14th International Research/Expert Conference
"Trends in the Development of Machinery and Associated Technology"
TMT 2010, Mediterranean Cruise, 11-18 September 2010

MACHINABILITY OF DIFFICULT MACHINING MATERIALS

Elso Kuljanic
University of Udine
via delle Scienze, 208, Udine
Italy

Marco Sortino
University of Udine
via delle Scienze, 208, Udine
Italy

Giovanni Totis
University of Udine
via delle Scienze, 208, Udine
Italy

ABSTRACT
The assessment of the machinability rating of an engineering material is a fundamental activity to increase the productivity and decrease the machining cost. It is also necessary to optimize materials selection in design of mechanical parts. However, it is not a simple task to summarize chemical, mechanical and tribological properties in simple statistical parameters and therefore a more reliable solution is to make machining tests. This paper deals with machinability index, short machinability testing, conventional machinability testing, effect of tool life data analysis on tool life equation, ISO standards for tool life testing and computerized machinability data system developed according to the Integrated Machinability Testing Concept. The paper also illustrates the difficulties of machining some important materials such as: hardened steels, titanium alloys, nickel-based alloys and molybdenum alloys. In addition, some research results together with advanced solutions and innovative approaches proposed in recent research works are described.
Keywords: machining, machinability testing, hardened steels, titanium alloys, nickel-based alloys.

1. INTRODUCTION

The present trend is to create new and smaller products of higher quality in a shorter time and at a lower cost. To achieve some of the stated objectives, there is a need to use hard and resistant materials which usually have low machinability. For example, the high evolutionary improvement of Diesel motor is mostly due to the fuel pump with working pressure of approximately 2000 bars. In this way the Diesel motor is more economical by approximately 5 liters/100 km, and the car acceleration is high. To achieve high pressure, the tolerances are very small and materials must have an elevated hardness in order to be wear resistant.

A lot of research is going on in machining of low machinability materials. Specifically, the new research is focused on manufacturing processes, new tools and machining systems. This keynote paper deals with machinability testing methods, standards and Integrated Machinability Testing Concept. It also describes new solutions in machining low machinability materials such as: hardened steel, titanium alloys, nickel based alloys and molybdenum alloys.

2. MACHINABILITY

Machinability means "easiness of machining" [1]. The general criteria are:

- tool life;
- surface roughness;
- surface integrity;
- magnitude of cutting forces or energy (power) consumption, etc.

Which criterion or criteria will be chosen for determining machinability varies in accordance with the requirements of the particular operation or task to be performed.

According to M.E. Merchant [2], F. W. Taylor was one of the most creative thinker who had done the most extensive machinability testing. In his work presented at the ASME Winter Conference in New York in 1906, more than a century ago, Taylor raised three significant questions: "What tool shall I use? What cutting speed shall I use? What feed shall I use?".
After so many years and having new facilities such as electron microscopes, computers, intelligent machining systems, etc., we still have serious difficulties to find the right answer to the questions.
Probably, we should apply new approaches to find the solution.
One approach could be the "Integrated Machinability Testing Concept" proposed by the first author which will be discussed in this paper later.

2.1. Machinability Index

One of the first publications in machinability of steel rating was done by J. Sorenson and W. Gates [3] in 1929. A graphical representation of the general relation of machinability ratings - relative cutting speeds to hardness for hot-rolled SAE steels was made. A 100% rating was given to SAE 1112 steel cold rolled. In 1943 Boston et al [4] published a general machinability index-rating for more common metals and alloys, Table 1.

