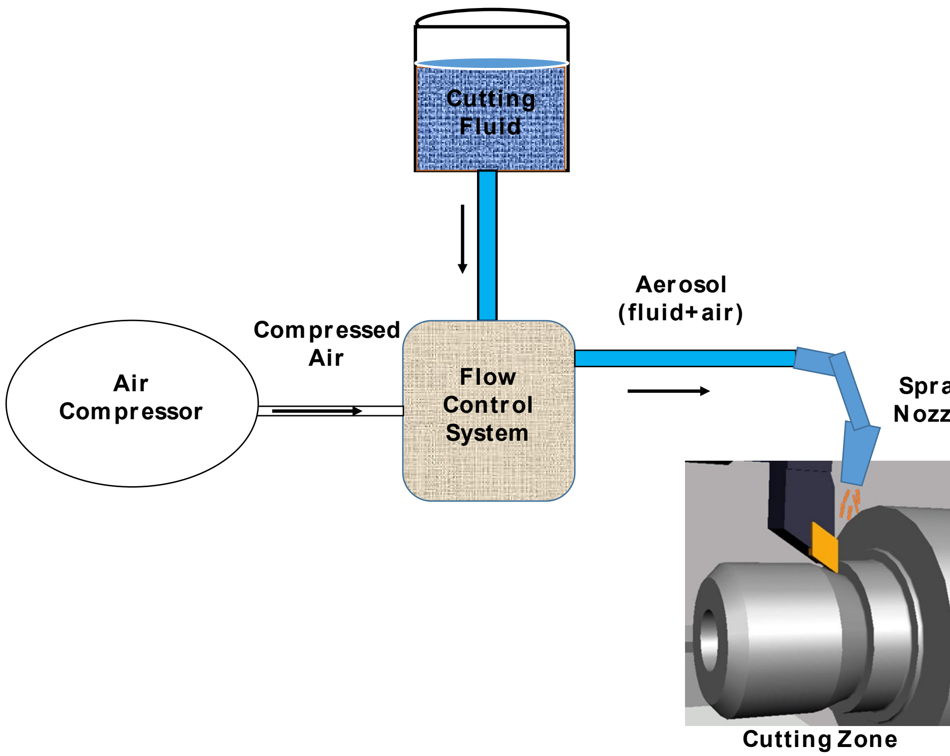

Fig. 2 Minimum quantity lubrication system

4. Cryogenic Cooling based Machining

In cryogenic cooling, highly cooled gases such as either liquid nitrogen, or helium, or carbon dioxide are supplied under high pressure to the machining zone (Yildiz and Nalbant, 2008). Liquid nitrogen is the most extensively used gas for cryogenic cooling based machining. There is another variant of this technique called as cryogenic cooling and lubrication is found more effective. In performs simultaneous cooling (by compressed low temperature CO2 or N2) and lubrication (through oil-mist at minimum quantity) for better machining zone environment which could facilitate chip removal, reduce temperature, enhance work surface quality and increase tool life. A typical cryogenic cooling system is shown in Fig. 3. A cylinder of cryogenic gas, pressure and flow control systems, tubing and nozzle are the important parts of this system. As the name implies, cryogenic cooling cools i.e removes machining heat from the tool-work interface. Nitrogen with a temperature of -200^0C, in liquid nitrogen based cryogenic cooling, absorbs the heat generated during machining before evaporation. A protection layer of gas between tool-work interface formed during process acts as lubricant and protect the tool. This technique also facilitates removal of chips, as the chips are not wetty and free from oil. The significant benefits of cryogenic machining are manifolds, such as machining possible at high speed, longer tool life, low pollution, safe, no hazard to operator's health, and easy disposal of chip waste etc. The initial cost of cryogenic system is quite high, and it requires careful storage and operating. Some of the important research investigations on cryogenic cooling based machining are discussed here as under.

