Methodology for the Study of Machining by Chip Removal and its Application to Milling and Drilling Precious Metals

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Abstract
In a research project, committed by industrial partners, a new method for the study of machining, particularly adapted to precious metals, was developed. The method is based on both the identification of minimum specific energy and the minimisation of machining costs. The kinds of machining considered in our study are milling and drilling. Nevertheless, the methodology can be adopted for the study of any form of machining by chip removal. The method involves the utilisation of some new software packages especially developed: a mechanistic model for the prediction of forces, specific energies and algorithms enabling research for economical optimisation.

Keywords:
Machining, Cutting parameters, Optimisation, Precious metals

1 INTRODUCTION, ASCERTAINING THE PROBLEM

When optimising cutting parameters several methods are used. One is based on the designs of experiments [1, 3] and is used mostly in order to reduce the effects of technological constraints (surface finish, accuracies, etc.) but is also suitable for the prediction of the tool life [2]. A second method is based on minimum specific energy, and has been specified in a French standard [4], but its ability to identify effective optimum parameters is not clearly demonstrated through a systematic comparison with the results obtained adopting different methods and machining different materials . Other methods aim to identify the minimum machining time or cost, some through the deterministic approach [5], others through a statistical approach allowing an estimation of the standard optimum deviation [6]. All of these methods require many tests, some of which are tool-life tests, involving large amounts of material (the tool must be worn out). In some cases tool life can be estimated or predicted through the observation of tool wear progression but in other cases (e.g. when drilling with small diameter tools) tool wear does not allow predictions for tool breakage. Therefore, these methods are unsuitable for studying precious metals, which require special care to avoid material and time wastage. On the other hand, pure mathematical simulations are neither reliable nor suitable enough for industrial applications on new, unusual or unknown materials.

Aiming to solve the above-mentioned difficulties, we developed a new methodology that allows these problems to be resolved. This methodology has been especially developed for the study of precious metals but can be used with any other materials, allowing an important reduction of the number of tests and improving the reliability of the results. This new methodology is described in this paper and its purpose is to attain:

1. The definition of the technical borders of the machining, i.e the definition of the machining application area.
2. The identification of the set of parameters corresponding to minimum specific energy in the space a_e, a_p, f_z, V_c.
3. The identification of the cutting conditions (f_z, V_c) corresponding to the minimum cost (economical optimum).
4. A comparison between the machinability of different materials.

All these targets need to be reached by using as little material as possible and without decreasing the reliability of the results. The method is based on empirical tests and includes:

- The realisation of a mechanistic model of the cutting forces, which allows verification of the measures.
- A non subjective method for the exploration of the machining application area, based on analogies with Digital Signal Processing technologies.
- The identification of cutting conditions (f_z, V_c) corresponding to minimum costs with only two machining tool life tests. This is a deterministic method but does not need the identification of the extended Taylor formulas (which would require more tests).
- The method is suitable for turning and milling, and with small modifications can be adapted to drilling (as demonstrated in this paper).

This paper shows the method adopted for the identification of: the machining application area, technological optimisation (identified as the set of parameters producing minimum specific energy), and economical optimisation (identified as the set of parameters producing minimum machining costs). Different precious metals were tested. Technically speaking, with the exception of platinum and palladium, precious metals are generally not very difficult to machine. Nevertheless, the price of these materials requires a method that avoids wasting material and time during their study. Therefore, the methodology especially adapted to the study of precious metals was developed during and is divided into two parts:

1. Research of technological optimisation (minimum specific energy).
2. Research of economical optimisation (minimum machining costs).

In research for technological optimisation, the first step consists in exploring machining possibilities (6 tests). The second step consists in building a mechanistic model suitable for reproducing the cutting forces and, therefore, the specific energy in any given space (V_c, f_z, a_e, a_p). No additional tests are required for this second step. The third step consists in building a regression surface, based on empirical values: this regression offers an estimation of the place where the optimum is located in the space (V_c, f_z).

This optimum is then empirically verified. The new empirical values contribute to building a new regression model. The number of tests required for this research depends on correlation between the values given by the regression model and the empirical values, this way offering an indication on the coherence of the tests and avoiding the need of test repetition.

For drilling, the same methodology is then applied to the space (V_c, f). The empirical values are validated through the mechanistic model. All tested values are presented in an efficient graphical form obtained through a Shepard polynomial interpolation algorithm [7].

