Optimization method applied to hard turning of steel at the shop floor using maximum efficiency interval methodology to determine the cutting speed

OTIMIZAÇÃO DO PROCESSO DE TORNEAMENTO DE PEÇAS ENDURECIDAS POR MEIO DA DEFINIÇÃO DO INTERVALO DE MÁXIMA EFICIÊNCIA DA VELOCIDADE DE CORTE

Luciomar de Abreu Campos
Fiat-GM Powertrain – GM Powertrain Ltd.
Manufacturing Engineering Department
Wisley Falco Sales
Pontifical Catholic University of Minas Gerais – PUC Minas
Manufacturing Research Centre
Mechanical and Mechatronics Engineering
Sandro Cardoso Santos
Federal Technological Centre – CEFET–MG
Mechanical Engineering Department
John Bonney
London South Bank University - LSBU
Machining Research Centre
Department of Engineering Systems

ABSTRACT

The main objective of this study is to propose a methodology to optimise the cutting processes when turning DIN 19MnCr5 G hardened steel. The method is based on Maximum Efficiency Interval (MEI), which considers the major process constraints involved. This enables the determination of the cutting conditions to be used at the shop floor. The MEI of the cutting speed, is determined mathematically, which is used as the bench mark value employed in the production process, of a serial production line for vehicle power transmission components. Polycrystalline Cubic Boron Nitride (PCBN) tools were used for the machining trials and tool life and tool wear mechanisms were evaluated. The results calculated by a mathematical model were in agreement with the experimental results. The use of this methodology could drastically reduce the machining costs at the shop floor.

KEYWORDS

Optimization. Maximum efficiency interval. PCBN tools. Hardened steel. Tool life.

RESUMO

O principal objetivo desse estudo é propor uma metodologia para otimização do processo de torneamento de peça de aço endurecido DIN 19MnCr5 G. Essa metodologia se baseia na definição do Intervalo de Máxima Eficiência (IME) considerando as restrições do processo e cenário produtivo. O IME da velocidade de corte, determinado matematicamente, forneceu os valores de referência e estes foram utilizados no processo produtivo em linha de produção seriada de componentes para a transmissão de automóveis. A partir dos resultados experimentais, foram estabelecidas comparações e gerou-se uma metodologia para utilização no chão-de-fábrica. Foram utilizadas nos ensaios ferramentas de corte de nitreto cúbico de boro policristalino (PCBN) e foram monitorados a vida útil e o desgaste das ferramentas. O uso da metodologia reduziu drasticamente os custos de usinagem no chão-de-fábrica.

PALAVRAS CHAVE

Otimização. Intervalo de Máxima Eficiência (IME). Ferramentas de PCBN. Aços endurecidos. Vida útil de ferramentas.

INTRODUCTION

Optimization of cutting conditions in order to minimize the manufacturing costs has been discussed over the last decade. It is not only due to the globalization of the markets that is demanding a more competitive posture, but also due to economical problems of companies involved on manufacture. In this way, the production should be optimised to obtain high quality components at minimum cost and maximum profit.

The first studies on metal machining economics were accomplished by Taylor in the United States and Schlesinger in Germany (Ferraresi, 1977).

Frequently, the cutting processes are optimised in relation to the capability of the tool, which can change the characteristics of the current process. In order to implement changes in the process usually machining experiments are conducted and the new costs obtained are compared with the existing thus providing a basis to legitimise its implementation. When justified, the new tool process is adopted together with the new cutting parameters, and the process is considered optimised. Other form of optimising the processes is to modify only the cutting strategy to attain shorter machining times without investing in the other resources.

According to Baptista (2000), the optimization of cutting speed through determination of Maximum Efficiency Interval (MEI) in production can provide a significant reduction in the cutting times, with consequent reduction of machining costs because it is composed of the cutting speeds of maximum production (v_{cmxp}), minimum cost limit speed (v_{cmcLim}), and minimum cost speed (v_{cmc}). However, the determination of MEI is not enough for the optimization process because the machining system has restrictions and characteristics that can influence the choice of the reference cutting speed.

