Database for Optimal Selection of Cutting Conditions, Forces and Power Consumption in Machining Processes

قاعدة بيانات للاختيار الأمثل لظروف القطع والقوى والقدرة المستهلكة في عمليات التشغيل

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الملخص العربي:

إن اختيار بيانات القطع (سرعة القطع، والتغذية، وعمق القطع) ونوع العدة القاطعة يلعبان دورا هاما في تقليل وقت وتكلفة الانتاج. وفى هذا البحث تم تصميم قاعدة بيانات باستخدام SQL server لتخزين كم كبير من المواد المختلفة التي يتم تشغيلها في الصناعة، وتخزين بيانات القطع، والأنواع المختلفة للعدد القاطعة، ومجموعة من عمليات التشغيل المختلفة. وتم أيضا عمل برنامج باستخدام Visual Basic.net لاختيار بيانات القطع المثلى، والعدة القاطعة المناسبة لثلاث عمليات تشغيل مختلفة (الخراطة والثقب والتفريز). ويمكن اختيار بيانات القطع المثلى والعدة القاطعة المناسبة لأقصى أو أقل سرعة قطع متاحة فى قاعدة البيانات، وذلك طبقا لقدرة الماكينة و كفاءتها ودرجة تشطيب السطح المطلوبة للشغلة. كذلك يتم حساب قوى القطع والعزم والقدرة المستهلكة، ويتم حساب الزمن الكلى لعمليات الإنتاج والتكلفة الكلية للمنتج، ثم يتم عرض كل العمليات وتفاصيلها في تقرير واحد في وقت قليل جدا. ومن خلال الدراسة التي أجريت على منتج تم تشغيله كنموذج للدراسة وجد أنه عند استخدام أقصى سرعة قطع يمكن توفيرحوالى ٣٤٪ من الوقت الكلى اللازم للإنتاج، وذلك مقارنة باستخدام أقل سرعة قطع. وفي المقابل وُجد أنه عند استخدام أقل سرعة قطع يمكن توفير حوالي ٢٨٪ من التكلفة الكلية للمنتج مقارنة باستخدام أقصى سرعة قطع.

Abstract

Selecting the cutting data (cutting speed, feed, depth of cut) and the proper cutting tools play a significant role in achieving minimum production time, consistent quality and in controlling the overall cost of manufacturing. However, searching for a proper tool/insert-job combination calls for a huge amount of data and an extensive knowledge base and may take a long time and effort if it is done manually. In this paper, a software has been designed and established using Microsoft Visual Basic.Net and SQL server to store all different types of tool grades with their available cutting data, inserts, and tool holders for all materials and some machining operations (turning, drilling and milling) in a database. The software is capable of selecting the suitable cutting data, tool grade, insert and tool holders for each operation in two cases. The first case uses the maximum cutting speed of the tool grade (minimum tool life) while the second case uses the minimum cutting speed (maximum tool life). In the two cases, the software considers the constraints of power, efficiency, and maximum spindle revolution of the machine as well as the required surface roughness of the workpiece. The software is capable of calculating the machining time, intermittent time, force, torque, power, spindle revolution and total production time and cost for each operation. In addition, the workpiece material, required operations, cutting data, force, torque, power, the suitable tool grade and its manufacturer, insert and tool holder are displayed in a single report as a process sheet . Another report can be used to show the total production time and the total cost. A case study has been done to test the proposed software and it was found that about 34% of the total production time could be saved by using the maximum cutting speed, compared with the minimum cutting speed. On the other hand, about 28% of the total production cost could be saved by using the minimum cutting speed, compared with the minimum cutting speed.

Keywords

Cutting conditions, databases, machining processes, optimal selection, power consumption

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Nomenclature

a	Thickness of undeformed chip (mm)
B	Milling cutter engagement (mm)
b	Width of undeformed chip (mm)
C_u	Unit cost (L.E)
C_l	Labour cost (L.E/min)
C_{mat}	Cost of raw material per part (L.E)
C_o	Overhead cost (L.E/min)
C_t	Cost of a cutting tool (L.E)
D	Diameter (mm)
F_z	Tangential force (main cutting force) (N)
F_μ	Force caused by friction (N)
h_m	Average chip thickness (mm)
i	Number of passes
k_c	Specific cutting resistance offered by the work material (N/mm2)
L	Travel of tool or workpiece in direction of the feed motion, (mm)
l	The machined surface length in the direction of the feed motion (mm)
M	Bending moment (N.mm)
M_μ	Moment caused by friction (N.mm)
mc	Rise in specific cutting force as a function of chip thickness
N_{cut}	Power consumed in cutting (kW)
N_e	Power rating of the electric motor (kW)
N_μ	Power caused by friction (kW)
n	Maximum spindle revolution (rpm)
n_{cal}	Calculated spindle revolution by the program (rpm)
s	Feed per revolution (mm/rev)
s_m	Feed per minute (mm/min)
s_z	Feed per tooth (mm/tooth)
T	Tool life (min)
T_m	Machining time (min)
t	Depth of cut (mm)
t_s	Setup time (min)
t_{tc}	Tool changing time (min)
v	Cutting speed (m/min)
y	tool approach (mm
z_n	Number of teeth of cutter
φ	Approach angle (degree)
Δ	Tool over travel (mm)
ω	Helix angle

