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REPLACING GRINDING WITH HARD TURNING – A SOLUTION FOR GREEN MACHINING

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Abstract: *The global competition forces the manufacturing industry players to permanently innovate, thus the pressure for eco-friendly and sustainable products arise. Once with the occurrence of novel geometries, materials and coatings for cutting tools as well as the development of high precision machine-tools hard turning has quickly become an important alternative for replacing grinding in many applications. The concerns for this solution have started about one decade ago and are applied in top-industries with a strong focus on competitiveness. This paper contains a systematic study of replacing grinding with hard turning which highlights the advantages, the challenges and some possible solutions to meet challenges, stresses the environment benefits of this phenomenon and provides quantitative models for determining the limits and conditions of using hard turning, incorporating both the relevant experiences presented in literature and the author's direct researches previously disseminated.*

Key words: *hard turning, cost-effective, green machining, vegetable oils.*

1. INTRODUCTION

The technological changes plays a key role in handling manufacturing limits and represent one of the main factor of competition. Furthermore, it plays an important role in changing the industries structure and contributes to launching new industries [1]. The precision manufacturing industry is characterized by high precision, accuracy and low roughness levels. These features can be obtain in traditional machining of parts with hardness higher than 55 HRC units by grinding, but once with the advancement of new materials and geometries for cutting inserts as well as the development of rigid and high precision machine-tools (lathes) hard turning has become quickly a serious alternative for replacing grinding in many applications [2].

In order that hard turning (HT) can replace grinding (GRI) on steel parts machining, heat treated and brought to a hardness higher than 55 HRC units, as a final cutting process, the hard turning process shall meet three criteria [3]:

- technological criteria – the cutting tool and the machine tool shall be capable to achieve the technical conditions required by the technical drawing;
- qualitative criteria – being final process, the surfaces must be lack of burns or cracks;
- cost-effective criteria - hard turning must be cheaper than grinding; if the hard turning cost/part is higher than grinding cost/part, then hard turning shall compensate this cost difference within productivity.

The materials which meet the hardness requirements and can be used for hard turning cutting insert, according to [4, 5, 6] are: sintered carbides (hardmetal) which are a mixture between tungsten and cobalt, ceramic materials e.g. aluminium oxide – Al2O3 and silicon nitride – Si3N4, polycrystalline cubic borod nitride (PCBN) and polycrystalline diamond (PCD). Over these materials, usualy is added physical (PVD – Physical Vapor Deposition) or chemical (CVD – Chemical Vapor Deposition) a layer (coating) of 3-7µm thickness with the purpose to obtain a longer tool life. The most usually coatings are: titanium nitride (TiN), titanium carbo-nitride (TiCN), titanium aluminum nitride (TiAlN) and aluminum oxide (Al2O3) [2].

2. THE ADVANTAGES AND THE CHALLENGES OF REPLACING GRINDING WITH HARD TURNING

2.1 Advantages of hard turning

The advantages that hard turning it has compared to grinding are described in [2, 5–9] as follows:

- at grinding the parts can be slightly deformed and very often can appear burns because of the large quantity of heat generated on the contact area - by hard turning these risks can be avoided;
- the complex surfaces, profiled, can be machined often with only one tool;
- the material remove rate is higher on hard turning than grinding – it means that machining time is lower on hard turning;
- the setup time for hard turning machine (lathe) is lower than grinding machine setup time;

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- the transition to green machining is easier and cheaper on hard turning than grinding, since on hard turning the coolant can be eliminated;
- the chip resulted from har turning can be recycled, that means that is a sorce ov revenue;
- hard turning inserts can be reground/resharpened and used for roughing operation;
- hard turrning machine is a lower asset than grinding machine;
- lathe energy efficiency is higher compared with grinding machine;
- mostly, the roughness (*Ra*, *Rz*) is superior at hard turning due to multi-radii (wiper) inserts.

2.2 Challenges and limits for HT

The challenges that hard turning have to overcome in order to replace grinding are presented in Table 1.

