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Recent developments in sustainable manufacturing of gears: a review

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ABSTRACT

Environment awareness is of the utmost importance to all socially responsible manufacturers. To be competitive on a global scale manufacturing needs to be aligned with various strict environmental regulations. The manufacturing industry at large is striving to improve productivity and product quality while maintaining a clean and sustainable environment. This can only be achieved by adopting sustainable techniques of manufacturing which include minimizing the number of manufacturing steps by employing advanced and alternative methods, environment-friendly lubricants and lubrication techniques while machining, reducing wastage, active waste management and minimizing energy consumption etc. Gear manufacturing industries, the major service providers to all other industrial and manufacturing segments are also focusing on to implement the techniques targeting overall sustainability. Some of the recent developments to achieve sustainability in gear manufacturing can be summarized as reducing the use of mineral-based cutting fluids by employing alternative lubrication techniques i.e. minimum quantity lubrication (MQL) and dry machining; material saving, waste reduction, minimizing energy consumption and maintaining economic efficiency by reducing the number of gear manufacturing stages (eliminating the necessity of finishing processes) by utilizing advanced methods such as gear rolling and wire electric-discharge machining (WEDM) and finally increasing productivity by minimizing tool wear at high gear cutting speeds through the use of alternative tool materials and coatings. This paper reviews and amasses the current state of technology for sustainable manufacturing of gears and also recommends ways to improve the productivity and quality while simultaneously ensuring environmental sustainability.

***Keywords*:** Sustainable manufacturing, Gear machining, Minimum quantity lubrication, Environmental conscious machining

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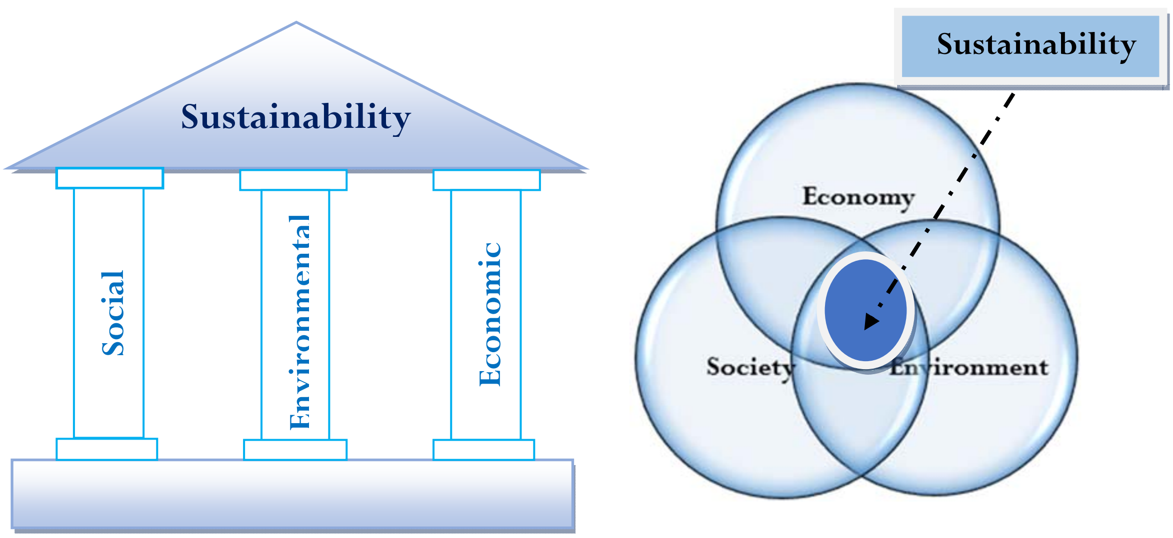
1. Primer

1.1 Introduction to sustainability and sustainable manufacturing

In general '*sustainability*' is the ability to continue a defined behavior indefinitely. The '*Brundtland Report-1987'* of *United Nations World Commission on Environment and Development* defines sustainability as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs *(United Nations General Assembly Report, 1987)*. Sustainability was defined in terms of sustainable development in the report. Higher demand for resources due to the increasing world population and the escalating environment impact are the drivers for global adaptation for sustainable development. The three pillars of sustainability as presented in the report are: the economy, the environment and social sustainability (Fig. 1). Because of the independence of the three pillars a failure of any one will lead to the system as a whole becoming unstable. Fundamentally this implies a systems thinking or multi-stakeholder approach to achieve overall sustainability. Ensuring environmental sustainability is also in the list of the millennium development goals of the *United Nations*. In general this aims to minimize the loss of environmental resources, to keep the environment clean and green by reducing the emission of carbon di-oxide and other harmful gases, to minimize wastage and to ensure its recycling and management *(www.un.org/millenniumgoals/environ.shtml)*.



(a) (b)

Fig. 1. Pillars of sustainability.

The manufacturing sector can significantly contribute to sustainable development, as it is a significant ~~the main~~ enabler of these goals *(Jovane et al., 2008; Pusavec et al., 2010)*. Environmental sustainability has therefore increasingly become an important aspect to achieve a competitive edge which implies economic sustainability. In other words, to achieve sustainability; products, processes, and services should meet the challenges not only concerning their functions, performance and cost, but also to environment and social issues. For a process to be deemed 'sustainable', it should have lower environmental impact, be beneficial to society and be economically sound. It is therefore required that the manufacturing industry continues to be proactive in developing cleaner manufacturing products and processes. This paper hopes to highlight the sustainable manufacturing aspects as related to the production of a specific product (gears) as far as cleaner and more efficient production is concerned. It does not however address the societal aspects of sustainability except where they are directly influenced by the production methods and/or relates to health and safety of the workers directly involved in the manufacturing. The direct societal benefits or lack thereof as related to gears and gear production falls outside the scope of this review.

Sustainable manufacturing can be defined as the production of manufactured products that use processes which minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers and are economically sound *(Davim, 2013; Garetti and Taisch, 2012; Pusavec et al., 2010)*. It includes: (a) the manufacturing of "sustainable" products; and (b) the sustainable manufacturing of all products. The former includes exploring sources of renewable energy, green and social equity-related products. The main aspects concerned with the latter i.e. sustainable manufacturing of products are developing and establishing energy efficient, non-polluting, economically viable processes for manufacturing of products.

According to *Davim, 2013* and *Pusavec et al., 2010* lower machining costs, environmental-friendliness, minimum energy consumption, waste reduction and management, and personnel health and operational safety can be identified as the hallmarks of sustainable manufacturing. Globally these efforts by the manufacturing industries includes implementation of advanced lubrication and cooling technologies, use of vegetable oils and other environment-friendly cutting fluids, selection of advanced tooling and employing advanced and hybrid manufacturing processes etc. *(Davim, 2013; Fratila, 2014)*.

The following section highlights the challenges encountered in gear manufacturing and presents possible solutions in order to improve overall sustainability.

1.2 Challenges and opportunities in gear manufacturing

Gears and subsequently the gear manufacturing industry plays an integral role in many industrial segments, as it supplies one of the basic mechanical components for transmission of motion and/or power to keep machines, instruments and equipment operational. Billions of gears are manufactured globally every year. Processes for manufacturing metallic gears can be broadly categorized into three groups namely (i) material removal (machining) processes such as hobbing, milling, shaping and broaching; (ii) forming processes such as stamping and extrusion and (iii) additive processes such as die casting and powder metallurgy *(Townsend, 2011)*. Material removal including hobbing, milling and shaping constitutes the bulk of this volume. Figure 2 depicts the typical processing sequence to machine a gear commencing with gear blank preparation in the selected material, followed by the cutting of the teeth and finally heat treatment to impart appropriate mechanical properties (both surface and interior) to end at the finishing stage for achieving the desired quality (tolerance, surface finish).