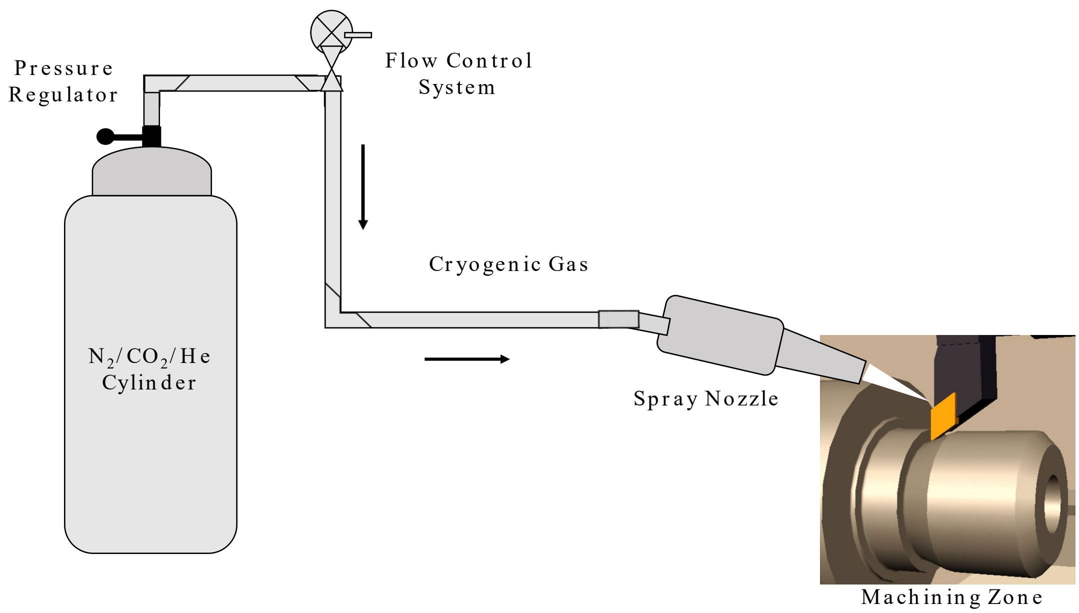

Fig. 3 Cryogenic cooling system.

Aramcharoen and Chuan (2014) found superiority of cryogenic cooling based machining over dry cutting and wet cooling machining for milling of Inconel 718. Contamination-free machined part, low energy consumption and less friction at deformation zone were the significant benefits identified. Kaynak (2014) studied that number of nozzles in cryogenic machining plays very important role and can reduce cutting force and power consumption. Furthermore, he found that cryogenic machining outperformed dry and MQL machining and resulted in better machinability of Inconel 718. A comprehensive investigation on sustainable machining of one of the most DTM materials NiTi shape memory alloy was done by Kaynak et al. (2013) and Kaynak et al. (2014). They investigated the tool wear and surface quality of NiTi shape memory alloy under dry, MQL, and cryogenic environment. For cryogenic cooling, liquid nitrogen was used at 1.5 MPa pressure; for MQL, green lubricant was used at 60 ml/f flow rate and 0.4 MPa pressure. Machining was performed at different levels of cutting speed. Cryogenic cooling was found more effective at high speed and significantly reduced tool wear and cutting forces. Some research on combination of vibration assisted machining and cryogenic cooling machining, and cryogenic cooling and MQL machining of DTM materials was also reported (Lin et al, 2011; Okafor and Jasra, 2019).

5. Summary

A state of art work on developments in conventional machining for sustainability is presented in this paper. Dry cutting, MQL, and cryogenic cooling etc. have extensively helped to decouple the environment unfriendly factors from conventional machining and not only contributed to attain sustainability, but helped to improve productivity also. The following points summarize the significance of the aforementioned techniques and provide future research avenues:

- With optimum parameter combination, the effect of dry cutting, MQL, and cryogenic cooling based machining is more pronounced.
- Dry cutting contributes to save a large amount of resources in terms of lubricants or cutting fluids. Furthermore, also saves environment from toxic gases, fumes, and exhaust products.
- MQL based machining was found in many cases much better than conventional wet machining with comparatively less environmental footprints.
- Cryogenic cooling based machining with combination of MQL is more effective.

- Optimization of machining processes for improved performance of these sustainable techniques could be a major focus area of future research.
- Life cycle assessment based comparative evaluation of various machining processes for development and selection of the best process is an important avenue for further research.

Acknowledgments

This work is supported by DHET University Capacity Development Grant (UCDG) 2019, University of Johannesburg, South Africa.

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Biography

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