1. Introduction

Machinability data plays an important role in the efficient utilization of machine tools and significantly influence the overall manufacturing costs. The most widely used source of machinability data is the Machining Data Handbook published by Metcut Research Associates, 1980, ASM International Handbook Committee and catalogues of companies that produce the cutting tools [1 - 5]. Machiniability data consists of the selection of the appropriate cutting tools and machining parameters, which includes cutting speed, feed rate and depth of cut. No doubt that determining of the suitable cutting data, selecting of a proper cutting tool (tool grade, insert and tool holder) from a huge amount of available data is difficult and takes along of times, also calculating the machining time, force, torque, power, total production time and cost for each operation needs a lot of time. Ribeiro, et al [6] presented a machining database system involving procedures to make comparative tests using different tools and optimize the attained results to find suitable cutting conditions for application at industrial scale.

Yeo, et al [7] developed an expert system for machinability data selection. The expert system automatically selectes cutting tools for external turning in both roughing and finishing operations, determined machining data and cutting fluid. Fuzzy-logic principles had been applied by Hashmi et al [8, 9] for selecting cutting conditions in machining operations. The presented results showed a very good correlation between the Machining Data Handbook's recommended cutting speed values and those predicted using the fuzzy logic model, which had been used in the drilling operation to select drilling speeds for three different materials. The development stages of an online fuzzy expert system (FES) were presented by Wong, et al [10-12]. It could be used by the process planner as an aid of establishing the strategy of machining data selection for a specific machining process and an implementation of an online knowledge-based system for machinability data selection was presented by them, Fuzzy logic had been incorporated as the reasoning mechanism behind the system.

Wang et al [13] presented an optimization analysis, strategy and CAM (computer aided manufacturing) software for the selection of economic cutting conditions in single pass turning operations using a deterministic approach. Juan et al [14] described the development of a model based on fuzzy logic for selecting cutting speed in single-point turning operations. A manual effort by Mookherjee et al [15] of searching were substituted for an expert system, which automatically selected the turning tool/insert or milling insert, the material and the geometry, based on the requirements of users. According to the author's knowledge there is no complete work in the subject of research.

The aim of this work is to construct and create a software to select the cutting data (speed, feed, depth of cut) from a database and calculate the machining time, cutting force, torque and cutting power consumed in two cases: (a) minimum tool life, (b) maximum tool life. In the two cases, the software considers the constraints of power, efficiency and max spindle revolution of the machine and the required surface roughness of the workpiece using different techniques of operations (turning, milling and drilling). It also used to determine the suitable tool grade, insert and tool holder of each operation, besides calculating the total machining time and cost in these two cases. All the operations which had been done, cutting data, machining time, force, torque, power, the suitable cutting tool and (insert/tool holder) are reported in a process sheet, besides showing the values of total production time and cost in a separate report.

2. Selection of cutting conditions

Selections of efficient cutting conditions are important to have short cutting time, long tool life and high cutting accuracy. Machining Data Handbook published by Metcut Research Associates, 1980 and catalogues of companies that produce the cutting tools are the commonly used source of cutting conditions. The data in the handbooks and catalogues were separated into different types of machining process. Then, the data grouped according to the types of workpiece material and the respective hardness (in BHN). The handbook and catalogues provide the cutting speed and feed rate for each workpiece material and hardness, one may scan through different tool materials. For examples, catalogues of Sandvik Coromant company show the values of feeds and cutting speeds of different grades for turning, drilling and milling operations. The values of feed and cutting speed differ with tool grades and material to be machined [3, 4].

Tool grades are numbered on a scale that ranges from maximum hardness to maximum toughness. Harder grades are used for finishing operations (high speeds, low feeds and depths), while tougher grades are used for roughing operations. The tool manufacturers assign many names and numbers to their product. While many of these names and numbers may appear to be similar, the applications of these tool materials may be entirely different. For example Sandvik Coromant Company gave names to its products of tool grade as follows: (CT5015, GC4015, GC2015, GC2025, GC2035, GC235, GC3025, CC620, H13A and so on). Each grade has its special composition.