Thus, the vector of machining parameters offering the minimum specific energy (technological optimum) is identified, and the explored space is graphically presented in an efficient manner.

For the second part of the study, identification of economical optimum in the space (V_c, f_z), a method requiring only two tests for the definition of the tool life was developed. This method, presented herewith, could also be successfully adopted for the machining of other materials.

2 RESEARCH OF THE MACHINING APPLICATION AREA.

In the space of the cutting parameters (V_c, f_z, a_e and a_p), one can define a region (the machining application area) where machining is technically possible (Figure 1 illustrates this case in the space (V_c, f_z)). Outside this space, machining is impossible because of catastrophic phenomena (tool breakages, unformed chips, etc.).

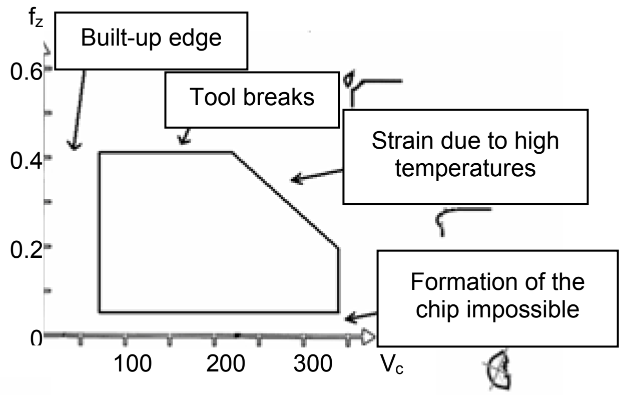


Figure 1: Machining application area in space (V_c, f_z).

The borders of the machining application area are usually widely spread in the space of the cutting parameters. They are defined within certain limits:

- The highest limit for f_z, which determines the force acting on the tool, is easily identified with a test where f_z is increased until the tool breaks.
- The highest limit for V_c, which determines the temperature reached by the tool, can be identified by increasing the rotation speed until the tool shows instantaneous (or almost instantaneous) wear.

Economically, the lower borders are usually less important. However, there are still limits:

- The lower limit for f_z is given by the radius of the cutting edge: if f_z is lowered, the tool slides on the surface of the material and the chip cannot form.
- The lower limit for V_c is due to the fact that a low cutting speed could lead to formation of a built-up edge.

In many cases, the borders are not imposed by the material but rather by the technical limitations of the machine. This happens frequently when machining precious metals for the watch or jewellery industries, where tools of small diameters are used. For materials that are easily machined, (e.g. gold) with tools of small diameters (3 mm), the limits are usually fixed by the machine (maximum spindle rotating speed) rather than by the tool or the material. This is not really a problem, since machines used for machining tests usually exhibit better performances than those available in production workshops.

When searching for the limits, it is also important to take care of economical interests: the borders of the area corresponding to high rates of metal removal are more important than those with very low rates of metal removal and need to be explored more accurately.

When machining, we are not on totally unknown (or unexplored) ground: for each material, we already know the parameters commonly adopted in common workshop practices, or are able to establish some similitude with other materials. Thus it is possible to explore and define machining application areas starting at this point. We are then able to identify the limits of the machining application area with at least 6 machining tests (Figure 2).

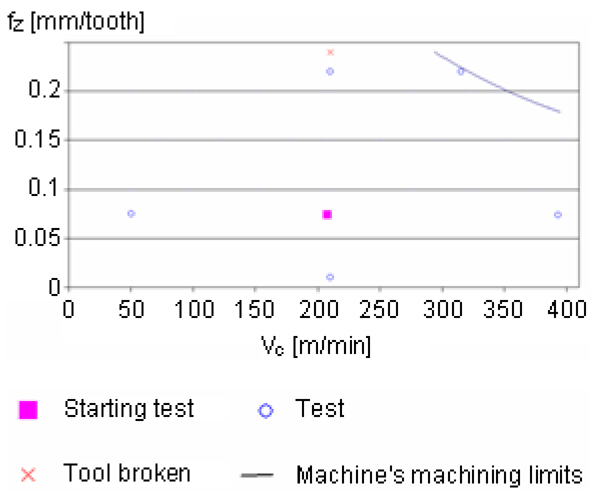


Figure 2: Example of exploration of the machining application area, case of milling.