Table 1. Machinability rating of various metals

Class I		
AISI	**Rating %**	**Brinell**
C1109	85	137-166
C1115	85	147-179
C1118	80	143-179
C1132	75	187-229
C1137	70	187-229
B1111	90	179-229
B1112	100	179-229
B1113	135	179-229
A4023	70	156-207
Class II		
AISI	**Rating %**	**Brinell**
A2515^{+}	30	179-229
E3310^{+}	40	179-229
E9315^{+}	40	179-229
Stainless 18-8^{+} austenitic	25	150-160

$^{+}$ Annealed prior to cold drawing or cold rolling in the production of the steel specially mentioned

The ratings are expressed in terms of relative values. These figures are often called “percent machinability”, and are representing the relative speed to be used with each given material in order to obtain a given tool life. For example, a material whose rating is 50 should be machined at approximately half the speed used for the material rating 100, if equal tool life is desired for either of them.
The rating values in Table 1 are based on a rating of 100 for steel AISI B1112, cold rolled or cold-drawn when machined with a suitable cutting fluid at cutting speed v_c = 56 m/min under normal

cutting conditions using high-speed-steel tools. In Table 1 the ratings given for different classes of alloys, represent their relative machinability within a given class, but the ratings for any class are not comparable with those for any other class.
The second approach in machinability rating is in terms of equivalent cutting speed. The cutting speed number is the cutting speed which causes a given flank wear land in 60 minutes. Such a cutting speed is called economical cutting speed. However, the tool life of 60 minutes is not economical any more. The economical tool life for minimum machining cost is about 10 minutes or less in turning. Therefore, the corresponding cutting speed is much higher than the tool life of 60 minutes.
The third approach in machinability ratings represents relative cutting speed values where the ratings are given as letters, Table 2. "A" indicates a high permissible cutting speed and "D" a lower cutting speed.

Table 2. Machinability rating of stainless steel (hot-rolled, annealed)

AISI	Hardness Brinell	Machinability rating
AISI 410	135-165	C
AISI 416	145-185	A
AISI 430	145-185	C
AISI 446	140-185	C
AISI 302	135-185	D
AISI 303	130-150	B
AISI 316	135-185	D

A – excellent, B – good, C – fair, D - poor

The fourth approach is the correlation of tool life and the microstructure of the metal. Generally speaking hard constituents in the structure (oxides, carbides, inclusions) result in poor tool life, and vice versa. In addition, the tool life is usually better when the grain size of the metal is larger.
The correlation of microstructure of steels and tool life was studied by Woldman [5]. Average relations of tool life and surface finish to microstructure of steel were reported as "good", "fair", "fair to good" and "poor", Table 3.

Table 3. Average relation of tool life and surface finish to microstructure of steels

Class of steel	Structure	Tool life	Surface finish
Low – carbon steels	Cold-drawn, small grain size	Good	Good
	Normalized	Good	Fair
Mild medium – carbon steel	Perlitic, moderate grain size	Good	Good
	Perlitic, small grain size	Fair	Good
	Perlitic, large grain size	Good	Fair
	Spheroidized	Fair	Poor

Machinability index is an approximate value indicating the machinability of different engineering materials. Such information can be useful in the design of mechanical parts. For example, if there are different materials that can be used for a given part and have different machinability index, the material with greater machinability index should be chosen in order to increase the productivity and decrease the machining cost. It has to be pointed out that data published approximately 70 years ago reflect the workpiece materials and especially the tool material which were very different from those in use today.

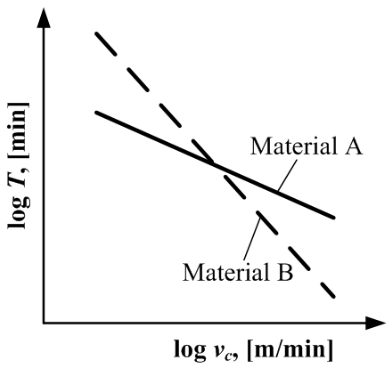

Figure 1. Comparison of tool life curves for different materials.

The machinability testing comparison of different materials is recommended when many of the same pieces have to be machined. In this case the design of experiments should be made and cutting speed should be at least on two levels with repeated tests. The curves determined by regression analysis of tool life data should be statistically compared , Figure 1.
The same methodology can be used for comparison of cutability of different tools.

2.2. Short Machinability Testing

In short machinability testing or in quick tool life tests for example the cutting speed is higher and therefore the tool life is shorter.