3. Cutting forces, torque and power consumptions

3.1 Cutting force, torque and power consumptions for turning operations

The tangential cutting force F_z can be calculated by the following empirical equation using the concept of specific cutting resistance:

$$F_z = s \times t \times k_c \quad (1)$$

Torque can be calculated by the following formula:

$$M = \frac{D}{2} \times F_z \quad (2)$$

Using the concept of specific cutting resistance, power is calculated as:

$$Ncut = \frac{v \times t \times s \times k_c}{60 \times 10^3} \text{ kW [3]} \quad (3)$$

Taking into consideration the efficiency η of the machine tool, there is no difficulty in calculating the required (design) power rating of the electric motor of the main drive. Thus:

$$N_e = \frac{\text{Ncut}}{\eta} \text{ kW} \quad (4)$$

3.2 Cutting force, torque and power consumptions for drilling operations

The tangential component F_z and the torque M and power can be calculated by using the concept of specific cutting resistance as the following:

1. For solid drilling:

Force can be calculated by this formula:

$$F_z = 0.5 \times \frac{D}{2} \times s \times k_c \times \sin\varphi \text{ N} \quad (5)$$

Torque can be calculated by this formula:

$$M = \frac{D \times F_z}{2} \text{ N.mm} \quad (6)$$

Power can be calculated by this formula:

$$N_{cut} = \frac{D \times s \times k_c \times v}{240 \times 10^3} \text{ kW} \quad (7)$$

2. For boring and trepanning:

Force can be calculated by this formula:

$$F_z = 0.5 \times t \times s \times k_c \times \sin\varphi \text{ N} \quad (8)$$

Torque can be calculated by this formula:

$$M = \frac{D \times s \times t \times k_c}{2}\left[1 - \frac{t}{D}\right] \text{ N.mm} \quad (9)$$

Power can be calculated by this formula:

$$N_{cut} = \frac{t \times s \times k_c \times v}{60 \times 10^3}\left[1 - \frac{t}{D}\right] \text{ Kw} \quad (10)$$

3. For deep drilling, deep trepanning and counter boring:

Force can be calculated by this formula:

$$F_z + F_\mu = 0.65 \times t \times s \times k_c \times \sin\varphi \text{ N} \quad (11)$$

Torque can be calculated by this formula:

$$M + M_\mu = \frac{D \times s \times t \times k_c}{2000}\left[1.17 - \frac{t}{D}\right] \text{N.mm} \quad (12)$$

Power for deep drilling can be calculated by this formula:

$$Ncut + N_\mu = \frac{s \times v \times D \times k_c}{240 \times 10^3} \times 1.34 \text{ kW} \quad (13)$$

Power for trepanning and counter boring can be calculated by this formula:

$$Ncut + N_\mu = \frac{s \times v \times D \times k_c}{240 \times 10^3} \times \left[1.17 - \frac{t}{D}\right] \text{ [16]} \quad (14)$$

3.3 Cutting force, torque and power consumptions for milling operations

The force F_z can be calculated by the following formula:

$$F_z = \frac{60 \times 10^3 \times Ncut}{v} \text{ N} \quad (15)$$

The tangent (peripheral) force F_z sets up the moment of resistance for cutting:

$$M = \frac{F_z D}{2} \text{ N.mm} \quad (16)$$

The power is calculated by the following formula using k_c:

$$Ncut = \frac{t \times B \times s_m \times k_c}{60 \times 10^6} \text{ kW [4]} \qquad (17)$$

4. Machining time and total production time and cost

4.1 Production time

The production time required for manufacturing a number of workpieces in a definite operation is made up of elements shown in Fig. 1.

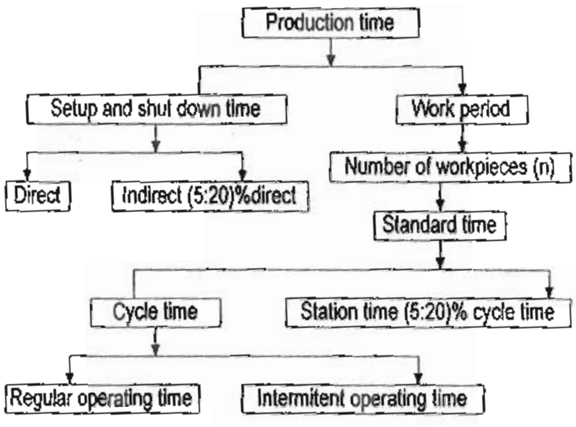

Fig. 1: Production time chart

The regular operating time (machining time) is calculated using some equations according to operation required as shown below:

For turning operation the time will be denoted by Tm:

$$T_m = \frac{L}{ns} \text{ min} \qquad (18)$$

$$L = l + y + \Delta \text{ mm} \qquad (19)$$

$$y = t \cot \varphi \text{ mm} \qquad (20)$$

For a number of passes of the same feed and speed, machining time will be:

$$T_m = \frac{L}{ns} i \text{ min} \qquad (21)$$

Machining time in drilling and enlarging holes is:

$$T_m = \frac{L}{ns} = \frac{l + y + \Delta}{ns} \text{ min} \qquad (22)$$

The length of travel *(y)* required before cutting the full diameter:

$$y = \frac{D}{2} \cot \varphi \text{ mm} \qquad (23)$$

Machining time in peripheral milling is:

$$T_m = \frac{L}{s_m} = \frac{l + y + \Delta}{s_z zn} \text{ min} \qquad (24)$$

Machining time in face milling is calculated by the formula:

$$T_m = \frac{l + y + \Delta}{s_m} \text{ min} \qquad (25)$$

4.2 Production cost

The ultimate objective of the manufacturing engineer is to produce the objects at the most economical cost. To do this he should be able to analyze the machining process for all possible costs. So that he would be able to optimize the process to get the minimum possible costs satisfying all the requirements.