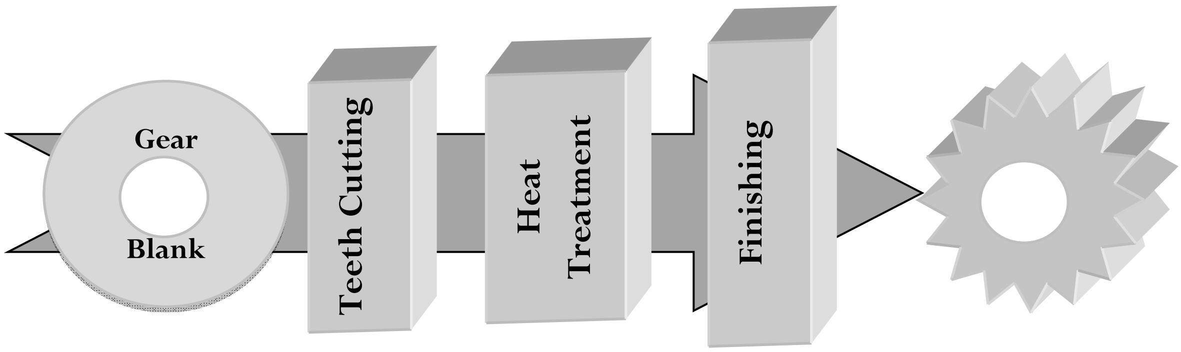


Fig. 2. Typical sequence of processes to machine a gear.

The requirements of the finishing operations have a significant impact on the overall sustainability because it usually implies high tool wear; high consumption of cutting fluid and energy and excessive waste management including handling, disposal and recycling *(Gupta and Jain, 2014a; Neugebauer et al., 2013; Yun et al., 2014)*. In short, the problems associated with manufacturing of gears by conventional processes can be summarized as follows:

- All conventional processes for manufacturing of gears necessitate finishing processes such as trimming, shaving, grinding, honing, burnishing etc. to produce quality gears.
- These subsequent finishing operations themselves require fabrication, repair and maintenance of the finishing tool; consumes large amounts of cutting fluid and energy; increases the burden of handling, recycling and disposal of waste and escalates the overall cost.
- Poor lubrication capability of conventional lubricant and lubrication/cooling systems imparts excessive tool wear during machining and affects the sustainability by necessitating the re-sharpening facilities and/or new tools.

- Supplying and pumping significant quantities of cutting fluid to the cutting zone during conventional lubrication and cooling implies elevated power consumption and may also affect the health and safety of the operator if the fluid has toxic properties.
- The handling and disposal of wet chips (metal cutting wastes) and used cutting fluid are difficult tasks to deal with and may consequently affect the environment.

These factors all adversely affect the overall sustainability.

Engineers and technologists are attempting to deal with these issues by adopting various sustainable manufacturing strategies (Fig. 3), these are (i) adopting alternative and advanced techniques for gear manufacturing and finishing such as gear rolling and wire electric-discharge machining (WEDM), (ii) minimizing the use and quantity of harmful cutting fluids and by using environment-friendly lubricants such as vegetable oils, synthetic esters and other bio-degradable lubricants and employing sustainable lubrication technologies such as minimum quantity lubrication (MQL), cryogenic cooling and dry cutting, (iii) selecting optimum machining conditions, suitable tool materials and coatings. Figure 3 presents a "road-map" to achieve overall sustainability by incorporation of various sustainable strategies and their consequences in gear manufacturing.

The aim of this article is to review the existing technologies related to sustainable gear manufacturing, understanding their operational principles and discussing the future prospects towards energy and resource efficient manufacturing of gears. A detailed review of the recent work conducted to achieve sustainable manufacturing of gears along with the details and mechanisms of the employed techniques and their perceived benefits are reported in the following section. The last section presents the summary, final concluding remarks along with some future recommendations.

Fig. 3. A "road map" to achieve sustainability in gear manufacturing.

Table 1

A summary of recent research work on sustainable gear manufacturing strategies including techniques.

Sr. No.	Sustainable manufacturing strategy	Corresponding technique	Reference
1.	Environment-friendly lubricants and lubrication strategies	Minimum quantity lubrication (MQL)	*Fratila, 2009; Fratila and Radu, 2010; Fratila, 2013; Filipovic and Stephenson, 2007; Matsuoka et al., 2013; Tai et al., 2014; Stachurski, 2012*
		Cryogenic cooling with MQL	*Zhang and Wei, 2010*
		Dry-hobbing	*Tokawa et al., 2001; Fukunaga et al., 2003; Abe and Fukunaga, 2010*
2.	Advanced manufacturing processes	Gear rolling	*Neugebauer et al., 2007; Neugebauer et al., 2010; Neugebauer et al., 2013; Milbrandt et al. 2013*
		Wire electric-discharge machining (WEDM)	*Gupta and Jain, 2014a; Gupta and Jain, 2014b; Gupta and Jain, 2014c; Gupta and Jain, 2014d*
3.	Other important strategies	Tool (hob) materials and coatings	*Karpuschewsk et. al., 2014; Lümkemann et al., 2014; Falk, 2012*
		Sustainable cold extrusion	*Jeong et al., 2013; Yun et al., 2014*

2. Strategies for sustainable manufacturing of gears

To maintain consistency and ease of reference the review is presented according to the structure as presented in Figure 3 and Table 1.

2.1. Environment-friendly lubrication techniques

The use of large amounts of mineral-based cutting fluids may adversely impact the environment because it may lead to increased ground contamination, implies increased energy consumption, increased wet chip handling and waste disposal and may increase potential health and safety issues *(Debnath et al., 2014; Kuram et al., 2013; Weinert et al., 2004)*. To address these issues, there has been a steadily increasing interest in performing machining operations dry or near-dry. Although dry machining may potentially completely eliminate the use of cutting fluids it may negatively affect other problems associated with overall machining performance, such as poor lubricity, reduced tool life, thermal damage to workpiece and tool etc. Therefore, near-dry machining techniques such as minimum quantity lubrication (MQL), minimum quantity cooling (MQC) and minimum quantity cooling and lubrication (MQCL) etc. were developed as a compromise between significant cutting fluid use and dry machining. Out of these near-dry machining techniques, MQL is the most extensively used. The multi-performance capability of the MQL technique such as heat management, cutting interface lubrication, efficient chip removal capability, environment-friendliness and energy efficiency *(Debnath, 2014; Kuram et al., 2013; Weinert, 2004)* is the primary motivation for its application in gear machining. The mechanism of MQL and some of the most significant contributions recently made in this regard are discussed in the following paragraphs:

2.1.1. MQL assisted Machining of gears

2.1.1.1. Overview

Minimum quantity lubrication (MQL) is a micro-lubrication technique that facilitates near-dry machining *(Astakhov and Joksch, 2012; Kuram et al., 2013)*. It eliminates large quantities of water and mineral oil-based cutting fluids and replaces them with a small quantity of lubricant mixed with air. Vegetable oils, synthetic ester and fatty alcohols are typically used as lubricant which is mostly environment friendly and biodegradable and therefore also less harmful to humans during use. *Weinert et al., 2004* reported that in implementing MQL by applying a small amount of cutting fluid (10–150 ml/h) with compressed air to the chip-tool interface in place of several liters per hour of conventional coolant a reduction in interface temperature and friction was observed. Supplying a small amount of cutting fluid consumes less power and thus reduces the cost. The main benefit of

MQL is that it primarily focuses on improving the frictional behavior therefore controlling the heat generation at its source rather than just trying to remove as much heat as possible such as conventional cooling does. This results in improved tool life and good workpiece surface integrity. Metal chips produced during MQL machining are nearly dry and are easy to recycle. The cutting performance and therefore the overall quality of the parts manufactured by utilizing MQL therefore depends on optimizing the appropriate process parameters including the type and flow rate of the lubricant, and the nozzle position and pressure *(Emami et al., 2014; Lawal et al., 2013; Sarıkaya and Güllü, 2015; Sharma et al., 2015; Tawakoli et al., 2010)*.