Even if HT has many advantages compared to grinding and can replace it in many applications, there are also some areas where grinding remains for the moment the right finishing operation. At the parts where the final surface can't be fully obtained with the same tool and an additional tool is required, this change would not be possible due to multiple factors e.g. tools measurement errors, cutting tools manufacturing accuracy, machine-tool components movement errors, which can affect the accuracy and the quality of the part [2]. In terms of expected tolerances, at hard turning is a little harder to obtain micron precision and regarding shape and position deviations, hard turning and grinding tend to be similar. However due to last advancements in machine-tools manufacturing the accuracy of hard turning was quite improved.

In medical engineering, aerospace engineering and some automotive divisions it is almost impossible, to change grinding with hard turning due to customers' severe requirements and due to lack of proves which can demonstrate that the turned and ground surfaces have similar characteristics [2].

3. THE ENVIRONMENTAL CONCERNS

The environmental issues have begun to be seriously considered by the companies from manufacturing industry, required on the one hand by quality standards and on the other by the employees' health. Green manufacturing, that emerged as a necessity for sustainable development, is a relatively new concept which aims to minimize the pollution through sustainable process and product design [31], to eliminate inappropriate use of resources, to improve the products recycling, to minimize polluting emissions [32], to create

Table 1

Challenges for hard turning

Challenge	Description	Possible solutions	Ref.
1. Process cost	It is widely known that PCBN and PCD insert are relatively expensive. Also, using minimal quantity lubrication (MQL) technique is required additional energy for high-air pressure (compressed air). Hence, the tool cost and energy cost are the main factors in achieving higher efficiency than grinding.	• Ceramic inserts are a low cost alternative; they hold high melting point, excellent hardness and good wear resistance; • PCBN and PCD inserts can be reground and used for roughing machining; • MQL technique using vegetable oil is the way to reduce the coolant cost.	[2, 3, 7, 10–18]
2. White layers (WL)	WL are often associated with a phase transformation. There are very slight and hard layers and can appear due to temperature in cutting zone e.g. rapid heating and cooling, cutting parameters, tool wear or surface reaction with different environments. The researches indicate that white layers influences negatively the component life.	• Optimal cutting parameters setting; • Minimal Cutting Fluid Application (MCFA) • Dry machining using shield gas (Argon 80% with CO2 20%) as coolant; • Cryogenic machining with liquid nitrogen jet (LN2) or carbon dioxide.	[19–25]
3. Tool wear	Tool wear is an important issues for eco-efficiency of HT. To achieve a low cost machining the tool life shall be as high as possible. The biggest challenge for HT regarding tool wear is the super-alloys machining.	• Statistical methods and models e.g. Taguchi's technique, analysis of variance and artificial intelligence approaches e.g. artificial neural network for modeling and prediction to obtain optimal tool life; • MCFA and MQL; these techniques lead to increase of tool life.	[7, 12, 13, 16, 18, 25–27]
4.Interrupted surfaces	The interrupted surfaces are a big challenge since the inserts for HT are brittle and have low mechanical shock resistance. These issues are leading to inserts breaking or chipping.	• CBN-ceramic mixture or CBN with an added ceramic phase cutting inserts with round edge or 0.1-0.3 mm × 20^o-30^o chamfer; • Optimal depth of cut in relation with the insert nose radius.	[27–30]

clean & safety workplaces [33], to reduce the environmental impacts of manufacturing [34] and to maximize resource efficiency [31].

The manufacturing industry is a major consumer of resources e.g. water, electricity, earth resources (iron, aluminum etc.) and therefore may represent the starting point for developing and adopting future strategies based on sustainable growth and decrease of greenhouse gas emissions. In machining field, the cutting processes are also resource-intensive, thus the concerns and future researches in green manufacturing can be targeted on four main elements, which can lead to green production and eco-innovation, namely green energy, energy-efficient machine-tool, recyclable cutting tools and biodegradable cutting fluids [35].