Unit cost—The unit cost has generally been represented by the following equation [17]:

$$C_u = c_{mat} + (c_l + c_o)t_s + (c_l + c_o)T_m + (c_l t_{tc} + c_t + c_o t_{tc})\left(\frac{T_m}{T}\right) \qquad (26)$$

In the case of multi-tool operations, tool changing time for each tool used must be considered regardless of this ratio. This changes the above equation to:

$$C_u = c_{mat} + (c_l + c_o)t_s + \sum_{i=1}^{m}(c_l + c_o)T_{mi} + \sum_{i=1}^{m}\left(c_t\left(\frac{T_{mi}}{T}\right)\right) + \sum_{i=1}^{m}(c_l + c_o)t_{tci} \qquad (27)$$

Where: m represents the number of machining features or operations required to produce the part.

5. The software and algorithm

Microsoft SQL server was used to design a database. To attach the designed database, calculate machining time, force, torque, power and total production time and cost for machining processes and showing results in a single report, the Microsoft Visual Basic.Net programming language was used. The link between Microsoft SQL server and Microsoft Visual Basic.Net programming language is maintained by Microsoft OLEDB Provider. The software consists of three parts: (1) the database, (2) Software algorithms (3) the graphical user interface GUI as follows.

5.1 The database

To store data of operations, workpiece materials, manufacturer of tools, tool grades, inserts, tool holders and cutting data, a number of tables were designed as shown in Fig. 2.

5.2 The software algorithm

The software algorithm is shown in Fig. 3. It is used to calculate the machining time either by using maximum cutting speed (minimum tool life) or by using minimum cutting speed (maximum tool life) of the stored tool grades. It is also used to determine the suitable cutting data, calculate the tangential force, torque, power and total production time and cost. In addition, it is used to select the suitable tool grades, insert and tool holder for different operations of turning, drilling and milling.

5.3 The Graphical User Interface

The graphical user interface (GUI) of the developed software deals with a number of windows that were designed to make it easy to the user to deal with the program. The main windows of the program (Fig. 4) contains four main menus, each of them includes a number of submenus. The first three main menus were designed to connect the database, for example by double clicking the tools grades submenu shown in Fig. 4, the window in Fig. 5 will appear and by double clicking the new button, the window shown in Fig.6 will appear.

