The Economic Efficiency of Replacing Grinding with Hard Turning

ARSENE Bogdan
Transilvania University of Brașov, Romania, arsene.bogdan@unitbv.ro
CALEFARIU Gavrilă
Transilvania University of Brașov, Romania, gcalefariu@unitbv.ro

Abstract
The precision manufacturing industry is characterized by high precision and low roughness levels. The hard turning operation became in the last years a serious alternative for replacing grinding at finishing machining of the parts with hardness bigger than 50 HRC units. Current papers present from technical and qualitative point of view, the advantages and disadvantages that hard turning can offer in order to perform a final finishing operation. Nevertheless the economic aspect of this process change was debated very slightly. This paper is summarizing the condition required as for hard turning to be more efficient then grinding. Likewise the paper target's to highlight all cost elements which, influences the manufacturing technology cost (not only the price for the cutting tool) and optimal solution choose, but also to bring the calculation method at the simplest formula possible in order to use it in future economical calculation.

Keywords
cost, manufacturing, hard turning, grinding

1. Introduction

In order that hard turning can replace grinding on finishing machining of steel parts, heat treated and brought to a hardness higher than 50 HRC units, like final operation, the process must be capable to meet many criteria, like:

- technological criteria – the cutting tool and the machine tool must be capable to realize the technical conditions required by the technical drawing;
- qualitative criteria – being final finishing operation, the surfaces must be without any burns or cracks.

Current papers present many researches that targeted the technical aspects like shape and dimensional accuracy and qualitative aspects like burns, cracks and white layers [2, 3, 4, 5].

In addition to these criteria there is also the matter of manufacturing cost, thus hard turning must be capable of meeting another third criteria such as economic efficiency criteria. The hard turning operation must be cheaper than grinding operation, or if the hard turning operation cost/part is higher than grinding operation cost/part, then the hard turning operation must compensate this cost difference within productivity. It's known that the cubic boron nitride (CBN)/polycrystalline cubic boron nitride (PCBN) inserts for hard turning are expensive, especially those with wiper geometry, but there are also cheaper solutions that can achieve the hardness requirements of the parts, like ceramic inserts (aluminum oxide – Al_2O_3) [6, 7, 8, 9, 10].

2. Indicators for Determining the Economic Efficiency

The economic efficiency of replacing grinding with hard turning is based on four indicators:

- time technical norm or manufacturing time of a part *p* - M_{T_p};
- production capacity of machine tool for a part *p* - C_p;
- part manufacturing cost - $C_{inf.tech_p}$, respectively part total cost - C_{total_p};
- part selling price - P_{v_p} .

For one part *p* and two machine-tool, lathe and grinding machine, the production capacity of each one for part *p* according to [11, 12] is:

$$C_{p_{p,i}} = \frac{F_{tef}}{M_{T_{p,i}}} \quad [pc/y] \tag{1}$$

where

$C_{p_{p,i}}$ – production capacity of machine tool for part *p*, using finishing operation *i;*

F_{tef} – total effective fund of time, which is calculated with the following formula:

$$F_{tef} = (D \times s \times h - t_{rep}) \times 60 \quad [min/y] \tag{2}$$

$M_{p,i}$ - time technical norm or manufacturing time of a part *p*, at *i* operation [min/pc];
min - minutes;
y - year;
pc - piece;
D - yearly work days;
s - daily shifts;
h - hours number/shift;
t_{rep} - yearly maintenance period [hours].

The general structure of manufacturing time for every manufacturing operation is represented in the figure 1.