Figure 1 depicts various components of a MQL system which includes, oil reservoir, source of compressed air, MQL device, piping and nozzle. Effective lubrication between the tool and workpiece is achieved with a flow of compressed air containing finely dispersed droplets of oil, a so called aerosol. The MQL device constitutes a micro-pump and nozzles and a special aerosol generator system that can produce aerosol with an oil droplet size of about 0.5 µm to 5 µm by mixing lubricant oil and compressed air. Due to this small size, the droplets of oil have hardly any inertia or rate of fall and is transported by compressed air to the zones of heat generation (Fig. 5) i.e. tool-chip and tool-workpiece interfaces.

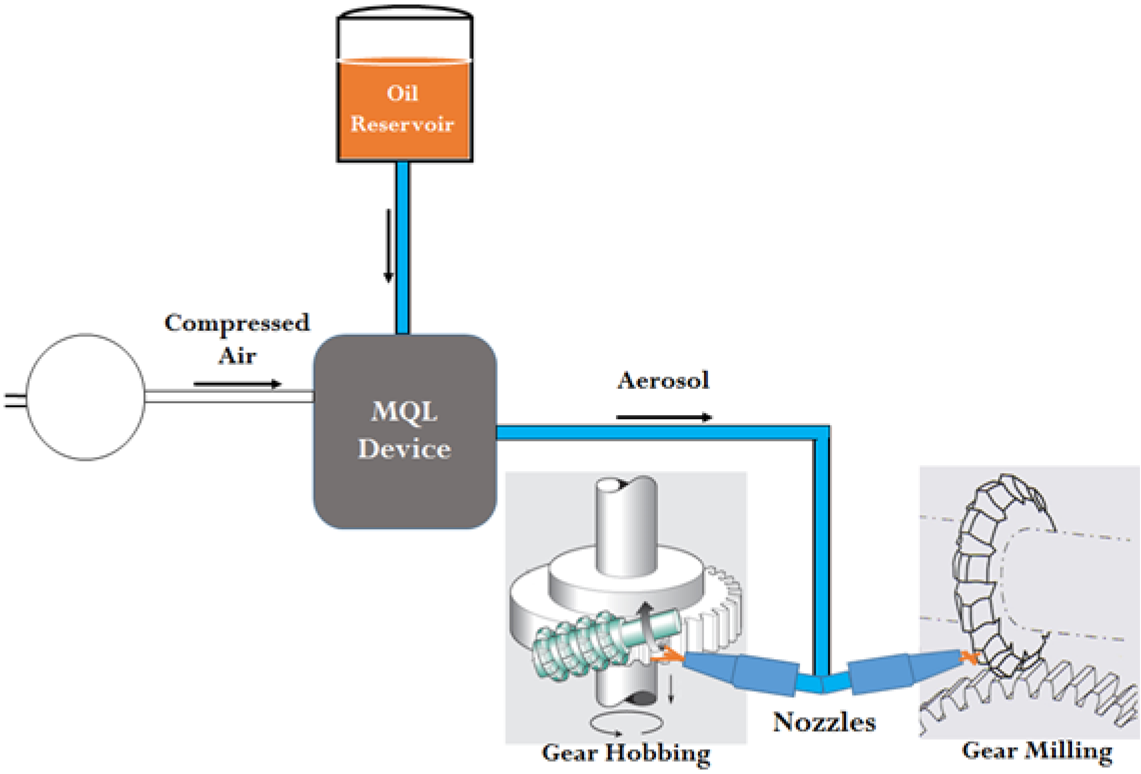


Fig. 4. Schematic representation of various components of a MQL system.

Figure 5 depicts the two most important shear zones that are the main sources of heat generation during a conventional cutting process. The heat generated at the primary cutting zone is due to shearing (atomic slip by largely dislocation movement) of the workpiece material and is unavoidable. The generation and transfer of heat at the secondary cutting zone i.e. tool-chip interface can however be managed by improved lubrication. Fundamentally, the small size and distribution of the oil droplets in the MQL aerosol are very homogenous (since the aerosol is atomized under controlled conditions) and therefore results in a high degree of surface wetting as well as the ability to reach inaccessible regions on the workpiece (Fig. 6b). The friction, and thus the generation and transfer of heat from the chip to the tool and workpiece, is reduced. Optimal lubrication during removal of the chips in the chip groove not only permits higher machining speeds but also results in an improved workpiece surface finish. In conventional flood cooling the coolant/lubricant particles are comparatively big and massive, and therefore uniform distribution over the surfaces of tool and workpiece becomes problematic and partial lubrication only results (Fig. 6a), which is ineffective to minimize heat generation.

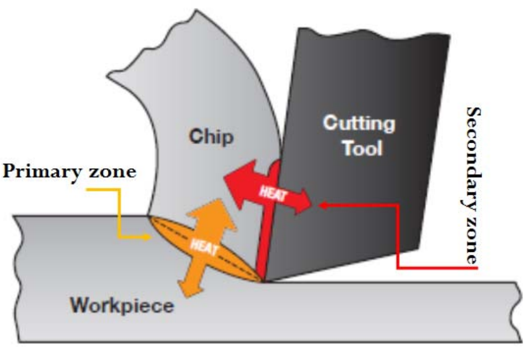


Fig. 5. Heat generation during machining.

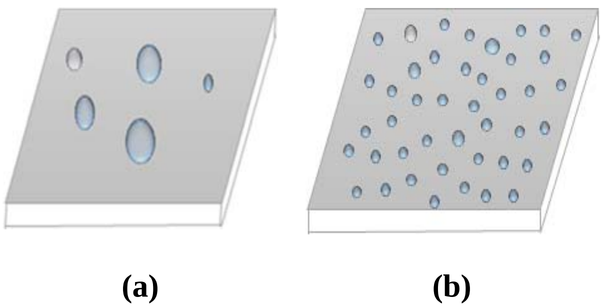


Fig. 6. **(a)** Poor wetting of the workpiece and tool due to uncontrolled atomization of the air/oil droplets at the nozzle in flood cooling; **(b)** MQL droplets wet the workpiece evenly due to much smaller, homogenous droplets.

MQL may achieve effective lubrication of the cutting process even with small quantities of oil allowing machining to be conducted at higher cutting speeds and achieving longer tool lives without the necessity to condition or dispose-off cooling lubricants, thus ensuring higher productivity and environment-friendliness.

2.1.1.2 Review of the past work on MQL assisted machining of gears

To date only a limited number of investigations have been conducted on MQL assisted machining of gears. A series of investigations concerning the implementation of environment-friendly techniques to gear milling was reported. This work was subdivided into the following: a study into the effect of environment-friendly lubrication techniques on tool wear and surface finish of gears *(Fratila, 2009)*, on generation of thermal stress and thermos-elastic displacements *(Fratila and Radu, 2010)* and on geometric accuracy of gears *(Fratila, 2013)*.

In the first of the series *Fratila, 2009* conducted some experiments to analyze the effects of dry and near-dry machining techniques on gear milling efficiency. The experiments performed were focused on the technical evaluation of cooling and lubrication effects, cutting force behavior and tool wear, while also emphasizing the effect of the above mentioned parameters on process quality by means of surface quality evaluation. This was all conducted while monitoring emitted particulates and gases in the environment during the process. A total of 400 right hand helical gears (material: 16MnCr5; module: 2.75 mm; outside diameter: 110 mm; number of teeth: 37, helix angle: 18^0 50') were machined on a CNC gear milling machine by using five cooling and lubrication techniques namely flood lubrication-FL, dry cutting-DC, minimum quantity lubrication-MQL, minimal cooling technique-MCT, minimal quantity cooling and lubrication-MQCL. Eighty gears were machined corresponding to each technique. The following cutting fluid media were used: FL, rotanor oil (fluid flow-100 l/min); MQL, vegetable oil (fluid flow-0.4 ml/min); MCT, emulsion with anticorrosion additives (fluid flow-25 ml/min) and MQCL, vegetal oil and compressed air (5 bar).