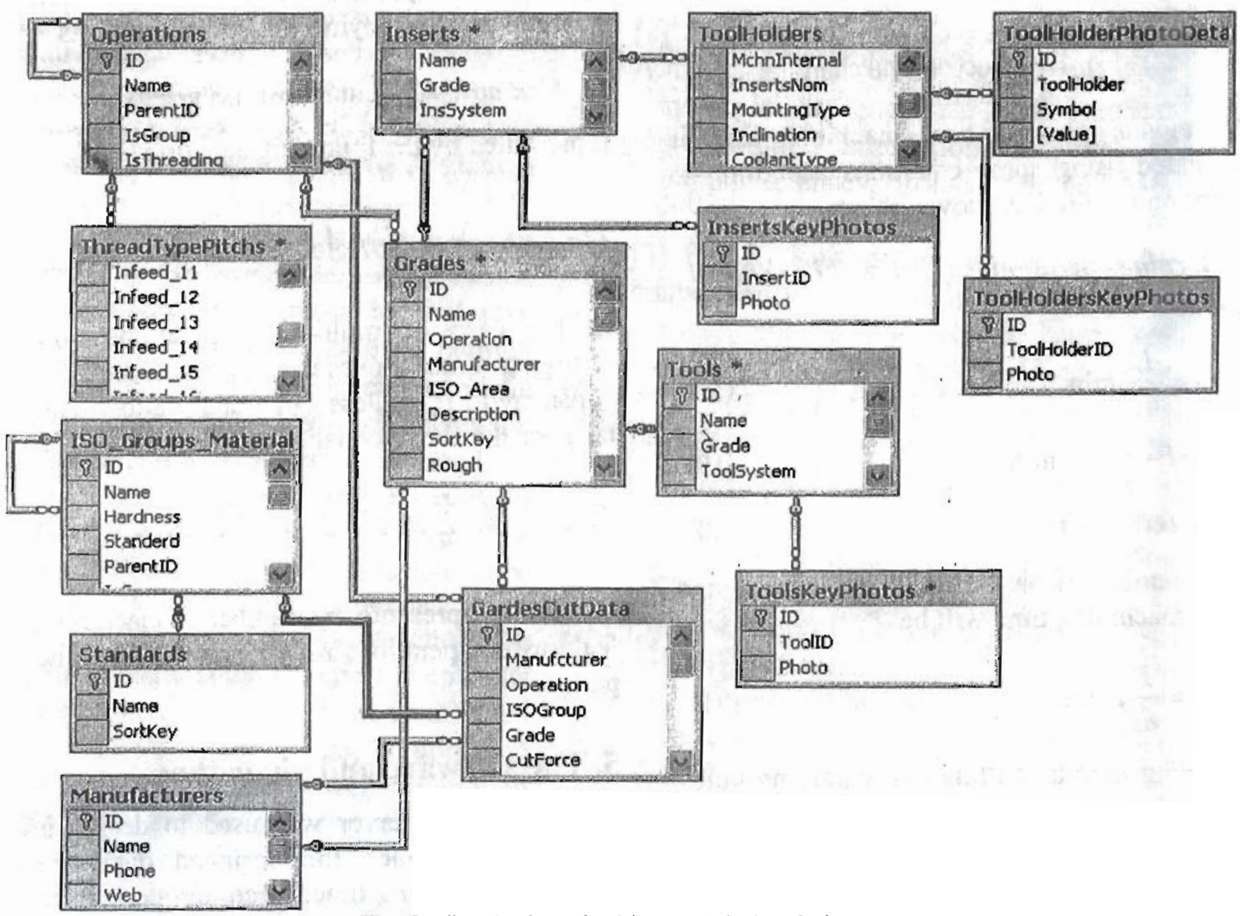

Fig. 2: The designed tables and their relations

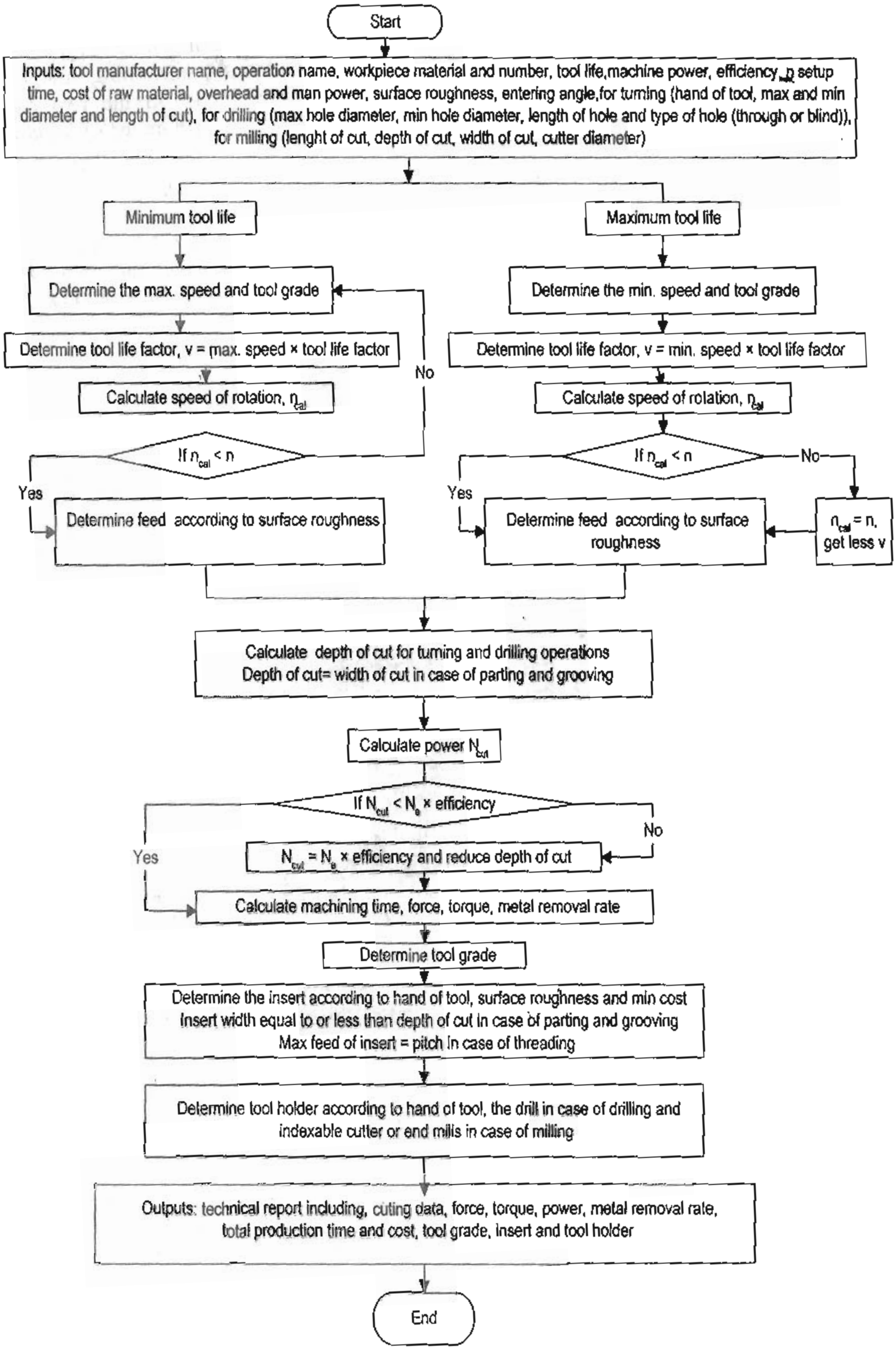

Fig. 3: Algorithm used for different techniques of turning, drilling and milling operations using minimum or maximum tool life