The optimization of cutting speed should therefore be done in relation to the MEI and the productive system at the same time. The process optimized in this condition will have mainly the reduction of costs, or, the reduction of the cutting time.

In spite of its advantages, the application of MEI in industries is met with resistance on the part of the process engineers. The main causes of this resistance is related to the need of solving calculations, need of analysis of the productive system, accomplishment of experiments to determine tool life based on appropriate tool rejection criterion as well as the selection of the cutting speeds and its validation (Baptista, 2000).

Cycles and machining times

The machining cycle of a work piece, from a lot size "*Z*", is constituted directly by the following phases (Diniz, 1999):

1. Locating and rigidity fixing the work piece;
2. Approach and positioning of the tool;
3. Cutting;
4. Removal of the tool;
5. Inspection if necessary and retreat of the work piece.

Besides these phases they participate indirectly in the machining cycle:

6. Machining setup;
7. Removal of the tool and its substitution by a new one;
8. Replacement and adjustment of the new tool.

Each one of the eight phases are denominated by the following nomenclature:

t_t = total machining time of a work piece
t_c = cutting time (phase 3)
t_s = secondary time (phases 1 and 5)
t_a = tool approach and removal time (phases 2 and 4)
t_p = machine setup time (phase 6)
t_{ft} = tool change time (phases 7 and 8)

The total time to machine a work piece, from a lot of size "*Z*", is represented by the Eq. (1).

$$t_t = t_c + t_s + t_a + \frac{t_p}{Z} + \frac{N_t}{Z}.t_{ft} \quad (1)$$

where:

Z = number of work pieces in the lot;
N_t = number of tool changes need to machine "Z" work pieces.

Costs in turning operations

The final cost of a component is composed of two parts, the direct and indirect costs. The indirect cost will not be considered in this study because it involves variables that are company dependent. The direct costs is expressed as,

$$K_p = K_{us} + K_{um} + K_{uf} \quad (2)$$

where:

K_p = production cost per work piece ($ / Piece);
K_{us} = labour cost involved in machining ($ / Piece);
K_{um} = machine tool cost ($ / Piece);
K_{uf} = tool cost ($ / Piece);

Maximum efficiency interval (MEI)

The Maximum Efficiency Interval (MEI) is defined as the cutting speeds at which minimum cost (v_{cmc}) and maximum production (v_{cmxp}) is achieved. Thus, machining at v_{cmc} the least cost per piece is obtained, while at v_{cmxp} the least production time is attained. Figure 1 illustrates the notion of MEI as defined by Rodrigues (1987).

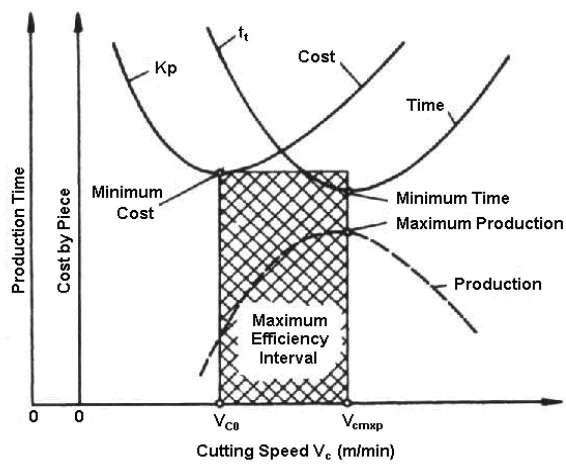

Figure 1 - Maximum Efficiency of Cutting Speed

Cutting speed for maximum production. The cutting speed corresponding to the machining of a component minimum time is called cutting speed of maximum production, as shown in the Fig. 1. The equation of cutting speed of maximum production (v_{cmxp}) is shown at Eq. (3).

$$v_{cmxp} = \sqrt[x]{\frac{K}{(x-1)t_{ft}}} \quad (3)$$

where:

K = constant of life equation according to Taylor;

x = exponent of life equation according to Taylor.

