ECONOMY OF TITANIUM MILLING

G. J. Trmal[1], P. Bach[2]
[1]RAMP, UWE, Bristol, United Kingdom
[2]Research Center for Manufacturing Technology, CTU in Prague
Czech Republic

e-mail: p.bach@rcmt.cvut.cz

This paper describes benefits of close collaboration between technologists and analysts of machine tools. After all, any innovation in machine design can only be proven by producing components of required quality more economically. The combined expertise can be utilized especially in machining new materials, such as titanium, which are more difficult to machine. The decisive factor in optimization of the production process is the cost: cost of labour, machine and tools. The cost of tools is important and the paper proposes a new model of tool life, which is experimentally verified. The model allows determination of a combination of machining parameters for minimum cost. Increase in axial depth of cut could improve the removal rate but is limited by stability of the cutting process. That is why the paper proposes machining at very low speeds, where the stability limit is higher and the lowest cost can be achieved. At these low speeds it is beneficial to use not carbide but HSS tools.

Keywords
titanium, cost of machining, tool wear

1. Introduction

There seems to be a difference between technologists and analysts of machine design in how they approach the machine and tool behavior during the machining process. The technologists have a lot of experience and knowledge about the process itself, its parameters and the resultant component quality. The machine analysts can contribute with the knowledge of machine properties such as stiffness and vibration, which have without doubt a strong effect on the process. Their close collaboration is highly desirable. After all, any innovation in machine design can only be proven by producing high quality components more economically. The combined expertise can be utilized especially in machining new materials, which are stronger and more difficult to machine.

There is another aspect of the collaboration. In the past, the machine operator not only turned the hand-wheels but listened to the noise, watched the process and learned. Now the CNC is driving the machine, the technologist is in the office and nobody is learning. And yet the CNC can process the information gathered by sensors, monitor the process and provide valuable information. There are attempts to provide adaptive control of the process. However, most parameters controlling the process must be at the optimum before the process starts. The control loop is much larger and involves management decisions based on available information on selecting the best tool and even machine for the job in order to achieve the most economical process at minimum cost. Machine designers and control specialists in collaboration with technologists can provide a significant progress in this area.

2. Cost of machining

The cost of machining is probably the most useful parameter for comparing machining operations. The total cost of machining consists of labour cost, machine cost and tool cost. In this study, in order to keep a general approach, the cost will be related to the removal of unit volume of 1 liter (1000 cm^3) of material. In general the higher is the machining rate the shorter the tool life. In other words the lower the machining cost, the higher is the tool cost and vice versa. However, not all machining conditions affect tool life and machining rate equally. There are therefore optimum conditions, which result in minimum overall cost.

There are economic parameters such as labour cost rate and machine cost rate (both per hour) and cost of the tool. They would depend on the country and the sophistication and complexity of the used machine and tool and will be specific to the company. They must be selected for specific conditions.

With easy to machine materials the tool life is high and tool cost low. It can be often neglected. With difficult to machine materials such as titanium the proportion of tool cost is high and must be considered [Trmal 2000 Metal]. It is therefore important to determine the relationship between the process conditions and tool life.

2.1. Tool life and Taylor's equation

The model usually used is the Taylor's model [Kalpakjian 1995] represented by well known equation:

$$T^n = Const/vc \qquad (1)$$

where ***T*** is tool life and vc cutting speed. The equation was developed almost 100 years ago for turning. It expresses the effect of cutting speed when the other parameters (depth of cut and feed per revolution) are kept constant. The equation is empirical; the parameters (constant and exponent) have no physical meaning and must be determined for any combination of cutting conditions. The equation has been extended to include the effect of depth of cut ***a*** and feed per revolution ***f*** into the following form:

$$vc * T^n * a^x * f^y = Const \qquad (2)$$

Although equation 2 has been developed for turning it is often used for milling while no attention has been paid to the differences between the two processes. There are some attempts but they are purely empirical with no effort to determine values of constants or exponents [Madl 1998].

3. New tool life model

The new approach takes into account the differences between turning and milling and introduces several parameters based on the cutting action.