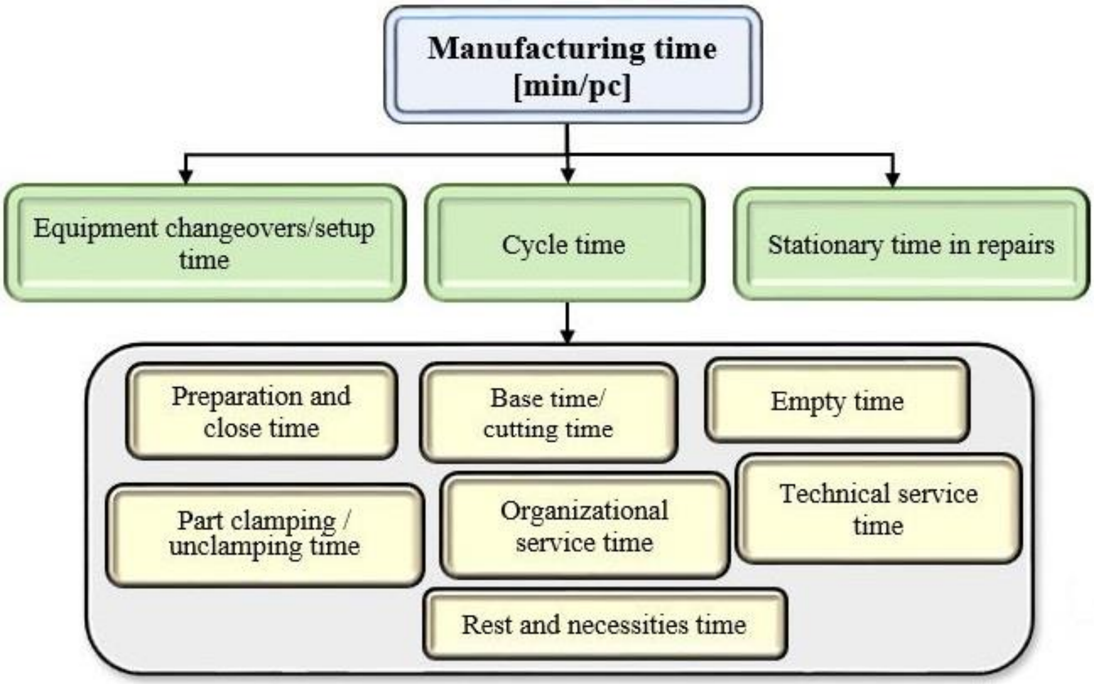

Fig. 1. Manufacturing time structure

The manufacturing time for one operation is calculated with the following formula:

$$M_{T_{p,i}} = T_c + T_{usr} + T_{eqs} = T_b + T_e + T_{cu} + T_{ts} + T_{os} + T_{rn} + T_{pc} + T_{usr} + T_{asr} \quad [min/pc] \tag{3}$$

where

T_c - cycle time [min/pc];
T_{usr} - unitary stationary time in repairs [min/pc];
T_{eqs} - unitary equipment changeovers / setup time [min/pc];
T_b - base time or cutting time [min/pc];
T_e - empty time (tool, spindle fast move) [min/pc];
T_{cu} - part clamping/unclamping time [min/pc];
T_{ts} - technical service time (tool change, feed rate change, rotations change) [min/pc];
T_{os} - organizational service time (cleaning, oiling) [min/pc];
T_{rn} - rest and necessities time [min/pc];
T_{pc} - preparation time (first off-last off sheet, part, tools, documents) [min/pc].

Generally the grinding manufacturing time is higher than hard turning manufacturing time. The most important components of manufacturing time through hard turning can achieve higher productivity than grinding are:

- base time or cutting time - T_b;
- empty time - T_e;
- equipment setup time - T_{eqs}.

According to [11, 12, 13] the total cost of a product can be determined as follows:

- splitting the costs in fixed costs and variable costs;
- splitting the costs in direct costs and indirect costs.

The economic efficiency of replacing grinding with hard turning can be determined using mathematic model of technology and endowment influenced costs [11, 12, 13]. This mathematic model, it actually contains differentiation elements of manufacturing technologies. In this way the total cost of a product *n* using finishing operation *i,* has the following formula:

$$C_{total_{p,i}} = C_{inf.tech_{p,i}} + A_c \quad [mu/y] \tag{4}$$

where

$C_{total_{p,i}}$ - total cost of part *p* in monetary units per year, using finishing operation *i* [mu/y];

$C_{inf.tech_{p,i}}$- total influenced cost of part *p*, using finishing operation *i* [mu/y];

A_c - the rest of the costs that make up the total cost of a part, these being the same regardless of the finishing operation chosen [mu/y];

Applying this model, the influenced cost is divided in fixed cost and variable cost. The others costs (A_c) which make up the total cost of a part ($C_{total_{p,i}}$) like, raw material, the machining cost before heat treatment, utility costs, cost with personnel (indirect) are the same despite of the finishing operation chosen.