In manufacturing, nowadays, the traditional flood cooling is a positive aspect since greatly increase the tool life, but at the same time is a negative aspect since the cutting fluid contain many synthetic additives harmful both, for workers and environment, requires proper and expensive infrastructure for transport, storing and recycle [33, 36] and is a fairly high cost for users, estimated at about 15% from manufacturing costs [26, 32, 33, 36]. These issues have pushed the scientific community to develop new, more environmentally friendly, methods and techniques to eliminate the traditional flood cooling and therefore appeared techniques as minimal quantity lubrication (MQL) and minimal cutting fluid application (MCFA), cryogenic machining and gas cooling. This section discusses only the MQL technique. MQL is, as its name implies, a technique that use a small quantity of metal working fluid (MWF) [36] in order to obtain cooling and lubrication in a cutting process [26, 32, 36]. The techniques consists in applying (spraying), in the form of mist [36], a small amount of oil in a compressed air jet in the cutting area, at a flow rate of 80-100mL/h [26, 32] as an eco-friendly alternative to flood cooling [32, 36]. Compared with flood cooling, this technique shown many advantages e.g. lower costs associated with cutting fluid and energy, provide a more efficient lubrication, ensure a cleaner workplace, minimize the ecological risks and lead to a better quality of products [32, 36]. Among the most environmentally friendly and cheaper lubricants that could substitute the flood cooling are found the vegetable oils which, according to [16], are superior to mineral-based oils in terms of performance. Many authors studied the capability of these lubricants, in different cutting operations, and the most used oils were soya bean oil, sunflower oil [16], palm oil, ground nut oil [17], coconut oil [16, 18] and castor oil [17, 26]. From the results of these studies we find that the features analyzed e.g. surface roughness, cutting forces and tool wear were superior when was used vegetable oil, compared to dry machining and flood cooling.

From previous researches it is know that the vegetable oils have a positive impact in machining and according cu [35] the perspective of hard turning on vegetable oil as bio cutting fluid using MQL technique is:

- reduction in cutting force and constant cutting speed which means decrease of energy consumption (lower energy cost) and lower tool wear i.e. higher tool life and lower tools cost;
- reduction in cutting force and an increase of cutting speed which means same energy consumption and an increase of productivity.

4. THE ECONOMIC PERSPECTIVE OF REPLACING GRINDING WITH HARD TURNING

The necessary condition for a factory to be more cost-effective when is manufacturing and finishing a part through HT instead of GRI, within a certain time period, according to [3] is:

$$(P_{s_p} - C_{total_{p,HT}}) \cdot Q_{p,HT} > (P_{s_p} - C_{total_{p,GRI}}) \cdot Q_{p,GRI} \quad (1)$$

in which: P_{s_p}- selling price of part p [mu/pc]; C_{total_p} – total cost of part p, using HT or GRI [mu/pc]; Q_p – production volume obtained of part p, using HT or GRI [pc/tu]; *mu* – monetary unit; *tu* – time unit; *pc* – piece.

The difference between selling price and total cost of a part is the profit obtained. Thus, the condition (1) become:

$$P_{r_{p,HT}} \cdot Q_{p,HT} > P_{r_{p,GRI}} \cdot Q_{p,GRI} \quad (2)$$

in which: P_{r_p} - the profit of a part p, using HT or GRI [mu/pc];

The condition (2) became:

$$\frac{Q_{p,HT}}{Q_{p,GRI}} > \frac{P_{r_{p,GRI}}}{P_{r_{p,HT}}} \quad (3)$$

If $\frac{Q_{p,HT}}{Q_{p,GRI}}$ is the productivity factor ($P_{,f}$) and $\frac{P_{r_{p,HT}}}{P_{r_{p,GRI}}}$ ($P_{r,f}$) is the profit factor, thus the necessary condition for hard turning to be more cost-effective than grinding, within a certain time period, in an short form, is:

$$P_{,f} > {P_{r,f}}^{-1} \quad (4)$$

Therefore, the benefit zone for each machining operation can be seen in Fig. 1.

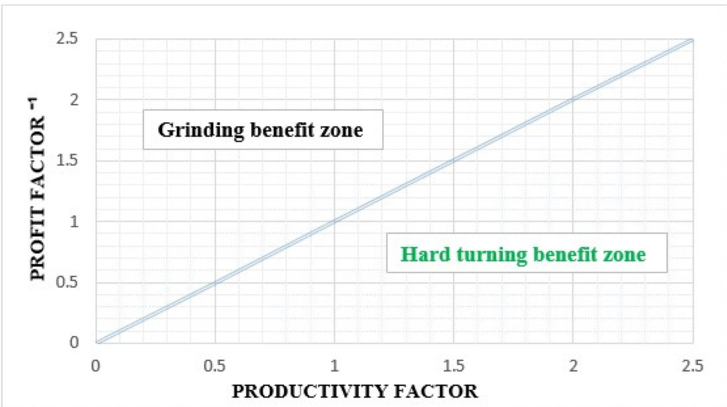

Fig. 1. The benefit zones of processess [3].