3.1. Edge life

The cutting edge is only wearing while it is in contact with machined material. As can be seen in fig. 1, in a single revolution the edge cuts over the angle αc, while the cutter 'cuts' over the angle of 2π. The cumulative edge life is therefore significantly shorter than the cutter life. The tool life ***T*** can be calculated from edge life ***Te*** as follows:

$$T\,[min] = Te / \alpha c * 2 * \pi \qquad (3)$$

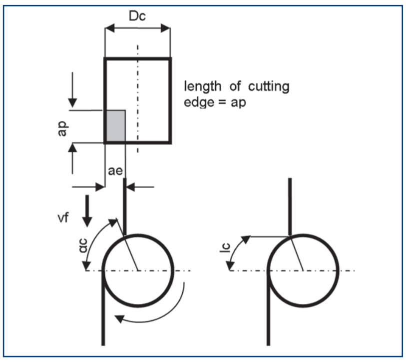

Figure1. *Cutting of a single edge.*

3.2. Edge load

The difference between average power and instant power taken by single edge (tooth) is shown in Figure 2. ***Pa*** is average power taken by the cutter. It is measured or calculated from the removal rate and specific energy. ***Pe*** is power taken by each single tooth in its time of cutting ***tc***. The power during this period is considered constant although is more likely declining after high initial value.

For calculation of power intensity the edge can be considered to consist of sections of unit length loaded by power intensity, power per unit edge length (***P'e=Pe/ap***). (See Figure1). Power intensity is likely to correspond to adhesive wear affected by temperature and more relevant to titanium milling. Force intensity is likely to characterize abrasive wear at low speeds.

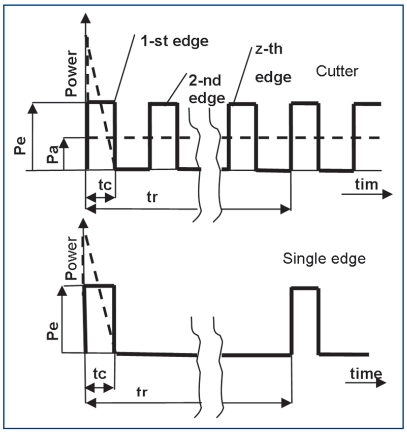

Figure 2. *Power supplied by the cutter and by a single ege.*

3.3. Rubbing rate

Rubbing rate can be defined as cutting length done by a single edge (tooth) in a unit of time (figure 2). The cut is interrupted so that the rubbing length is always lower than the cutting speed. The rubbing rate can be calculated as follows:

$$Rr = n * \alpha c * Dc/2/1000 \qquad (4)$$

Where n is spindle speed [rpm], αc is angle of contact and Dc is cutter diameter.

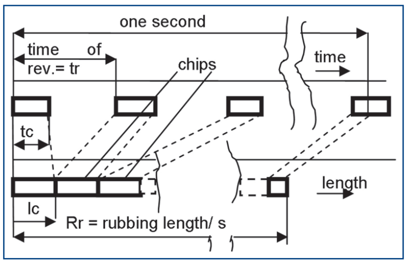

Figure 3. *The rubbing rate.*

3.4. Edge life calculation

It seems logical that the wear rate of the cutting edge will be calculated as the wear of any slider – load intensity multiplied by the rubbing rate. The wear will increase in time and the end of life is defined as the point in time, when the edge wear reaches an un-acceptable value.
The edge life can be calculated as follows:

$$Te = Const/(P'e^{x} * Rr^{y}) \qquad (5)$$

where: P'e = power intensity [$W.mm^{-1}$], Rr = rubbing rate [$m.min^{-1}$]

The exponents x and y are introduced to express any possible non-linearity. However, this was not necessary in this stage of investigation(set x=1, y=1).

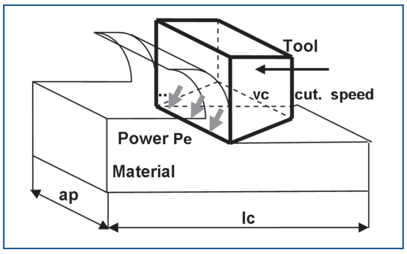

Figure 4. *Simplified conditions in the interface.*

Tool life can be then calculated from the edge life as shown in equation (3).

3.5. Experimental verification

Four tests were performed on Titanium Ti6A14V by solid carbide tool of 16mm diameter and with 3 teeth. The tests were performed with coolant. The tests are explained in detail in [4]. Four conditions involving axial and radial depth of cut (***ap*** and ***ae***) and cutting speed ***vc*** were changed in such a way that the removal rate remained the same (**Q**. = 2.7 ccm/min) These conditions are shown in Table 1.