The outstanding lubricating action of the MQL system resulted in minimum wear of the hob (gear cutter) along with satisfactory and acceptable surface roughness of the gear teeth. FL and DC produced satisfactory surface finish at the gear flanks but resulted in higher hob wear. An analysis of the cooling effect by measuring the gear temperature found a significant temperature rise for MQL exhibiting its reduced cooling effect and its close similarity with DC. FL, MQCL and MCT were all found to have nearly similar temperature increases. The level of environment pollution corresponding to all the lubrication techniques was monitored by air volume analysis through a multi-gas monitor device. The concentration of pollutant gases and particulates demonstrated no significant pollution effects of MQL equipped gear milling when compared with the other techniques.

As a final conclusion *Fartila, 2009* reported that MQL equipped gear milling is a good alternative to the conventional (flooded) gear milling processes as it offers reduction of cost associated with lubricants and power consumption, increased tool life, improved surface quality of gears, improvements in the chip handling and recycling process and a cleaner environment (most important).

In another part of this series *Fratila and Radu, 2010* reported on work conducted to evaluate the extent that these environment-friendly lubrication techniques can solve the requirements of the cutting fluids i.e. cooling, lubrication and what are the consequences of thermal stress and thermos-elastic displacements during gear milling. Finite element analysis followed by a series of experiments was conducted for the thermal investigations. The experimental work performed employed a lubrication device equipped with two nozzles for MQL whereas two devices were used with additional pressure for MCT (minimal cooling technique). Raps oil, a green lubricant, a kind of vegetable oil (0.4 ml/min) was used as a lubricant during MQL. Water (20 ml/min) was added as an auxiliary lubricant in MCT. The cooling and lubrication effects were then evaluated separately for MQL and MCT and together (by minimal quantity cooling and lubricating 'MQCL' for comparison purpose. Gear temperature was measured with a contact thermometer immediately after the completion of the milling operation.

Steady state finite element thermal models corresponding to all lubrication-cooling techniques, viz., MQL, MCT, MQCL, FL and DC were created using the experimental results. Theoretical analysis of thermo-elastic strains using the finite element method confirmed the results of experimental research. The conclusions of thermal process study confirmed the results obtained in the experimental research i.e. cooling and lubrication are unsatisfactory at dry cutting and the combination of minimal cooling and lubricating improved both, the cutting conditions and the process accuracy.

In terms of heat stress in the wheel at the end of gear milling, the cutting with flood cooling was found to be the most unfavorable case. Intense cooling caused a high temperature gradient which led to increased thermal strain. The lowest values of thermal stress were obtained for DC but the process was adverse as regards to thermo-elastic displacements. It was summarized that the minimum quantity lubrication and minimal lubrication-cooling techniques were favorable alternatives, and the strains and thermal stresses displayed intermediate values in comparison with DC and FL based gear milling.

One more and recently reported article of this series of research work by *Fratila, 2013* constitutes the findings based on the effects of environment-friendly lubrication techniques on the geometric accuracy of the milled gears. The manufacturing quality of any gear is largely a function of the geometric inaccuracy of that gear and mainly affected by the cutter (tool) condition, tool and gear blank spindle position and the induced vibrations of machine tool *(Townsend, 2011; Gupta and Jain, 2014a)*. A similar set of parameters and experimental conditions as reported by *Fratila, 2009* were employed while investigating the effects of cooling and lubrication techniques on gear accuracy. Tooth thickness, span, total tooth profile deviation, total tooth flank line deviation and pitch deviation were considered as the parameters of gear geometric accuracy. Results of the investigations revealed that for all variants of cooling/lubrication processes, the gear quality in terms of tooth profile, total tooth flank line and pitch deviation was similar to that obtained in the FL processing. However, the variation analysis of tooth distances on gear circumference identified the superiority of MQL over conventional cooling methods. In terms of tooth thickness the performance of flood cooling was the best, followed by MCQL and MCT. Finally, it was concluded that only one parameter of gear accuracy i.e. tooth thickness was affected by the lubrication techniques and that gear milling with a dry cutting environment was not recommended in order to mill good quality gears.

Investigations on the application of minimal quantity lubrication in gear hobbing focused on hob (cutter) wear and cutting force were done by *Stachurski, 2012*. Spur gears made of two different materials, viz., normalized carbon steel and alloy steel 42CrMo4 were hobbed with a cutter made of high speed steel with MQL and conventional flood cooling. The flow rate of oil in MQL was 25 ml/h and in flood cooling was 10 l/min. The investigations on hob wear rate were found similar for MQL and conventional flood cooling. Progression of cutting forces with hobbing time for both methods was comparable and on that basis alone application of the MQL method in gear hobbing was recommended as an economic and environment-friendly alternative.

Another important series of efforts based on gear hobbing with MQL was conducted by *Matsuoka et al., 2013.* A significant drawback of this work was however that the experiments were conducted by simulating gear hobbing through coated and un-coated fly tool cutting of chromium molybdenum steel on a milling machine under different lubrication conditions i.e. MQL, dry and flooded cooling. Results in terms of flank and crater wear of the tool; and surface roughness of the job during machining with a coated tool under MQL were comparatively good. Based on the co-relation with fly-tool milling, the MQL assisted gear hobbing with coated hob and at high speed was recommended.

A study reported by *Zhang and Wei, 2010* on cold air MQL gear hobbing highlights some important aspects of simultaneous minimization of gear teeth surface roughness and hob wear. A Taguchi technique integrated utility concept was employed for multi-response optimization of the gear hobbing process. Their study also aimed to determine the optimum amount of MQL, the most appropriate cold air temperature and feed rate during hobbing of medium carbon steel (C45) by YG6X hard alloy tool. The results of experimental investigations and optimization revealed 40 ml/h MQL flow rate, -45^0 C cold air temperature and 0.2 mm/rev feed rate as the optimum parameters to simultaneously minimize tool wear and surface roughness of gear teeth.

There are however also some recent developments not specifically based on gear manufacturing but rather from the perspective of complete powertrain machining e.g. crankshaft manufacturing, machining of aluminum components and fabrication of gear-box housings etc. by employing MQL techniques *(Filipovic and Stephenson, 2007; Tai et al., 2014)*, which advocate the conversion of whole powertrain machining from conventional to MQL based machining.

2.1.2. Dry-hobbing of gears

2.1.2.1. Overview

Recently the most significant advancement in gear manufacturing technology, regardless of type and size, has been demonstrated in the area of dry-hobbing. Changing from simple hobbing to dry-hobbing is an outcome of strong demand to increase productivity and reduce manufacturing cost while cutting gears *(Kage, 2004; Tokawa et al., 2001; Winkel, 2010)*. Dry-hobbing not only dramatically improves environmental issues by eliminating the need of cutting fluids and wet-chip disposal, but also effectively improves the machining efficiency and reduces the manufacturing cost by ensuring operation at high cutting speed and with minimum power consumption (Fig. 7).

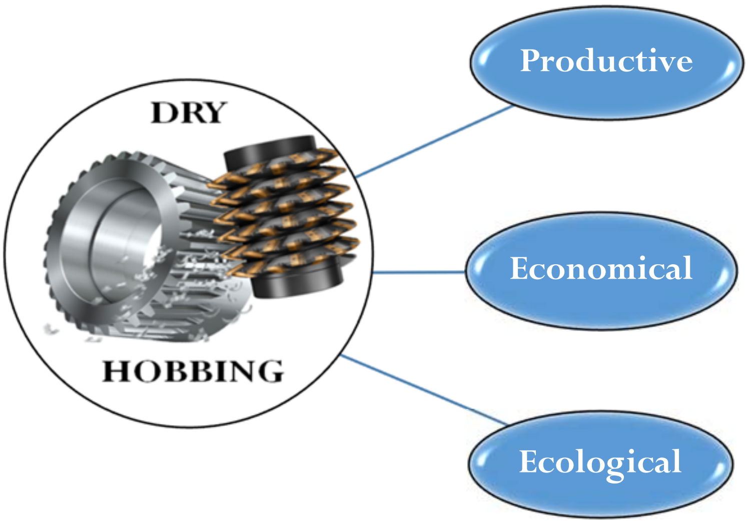


Fig. 7. Benefits of dry-hobbing.