The mathematic model of influenced costs is:

$$C_{inf.tech_t} = C_{fix_t} + C_{var_t} \quad [mu/y] \tag{5}$$

where

$$C_{fix_t} = C_A + C_R \quad [mu/y] \tag{6}$$

C_{fix_t} -total fixed costs [mu/y];

C_A - annual depreciation costs [mu/y];

C_R - annual equipment maintenance cost [mu/y],

and

$$C_{var_t} = Q \times C_{vup} = Q \times (C_E + C_m + C_s + C_D) \ [mu/y] \tag{7}$$

C_{var_t} - total variable costs [mu/y];

Q - annual production volume [pc/y];

C_{vup} - operating variable cost per product unit [mu/pc];

C_E – energy cost [mu/y];

C_m – labour cost [mu/y];

C_s – tools cost [mu/y];

C_D – specific tool (devices) cost [mu/y].

3. The Mathematical Model of Economic Efficiency

The mathematic model in order to determine the optimal machining process uses the following hypotheses:

- load of the machine-tool is considered 100%, thus, the fixed cost will be attributed to each part;
- the cost is splitting in variable cost and fixed costs;
- the production capacity $C_{p_{p,i}}$ is equal to production volume $Q_{p,i}$;
- only the manufacturing cost after heat treatment are taken into account.

Starting with relations (6) and (7), the influenced cost, for one part *p*, using finishing operation *i*, is calculated with the relation:

$$C_{inf.tech_{p,i}} = C_{fix_{p,i}} + C_{var_{p,i}} = \\ = \left(\frac{C_{a_i} + C_{r_i}}{Q_{p,i}}\right) + C_{uE} \times N_{kW_{p,i}} + C_{m_i} \times M_{t_{p,i}} + \frac{P_{pr_i} \times T_{B_{p,i}}}{D_i} + C_{d_i} \quad [mu/pc] \tag{8}$$

where

$C_{inf.tech_{p,i}}$ - the influenced cost for one part *p*, on machining operation *i* [mu/pc];
$C_{fix_{p,i}}$ - the fixed cost of a part *p* associated with machining operation *i* [mu/pc];
$C_{var_{p,i}}$ - the variable of a part *p* associated with machining operation *i* [mu/pc];
C_{a_i} - depreciation cost of machine tool associated with machining operation *i* [mu/y];
C_{r_i} - equipment maintenance cost associated with machining operation *i* [mu/y];
$Q_{p,i}$ - production capacity of the machine tool for a part *p*, associated with operation *i* [pc/y];
C_{uE} - the cost of energy [mu/kWh];
N_{kW_i} - number of kWh consumed for a part *p*, on machining operation i [kWh/pc];
C_{m_i} - labour cost associated with machining operation *i* [mu/min];
$M_{t_{p,i}}$ - manufacturing time of a part *p*, associated with machining operation *i* [min/pc];
P_{pr_i} - purchasing price of tool that are used on machining operation *i* [mu];
$T_{B_{p,i}}$ - base time for a part *p*, associated with machining operation *i* [min/pc];
D_i- tool life (durability) associated with machining operation *i* [min];
C_{d_i}- specific tools cost associated with machining operation *i* [mu/pc];
i - mean hard turning (HT) or grinding (GRI).

The economic efficiency of replacing grinding with hard turning, considering the technology influenced costs ($C_{inf.tech_{p,i}}$), the technology productivity ($Q_{p,i}$) and part selling price (P_{v_p}), in a period of time determinated (F_{tef}) is given by the following formula:

$$\left[P_{v_p} - \left(\frac{C_{a_{HT}} + C_{r_{HT}}}{Q_{pHT}} + C_{uE} \times N_{kW_{p,HT}} + C_{m_{HT}} \times M_{t_{p,HT}} + \frac{P_{pr_{HT}} \times T_{B_{p,HT}}}{D_{HT}} + C_{d_{HT}}\right) - A_c\right] \times Q_{p,HT} > \\ > \left[P_{v_p} - \left(\frac{C_{a_{GRI}} + C_{r_{GRI}}}{Q_{p,GRI}} + C_{uE} \times N_{kW_{p,GRI}} + C_{m_{GRI}} \times M_{t_{p,GRI}} + \frac{P_{pr_{GRI}} \times T_{B_{p,GRI}}}{D_{GRI}} + C_{d_{GRI}}\right) - A_c\right] \times Q_{p,GRI} \tag{9}$$

where

P_{v_p} - part *p* selling price [mu/pc].