There are different criteria for short machinability testing: drilling torque or thrust, drilling time or rate for penetration, energy adsorbed in pendulum-type milling cut, temperature of cutting tool or chip, the degree of hardening of chip during removal, etc.

In the 1950s and 1960s some new machinability testing methods came out. For example, short tool life testing method was developed by applying face turning. In this case, face turning is done at a constant number of revolutions, starting cutting at a smaller diameter and moving to a greater diameter. In such a way the cutting speed is increased as the diameter increases according to:

$$v_c = \frac{\pi D n}{1000} \qquad (1)$$

Where *D* is the diameter in mm and n is the number of revolutions in rev/min.

The linear increase of the cutting speed increases the tool wear and decreases the tool life, thus making the test shorter. The reliability of such a method is small due to the different tool wear mechanisms, at a lower and at a higher cutting speeds. The tool wear is a sum of wear obtained by different tool wear mechanisms. The obtained data cannot be applied for different machining operations. In such cases not only the tool wear mechanisms are different but the chip formation is different in different machining operations.

Generally speaking, the reliability of machinability data obtained by short machinability testing methods is low. Therefore, short machinability testing could be applied only in some cases, i.e. in some machining operations as a preliminary test.

2.3. Conventional Machinability Testing

The Taylor tool life equation was one of the important result of his very long research in machining

$$v_c = \frac{C}{T^m} \quad \text{or} \quad T = K v_c^{\,k_v} \qquad (2)$$

where T is the tool life in minutes, v_c is the cutting speed in m/min, C and K are constants, k_v and m are exponents and $m = -1/k$.
The extended Taylor's tool life equation is:

$$T = Kv_c^{k_v} f_z^{k_f} a_p^{k_a} \tag{3}$$

where f_z is the feed per tooth in milling in mm, a_p is the depth of cut in mm, and k_f and k_a are exponents.
Kuljanic's tool life equation takes into consideration the effects of interactions too.

$$T = Kv_c^{k_v} f_z^{k_f} a_p^{k_a} \left(v_c f_z\right)^{k_{vf}} \left(v_c a_p\right)^{k_{va}} \left(a_p f_z\right)^{k_{af}} \left(v_c f_z a_p\right)^{k_{vfa}} \tag{4}$$

where $(v_c f_z)$, $(v_c a_p)$, $(a_p f_z)$, $(v_c f_z a_p)$ are the interactions.
For example, the Kuljanic's tool life equation for face milling stainless steel is [6].

$$\begin{aligned} T = 211.79 \cdot 10^5 v_c^{-4.023} f_z^{-1.454} z^{-10.267} S^{-1.329} \left(v_c z\right)^{2.3913} \left(v_c S\right)^{0.3880} \cdot \\ \cdot \left(zS\right)^{0.8384} \left(v_c f_z S\right)^{0.0190} \left(v_c z S\right)^{-0.1972} \end{aligned} \tag{5}$$

where S is machining system stiffness and z is number of teeth in the cutter.

Only significant single factors and significant interactions are included in the equation. Also, from the comparison of Taylor's equation (2) and Kuljanic's equation (4) the effects of machining system stiffness S, number of teeth z as well as of some their interactions which have a significant effect on tool life have to be considered. Not significant factors and interactions have to be dropped out in (3) as it was done in (4).

The tool life equations are important for increasing productivity and decreasing machining cost, i.e. for optimization of the machining process. In this case the identification of machining process is done by tool life equation. Since tool life has a stochastic behavior, regression analysis and other statistical techniques should be used for data analysis.