In a detailed form, the condition take another form. The total cost of part is:

$$C_{total_{p,i}} = C_{teh_{p,i}} + A_c \text{ [mu/pc]} \quad (5)$$

in which: $C_{te\ p,i}$ – the technology influenced cost of part p, using i process (HT or GRI) [mu/pc]; A_c – the rest of costs which compose the total cost of a part (e.g. raw material, heat treatment etc.), these being the same regardless of the finishing process chosen [mu/pc].

The technology influenced cost [37] in an extended form is made up of the following cost elements:

$$C_{the_{p,i}} = \frac{C_{a_i} + C_{r_i}}{Q_{p,I}} + C_e \cdot N_{Kw_{p,I}} + C_{l_i} \cdot M_{t_{p,i}} + \frac{A_{t_i} \cdot T_{M_{p,i}}}{D_i} + C_{d_i} + C_{col_i} - R_{rec} \quad (6)$$

where C_a – depreciation cost of machine tool [mu/tu]; C_r – equipment maintenance cost [mu/tu]; C_e – the cost of energy [mu/kWh]; N_{kW_i} – number of kWh consumed for a part p [kWh/pc]; C_l – labour cost [mu/min]; M_{t_p} – manufacturing time of a part p [min/pc]; A_t – acquisition price of tool [mu]; D – tool life (durability) [min]; T_{M_p} – machining time for a part p [min/pc]; C_{col} – coolant cost [mu/pc]; C_d – specific tools cost associated to process (e.g. turning knifes, jaws etc.) [mu/pc]; R_{rec} – revenues from waste recovery (chip, tools) [mu/pc].

As we discussed in chapter 2 an advantage of HT is that the insert can be reground. To obtain similar features as on GRI, at low cost, it is mandatory to use two kind of insert in hard turning: one shall be a wiper insert for finishing and one for roughing, cheaper, which can be reground. The machining time T_M is shared in two categories: roughing time $T_{M,R}$ and finishing time $T_{M,F}$. In this case the tool cost, $A_{t_i} \cdot T_{M_{p,i}}/D_i$ in rel. 6, for hard turning will be:

$$C_{t_{HT}} = \frac{A_{t_F} \cdot T_{M,F}}{D_F} + \left(\frac{\frac{A_{t_R} \cdot T_{M,R}}{D_R} + \frac{R_{t_R} \cdot T_{M,R}}{D_{Rec}} \cdot n}{n+1} \right) \quad (7)$$

where: $C_{t_{HT}}$ – hard turning tool cost [mu/pc]; A_{t_F} – acquisition price of finishing tool [mu]; D_F – tool life of finishing insert [min]; A_{t_R} – acquisition price of roughing tool; D_R - tool life of roughing insert [min]; R_{t_R} – reground price of roughing tool; D_{Rec} – tool life of reground insert; n – number of regrounds.

5. CONCLUSIONS

In this paper the economic and ecological advantages of HT are highlighted and discussed. It is proved that HT, now, is the best option to replace GRI in many application. Even if it has to face some challenges, the researches in this field shown that HT is a flexible alternative and most often it is more cost-effective than GRI due to higher productivity. The environmental concerns in industry will play a key role in transition to green manufacturing since the importance of green machining for sustainable manufacturing is obvious and hard turning yields lots of environmental benefits e.g. elimination of flood cooling and implementation of biodegradable vegetable oils. The vegetable oils seems to be cheap and viable choice to replace traditional flood cooling in many industrial application since the outcomes proved that these biodegradable oils yield better performance in terms of roughness, cutting force, power consumption, tool wear and specific energy [36]. Further the paper reveal that hard turning is an appropriate choice towards sustainable development, environmentally friendly machining and energy saving.

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