Specialized hobs (mostly coated with TiAlN) are used for dry-hobbing without the addition of any cutting oil and are performed immediately after the heat treatment process. However, it is not used for high precision gear applications but it does produce gear qualities comparable with those produced by other finishing processes. From a safety point of view proper arrangements for swarf (waste chips) removal such as the fitment of air nozzles and dust collectors at suitable locations in the machine tool and using stainless steel covers to prevent the heat transfer to the machine tool etc. needs to be incorporated. Figure 8 depicts some essentials for ensuring high productivity during dry-hobbing of gears.

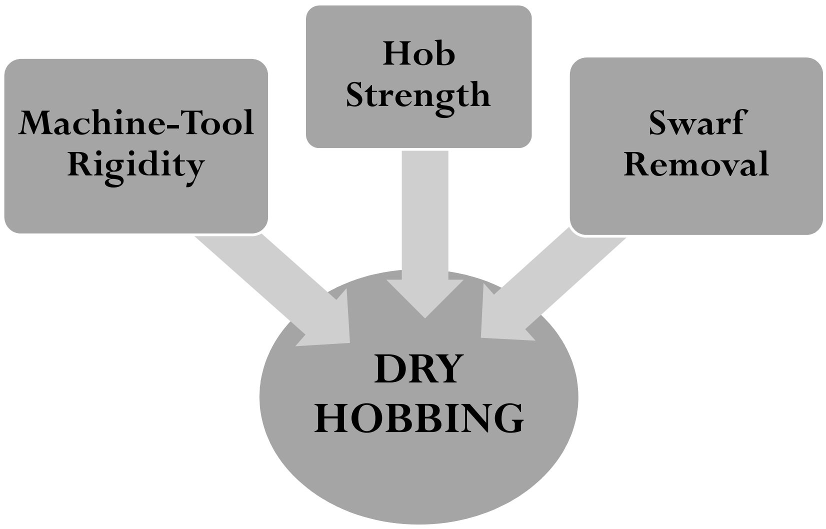


Fig. 8. Essentials for dry-hobbing.

2.1.2.2. Review of previous work on dry-hobbing of gears

The concept of dry-hobbing of gears was introduced several years ago by *Liebherr Verzahntechnik GmbH* (*Joyace, 2007*); and the significant research and development work in this field has also been conducted by *Mitsubishi Heavy Industries Ltd.*

Tokawa et al., 2001 of *Mitsubishi Heavy Industries Ltd.* reported a reduction of total hobbing cost by 34 %, a two-fold increase in cutting speed, a five times tool life extension and a 51 % reduction in electricity cost after developing a gear dry-hobbing machine tool equipped with TiAlN coated hob of high-speed steel. Considering the problems associated with carbide hobs that include high cost and unexpected chipping, TiAlN coated high-speed steel hobs were developed in order to ensure a sustainable tool life. The hob developed was termed as a ‘super dry hob’ and had excellent heat and wear resistance because of the TiAlN coating. These hobs demonstrated a fivefold increase in tool life when used to cut gears of materials such as SCM415, SCM420 and SCr420 at twice the speed of conventional wet-hobbing. After developing the advanced hob a dedicated dry-hobbing machine tool was developed by *Tokawa et al., 2001*. Firstly, an arrangement for efficient disposal of chips from the machining zone is ensured by providing a large opening under the machining zone to allow the swarf (chips) to fall through under gravity onto the chip conveyor. Thermal deformation of the hobbing machine tool was be minimized by ensuring efficient chip disposal. Secondly, a finite element analysis was conducted to so improve the bed rigidity of the machine. Three variants of the machine were developed to allow for a wide range of gear sizes

During the development of high performance and low cost gear motors *Fukunaga et al., 2003* cut helical gears by dry hobbing with special carbide hobs installed on a highly rigid CNC gear hobbing machine, directly after heat treatment. The hobbed gears had a profile accuracy of AGMA (American Gear Manufacturers Association) 11-12. Commercial production of gear motors equipped with these dry-hobbed gears were initiated with positive feedback about performance received from customers.

Abe and Fukunaga, 2010 used dry-hobbing to cut miniature gears of brass. Gear precision measurement based on the process capability index of tooth profile and tooth lead errors and cutting force were found to be similar for both dry and wet-hobbing. It was therefore suggested that dry hobbing is an environment-friendly alternative to conventional wet-hobbing.

In general dry gear cutting i.e. dry-hobbing has presented a major breakthrough in productivity, economy and ecology.

The next section presents the recent developments for achieving sustainability in gear manufacturing using some advanced gear manufacturing processes.

2.2. Advanced gear manufacturing processes

2.2.1. Overview and recent developments

As discussed in section 1.2 that all conventional gear manufacturing processes have inherent limitations and will usually require a subsequent finishing operation to produce a fit for purpose quality (Table 2) *(Gupta and Jain, 2014b)*. This finishing process adds to the consumption of extra energy, material and cutting fluids and therefore negatively affects overall sustainability. Potential single stage manufacturing of gears by wire electric-discharge machining (WEDM) and gear rolling are some of the recent developments that seek to overcome some of the drawbacks of traditional manufacturing processes by improving energy and resource efficiency. These advanced processes may have significant benefits when compared to the traditional processes, i.e. *(Gupta and Jain, 2014a; Neugebauer et al., 2013)*:

- No chip generation (in gear rolling) and significantly lower material removal (in WEDM) ensures material efficiency.
- Lower set-up time, cycle time and overall process time.
- Manufacturing and finishing of gears in a single stage not only brings about a reduction in the process chain, but also increases energy efficiency.
- Economic efficiency i.e. lower cost due to low consumption of power, material, cutting tool and fluid.
- Improved manufacturing quality of gears.
- Improved surface integrity of gears.
- Better ecological prospects.

Table 2
Limitations and corresponding gear quality of the conventional processes used for gear manufacturing *(Gupta and Jain, 2014a)*.

Gear manufacturing process	Limitations	Corresponding gear quality (*DIN No.)
Gear hobbing	➢ Generates tool marks on gear teeth ➢ Requires subsequent polishing operation for further improvement in quality ➢ Long setup time ➢ Tool wear is a major problem	9
Stamping	➢ Shaving operation is needed for final finishing ➢ Gears made by this process have tooth thickness limitations ➢ Wear and tear of die-punch is a major problem ➢ Applicable for no load to medium duty gears only	10
Extrusion	➢ To get the accuracy required for gears, a secondary drawing operation is required after extrusion ➢ Wear of extrusion die is problematic ➢ Not suitable for fine-pitched gears	12
Die casting	➢ Cannot be used for extremely accurate gear ➢ Trimming operations are necessary after the gear has been removed from the die	11
Powder metallurgy	➢ Arrangement of fine metal powder of all type is difficult ➢ Generally not suitable for gears other than spur types ➢ Where higher accuracy is required, secondary operations such as sizing, shaving, burnishing, and grinding are required	10

**Deutsche Normen- German standards for gear quality, ranges from 1(highest)-12(lowest)*

2.2.1.1. Gear rolling

Gear rolling is a cold work manufacturing technique that may be done in one of two ways i.e. flat rolling and round rolling *(Neugebauer et al., 2013)*. Cold flat rolling functions with two flat rolling tools moving in opposite directions that mesh with the rolling gear blank symmetric to rotation. A more detailed description of the technique can be accessed from *Neugebauer et al., 2007*. The scope of present paper is mainly based on some recent developments in round rolling techniques.