Effect of tool life data analysis on tool life equation

The reliability of tool life equation poses a problem in practice. There are many factors that affect both the exponent and the constant in the tool life equation. One of the factors, which is usually neglected, is the way of analysis of tool life data, i.e. the different ways of plotting: tool life versus cutting speed or cutting speed versus tool life.
F.W. Taylor applied the approach for the analysis of tool life data cutting speed versus tool life, without regression analysis and the result was the equation (1). However in Europe the opposite is used usually, tool life versus cutting speed and corresponding tool life equation is (2).
The first author did two different regression analysis: tool life versus cutting speed and cutting speed versus tool life by applying A. Henkin tool life data [7], in order to prove to Max Kronenberg in Cincinnati in 1971, that there would have been different tool life equations from the same tool life data [8]. The results can be seen in Figure 2.
The following tool life equation was determined by regression analysis: cutting speed versus tool life:

$$v_c T^{0.077} = 24.9 \tag{6}$$

and

$$v_c T^{0.108} = 26.4 \tag{7}$$

was determined by regression analysis - tool life versus cutting speed, in both cases from the same tool life data.
The differences obtained from the same tool life data, but with different approaches in data analysis, can be explained by taking for calculation the values y_1, y_2,... in the first case - tool life versus cutting speed v_c, and by applying the values x_1, x_2,... in the second case - cutting speed v_c versus tool life, see Figure 2. It can be seen that $y_1 \neq x_1$, $y_2 \neq x_2$, ... The results have to be different since the analysis are done with different values. Cutting speed versus tool life analysis is usually used in the U.S.A. [1]. In the doctoral thesis [6] Taylor equations were obtained with the cutting speed versus tool life approach. In a machining process the cutting speed is set in advance and tool life or tool wear depends on cutting speed. Therefore, tool life is a dependent variable and cutting speed is independent, equation (2). This should be taken into account when determining the tool life equation.
It has to be pointed out that Taylor's exponent m=0.108 obtained with tool life versus cutting speed analysis is greater by approximately 40% than Taylor's exponent m = 0.077 determined with cutting speed versus tool life analysis from the same tool life data in turning steel with HSS tool.

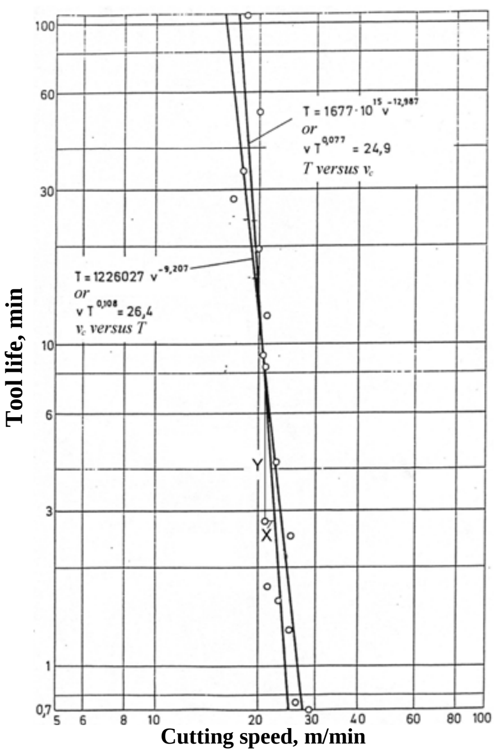

Figure 2. Effect of tool life data analysis on tool life equations

Usually, the Taylor equation is used in optimization of machining process for the identification of the cutting process. The effect of the differences of Taylor exponent is even greater on optimal tool life for minimum machining cost T_e or maximum productivity T_p due to 1/m equations (8) and (9):

$$T_e = \left(\frac{1}{m} - 1 \right) \left(t_c + \frac{C_t}{C_g + C_m} \right) \tag{8}$$

$$T_p = \left(\frac{1}{m} - 1\right) t_c \qquad (9)$$

where: m is the Taylor's exponent, t_c is the tool change time in min, C_t is the cost of tool per cutting period, C_m is the general cost i.e. the value of machine tool and operator per minute and C_g is the overhead cost.

The question is which methodology is right? Since physically the tool life depends on cutting speed and not cutting speed on tool life, the regression analysis should be done: tool life versus cutting speed.