The above relation highlights all the cost elements that differentiate these two finishing processes and the most important and significant are:

- the purchasing price of the machine-tool;
- energy consumption;
- manufacturing time_which determines the production volume;
- the cost of the tool.

Using relation (4) it's determined the condition required so that hard turning to be more advantageous then grinding operation and this condition would be:

$$(P_{v_p} - C_{total_{p,HT}}) \times Q_{n,HT} > (P_{v_p} - C_{total_{p,GRI}}) \times Q_{p,GRI}; \tag{10}$$

$$Q_{p,HT} - Q_{p,GRI} > \frac{C_{total_{HT}} \times Q_{p,HT} - C_{total_{GRI}} \times Q_{p,GRI}}{P_{v_p}}. \tag{11}$$

The relation (10), is divided throughout by $Q_{p,GRI}$ and is obtained:

$$\left(\frac{Q_{p,HT}}{Q_{p,GRI}} - 1\right) > \frac{\left(C_{total_{HT}} \times \frac{Q_{p,HT}}{Q_{p,GRI}} - C_{total_{GRI}}\right)}{P_{v_p}} \quad (12)$$

where $\frac{Q_{p,HT}}{Q_{p,GRI}}$ represent the productivity factor F_p.

By replacing $\frac{Q_{p,HT}}{Q_{p,GRI}}$ in relation (11), is obtained:

$$Q_{p,GRI} \times (F_p - 1) > \frac{Q_{p,GRI} \times (C_{total_{HT}} \times Fp - C_{total_{GRI}})}{P_{v_p}}; \quad (13)$$

$$F_p > \frac{P_{v_n} - C_{total_{GRI}}}{P_{v_n} - C_{total_{HT}}}. \quad (14)$$

The difference between part selling price and total cost of part represent the profit obtained for one part sold. As a result, the relation become:

$$F_p > \frac{P_{r_{p,GRI}}}{P_{r_{p,HT}}}; \quad (15)$$

$$F_p > \frac{1}{\frac{P_{r_{p,HT}}}{P_{r_{p,GRI}}}}; \quad (16)$$

$$F_p > \frac{1}{F_{profit}}, \quad (17)$$

where

$P_{r_{p,HT}}$ - represent the profit of a piece *p* produced by hard turning;

$P_{r_{p,GRI}}$- represent the profit of a piece *p* produced by grinding;

F_{profit} - represent the profit factor.

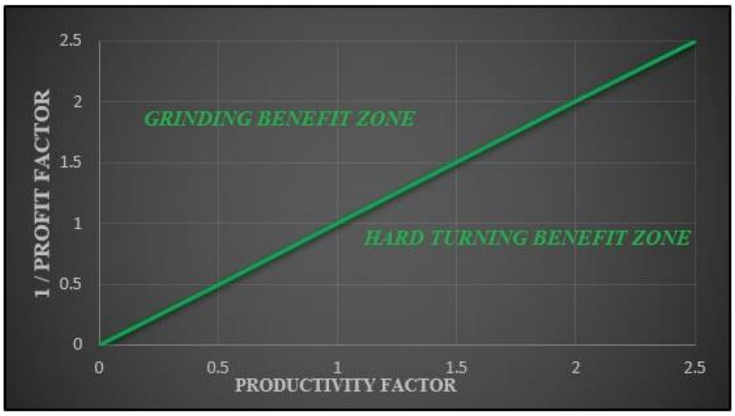

Fig. 2. Benefit map

In Figure 2 it is observed that the area below of green line represent the area where the hard turning is more profitable than grinding, the green line represents the set of points in which the hard turning is equal to grinding and over green line the grinding in more profitable than hard turning, from benefit point of view, all these by taking in consideration the technology influenced costs ($C_{inf.tech_{p,i}}$), the technology productivity ($Q_{p,i}$) and part selling price (P_{v_p}), in a period of time determinated (F_{tef}).