Round rolling of gears is an efficient incremental cold-massive forming process which forms a complete gear into a material. The bored gear blank (rotationally symmetric) coupled with small shaft is clamped in a fixture (in axial direction) which allows its rotational and axial movement. A set of rolling dies (two or three gears of the same profile and geometry) is used to form the gear teeth by compressive loading (Fig. 9). The forming process is generally divided into three phases, viz., the first phase in which a tool is punched into the pre-determined pre-forming diameter of the gear; the second is the penetration and reversal of rotation at synchronous feed and rotation speed to roll the exact number of teeth and desired tooth root diameter; and lastly the calibration of the full formed gearing profile by optimizing the surface and geometry through some additional form cycles which is followed finally by a release of the finished gear to restart the same process on new gear blank *(Milbrandt et al. 2013; Neugebauer et al., 2007)*. Mainly, carbon and alloy steels with carbon content below 0.2% such as 16MnCr5, 20MnCr5, 15CrNi6 and 20MoCrS5 are typically rolled in this manner.

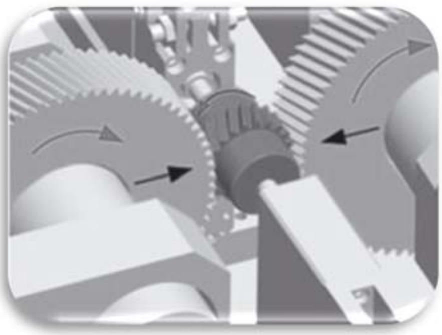


Fig. 9. Gear rolling

Controlling the material flow and the size of the rolling force remains significant challenges that must be overcome by proper tool design and multi stage rolling operations. These gears display some useful properties. Because of the material flow during the process, these gears have a contour following texture orientation. This characteristic leads to improved surface mechanical properties. A superior surface quality is another attribute of rolled gears.

Not only does rolling usually need no finishing operation, but it refines the microstructure of the gear also.

As discussed above, the rolling process is an efficient alternative to conventional cutting processes to manufacture gears as it possesses several advantages i.e. significantly shorter process times, no material loss and subsequently no chip disposal, a high surface quality up to 0.4 μm and geometric accuracy up to DIN-7 *(Neugebauer et al., 2013)*. Previously, this process was used almost exclusively for finishing of gears only but with the advent of new technologies this process may be employed for gear manufacturing as well. The work conducted by *Neugebauer* and his team at *Fraunhofer IWU in Chemnitz, Germany* for gear rolling, set the new standards in gear manufacturing for producing high quality gears. A detailed investigation and analysis of the interaction between tools, machine and forming processes in gear rolling was reported by *Milbrandt et al., 2013; Neugebauer et al., 2007; Neugebauer et al., 2010*.

Neugebauer and his team also developed a cold rolling process for manufacturing of helical gears. Research was conducted to improve the process efficiency and accuracy using optimization techniques including tool load analysis, finite element analysis (to determine pre-formed geometry of gear) and material flow analysis *(Milbrandt et al. 2013; Neugebauer et al., 2010)*. For tool load analysis strain gauges were installed underneath the tool gearing and succeeded in obtaining quality strain information throughout the rolling process. Methods of visco-plasticity was used for material flow analysis in which the phased penetration of the tools into the rotationally symmetric pre-form gear blank was analyzed at different values of penetration rate and rotational tool speed. The results of the visco-plastic analysis was implemented into the finite element model and the optimized model then produced comparative and useful results for material flow analysis in the form of natural strains. This laid the foundation of gear rolling and its simulation with the ultimate aim of shorter gear rolling development time and improved gear quality.

2.2.1.2. Wire Electric-Discharge Machining

Electric discharge machining (EDM) and its variants such as wire electric-discharge machining (WEDM), wire electric discharge grinding (WEDG), micro-EDM and micro-WEDM have been acknowledged as potentially significant substitutes for conventional processes because of their excellent repeatability, geometrical accuracy, surface integrity quality, short set-up time, running un-attendant for long time periods, ease of cutting complex shapes and geometries, elimination of mechanical stresses during machining, ability to cut any electrically conductive material irrespective of its hardness, toughness or melting point, and mostly avoiding the need of subsequent finishing operations *(Davim, 2013; Gupta and Jain, 2014a; Rahman et al., 2014)*.

Wire electric discharge machining, an important variant of EDM, is currently recognized widely as an alternative method for sustainable manufacturing of gears. WEDM produces small quantities of precision gears with unique shapes by eliminating the need for special tooling, cutting fluid and most importantly post finishing operation. Moreover, the gears produced by WEDM are higher in quality and cheaper in cost comparatively *(Gupta and Jain, 2014a)*.

The WEDM process removes the workpiece material through a series of high frequency spark discharges, with each discharge removing a small volume of workpiece material by melting and vaporizing it. The volume removed by a single spark may be in the range of 10^{-6} to 10^{-4} mm^3 but this basic process is repeated typically about 10,000 times per second *(El-Hofy, 2005)* . Figure 10 depicts the schematic of a typical wire-EDM process of a gear.

The gear blank is mounted and clamped on the main work table of the WEDM machine tool which moves along the X and Y-axes, in steps of a few microns by means of a stepper motor. A travelling wire that is continuously fed from a wire feed spool passes through the gear blank towards the waste-wire box. Along its travelling path, the wire is kept under tension, between a pair of wire guides which are situated on both (lower and upper) sides of the gear blank. As the material removal or machining proceeds, the work table carrying the gear blank is displaced transversely along a predetermined path (based on the geometry of the gear) which is stored in terms of linear and circular elements in the controller via a computer numerically controlled (CNC) program that strives to maintain a constant machining gap. During machining the cutting zone is continuously flushed with deionized water as dielectric. An ion exchange resin is used in the dielectric distribution system, in order to prevent an increase in conductivity and therefore to maintain a constant water conductivity *(Gupta and Jain, 2014b)*.

Various investigations have reported on machining of gears by WEDM *(Ali et al., 2010; Gupta and Jain, 2014a, b, c, d; Talon et al., 2010)*. Recently work was conducted to provide a more in depth understanding on WEDM of gears more specifically to assess its feasibility as a superior substitute to conventional methods for gear manufacturing *(Gupta and Jain, 2014a, b, c, d)*. These investigations were based on evaluating the effects of WEDM parameters on gear geometry and surface integrity and to improving them at later stage.

High quality miniature gears were manufactured by ensuring minimum **wire-lag* to improve the geometric accuracy *(Gupta and Jain, 2014c)* and non-violent spark discharges at low energy to improve the surface finish *(Gupta and Jain, 2014d)* without the aid of any post finishing operation. The WEDMed miniature gears achieved a manufacturing quality to DIN-5 which is superior to the quality of gears manufactured by other conventional processes and on par with gears finished by grinding, honing, and shaving.

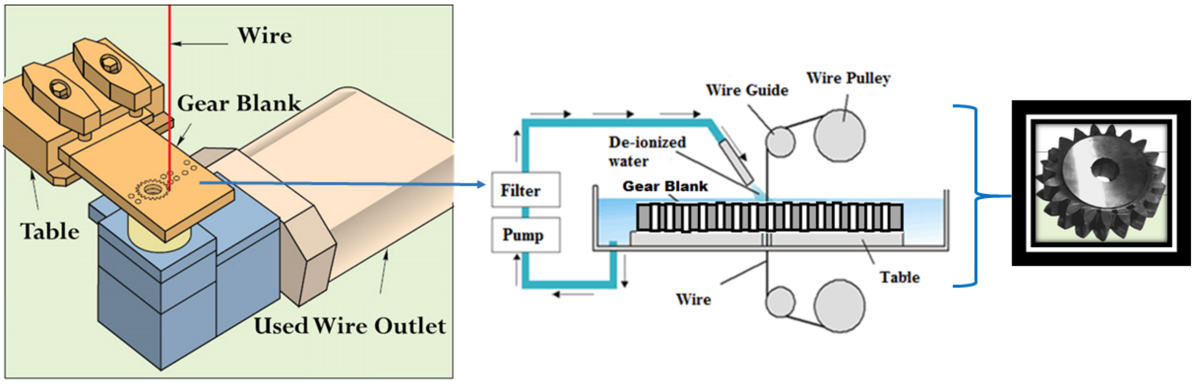


Fig. 10. Schematic representation of wire electric-discharge machining of a gear.