2.4. ISO standards for tool life testing

The first author had the idea to make a standardized methodology for tool life testing in milling. As Chairman of the Working Group "Milling" of the Scientific Technical Committee "Cutting" of the CIRP (International Academy for Production Engineering) he proposed to work on the document. When the work was completed in CIRP, ISO accepted the document as a basic ISO document to work on ISO standard. After eight years the Working Group 22 - Unification of Tool Life Cutting Test of ISO Technical Committee 29 (of which the first author was part) produced the following ISO standards: Tool Life Testing in Milling, Part 1 - Face Milling 8688/1 and Tool Life Testing in Milling, Part 2 - End Milling 8688/2 [9][10]. The CIRP document "Tool Life Testing for Face Milling" [11] and the ISO Standards are significant basic documents in machinability testing. A survey and discussion of the ISO Standards including the Volvo Machinability Test [12] are given in [13]. After 25 years the document should be updated.

2.5. Integrated Machinability Testing Concept

The machinability data can be obtained during production from the machining process in new industrial conditions. The first author proposed the Integrated Machinability Testing Concept, I.M.T. Concept, at the International Conference of Advanced manufacturing Systems and Technology, AMST'93 [13].

The integrated machinability testing is an approach in which tool life data and/or tool wear, tool wear images, machining conditions and significant data such as dimension changing of the machined workpiece, surface roughness, chip form, etc., are registered and analyzed in an unmanned system, i.e., in intelligent machining system.

The main data, that should be quoted to determine the conditions of machining, are as follows: machine tool and fixturing data, workpiece data - material, heat treatment, geometry and dimensions, tool characteristics - tool material and coating, tool geometry, coolant data. These data will be registered automatically. The cutting conditions: cutting speed, feed and depth of cut could be chosen by a computer applying the design of experiments.

The tool wear and tool life can be determined by intelligent sensor systems with decision making capabilities [14]. The tool wear images and the dimensions of tool wear, like VB - the average tool wear land, could be measured, analyzed and saved automatically in a computer.

The surface roughness and the dimensions of the machined workpiece can be analyzed and saved too. From such data tool wear or the tool life equations (2) or (4), or some other relationships for the identification of machining process, can be easily determined by regression analysis.

The tool life equations obtained by integrated machinability testing can be used for different purposes. First for in-process optimization of machining conditions. Secondly, to build up the machinability databank with more reliable data. Such a databank would receive the machinability information, as tool life equations, etc., directly from the intelligent machining systems. Thus the data in such data bank would be more reliable. The machining databank would be self-generative and the factory could have a proper machinability databank.

3. DIFFICULT MACHINING MATERIALS

Some of engineering materials are characterized by low machinability. In the following paragraphs, the results of current research and new experimental data on the machinability of hardened steel, titanium alloys, nickel-based alloys and sintered molybdenum will be presented.

3.1. Hardened steels

The tool selection for machining hardened steel is strongly influenced by specific demands of the components to be produced. The most common difficulties, when machining hardened steel, are the rapid tool wear rate, cracking or chipping of the tool, workpiece dimensional accuracy and surface roughness of the machined surface. Carbide tools can be applied for some operations at low cutting speeds in special cases, whereas ceramic and cubic boron nitride are the most preferred choice.

The main fields of investigation for improving the machinability of hardened steel in recent years are: investigation of tool wear mechanisms, comparison of tool materials and tool coatings, application of innovative lubrication strategies.

Poly-crystalline Cubic Boron Nitride has proven to be effective and economical in machining hardened steels by using a cutting tool with defined cutting edge geometry [15]. A comparative study on different grades of CBN for turning bearing steel was performed by Chou et al in 2003 [16] and 2004 [17]. Surprisingly, the results evidenced that tools with 70% CBN content has longer tool life compared to tools with 92% CBN content due to higher toughness of the bulk material. It is likely that machining of hardened steel may be improved by optimizing the content of CBN for each application.

The tool wear mechanisms affecting the CBN tool during hard turning were investigated by Poulachon et al in 2004, [18]. The main result was that the type of microstructure and amount of carbides in the workpiece material play a fundamental role for tool wear progression and tool life when applying CBN tool. Specifically, he determined that the effect of cutting speed on tool life is greater when only martensitic phase is present, whereas it is moderate when carbides are also present.