Cutting speed for minimum cost. Different from the expression of cutting speed for maxim production, the expression for cutting speed for minimum cost (Fig. 1) has parameters, which are difficult to obtain in the production process, as shown in Eq. (4).

$$v_{cmc} = \sqrt[x]{\frac{K.(S_h+S_m)}{60.(x-1)\left[K_{ft}+\left(\frac{S_h+S_m}{60}\right).t_{ft}\right]}} \quad (4)$$

where:

S_h = salary and social responsibilities of the operator ($ / hour);

S_m = machine tool cost ($ / hour);

K_{ft} = cost of each cutting edge of the insert ($).

The machine tool cost (S_m) is calculated as in Equation (5):

$$S_m = \frac{1}{H}\left[\left(V_{mi} - V_{mi}\cdot\frac{i_m}{M}\right).j + \frac{V_{mi}}{M} + K_{mc} + E_m.K_e.j\right] \quad (5)$$

where:

H = number of working hours per a year;

V_{mi} = initial machine tool cost ($);

i_m = age of machine tool (years);

M = life of the machine tool (years);

j = annual interests rate;

K_{mc} = machine tool maintenance costs per year ($ / year);

E_m = space occupied by the machine tool (m^2);

K_e = cost of the area (m^2) occupied by the machine ($ / m^2.year);

The cost of each cutting edge of the insert (K_{ft}) is calculated as in Eq. (6):

$$K_{ft} = \frac{V_{si}}{N_{fp}} + \frac{K_{pi}}{N_s} \quad (6)$$

where:

V_{si} = cost of tool holder acquisition ($);

N_{fp} = medium life for the tool holder in number of changes;

K_{pi} = cost of insert ($);

N_s = number of cutting edges available on each insert;

Considering the use of a tool with quick change system, the t_{ft} is least, while for flexible a manufacturing system that value is zero. The product of t_{ft} for the sum of S_h and S_m is despicable in relation to the cost of the tool. In this case, they are obtained from v_{cmcLim}. V_{cmcLim} is not less than the v_{cmc} and more than v_{cmxp} and can be calculated using Eq. (7) (Malaquias, 1999).

$$v_{cmcLim} = \sqrt[x]{\frac{K.(S_h+S_m)}{60.(x-1)K_{ft}}} \quad (7)$$

Experimental Procedures

Methodology to define the maximum efficiency interval (MEI)

The methodology to determine MEI consists of the following stages:

A) The cutting parameters were obtained in agreement with the procedures by the process engineer (values from tool manufacturers' reports, values based on the experience of the operator, values stored in database originating from previous experiments). The depth of cut (*doc*) and feed rate (*f*) adopted were the highest values possible in relation to the inherent restrictions to the machine-tool-work piece system.

B) The machining of the first batch of work pieces was conducted at a cutting speed (v_{c1}) until the end of the life of the cutting edge of the tool, in agreement with an established tool life criterion. The tool life is then recorded.

C) The second cutting speed (v_{c2}) used is 20% higher than (v_{c1}). This speed is used to machine the second batch of work pieces until the tool rejection when the tool life is recorded.

D) After the machining, it is obtained the values of the tool life expressed in number of pieces (Z_t), which are used in the calculations of the "*K*" constant and of the "*x*" coefficient of the Eq. (8) and Eq. (9). The recorded tool lives are then expressed relative to the number of work pieces (Z_t), which is used to calculate the value of the coefficient "*x*" in Eq. (8) and the constant "*K*" in Eq. (9).

$$x = \frac{\log\left(\frac{Z_{t1}}{Z_{t2}}\right)}{\log\left(\frac{V_{c2}}{V_{c1}}\right)} + 1 \qquad (8)$$

where:

Z_{t1} = life of cutting tool edge expressed in number of work pieces produced for v_{c1};

Z_{t2} = life of cutting tool edge expressed in number of work pieces produced for v_{c2};

v_{c1} = first cutting speed (m/min);

v_{c2} = second cutting speed (m/min).

$$K = Z_{t1} . t_{c1} . V_{c1}^{x} \qquad (9)$$

where: t_{c1} = effective time of cut for v_{c1} (min);

A) The cutting speeds that compose the MEI is calculated using Equations (3), (4) and (7). This speed is within the interval of cutting speeds used in the experiment. The calculated value is ±10% accurate, except for the v_{cmxp} that because of the influence of t_{ft} can have a higher tolerance value.