Other surface integrity descriptors such as an average roughness of up to 1 μm and a maximum roughness of 6.4 μm were satisfactory and suggests an extended service life *(Gupta and Jain, 2014d)*; Good bearing area characteristics with favourable skewness (-0.165) and kurtosis (2.455) parameters suggest tribology fitness while negligible thermal effects and burr-free uniform tooth profiles implies defect-free tooth flank surfaces *(Gupta and Jain, 2014a,b)*. It was also reported that material wastage during WEDM is appreciably less and more comparable with a punching process. Moreover, if the process is controlled precisely then simultaneous manufacturing of both the external and internal gears are possible.

Gupta and Jain reported that the best quality gear produced by WEDM achieved DIN-5 and was fabricated in about 15 minutes at a cost of approximately €5 whereas the cost of a similar gear of comparable quality if manufactured by conventional means including cutting and finishing processes is nearer to €100. In terms of overall productivity related to manufacturing of high quality gears, WEDM seems to have a distinct advantage when compared to other conventional processes *(Gupta and Jain, 2014a)*.

** Deviation of wire from its intended path*

The experimental investigations conducted suggests that wire electric discharge machining (WEDM) is a superior, economical, and viable alternative to conventional processes of gear manufacturing.

The next section presents a number of other recent strategies for sustainable manufacturing of gears.

2.3. Other strategies used for sustainable manufacturing of gears

This section briefly discusses implementation of some other important strategies to achieve sustainability in gear manufacturing. Gear manufacturers globally are attempting to achieve a new paradigm in gear hobbing by ensuring extended tool life at high hobbing speeds by employing advanced materials for hob (tool) manufacture and coating. Cemented carbide has been suggested as a substrate material for hob manufacture to obtain high speed and economical hobbing *(Karpuschewsk et. al., 2014).* Hob wear can be minimized and increasing productivity obtained by dry-hobbing using Ti-doped AlCrN coatings *(Lümkemann et al., 2014).* The evolution of new high speed hobs where the core material is carbon-free iron cobalt and molybdenum to overcome the problems associated with high temperature hardness *(Falk, 2012)*.

Jeong and his team claimed to have developed a sustainable cold extrusion process for manufacturing of helical gears used in automatic transmissions *(Jeong et al., 2013; Yun et al., 2014)*. Finite element analysis (FEA) was used to design the punch-dies used in the cold extrusion of gears while maintaining the gear accuracy as the main aim out of various other aspects considered. Based on the outcomes provided by the FEA helical gears were extruded. A detailed investigation of the environmental effects of the cold extrusion process and a comparative study between conventional machining and cold extrusion based on life-cycle assessment was also reported. Energy consumption and CO_2 emissions of the helical gear manufacturing processes were investigated. Manufacturing of helical gears with the cold extrusion process resulted in a reduction in energy consumption of 25-49 % and a reduction in CO_2 emissions of approximately 45% when compared to conventional gear manufacturing. Potential improvements in strength of the extruded helical gears were suggested as the durability and fatigue strength of machined gears are generally lower due to the flow-line interruption. Improved geometric accuracy of the cold extruded gears was also measured. Overall improved performance and a reduction in emissions and energy consumption were used as motivation for concluding that cold extrusion is more environment-friendly and a viable alternative to conventional machining processes for manufacturing of helical gears.

Other significant developments as regards to efficient and sustainable gear manufacturing systems are ongoing as part of research and development of various large gear manufacturing industries but, due to the proprietary nature of the technologies and professional competitiveness those are not available or disclosed in the public domain.

The next section briefly summarizes the review and recommends some future tasks to be achieved towards sustainability in gear manufacturing.

3. Outlook

Strict environmental regulations and international competitiveness are forcing industries worldwide to adopt efficient, economical and ecological means to produce products. The present article provides a review of the current state of the technology and the level of the effort being conducted by engineers and manufacturers in developing sustainable ways of gear manufacturing. Several strategies and techniques to achieve sustainability in gear manufacturing have been reviewed and discussed. These include: using environment-friendly lubricants and lubrication techniques such as MQL assisted gear cutting, cryogenic and dry gear hobbing, employing advanced gear manufacturing processes such as gear rolling and WEDM. Significant improvements have been reported in productivity, cost, tool life, gear quality, energy usage, waste generation and waste management strategies that all collectively improve the sustainable manufacturing of gears.

Nevertheless, further effort is required in exploring the sustainability aspects of other gear manufacturing processes including stamping, die-casting and powder metallurgy.

Other areas where further work required are employing advanced manufacturing processes for other types of gear shapes, size and materials; sustainability at process planning level; new materials and coatings for gear hobs; detailed investigation to determine the possible benefits of MQL and cryogenic cooling type lubrication techniques to gear hobbing, shaping and milling operations; new efforts towards minimizing the number of manufacturing stages or shortening the process chain, to produce gears of high manufacturing quality and surface integrity; to maintain energy and economic efficiency; clean, green, safe and healthy environment or simply for overall sustainability.

References

Astakhov, V.P., Joksch, S., 2012. Metalworking fluids for cutting and grinding, fundamental and recent advances. Woodhead Publishing Ltd., New Delhi.

Abe, T., Fukunaga, K., 2010. Gear precision and gear cutting force at dry hobbing gear cutting for gears made of brass material. Key Engineering Materials. 447-448, 297-300.

Ali, M.Y. et al., 2010. Comparative study of conventional and micro-WEDM based on machining of meso/micro sized spur gear. International Journal of Precision Engineering and Manufacturing 11(5), 779-784.

Davim, J.P., 2010. Sustainable Manufacturing, First ed. John Wiley & Sons, Inc., New Jersey.

Davim, J.P., 2013. Nontraditional Machining Processes: Research Advances, First ed. SPRINGER, London.

Debnath, S., Reddy, M.M., Yi, Q.S., 2014. Environmental friendly cutting fluids and cooling techniques in machining: a review. Journal of Cleaner Production. 83, 33-47.

El-hofy,H., 2005. Advanced Machining Processes, Non-traditional and Hybrid Machining Processes, First ed. Tata McGraw-Hill Companies Inc., New York.

Emami, M., Sadeghi, M.H., Sarhan, A.A.D., Hasani, F., 2014. Investigating the minimum quantity lubrication in grinding of Al_2O_3 engineering ceramic. Journal of Cleaner Production. 66, 632-643.

Falk, T., 2012. A new material for high speed hobbing. Gear Solutions Magazine, pp. 31-37.

Filipovic, A., Stephenson, D.A., 2007. Minimum quantity lubrication (MQL) applications in automotive powertrain machining. Machining Science and Technology. 10, 3–22.

Fratila D., 2009. Evaluation of near-dry machining effects on gear milling process efficiency. Journal of Cleaner Production. 17, 839–845.

Fratila, D., Radu, A., 2010. Modeling and comparing of steady thermal state at gear milling by conventional and environment-friendly cooling method. International Journal of Advanced Manufacturing Technology. 47, 1003–1012.

Fratila, D., 2013. Research of environment-friendly techniques influence on gear accuracy in context of sustainable manufacturing. Proceedings of the Romanian Academy, Series A, 14, 56–63.