During the exploration of the space, the region below V_c = 50 m/min is neglected. We, assume that lower cutting speeds are not economically admissible due to a low rate of metal removal.

At each point tested we measure the cutting forces and calculate corresponding specific energy. The values obtained feed the algorithms for the realisation of a mechanistic model, which predicts the cutting forces and specific energies in all the space (V_c, f_z, a_e, a_p).

The original purpose of our mechanistic model was to verify results obtained during machining tests. We discovered that data supplied by the mechanistic model, where precious metals are concerned, were found to be in close accordance with the measurements. Moreover, the use of the mechanistic model allows research in the full space (V_c, f_z, a_e, a_p). Therefore, our next step could be the research of minimum specific energy without any machining tests (or with very few tests).

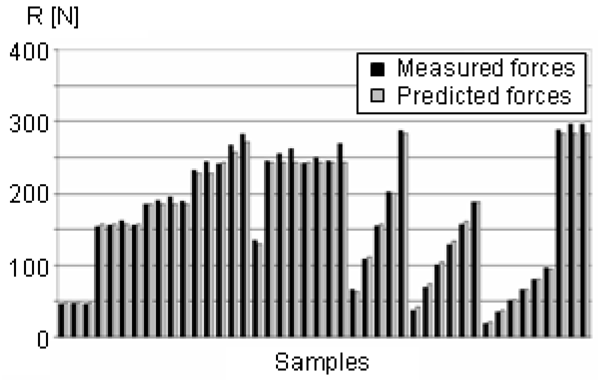


Figure 3: Mechanistic model. Comparison between measured (black) and predicted (gray) forces (average in a tool rotation), applied on each milling tests (with tool ø3mm) realized on the work-hardened red gold. Each couple of bars represents a test under different machining conditions

Nevertheless, our work on precious metals was inspired by the French standard (AFNOR NF E 66-520 “Couple outil-matière”) [4] which suggests practical machining tests and research based on the definition of the optimum as “the minimum specific energy”. It is carried out step by step, optimizing V_c and f_z first, followed by a_e and a_p.

3 TECHNOLOGICAL OPTIMUM RESEARCH

A basic principle for the optimization of cutting parameters, well known in literature and used in the French standard, is based on the research of the set of parameters offering the optimal ratio between machining power and rate of metal removal.
The values of specific energy corresponding to the first 6 tests offer the possibility of building a regression surface based on minimum of square deviation. On this surface, minimum specific energy can be identified, and cutting parameters corresponding to this point will undergo further testing. The difference between the points tested and the regression surface is a measure of the correlation between experiments and the regression surface. We fixed two criteria for stopping the process:

1. Correlation between the regression surface and the empirical values around the optimum of higher than 90%. If the correlation is too low, data far away from the optimum will be removed, and new tests will be added in the vicinity of the optimum.

2. Sufficient exploration of the full space.

The idea behind the concept of “sufficient exploration” is that the empirical exploration of a space for the identification of an optimal value is a problem very similar to that of the choice of the sampling time for the reconstruction of sampled signals. The sampling time needs to be as long as possible in order to reduce the measurements, but frequent enough to ensure the reconstruction of the “signal” (in our case: the reconstruction of the surface describing specific energy as a function of cutting parameters).
In each case, possible “natural frequency” or “bandwidth” has to be estimated, and therefore the number of possible oscillations in a given range of variation for each parameter. The Nyquist-Shannon theorem gives the relation that should be used to choose the sampling frequency:

$$f_s \geq 2B \qquad (1)$$

f_s: sampling frequency.

B: frequency of the value that has to be sampled.

Each case of signal acquisition requires an estimation of the “bandwidth”. This estimation ensures the possibility of evaluating sampling frequency. Based on previous machining performances, we can assume that variations of specific energy as a function of V_c are easily identified if the “bandwidth” is 3 (1 being the maximum machining interval), and 2 a function of f_z. To identify the “signal” until this “bandwidth” we need at least:

- 2*3 = 6 segments in V_c (7 samples)
- 2*2 = 4 segments in f_z (5 samples)

Therefore, the space should be explored with those sampling frequencies in the region of the first identified optimum. The analysis of the results obtained during this first exploration will determine the required sampling frequencies (horizontal and vertical) so that the space can be correctly explored.
The regression surface is a powerful tool for the research of minimum specific energy, but is inadaptable for a graphical result representation. This is due to the fact that the regression surface is an approximating surface, which means that it does not show the real values of empirically tested specific energy. Therefore, for an efficient representation of the surface interpolating the real tested values, we adopted a 3D-surface based on the algorithms of Shepard [7]. An example is shown on Figure 4.