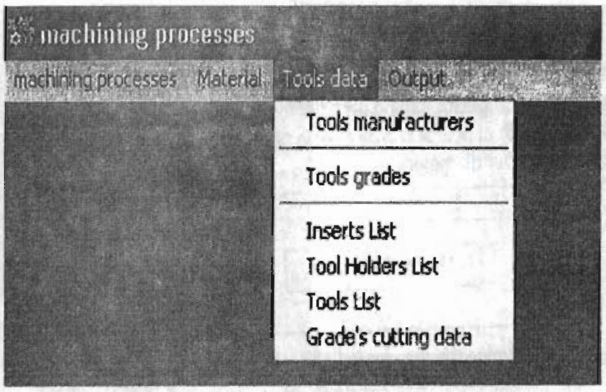

Fig. 4: The main window of the designed software

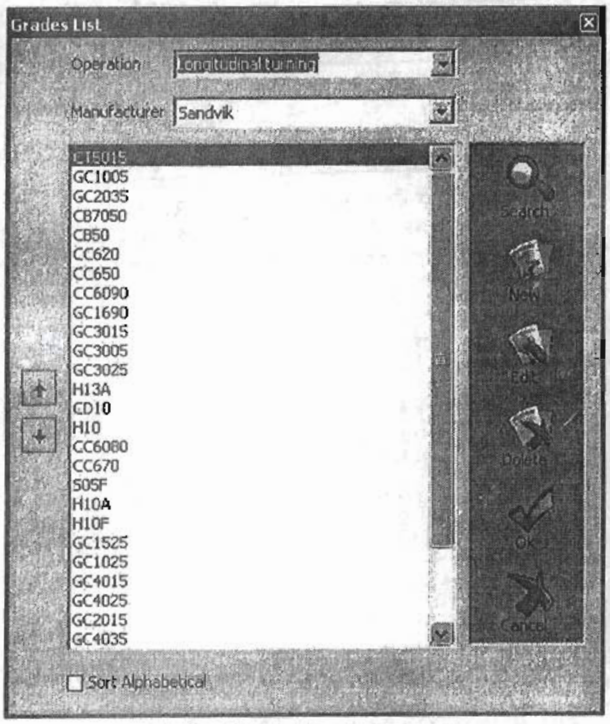

Fig. 5: Grades list windows

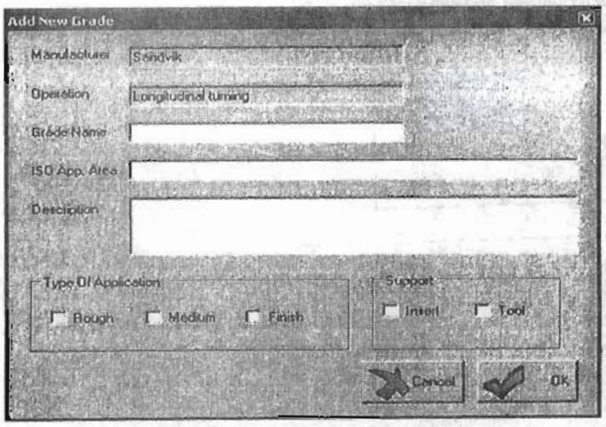

Fig. 6: Add new grade window

The fourth main menu of output (Fig. 7) was designed to calculate the machining time, total production time and cost in the two cases mentioned above. Also a number of windows were designed for different techniques of turning, drilling and milling operations. For example, for any operation done using maximum cutting speed of the tool grades, the user first double clicks the machining time using max. speed submenu, shown in Fig. 7, to display the window shown in Fig. 8. Through this window, the user can select the tool's manufacturer; determine the operation required, material of the workpiece. In addition, the user can enter the values of machine power, efficiency, and so on (Fig. 9) by clicking the next button in this window. Finally, by double clicking the OK button in Fig. 8, the window of the required operation will appear as shown in Fig. 10.