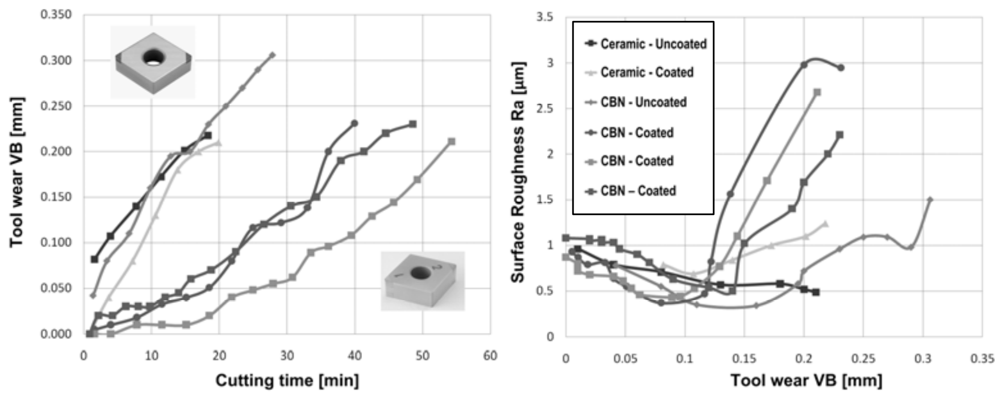

Figure 3. Comparison of ceramic and CBN tools, both coated and uncoated for tuning hardened 100Cr6

The ability of CBN cutting tools to maintain a sharp cutting edge at elevated temperature, is comparable with some newer ceramic tools materials. The comparison of obtained tool lives and surface roughness with CBN and ceramic tool were investigated by Benga et al [19]. More recently, Oliveira et al [20] reported the results of application of CBN and ceramic tools in continuous and interrupted cutting applications. In both cases, the CBN tools obtained better results than ceramic tools.

The development of new coating technologies and their application on commercial CBN tools were investigated by Galoppi et al in 2006 [21]. According to the authors, the cracking of the coating was the main reason of reduced tool life of coated tools in comparison to uncoated tools.

Recently, the authors have investigated the application of coated CNB tools and ceramic tools for hard turning of 100Cr6 hardened steel, as shown in Figure 3.

The tool life was significantly longer when coated CBN tools were applied compared to uncoated CBN tools and ceramic tools. Nevertheless, the obtained average surface roughness when applying coated tools is greater probably due to ploughing of the cracked coating on the workpiece surface. From an economical point of view, coated CBN tools are slightly advantageous compared to uncoated CBN tools and ceramic tools.

Environmental concern for the disposal of cutting fluids led to the interest in ecologic machining strategies such as minimum quantity lubrication - MQL, in which extremely small quantity of specially prepared cutting fluid is applied precisely at the cutting zone. Due to economical reasons, the application of the right quantity of lubricant for machining hardened steel is of major concern [22]. In 2007, Kumar et al [23] investigated the effect of different lubricant systems (standard, dry and minimal quantity lubrication) in hard turning. The results showed that the overall performance of the cutting tools such as cutting force, temperature and surface finish, with minimal cutting fluid application, was better than in dry turning and turning with conventional lubrication conditions.

3.2. Titanium alloys

Machining of Titanium alloys is difficult, because of their peculiar characteristics, as reported by [24][25]. Generally high cutting temperatures occur when machining Titanium alloys due to their low thermal conductivity, therefore cutting tools are subjected to high thermal loads. The specific cutting force is rather high due to small chip-tool contact area on the rake face and high resistance of Titanium alloy to deformation at elevated temperatures. Anomalous vibrations such as chatter may also arise because of the low modulus of elasticity of titanium. Moreover, dynamic cutting force fluctuations affecting chip formation tend to produce sawtooth-like chips [31]. The rapid tool wear progression may even be accelerated by high chemical reactivity of titanium at elevated temperatures.