Test	1	2	3	4
		Cutting speed		
vc [$m.min^{-1}$]	226	226	113	113
		Feed per tooth		
fz [mm]	0,03	0,03	0,06	0,06
		Ax. depth of cut		
ap [mm]	1	5	1	5
		Rad. depth of cut		
ae [mm]	5	1	5	1

Table 1.

Experimental results of tool life and results obtained from the above described model shown in Figure 5. For the same removal rate there is an amazing difference in tool life between 3 and 65 minutes. There is also a remarkable agreement between the model (equations 3 and 5) and experimental data.

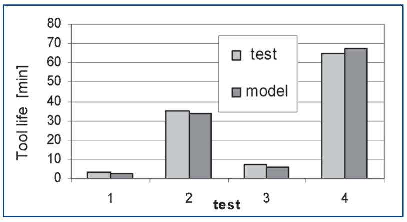

Figure 5. *Comparison of model output with test results.*

4. Cost of machining

Cost of machining must be related to a particular component or to specific volume removed as a benchmark. The second method was selected in order to make results more general and easy to apply to any component. Volume of 1000 ccm (one litre) was selected. The machining process is represented by removal rate ***Q***, tool life ***Tlife*** and ***Rq***, which is the ratio of production time, which includes both, machining and preparation (clamping, measurement, etc), to the time of machining itself. The ratio is expressed in percents.

Economic parameters (selected)		
Labour rate	Lr [euro/hour]	= 20
Machine rate	Mr [euro/hour]	= 40
Tool cost	TC [euro]	= 50
Production parameters (selected) – 1st trial		
Prod/Mach ratio	Rq [%]	= 150
Volume to remove	V [cm^3]	= 1000
Tool life	Tlife [min]	= from fig.5.

Table 2.

The economic parameters can vary from case to case, from machine to machine, from tool to tool. They are specified as machine and operator hourly rates and the tool cost. Machine rate consists of the cost of the machine (including services such as energy, space, machine, power, etc.), The Labour rate represents the cost of operator (wages, insurance etc). These and other selected parameters are shown in table 2. They were selected to suit average EU conditions [Trmal 2000 Matar].

Machine time	Mati [min]	= V / Q
Prod. Time	Proti [min]	= Mati * Rq/100
Labour cost	Lcost [euro]	= Lr * Proti/60
Machine cost	Mcost [euro]	= Mr * Proti/60
Tool cost	Tcost [euro]	= TC*Mati/Tlife
Total cost	Total [euro]	= Mcost+Lcost+Tcost

Table 3.

For machining 1000 cm^3 of material the Machine cost can be calculated as Machine rate multiplied by production time. This and other formulae are shown in table 3 and are valid not just for the verification test but for calculation of cost under any conditions.

4.1. Effect of edge length – 1st trial

The results of calculation of the cost are shown in Figure 6. As stated before the trial conditions were selected to result in the same removal rate in all 4 tests of the first trial. The Machine and Labour costs was therefore the same. However, there were significant differences in the tool life and therefore the total cost differed from 780 to 5 500 euro/liter. The lowest cost corresponds to the highest axial depth of cut (***ap=5*** mm) and the lower cutting speed (***vc=113*** $m.min^{-1}$). The effect of just speed is not great: cutting speed higher by a factor of two (***vc***=226 $m.min^{-1}$ against 113 $m.min^{-1}$ increased the cost from 780 to only 980 euro/liter).

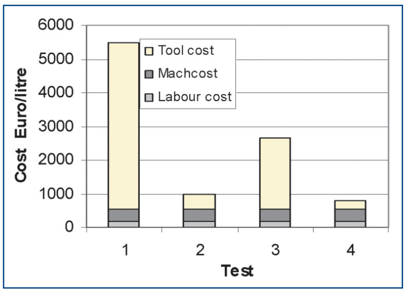

Figure 6. *Cost corresponding to the 1st trial.*

4.2. Effect of speed and removal rate – 2nd trial

The new 'verified' model (the verification was rather basic and more experimental data of tool life are required) was then used to establish the effect of cutting speed while the feed per tooth was kept constant. Other conditions were equal to test 4 in the 1st trial. In this case it was not just the speed, which is increasing; it is also the removal rate. This is the condition usually associated with the use of Taylor's formula.