4. Conclusions

Hard turning can bring a bigger benefit than grinding for many manufacturing systems, even if sometimes the hard turning is more expensive then grinding. The cost difference can be recovered through productivity because generally the base time, respectively manufacturing time is lower on hard turning than grinding. Even if the inserts (CBN, PCBN) for this king of machining are relative expensive, there are many cheapest solutions, like ceramic inserts, who can lead to a lower tool cost and a lower total cost of the part. However, for identifying the economic solution for finishing machining of hardened parts must be considered all the cost elements listed above, not only the cutting tool.

References

1. Arsene, B., Calefariu, G. (2017): *Qualitative Analysis of Replacing Grinding with Hard Turning.* **RECENT**, eISSN 2065-4529, Vol. 18, no. 1(51), p. 6-11
2. Kundrak, J., Karpuschewski, B., Gyani, K., Bana, V. (2008): *Accuracy of hard turning*. Journal of Materials Processing Technology, ISSN 0924-0136, Vol. 202, iss. 1-3, p. 328-338
3. Waikar, R.A., Guo, Y.B. (2008): *A comprehensive characterization of 3D surface topography induced by hard turning versus grinding*. Journal of Materials Processing Technology, ISSN 0924-0136, Vol. 197, iss. 1-3, p. 189-199
4. Grzesik, W., Krzysztof, Ż., Kiszka, P. (2014): *Comparison of surface textures generated in hard turning and grinding operations*. Procedia CIRP, ISSN 2212-8271, Vol. 13, p. 84-89
5. Kundrak, J., Gyani, K., Bana, V. (2008): *Roughness of ground and hard-turned surfaces on the basis of 3D parameters*. International Journal of Advanced Manufacturing Technology, ISSN 0268-3768, Vol. 38, iss. 1-2, p. 110-119
6. Karpuschewski, B., Schmidt, K., Prilukova, J., Beno, J., Mankova, I., Hieu, N.T. (2013): *Influence of tool edge preparation on performance of ceramic tool inserts when hard turning*. Journal of Materials Processing Technology, ISSN 0924-0136, Vol. 213, iss. 11, p. 1978-1988
7. Kamely, M.A., Noordin, M.Y., Ourdjini, A., Venkatesh, V.C., Razali, M.M. (2008): *Alternative low cost cutting tool for hard turning of Aisi D2*. Journal of Advanced Manufacturing Technology, ISSN 1985-3157, Vol. 2, iss. 2, p. 29-37
8. Ranjan Das, S., Panda, A., Dhupal, D. (2017): *Analysis of surface roughness in hard turning with coated ceramic inserts: Cutting parameters effects, prediction model, cutting conditions optimization and cost analysis.* Ciência e Técnica Vitivinícola, ISSN 0254-0223, Vol. 32, p. 127-154
9. Ozel, T., Karpat, Y., Figueira, L., Davim, J.P. (2007): *Modelling of surface finish and tool flank wear in turning of AISI D2 steel with ceramic wiper inserts.* Journal of Materials Processing Technology, ISSN 0924-0136, Vol. 189, iss. 1-3, p. 192-198
10. Ferreira, R., Carou, D., Lauro, C.H., Davim, J.P. (2016): *Surface Roughness Investigation in the Hard Turning of Steel Using Ceramic Tools.* Materials and Manufacturing Processes, ISSN 1042-6914, Vol. 31, iss. 5, p. 648-652
11. Calefariu, G., Barbu, M. (2011): *Sisteme de producție. Teorie și aplicații* (*Production systems. Theory and applications*). Editura Lux Libris, ISBN 978-973-131-112-8, Brașov, Romania (in Romanian)
12. Abrudan, I., Candea, D. (2002): *Manual de Inginerie Economică. Ingineria și Managementul Sistemelor de Producție* (*Economic Engineering Handbook. Engineering and Management of Production Systems*). Editura Dacia, ISBN 9733515884, Cluj-Napoca, Romania (in Romanian)
13. Buda, T., Calefariu, E., Gheorghe, C., Calefariu, G. (2014): A *new approach regarding investment decision in manufacturing systems.* **RECENT**, eISSN 2065-4529, Vol. 15, no. 2(42), p. 64-71

Received in February 2017