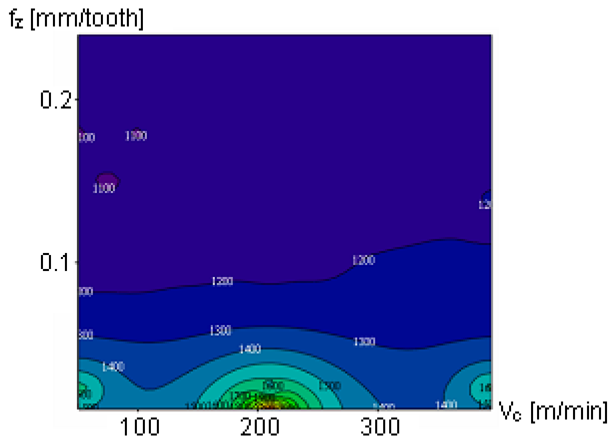


Figure 4: Palladium, work-hardened, in the case of milling. Specific energy [N/mm^2] in the space (V_c, f_z).

4 ECONOMICAL OPTIMUM RESEARCH

Technological optimum research includes parameters related to cutting i.e. cutting forces or specific energies. However, economical aspects are neglected: tool and machine prices, personnel, etc. Technological optimum alone doesn’t allow the optimization of industrial processes. A study including tests of tool life is required, so that economical aspects of the cutting process are included in the global analysis.
The methodology adopted is based on a simple and general observation: the economical optimum is located near the region where machine costs equal tool costs. Research is conducted in order to identify this point, which in some cases is already the optimum. A more accurate position of the economical optimum is then identified by

using local slopes of the surfaces representing machine and tool costs. A summary of the methodology adopted shows 3 different phases:

1. Identification of a criterion related to the tool life, allowing knowing when a tool can be considered as worn out.
2. Identification of the set of parameters producing the same costs related to the machine and to the tool. This represents a first approximation for the economical optimum. Local derivatives of the surfaces of the costs are calculated.
3. Total machining costs (C_{tot}) and local derivatives allow identification of the economical optimum in the space (V_c, f_z, C_{tot}).

4.1 Case of milling

Research for the economical optimum is based on the definition of tool wear that stops its utilisation. Several criteria are used in the laboratories. We decided to adopt a value based on tools used in production workshops when machining precious metals. The wear (VB) of several tools considered as totally worn out was measured and critical wear, VB_{lim}, was defined as

$$VB_{lim} = VB - 2 * \sigma_{VB} \quad (2)$$

In this equation, σ_{VB} is the standard deviation of the measurements. This value represents the first criterion for the tool life. A tool is considered as worn out when one of the following criteria is reached:

1. $VB = VB_{lim}$.
2. Break of the tool.
3. Tabs > 20 µm.

In order to find the economical optimum, the minimum of the total cost (C_{tot}) as a function of V_c and f_z must be identified. The two contributions to the total cost are the costs related to the machine (C_{ma}), well known from industrial data (costs induced by the use of the machine and time required for a given operation), and the costs related to the tool (C_{tool}), unknown (depending on the variation of tool life for different cutting parameters). Therefore, it is necessary to evaluate the function describing the cost related to the tool as a function of V_c and f_z, in the vicinity of the economical optimum. The initial situation is illustrated on Figure 5, with a simplified 2D-representation (Cost as a function of V_c), but the research also includes f_z. The first machining test adopts the parameters corresponding to the maximum rate of metal removal, placed at the borders of the machinability application area.

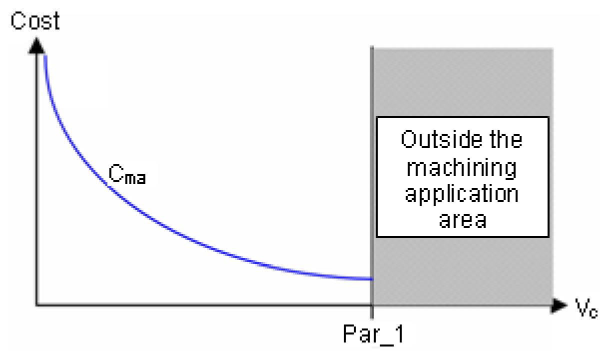


Figure 5: Initial situation: costs related to the machine are well known, but those related to the tool must be identified. The first test is performed with the set of parameters Par_1, offering the maximum rate of metal removal.