As before the Power intensity and the Rubbing rate were calculated and then the edge life was determined using the formula in eq.1.

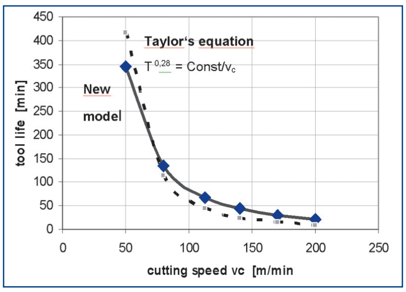

Figure 7. *Effect of speed determined by the new model and compared with Taylor's formula.*

Then the tool life was determined for a speed from 50 to 200 $m.min^{-1}$. Machining rate Q [$cm^3 .min^{-1}$] was also determined.

Graph of tool life against the cutting speed determined by the new model is shown in Figure 7. Comparison with Taylor's formula graph shows the best fit obtained with exponent n = 0,28. Normal expectations are between 0,2 and 0,5 for carbide tools [Madl 1998]. This serves as an indirect verification that the new model formula for tool life works well.

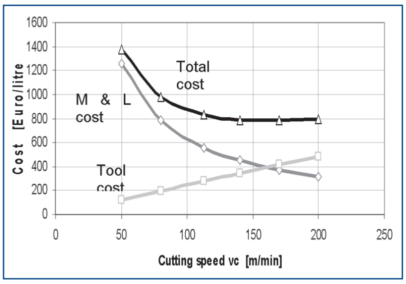

Figure 8. *Optimum cutting speed for the lowest machining cost (2nd test model).*

The cost of machining for the 2nd trial (set of conditions showing the effect of speed and removal rate) is shown in Figure 8. The figure shows that for machining the Ti6Al4V titanium alloy by a carbide cutter of 16 mm diameter the total cost is at its minimum at speeds between 120 to 200 $m.min^{-1}$. The minimum cost is about 800 euro/liter. At low speed of about 50 $m.min^{-1}$ the cost is already reaching 1400 euro/liter and rapidly increasing.

5. Dynamics of machining

Performance of any machining operation is limited by dynamic properties of the entire machine tool structure. Process of machining can be stable or instable. Instability means heavy chatter of the machine tool structure as showed in [Tlusty 1963] and [Tlusty 1999] and very poor surface finish. It is not possible to machine in the instable region. A special stability diagram can be constructed to find stable depth of cut for any spindle speed. Stable depth of cut level depends on cutting speed and on dynamic stiffness of the tool – spindle mechanical system. Titanium milling needs a stiff tool-spindle structure powered by a strong motor. The flexibility less then 0,55 $\mu m/N$ is proper value for milling of titanium [Bach 2007]. More stable conditions can be expected at very low speeds below 40 $m.min^{-1}$ (400 rpm for tool diameter 32 mm).

5.1. Machining with HSS cutters – 3rd trial

It has been known that at low speeds the process is more stable allowing higher axial depth of cut without chatter. It has been confirmed again in this investigation with results shown in Figure 9. It is also shown in the figure that cutters with irregular tooth pitch were superior to cutters with regular pitch. It is also expected that at low speed the HSS cutters will perform better than carbide cutters because the temperature is low and HSS is tougher and might be superior to more brittle carbide.

First the stability of the process (stable axial depth of cut at low speeds) was determined experimentally. This was done for cutters

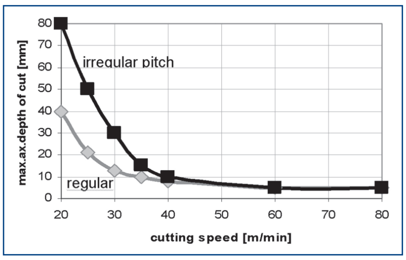

Figure 9. *Stability limit (max. axial depth of cut).*

with regular and irregular pitch. Irregular pitch is expected to make the process more stable and allow machining with higher depth of cut, which, together with low speed, has been shown to increase tool life.

5.1.1. Tool life

Figure10 provides an example of measured flank wear on tool life on HSS cutter running at 20 m.min^{-1}.