Uncoated and coated carbide inserts are mainly applied for machining Titanium alloys, as reported by several authors [26][27][28][29][30]. Uncoated carbides of ISO grade K are mostly applied and experimental results showed that micro grain core is preferable. However, PCD tools seem also to be very promising, as demonstrated by Nabhani in 2001 [31]. According to the same author, the best choice for machining titanium alloys are PCD tools, CBN tools are intermediate, whereas carbide tools are not recommended for this application.

The first research of finishing milling titanium alloy TiAl6V4 of a very slim compressor gas turbine blades, Figure 4, with polycrystalline cubic diamond PCD cutter was done by E. Kuljanic, the first author, in 1998 [32]. The tool life of PCD cutter was T = 381 minutes with cutting speed of 110 m/min, applying cooling lubricant solution. It was proved that in spite of very low stiffness of the working piece (blade) it was possible to use PCD cutter for milling titanium alloy, and to increase the tool life for approximately twenty times and also to increase the cutting speed for three times versus carbide tools that are usually applied for this purpose. Both surface roughness of the machined surface and geometrical accuracy were satisfactory. Better result were obtained when cooling refrigerant was applied.

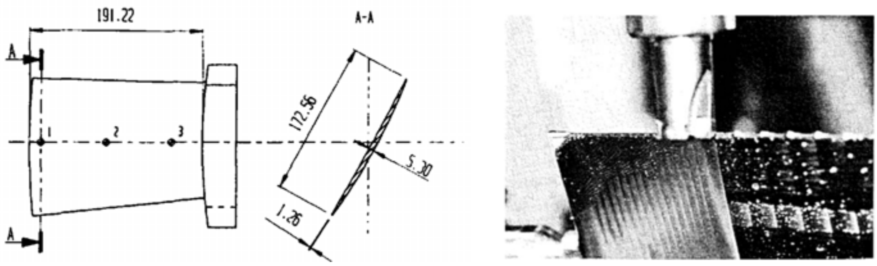

Figure 4. Milling of TiAl6V4 turbine compressor blades with PCD cutter

Because of high local temperatures at the tool-chip interface and of the chemical reactivity of workpiece material, the cutting fluid has a strong influence on the cutting process. However, standard lubrication is not sufficient to assure a good process performance. New approaches for increasing tool life and extending cutting parameter ranges towards higher speeds are being proposed, which are based on innovative lubrication systems. For instance, cryogenic machining is a very appealing technique based on liquid nitrogen directly injected into the chip–tool interfaces [29][26]. According to Hong et al, by properly directing micro-nozzles and by selecting adequate operating parameters, when machining Titanium alloys with cryogenic cooling, it is possible to achieve considerably longer tool life and economical savings [27]. Alternatively, standard oil-based cutting fluid injected at high pressures may significantly increase tool wear resistance both of uncoated carbides and CBN tools. Performance of CBN tools is generally considered poor [33] due to the rapid notching and excessive chipping of the cutting edge.

Good results are obtained by applying Laser Assisted Machining - LAM in machining Titanium alloys[30]. Specifically, the tool life was longer with higher cutting speed (107 m/min) than conventional machining (60 m/min). According to the same author, hybrid machining – which is based on the joint application of LAM and cryogenic cooling – is very interesting from an economical point of view.

3.3. Nickel based alloys

The machinability of Nickel based alloys is poor due to their intrinsic metallurgical nature. The material crystalline structure is austenitic, and like stainless steel work hardening rapidly occours during machining. This hardening effect reduces the machinability for further machining operations and sometimes can cause distortions of the workpiece surface. The presence of hard phases such as carbides, nitrides, oxides, silicates, the tendency to weld with the tool material and the large amount of heat generated during machining are other causes of poor machinability. Moreover, nickel alloys have low thermal diffusivity and the temperatures in the cutting area are high.

In order to improve the machinability of Inconel, several research actions have been carried out in the last years: application of new tool material, improvements of coatings, optimization of tool geometry, non-conventional machining processes.