The machining test performed with the set of parameters Par_1 stops when a critical time, $T_{ma=tool}$, is reached. This time is the tool life (expressed in minutes) corresponding to the situation where $C_{ma} = C_{tool}$ (as mentioned above, it is expected that this equality will be satisfied, or almost, at the economical optimum). It is calculated with the following equation:

$$T_{ma=tool} = \frac{Px_{tool}}{C_{ma}} \cdot 60 \quad (3)$$

$T_{ma=tool}$: Time of tool life (in minutes) that produces: $C_{ma} \approx C_{tool}$.

C_{ma} : Machine cost (per hour)

Px_{tool} : Tool price

The result of the first machining test is illustrated on Figure 6. During the test, wear measurements are realized, so that T_1, the time required to reach the critical wear VB_{lim} defined by equation 2, can be identified. If this time is shorter than $T_{ma=tool}$, the test is stopped when VB_{lim} has been reached.

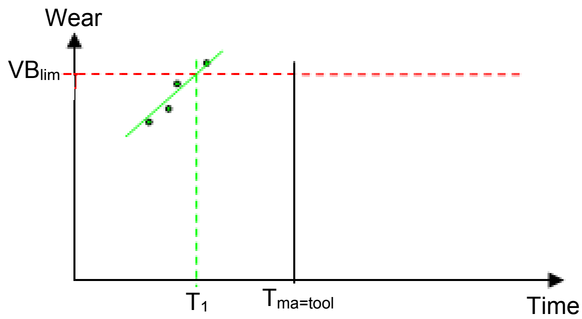


Figure 6: Typical results obtained after the first machining test. The points (small circles) represent different wear measurements realized during the test. In the case illustrated, the critical wear VB_{lim} was reached before $T_{ma=tool}$ so that the test was stopped.

The identification of T_1 allows the calculation of C_1, the cost related to the tool when machining with the set of parameters Par_1. This cost can be added on Figure 5. Three situations are possible (Figure 7):

1. $C_1 > C_{ma}$ ($T_1 < T_{ma=tool}$): the cost related to the tool is higher than the cost related to the machine (the most probable case). In this case, the cost related to the tool should be reduced using more cautious cutting parameters.
2. $C_1 = C_{ma}$ ($T_1 = T_{ma=tool}$): costs related to the tool and to the machine are equal. It is expected that the set of parameters corresponding to the economical optimum is not far away from Par_1.
3. $C_1 < C_{ma}$ ($T_1 > T_{ma=tool}$): the cost related to the machine is higher than the cost related to the tool. In this case, the cutting parameters should be increased in order to produce a more rapid tool wear. But as the first machining test is already performed at the technical limits of the machine, it is impossible to use higher cutting speeds or feed per tooth. Therefore, the economical optimum technically reachable is identified as Par_1.

Those 3 cases are illustrated on Figure 7, which also describes the next step of the research: the definition of a second set of cutting parameters (Par_2) which is defined as the intersection between the line connecting Par_1 and the origin of the axis and the surface representing the costs related to the machine. This represents a rough estimation of the set of parameters (Par_2) that could produce a cost of the machine per operation equal to the cost of the tool.

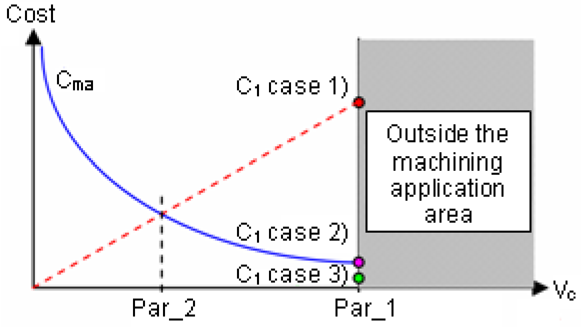


Figure 7: Illustration of the 3 situations possible after the first machining test. The broken line between “C1 case 1)” and the origin of the axis allows the identification of the set of parameters Par_2, used for the second machining test.