The axial depth of cut ***ap*** = 18 mm, the radial depth ***ae***=1 mm, 4 teeth, feed per tooth ***fz*** = 0,1 mm. These conditions provide removal rate ***Q*** = 1.44 ccm.min^{-1} The HSS cutter was of 32 mm diameter. As can be derived from the figure the tool life was determined as 205 min, time after which the flank wear begins to rise rapidly. According to the model the tool life remains the same even if the axial depth of cut is increased to 80 mm, the limit of stability at cutting speed 20 m.min^{-1}.

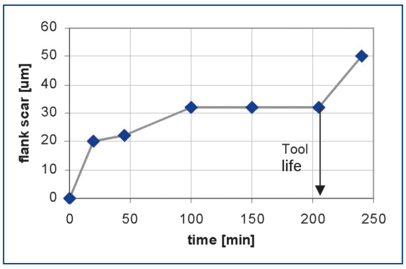

Figure 10. *Wear scar VBB on HSS cutter at 20m/min.*

5.1.2. Tool life using the model

It is necessary for the analysis to provide the tool life for a range of lower speeds. For this reason the tool life model was tuned to the new conditions. The constant for HSS tool was determined on the basis of providing tool life 205 min to suit the experimental results. Predictions for tool life using the tuned model are shown in Figure 11.

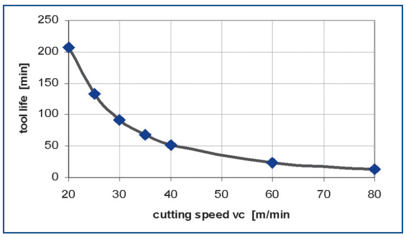

Figure 11. *Life for HSS tools using the new model.*

The results confirm experience of the technologists that tool life is increasing at low cutting speed. However, there is a limit. If the force intensity is too high it could result in chipping and significant reduction of tool life. This is not the case. The conditions include increase of axial depth of cut allowed by higher stability at low speeds shown in Figure 9. The increase of axial depth of cut increases the removal rate and therefore the power and force, but not the power and force intensity which, are decisive for tool wear. Under these conditions the tool life is kept long and removal rate high, which results in low value of all components of cost: labour, machine and tool. It must be noted that the economic factors as machine and labour hourly rates were kept the same as in the previous trials with carbide tools. Only the cutters were different. The ones used in this trial were made of HSS and were of larger diameter (32 mm) than the previously used carbide cutters (16 mm dia). The HSS cutter cost was also higher (135 euro). The results of cost calculation are shown in Figure 12 below.

As can be seen in the figure between 80 and 40 m.min^{-1} the machine and labour cost stops rising and starts to go down. This is the range of speed, when the stability of the process starts increasing. This is characterized by the increase of the maximum axial depth of cut. When this axial depth of cut is fully utilized, the removal rate increases rapidly. This means sharp reduction in labour and machine cost. The lowest speed, which has been tested is 20 m.min^{-1}. The cost at this speed was 340 euro/liter, significantly below the cost in previous trials.

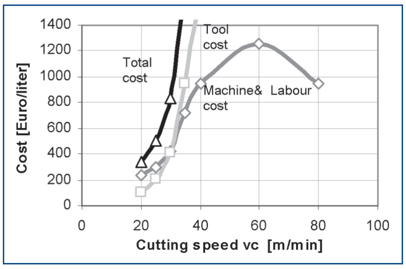

Figure 12. *Cost of machining in high stability region.*

The shape of the cost curve suggests a minimum total cost of about 200 Euro/liter. This should happen with the cutting speed is between 10 and 15 m.min^{-1}. The cost must later rise, because at zero speed it must be reaching infinity. Although not many components can be machined with axial depth of 80 mm, this area would be worth exploring.

6. Discussion

The investigation covers machining titanium with carbide and HSS cutters. The evaluation of the performance considered three aspects: cost of machining using economic model, model of tool wear as an important input into the economic model and stability of the machining process occurring at low speeds. Three trials were evaluated:

Trial 1 used carbide cutters in four tests, which were carried out at constant removal rate and tested the effect of cutting speed and the radial and axial depth of cut. This test was also used to verify the tool life model. Long cutting edge and low speed provided the optimum economy with cost of 800 euro/liter.

Trial 2 also used a carbide cutter and established the effect of cutting speed at constant feed per tooth at increasing removal rate and achieved good agreement of the tool life model with analysis using Taylor's equation. The optimum cutting speeds were 120 and 180 m.min^{-1} and cost of about 800 euro/liter at these speeds.