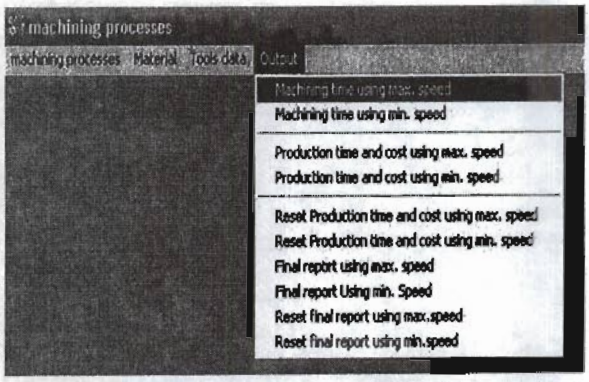

Fig. 7: The output menu and its submenus

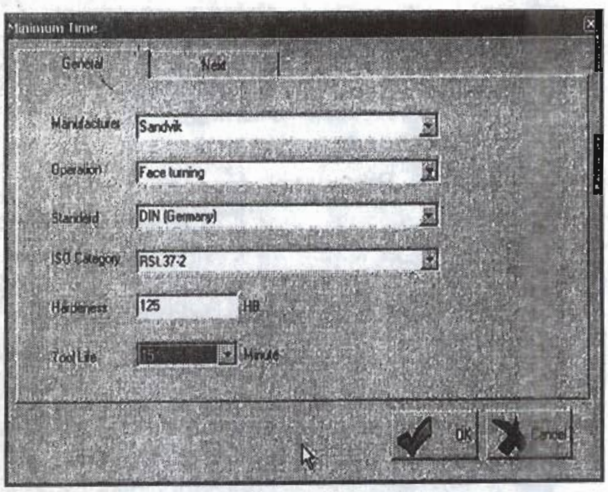

Fig. 8: Minimum time window

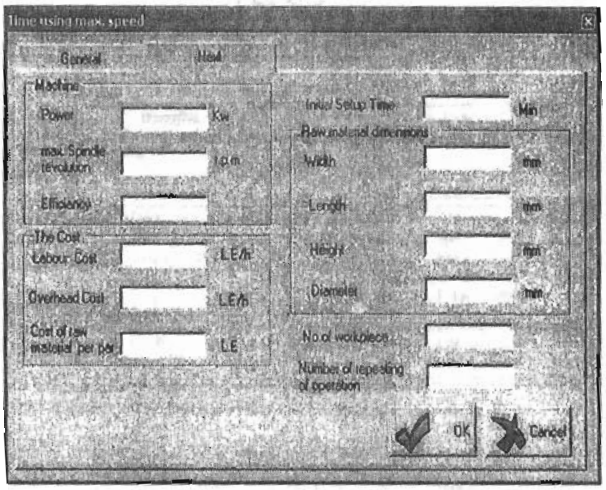

Fig. 9: Next window

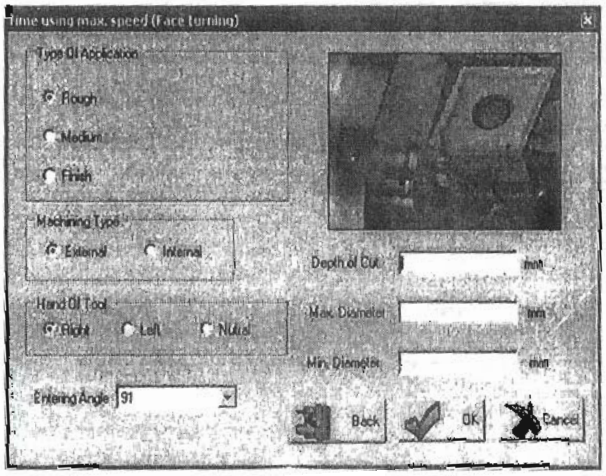

Fig. 10: Face turning window

6. Case study

The product drawing of the case study is shown in Fig. 11. The dimensions of the raw material are 155 mm length and 100 mm diameter. It is required to determine the suitable cutting data, calculate the regular operating time, intermittent operating time, total production time and cost, force, torque and power required for cutting in two cases, the first using minimum tool life and the second using maximum tool life then selecting the suitable tool. There were about twenty steps to manufacture this product including chucking, releasing and chucking, turning, drilling and milling operations. All of these steps appear in detail in the final report. A part of the final report using maximum cutting speed (minimum tool life) for this product is shown in Fig. 12. The number of each operation is shown in this report.

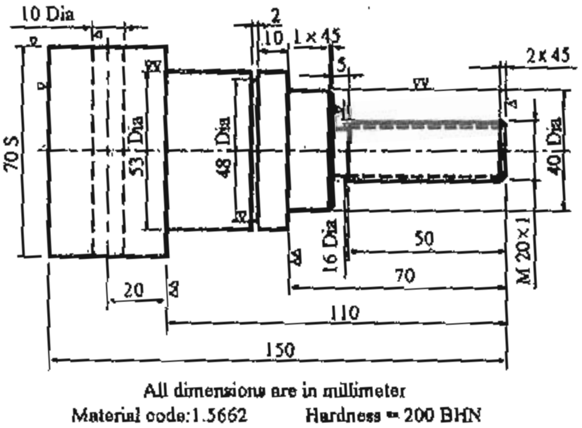

Fig. 11: Working drawing of the product

Specifications of the machine, material and constants are given below.