The third case has already been discussed above; it doesn’t require any additional test to identify the economical optimum. For the first case, the situation is illustrated on Figure 7, with the identification of the set of parameters Par_2 used for the second machining test. For the second case, it is not possible to use the same method as for case 1, but it was observed that it is necessary to add a second machining test to identify more accurately the economical optimum. In this second test, V_c and f_z must have different values than for the first machining test.
As for the first test, a time T_2 will be identified on the basis of wear measurements (see Figure 6 for the illustration of the method) and a cost (C_2) will be identified for the set of parameters Par_2. We know that the economical optimum is located where the derivatives of the two components of the total machining cost are identical, and therefore satisfy the following relationships (4).
The final step is then to move from the set of parameters Par_2, searching for the coordinates (V_c, f_z) satisfying the equation 4. A software package which helps in this search has been developed during this work. It should be noticed that the method is very efficient: with only two machining tests, a good approximation of the economical optimum can be identified in a space of two parameters.

$$\frac{\partial C_{ma}}{\partial V_c} = -\frac{\partial C_{tool}}{\partial V_c} \qquad \frac{\partial C_{ma}}{\partial f_z} = -\frac{\partial C_{tool}}{\partial f_z} \tag{4}$$

4.2 Case of drilling

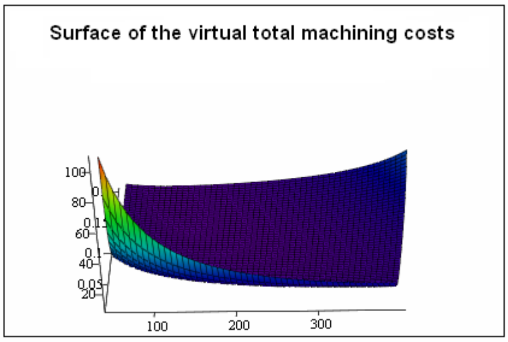
The research of the economical optimum in the case of drilling is somehow similar to what was described for the case of milling. Nevertheless, the drilling process presents several specificities that require few modifications. Indeed, in the case of drilling (tools are of 1 mm of diameter), it is not possible to identify and measure a tool wear, predicting or estimating the tool life, because the measures of the tool wear are not correlated to the tool life. Therefore, the tool life is essentially limited by:

1. The break of the tool.
2. The lack of precision of the drilled hole.

When working with materials easy to machine (e.g. gold), the tool life can be very long, so that tests require a lot of time and a large amount of expensive materials. As the contribution of the tool to the total machining costs decreases continuously during the tool life, it becomes negligible after a high number of operations (in the case of drilling, one operation is the drilling of one hole). An arbitrary limit was chosen as $2.5 \cdot N_{ma=tool}$, where $N_{ma=tool}$ is the number of operations for which the contribution of the tool and of the machine to the total cost are equal.

5 VALIDATION OF THE METHOD FOR THE RESEARCH OF THE ECONOMICAL OPTIMUM

The method for economical optimum research has been validated. For this validation a virtual function of the tool life and, therefore, the tool cost per operation, C_{tool}=f (V_c, f_z) were analytically defined in order to reproduce values similar to practical and known cases.
Observations show that the method allows rapid, (only two tests) systematic, significant and reliable cost reduction. (When the starting point is not the optimum, machining costs are reduced).



	Optimum	Par_1	Par_2	Pop_ec2
Vc	152	350	61	118
fz	0.12	0.2	0.035	0.068
Costs (CHF/cm^3)	11.238	24.746	29.812	13.26
	Optimum	Par_1	Par_2	Pop_ec2
Vc	152	40	110	185
fz	0.12	0.03	0.082	0.138
Costs(CHF/cm^3)	11.238	48.208	12.721	11.599
	Optimum	Par_1	Par_2	Pop_ec2
Vc	152	152	88	153
fz	0.12	0.12	0.069	0.121
Costs (CHF/cm^3)	11.238	11.238	15.008	11.238

Table 1: Some of the results of the validation tests.

6 AN EXAMPLE: DRILLING ANNEALED WHITE GOLD.

This method has been adopted for the study of several materials such as white and red gold, palladium and platinum, in different metallurgical states - annealed, work or age-hardened.
An example shows the results of the study of drilling annealed white gold.