The methodology is illustrated by the flowchart in the Fig. 2. Note the following abbreviations: r_ε, is the tool nose radius and K_T, is the measurement of the maximum crater depth (tool wear).

The flowchart bellow demonstrates the Experiment 4 is just being made "for registration" and the Experiment 3 represents the ratified experiment, these choices contain the "restrictions of the process and productive scenery": The process in optimization represents one of the most expensive operations in the productive mesh; the tool has the quick change s

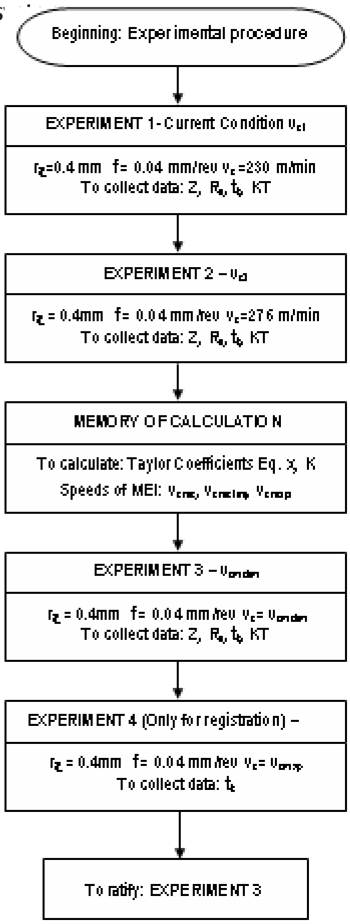

Figure 2 - Flowchart of the experiments

Used resources (piece, tool and machine)

The work material is DIN 19MnCr5 G steel hardened to 58 HRc after carbonitriding and quenching. Figure 3 shows the machined component. The cutting fluid employed for the machining trials was synthetic based (Syntilo 900) coolant applied at 4% concentration and at a pressure of 30 MPa.

Finish turning with PCBN-L tool was carried out on a CNC lathe with the following cutting parameters: feed rate, *f* = 0.04 mm/rev and depth of cut, *doc* = 0.15 mm. The machining cycle involves, facing, outer diameter turning using ramping tool path programming. Tool rejection criterion was based on surface roughness value in excess of R_a = 0.8 μm.

Figure 3 - The machined component

The insert consist of a thin layer of PCBN-L brazed onto a cemented carbide base with a nose radius of 0.4 mm and edge chamfer of 0.2 mm. Figure 4 illustrates schematically the tool with a special design featured to enable access to the surfaces to be machined.

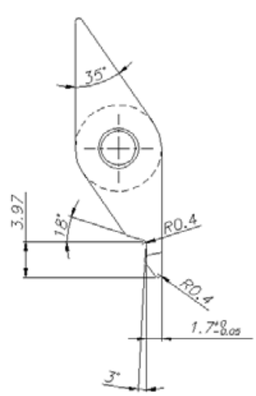

Figure 4 – Schematic illustration of the special insert with a brazed PCBN-L tip

The tool holders are ISO C4-MVJNR-27050-16 (right hand) and C4-MVJNL-27050-16 (left hand) with Capto 4 tool fixture system as illustrated in Fig. 5. The PCBN-L insert consist of 50% CBN content with 50% of Ti and Al.

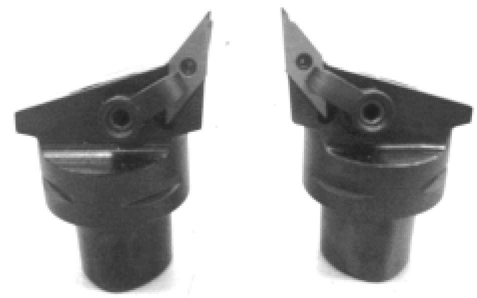

Figure 5 – Tool holder

The criterion of the tool life end

The tool rejection criterion initially adopted was based on the evolution of the R_a parameter of the topography of the surfaces. However, after start the trials, it was observed that the roughness values stayed below of the stipulated limit. Catastrophic failure therefore was adopted as tool rejection criterion without compromise the quality of the machined work pieces.