Machine tool data:

- CNC turning machine with driven motor of 20 kW
- Max spindle revolutions = 3200 rpm
- Efficiency = 95%

Material data:

- Material code: 1.5662
- Standard reference: W.-nr.
- ISO group: P (High-alloy steel, Annealed)
- Hardness = 200 N/ mm2
- Tensile strength = 700 N/ mm2

Constants:

- Setup time = 12 min
- Cost of raw material per part = 200 L.E
- Labour cost (high expertise) = 13 L.E/h
- Overhead cost = 2 L.E/h

In case of using min. cutting speed:

- Labour cost (medium expertise) = 8 L.E/h

7. Results and discussion

For all operations done, the consumption of power for the same feed in the first case using maximum cutting speed (minimum tool life) is greater than that in the second case using minimum cutting speed (maximum cutting speed), so the tool life of the tool grade decreases and the cost of tool grade increases in the first case. The values of force and torque

Final report using max.speed of the stored grades.

workpiece material 1.5662 Standard W.-nr. ISO group P
Categories High-alloy steel. Hardness 200 HBN

No	Operation	Cutting data, force, power and time	Tool grade	Insert	Tool holder
1	Chucking	Time 1.5000 min			
2	Face turning Max.Diameter 100.0 mm Min.Diameter 0.0 mm Hand of tool Right No of repeating of operation 1	Cutting speed 335 m/min Spindle revolution 812 rpm Feed 0.80 mm/r Depth of cut 1.0 mm No of passes 1 Force 4000 N Torque 100000 N.mm Power 17.0 kW Time 0.0800 min	GC4035 ISO area P35 (P20- P45), M25 (M15- M30) Description CVD-coated carbide grade. The tough substrate allows the grade to handle interrupted cuts at high metal removal Tool manufacturer Sandvik Web site www.sandvik.com Local distributor Egypt	TNMM 16 04 08-PR	DTFNR 2020K16
3	Longitudinal turning Length 41.0 mm Max.Diameter 100.0 mm Min.Diameter 99.0 mm Machining type External Hand of tool Right No of repeating of operation 1	Cutting speed 225 m/min Spindle revolution 717 rpm Feed 0.80 mm/r Depth of cut 0.5 mm No of passes 1 Force 1600 N Torque 80000 N.mm Power 3.8 kW Time 0.0750 min	GC4035	TNMG 22 04 08-PR	PTFNR 2525M22
4	Face milling with endmill Length 70.0 mm Workengagement 33.3 mm Cutter diameter 40 mm Width of cut 41.0 mm No of repeating of operation 4	Cutting speed 225 m/min Spindle revolution 1791 rpm Feed 0.10 mm/r Depth of cut 14.500 mm No of passes 1 Force 391313 N Torque 11826463 N.mm Power 13.3 kW Time 0.0687 min	GC4030 ISO area P25 (P10 -P40) Description Coated carbide grade for light to heavy milling Tool manufacturer Sandvik Web site www.sandvik.com Local distributor Egypt	R390-17 04 16M-PH	R390-040A32-17L
5	Short drilling Length 70.0 mm Hole diameter 10.6 No of repeating of operation 1	Cutting speed 80 m/min Spindle revolution 3200 rpm Feed 0.20 mm/r Force 1174 N Torque 3073 N.mm Power 1.7 kW Time 0.1183 min	1120 ISO area P,M, K Description PVD-coating. Assure tough coating, also adherence to the substrate and improved resistance to crater wear Tool manufacturer Sandvik Web site www.sandvik.com Local distributor Egypt		R840-1060-70-A1A

Fig. 12: Apart of the final report using minimum tool life

are the same in the two cases. The calculated machining time in the first case is less than that in the second case because of using tool grades that gives maximum cutting speed. This means that about 34% of the total production time can be saved by using maximum cutting speed (minimum tool life) of the available tool grade, if compared with the case of using minimum cutting speed (maximum tool life). Similarly, about 28% of the total production cost can be saved by using minimum cutting speed (maximum tool life) of the available tool grade, if compared with the case of using maximum cutting speed (minimum tool life).

8. Conclusion

In this paper, a software has been developed to store the cutting data, different types of tool grades, inserts and tool holders suitable for each operation of different machining processes in a database. Through a user friendly GUI, the user can select the suitable cutting data, tool grade, insert and tool holders for each operation. The software is capable of calculating the machining time, force, torque, power, total production time and cost in two cases: (a) minimum tool life, (b) maximum tool life. In both cases, a final report including all the operations done, machining time, force, torque, power, the suitable tool grade, insert and tool holder for each operation can be obtained and printed.

The following points can be concluded:

1. According to the results shown in the case study, about 34% of the total production time can be saved by using minimum tool life (maximum cutting speed of the available tool grade).
2. On the other hand, about 28% of the total production cost can be saved by using

maximum tool life (minimum cutting speed of the available tool grade).

3. The software saves a lot of time in selecting the suitable tool grade, insert and tool holders and in calculating the machining time, force torque, power and total production time and cost for each operation.

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