The first step is the exploration of the working limits:

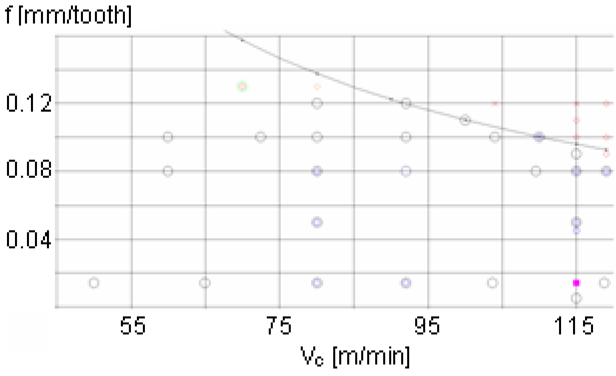


Figure 8: Machining application area in the space (V_c, f) when drilling annealed white gold.

Figure 8 shows the points where the measurements of specific energy have been carried out. The continuous curve shows the border of the region where the feeds of the machine are respected (the acceleration of the machine and the pecking cycle, impose the limits).
The first six points, allow the realisation of a mechanistic model (equations 5).

$$F_z = F_{0z} + Kc_{1z} h_0^{\,1-m_z} D$$

$$M = M_0 + Kc_{1M} h_0^{\,1-m_M} \frac{D^2}{4} \left(\frac{1}{\sin(\frac{\varphi}{2})} \right) \qquad (5)$$

The mechanistic model is identified through the parameters shown in the Table 2.

F_{0Z} [N]	Kc_{1Z} [N/mm2]	m_Z	M_0 [Nm]	Kc_{1M} [N/mm2]	m_M
2	1300	0.1	0.05	480	0.7

Table 2: Values of the mechanistic model.

The Figure 9 represents the specific energy as function of the variables V_c, f. The representation is based on the Shepards algorithm.

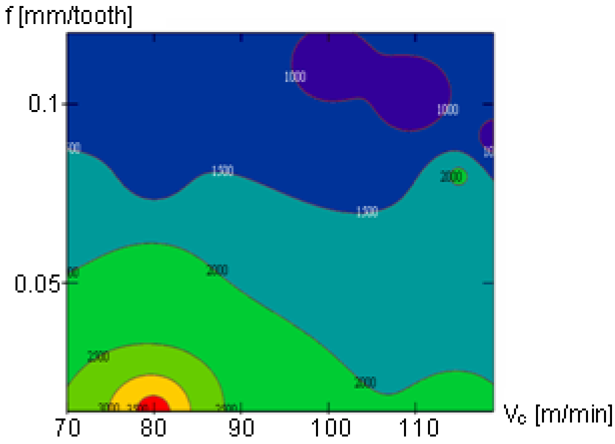


Figure 9: Map of specific energy (V_c, f) in case of drilling annealed white gold.

The minimum specific energy is placed at the values of Table 3.

V_c [m/min]	f [mm]	K_c [N/mm^2]
100	0.110	767

Table 3: Location and value of the minimum specific energy.

The research of the economical optimum is reproduced in the plots of the Figure 10.

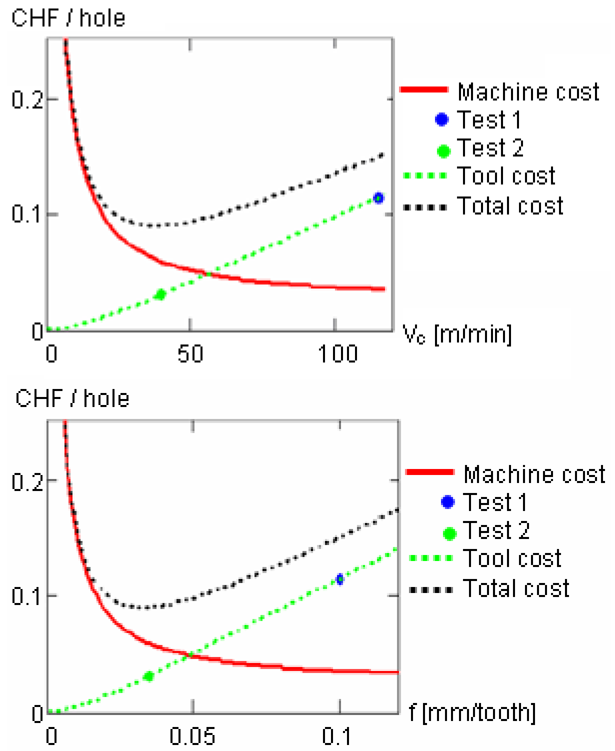


Figure 10: Identification of the curves of machine cost, tool cost and total machining cost per hole machined.