Results and Discussion

Determination of MEI

The initial cutting speed of 230 m/min obtained from the database analysis, previous experiences and tool manufacturers' recommendations. The cutting speed of 276 m/min is 20% superior to the initial speed. The results of the tool life experiments are presented in the Table 1.

Table 1 - Tool life

v_c (m/min)	Z_t (pieces)	t_c (min)	t_t (min)
230	731	0.2975	0.60
276	485	0.2479	0.55

The times were obtained using a chronometer.

The information in the Table 1 was used to determination the coefficients "*K*" and "*x*" of the tool life Eq. (8) and Eq. (9). The calculated values are: x = 3.25022 and K = 10317307308. These enabled the speeds for maximum production and minimum cost to be calculated from Equations (2), (4) and (7), given the following results:

- Cutting speed of maximum production

v_{cmxp} = 669.4 m/min;

- Cutting speed of minimum cost v_{cmc} = 215.4 m/min;
- Cutting speed of minimum cost limit v_{cmclim} = 217.1 m/min.

VALIDATION OF THE CALCULATED VALUES

Table 2 show the results of test conducted using the calculated values of v_{cmclim} and v_{cmxp}.

Table 2 - Tool life for the calculated cutting speeds

v_c (m/min)	Z_t (pieces)	t_t (min)
217	859	0.64
669	279	0.52

Figure 6 shows a worn cutting tool showing flank and crater wear as the dominant wear modes.

In order to evaluate the reliability of the results, tool life equation was based on crater wear measurements during the machining process (Fig. 7).

Crater depth of K_T = 0.13 mm was adopted as the tool rejection criterion. The tool life is expressed in terms of the number of components machined. The equation defined in Table 3 is used to plot the curves shown at Fig. 7.

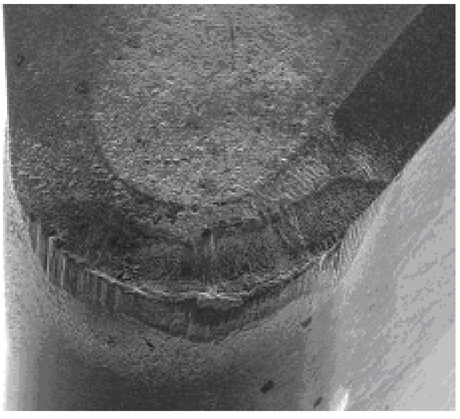

Figure 6 - Wear modes observed in the cutting tools

Table 3 - Tool life according to the criterion of crater wear

vc (m/min)	Equation	KT standard (mm)	Zt (pieces)
276	Zt = KT / 0.0003240679	0.13	401.15
230	Zt = KT / 0.0001834019	0.13	708.83
217	Zt = KT / 0.0001449804	0.13	896.67

The choice of the wear value of reference K_T = 0.13 mm, was not based on the standardisations reports,

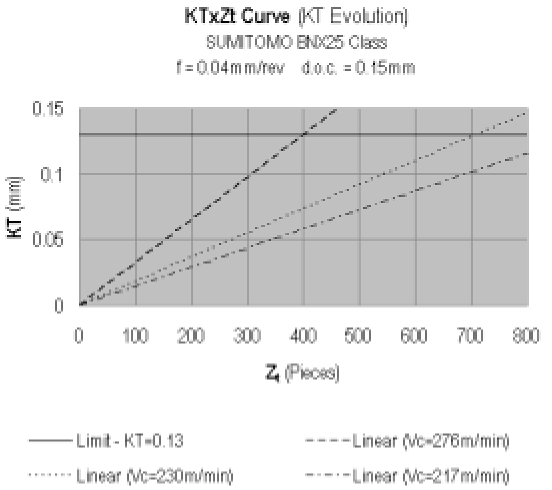

Figure 7 - Evolution of the crater wear along the tool life (tendency lines)

but due to good relation showed between this maximum crater depth and the imminence of the catastrophic failure. Fig. 8 is a plot of tool life (relative to number of components machined (Z_t)), and the corresponding logarithmic curve of the tool life. The equation is shown in Table 4. Table 4 also gives the calculated and actual tool life (Z_t).