Trial 3 used HSS cutters and utilized higher stability of machining process at low speed so that the axial depth of cut could be increased to 80 mm and the cost was down to 340 euro/liter. This was because of long cutting edges (high axial depth of cut) the removal rate increases and low speeds (20 m.min^{-1}) and low edge load result in long tool life. The higher stability of the machining process cannot be used in case of carbide cutters because running them at low speeds would eliminate their main advantage – ability to withstand high temperature. On the other hand the HSS cutters are less brittle and therefore more suitable for higher forces expected at lower speeds. They are also sharper and in fact reduce cutting forces.

At this stage the new model of tool life is only a proposal. Its experimental verification is far from complete. There has already been additional testing and there will be more. There is also an alternative to testing in research laboratory. It is envisaged that an industrial company might get interested in determining optimum conditions for minimum cost. In such a case the production monitoring could provide enough information of tool wear and tool life and subsequently tool cost in the company machining operations. In addition it can provide more detailed information about removal rates and a comparison of individual operations.

Individual operations use different cutters are made on different machines and produce different components. Comparison and determination of the measure of efficiency of operations can be best achieved on the basis of cost model. The model proposed in this investigation is logical and allows fine tuning to achieve good agreement with production results.

Comparison of the machining operations in the company provide a basis for management decisions on purchasing new machines, using the existing machines more efficiently, introducing new and successful technologies, introducing new tools and using existing tools more efficiently.

At present most companies concentrate on operations, which have difficulties of providing the required quality of components. In many cases it is because the process is pushed too close to and perhaps even beyond the limit. However, there is a reluctance to relax the conditions, while less severe machining would probably achieve the required result. On the other hand there are operations, which have no problem to achieve the required quality only because the process and the machine are not working to their full potential. It is very likely that concentrating the effort on such operations has more scope for making savings than concentrating on operations, which give trouble.

7. Conclusions

- A model of tool life assessment has been proposed and verified;
- The model allows the machining cost for difficult-to-machine materials to be determined;
- The machining process has been optimized and optimum parameters for machining with carbide cutter determined;
- For machining with HSS cutters the region of process stability at low speeds can be utilized;
- With increased stability of the process at low speeds the HSS cutters can outperform the carbide cutters for suitable components;
- The theory looks very promising and should be further tested.

8. Acknowledgements

Thanks are due to the RAMP Centre of the University of the West of England, Bristol for supporting the research, results of which have been used in this investigation. Thanks are also due to Robert Zapp Werkstofftechnik GMBH, Germany, which provided material for HSS cutters, including the PM material (powder metallurgy). The cutters were manufactured by ZPS-Milling Tools. Authors are also grateful to Kovosvit-MAS, Sezimovo Usti, CZ for providing the CNC milling centre for the experimental work. The research at CVUT has been funded within the framework of the grant 1M6840770003 of the Ministry of Education and Youth of the Czech Republic.

References

[Bach 2007] Bach P.: Milling of Titanium Using HSS Tools, Proceedings of the conference Frezovani, Brno, 2007, pp. 87–100

[Kalpakjian 1995] Kalpakjian S.: Manufacturing Engineering and Technplogy, 3rd edition, 1995 Addison Wesley, ISBN 0-201-84552-0

[Madl 1998] Madl J., Kvasnicka I.: Optimalization of the cutting process, Vydavatelství ČVUT, Praha, 1998

[Tlusty 1963] Tlusty J., Polacek M: The Stability of the Machine Tool Against Self Excited Vibration in Machining. Prod. Eng. Res. Conf. ASME, Pittsburgh, 1963. pp. 16 – 28.

[Tlusty 1999] Tlusty J.: Manufacturing Processes and Equipment. Prentice Hall, New Jersey,1999.

[Trmal 2000 Metal] Trmal G.J., Mortimer L.: Effect of Tool Life in High Performance Milling, Metal working Production, 2000

[Trmal 2000 Matar] Trmal G.J.: High Performance Milling of Aerospace Materials, International Congress Matar 2000, CVUT Prague, June 2000, pp 112–118

Contacts:

Dipl. ing., Dr. George Jiri Trmal, PhD.
University of the West of England, Bristol,
Coldharbour Lane, Frenchay Bristol, BS16 1QY, UK
tel.: +441 173 289 523, e-mail: trmal.jiri@seznam.cz.