The economical optimum is placed at the values shown in Table 4, and which illustrates the uncertainty of the estimation due to disparities in the values of tool life.

Parameters of the Economic Optimum	
V_c [m/min]	f [mm/rev]
37±3	0.033±0.003

Table 4: Location of the economical optimum.

7 INDICATIONS OBTAINED FROM THE STUDY OF SOME PRECIOUS METAL

The method has been applied for the study of white gold, red gold, and palladium. In the next future it will be applied on the study of platinum. All the materials have been examined in different states (annealed, work hardened, age hardened). Based on the study already done, we may confirm some expected relations as that of the dependence of the specific energy with the hardness of the material. (See Figure 11). In case of milling, even though less important than expected, this correlation is evident. At the opposite, in case of drilling, the cutting forces are influenced by the evacuation of the chip and this correlation disappears.
The study makes evident also the fact that the technological optimum (based on the minimum of specific energy) and the economical optimum are not correlated (see Table 5).
A third important result is the fact that frequently, in case of milling, the economical optimums are placed outside of the limits of functioning of the machine. That means that the machines on the market are not especially designed for the machining of precious metals and using tools of small diameters.

Figure 11: Correlation between hardness and specific energy (measured in identical working conditions) in case of milling.

A particular consideration is that of the results in milling and drilling Palladium. This material is very difficult to be machined due to the strong abrasion and the very short tool life.
As known in the domain of the machining of precious metals, the practice in machining this material is that of adopting a very low cutting feed, this way increasing the tool life. Our study shows that, when using common tools in carbide, this practice is not convenient from the economical point of view: lower machining costs are obtainable adopting high cutting feeds even though the tool life is very short. Also in this case the structures of the machines should be adapted to this need, allowing a very fast change of an huge number of tools in short time.

		MILLING				DRILLING			
Alloy	State	Vc	fz	Vc_{eco}	fz_{eco}	Vc	f	Vc_{eco}	f_{eco}
White gold	Work-hardened	210	0.12	396	0.18	100	0.11	50-57	0.007-0.076
	Annealed	212	0.1	225-396	0.073-0.18	100	0.11	35-40	0.03-0.035
	Age-hardened	210	0.08	396	0.18	90	0.11	50-53	0.053-0.056
Red gold	Work-hardened	210	0.16	396	0.18	95	0.116	118	0.2
	Annealed	395	0.1	396	0.18	115	0.096	63-66	0.053-0.056
	Age-hardened	150	0.15	396	0.18	85	0.13	85	0.13
Palladium	Work-hardened	210	0.15	396	0.18	60	0.095	118	0.2
	Annealed	275	0.22	396	0.18	60	0.15	118	0.079
	Age-hardened	75	0.15	396	0.18	60	0.16	118	0.2

Table 5: Technological optimums and economical optimums. The parts in grey are corresponding to the limits of the machine, in these cases the machine hinders to reach the optimum.

8 CONCLUSIONS

The method developed during this project includes the identification of machining application area and the research for the technological and economical optimums. The method is simplified and the waste of material reduced when intensively using the mechanistic model originally developed to increase the reliability of the empirical measurements. The results obtained using this method whilst studying several precious metals show a significant discrepancy between the technological and the economical optima. This discrepancy does probably not apply specifically to precious metals, but rather to a general situation. This reduces the importance and the significance of the methods based only on research for minimum specific energy.

Nevertheless, this method allows the analysis of both of the most important optimization factors (Technological, based on the measure of specific energy, and economical, based on the calculation of machining costs). This way the method allows an evaluation of the machining performance of a particular machine, several machines or an entire workshop, comparing where the machining process is positioned in comparison with the two optimums.

This method has been developed especially for precious metals and validated through several practical applications, but it is also suitable for the study of machining by chip removal for different materials (steels, titanium, etc.) and in several machining conditions like high speed cutting.

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