The equation shown in Table 4 can be used to estimate the tool life in the interval contained between the speeds of 217 m/min and 276 m/min.

After the speeds that constitute MEI have been calculated, they were validated through practical tests. The v_{cmxp} was easily confirmed as it can be seen in the Tables 1 and 2. The v_{cmcLim}, in practice did not correspond to smaller cost. This is due to the fact that the speeds v_{cmcLim} and v_{c1} are close, varying only by 5%. Baptista (2000) stated that the cutting speeds that constitute MEI should belong to the interval used in the rehearsal (v_{c1} and v_{c2}), with a tolerance of 10%, except for v_{cmxp}, that due to its influence by t_{ft}, can reach very high values. If this is not the case, it will be necessary to determine a new interval, through a new experiment. Based on the considerations above, it can be affirmed that the cutting speed for minimum cost, to be considered for the system should be, v_{cmcLim} = 230 m/ min. This adjustment of the original value is due to the precision and quality of the previous tests values.

CONCLUSIONS

Based on the obtained results, it can be concluded that:

1. The methodology used to determine the cutting speed for minimum cost is effective when used at the

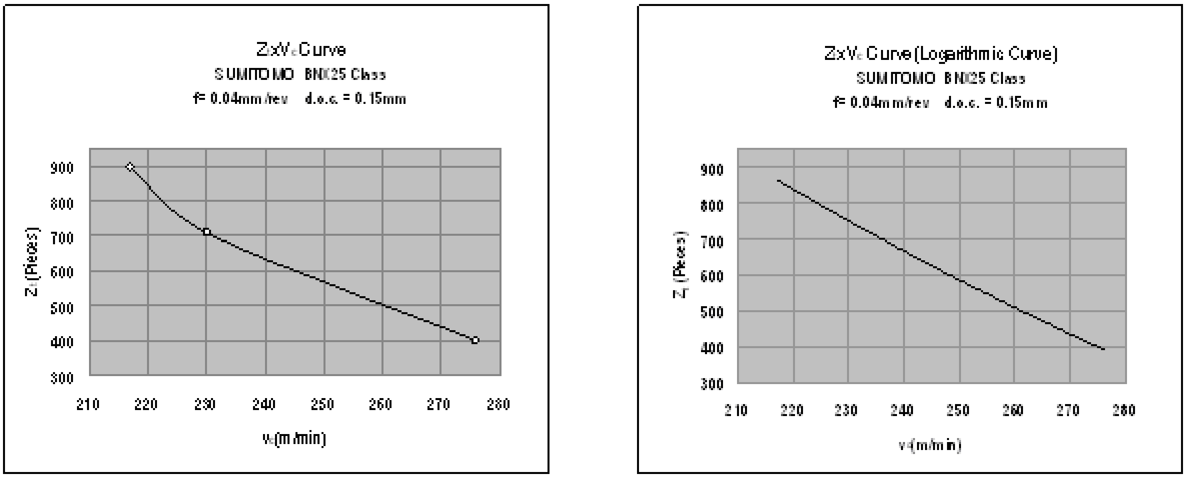

Figure 8 – Tool life curve

Table 4 - Validation of the tool life equation results

v_c (m/min)	Equation	Z_t (calculated)	Z_t (real)	Error (%)
276		391.19	485	19.34
230	$Z = -1971.\ln(v_c) + 11469$	750.55	731	-2.67
217		865.22	859	-0.724

shop floor;

2. The proposed method was validated in real machining conditions and it can be used in other operations and processes;

3. The study of process optimization increased the production by 110 pieces to 731 pieces, resulting in earnings of 665%.

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