Fratila, D., 2014. Environment friendly manufacturing processes in the context of transition to sustainable production, in: Hashmi, S. (Eds.), Comprehensive Materials Processing. Elsevier, Amsterdam, pp. 163-164.

Fukunaga, K., Inoue, S., Yonekura, M., Sakuragi, I., 2003. Direct dry hobbing of high hardened material: RGC (Round bar gear cutting) method. In: Proceedings of the 9th International Power Transmission and Gearing Conference, Illinois, pp. 551-557.

Garetti, M., Taisch, M., 2012. Sustainable manufacturing: trends and research challenges. Production Planning & Control: The Management of Operations. 23, 83-104.

Gupta, K., Jain, N.K., 2014a. Comparative study of wire-EDM and hobbing for manufacturing high quality miniature gears. Materials and Manufacturing Processes. 29, 1470-1476.

Gupta, K., Jain, N.K., 2014b. On surface integrity of miniature spur gears manufactured by wire electrical discharge machining. International Journal of Advanced Manufacturing Technology. 72, 1735-1745.

Gupta, K., Jain, N.K., 2014c. Analysis and optimization of the micro-geometry of miniature gears manufactured by wire electric discharge machining. Prec Eng. 38, 728-737.

Gupta, K., Jain, N.K., 2014d. Analysis and optimization of the surface finish of wire electrical discharge machined miniature gears. Proc IMechE B J Eng Manuf. 228, 673-681.

Jeong, M.S., Lee, S.K., Yun, J.H., Sung, J.Y., Kim, D.H., Lee, S., Choi, T.H., 2013. Green manufacturing process for helical pinion gear using cold extrusion process. International Journal of Precision Engineering and Manufacturing. 14, 1007-1011.

Joyce, K., 2004. Producing green gears. Gear Production, downloadable at http://www.machinery.co.uk.

Jovane, F., Yoshikawa, H., Alting, L., Boer, C.R., Westkamper, E., Williams, D., Tseng, M., Seliger, G., Paci, A.M., 2008. The incoming global technological and industrial revolution towards competitive sustainable manufacturing. CIRP Annals – Manufacturing Technology. 57, 641–59.

Kage, H., 2004. A new design for dry hobbing gears. Gear Solutions Magazine, pp. 18-24.

Karpuschewski, B., Beutner, M., Wengler, M., Kochig, M., 2014. High speed gear hobbing with cemented carbide hobs. MM Science Journal. 527-532.

Kuram, E., Ozcelik, B., Demirbas, E., 2013. Environmentally friendly machining: vegetable based cutting fluids. In: Paulo Davim, J. (Ed.), Green Manufacturing Processes and Systems. Springer, Berlin Heidelberg, 23-47.

Lawal, S.A., Choudhury, I.A., Nukman, Y., 2013. A critical assessment of lubrication techniques in machining processes: a case for minimum quantity lubrication using vegetable oil-based lubricant. Journal of Cleaner Production. 41, 210-221.

Lumkemann, A., Beutner, M., Morstein, M., Köchig, M., Wengler, M., Cselle, T., Karpuschewski, B., 2014. A new generation of PVD coatings for high-performance gear hobbing. In: Proceedings of the 11th International Conference 'The-A Coatings', Thessaloniki, pp. 149-158.

Matsuoka, H., Ryu, T., Nakae, T., Shutou, S., Kodera, T., 2013. Fundamental research on hobbing with minimal quantity lubrication of cutting oil-comparison of cutting performance with dry cutting. Advances in Materials Science and Applications. 2, 88-100.

Matsuoka, H., Ryu, T., Nakae, T., Shutou, S., Kodera, T., 2013. Fundamental research on hobbing with minimal quantity lubrication of cutting oil- influence of hardness of work materials under several cutting conditions. Advances in Materials Science and Applications. 2, 154-167.

Milbrandt, M., Lahl, M., Hellfritzsch, U., Sterzing, A., Neugebauer, R., 2014. Rolling processes for gear manufacturing – potentials and challenges. In: Proceedings of the 13th International Conference on Competitive Manufacturing, Stellenbosch.

Neugebauer, R., Putz1, M., Hellfritzsch, U., 2007. Improved process design and quality for gear manufacturing with flat and round rolling. Annals of the CIRP. 56, 307-312.

Neugebauer, R., Hellfritzsch, U., Lahl, M., Schiller, S., Milbrandt, M., 2010. Innovations in rolling process of helical gears. In: Proceedings of the International Conference on Advances in Materials and Processing Technologies, Paris, pp. 569-574.

Neugebauer, R., Hellfritzsch, U., Lahl, M., Milbrandt, M., Schiller, S., Druwe, T., 2013. Gear rolling process, Process machine interactions, Lecture Notes in Production Engineering, SPRINGER, Berlin Heidelberg, pp. 475-490.

Pusavec, F., Krajnik, P., Kopac, J., 2010. Transitioning to sustainable production – Part I: application on machining technologies. Journal of Cleaner Production.18, 174–184.

Rahman, M., Asad, A.B.M.A., Wong, Y.S., 2014. Introduction to advanced machining technologies, in: Hashmi, S. (Eds.), Comprehensive Materials Processing. Elsevier, Amsterdam, pp. 1-13.

Sarıkaya, M., Güllü, A., 2015. Multi-response optimization of minimum quantity lubrication parameters using Taguchi-based grey relational analysis in turning of difficult-to-cut alloy Haynes 25. Journal of Cleaner Production. 91, 347-357.

Sharma, V.S., Singh, G.R., Sørby, K., 2015. A review on minimum quantity lubrication for machining processes. Materials and Manufacturing Processes. DOI: 10.1080/10426914.2014.994759.

Stachurski, W., 2012. Application of minimal quantity lubrication in gear hobbing. Mechanics and Mechanical Engineering. 16, 133–140.

Tai, B.L., Stephenson, D.A., Furness, R.J., Shih, A.J., 2014. Minimum quantity lubrication in automotive powertrain machining. Procedia CIRP. 14, 523 – 528.

Talon, J. L. H. et al., 2010. Manufacturing of a spur tooth gear in Ti-6Al-4V by electrical discharge. Computer Aided Design. 42, 221-230.

Tawakoli, T., Hadada, M.J., Sadeghi, M.H., 2010. Influence of oil mist parameters on minimum quantity lubrication (MQL) grinding process. International Journal of Machine Tools and Manufacture. 50, 521–531.

Tokawa, T., Nishimura, Y., Nakamur, Y., 2001. High productivity dry hobbing system. Technical Review of Mitsubishi Heavy Industries Ltd. 38, 27-31.

Townsend, D.P., 2011. Dudley's Gear Handbook. Tata McGraw-Hill Publishing Company, New Delhi, India.

United Nations General Assembly, 96th plenary meeting, 11 December 1987, Report of the World Commission on Environment and Development, A/RES/42/187.

Weinert, K., Inasaki, I., Sutherland, J.W., Wakabayashi, T., 2004. Dry machining and minimum quantity lubrication. CIRP Ann Manuf Technol. 53, 511–537.

Winkel, O., 2010. New developments in gear hobbing. Gear Technology Magazine, pp. 45-52.

Yun, J.H., Jeong, M.S., Lee, S.K., Jeon, J.W., Park, J.Y., Kim, G.M., 2014. Sustainable production of helical pinion gears: environmental effects and product quality. International Journal of Precision Engineering and Manufacturing-Green Technology. 1, 37-41.

Zhang, G., Wei, H., 2010. Selection of optimal process parameters for gear hobbing under cold air minimum quantity lubrication cutting environment. In: Proceedings of the 36th International MATADOR Conference, Manchester, pp. 231-234.

United Nations, Millennium development goals. Downloadable at: http://www.un.org/millenniumgoals/environ.shtml.

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Fig. 3. A "road map" to achieve sustainability in gear manufacturing.

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Table 1

A summary of recent research work on sustainable gear manufacturing strategies including techniques.

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