The most common tool materials for machining nickel-based alloys are coated carbides, CBN and whiskers-reinforced ceramics. A comparison between ceramic tools and CBN tools for high speed machining of nickel-based alloys was performed by Coelho et al in 2004 [34]. According to his results, both tool life and surface roughness obtained with ceramic tools were better than those obtained with CBN tools.

The optimization of tool geometry is also a very interesting field of investigation. For instance, Altin et. al. for ceramic tools and Pawade et. al. for CBN tools investigated the effect of tool geometry on machinability [35][36][37]. In both cases, the optimal geometry was strongly influenced by cutting conditions, therefore it is recommended to carry out tool wear tests for determining the best geometry for each application.

Costes in 2007 published the results of the research on the influence of the CBN tool composition, grain size and binder type on tool wear mechanisms and tool life [38]. According to his observations, the main tool wear mechanism was diffusion, and longer tool life was obtained with low content of CBN (45-60%), small grain size and ceramic binder.

In the last years, several significant improvements have been obtained with the development of new tool coating technologies. For instance, the application of PVD coatings (CrN and TiAlN) on alumina-based ceramic tools was investigated by Gatto in 1998 [39]. The results showed that the thermal barrier effect of the coating was beneficial for tool life and that CrN coatings were preferable than TiAlN coatings.

Ducros et al investigated the application of multilayer coatings for machining Inconel 718 [40] with carbide tools. Nanolayer coatings (especially TiN/AlTiN) significantly enhance productivity when abrasive wear is the main cause of tool failure. Similarly, Biksa et al compared several nano-multilayer coating technologies for carbide tools applied in turning Inconel 718 [41]. Their results showed that it is very important to adapt the coating methodology to the specific application of the tool.

Good results have been obtained by Uhlmann et al in 2009 [42], with the development of a coating technology capable of deploying a super-hard layer of CBN on carbide tools. When machining Inconel 718, the tool life with CBN-coated carbide tool is two times the tool life of a conventional TiAlN coated carbide tool, at the same machining conditions.

The application of laser assisted machining – LAM in machining nickel based alloys is promising, as it was shown by Anderson et al. in 2006 [43].

Another innovative methodology was reported by Courbon et al. and consisted in the application of High Pressure Jet Assisted – HPJA in turning of Inconel 718 with carbide tools [44]. This technique causes good chip breakability, reduction of built-up-edge formation, improvement of surface roughness and lower tool temperature in comparison with dry cutting and conventional cooling.

3.4. Molybdenum alloys

Molybdenum is a refractory metal which has high melting point (2600°C), it is heat resistant and presents high hardness at high temperatures. The main property of pure molybdenum which strongly influences its machinability is the grain structure. In the sintered condition, molybdenum can be machined relatively easily, but it is somewhat more difficult to machine after the first cut. However, if there is a uniformly fine grained and fibrous structure, the machinability is better. Molybdenum has a tendency to chip while being machined, and care must be taken in order to prevent it. The workpiece should be firmly chucked, tools rigidly supported, and machines should be sufficiently powerful and free from chatter or backlash. A copious supply of coolant and low cutting speeds (less than 120 m/min) are strongly recommended in order to avoid excessive tool wear rate [45].

Sulphur base cutting oil can be used as a coolant for rough machining, and kerosene or sulphur base cutting oil can be used for finishing. Chlorinated oil and solvents have also proved very satisfactory as a machining coolant (for instance: trichloroethylene).

Dry machining of sintered molybdenum is very interesting both from economical and environmental viewpoints. Recently, the authors have investigated the application of commercial coated carbide tools for turning sintered molybdenum alloy without lubricant. Surface roughness of the machined workpiece and tool wear against cutting speed v_c were determined, as illustrated in Figure 5 a). The surface roughness is lower when cutting speed v_c is increasing , and it is necessary to apply cutting speeds above 150 m/min for a good surface finish. Tool life, at cutting speed v_c 200 m/min with a M15 TiAlN coated carbide insert was around 20 minutes, see Figure 5 b). These results have demonstrated that it is possible to apply relatively high cutting speeds and avoid the use of coolant for an efficient machining of molybdenum.

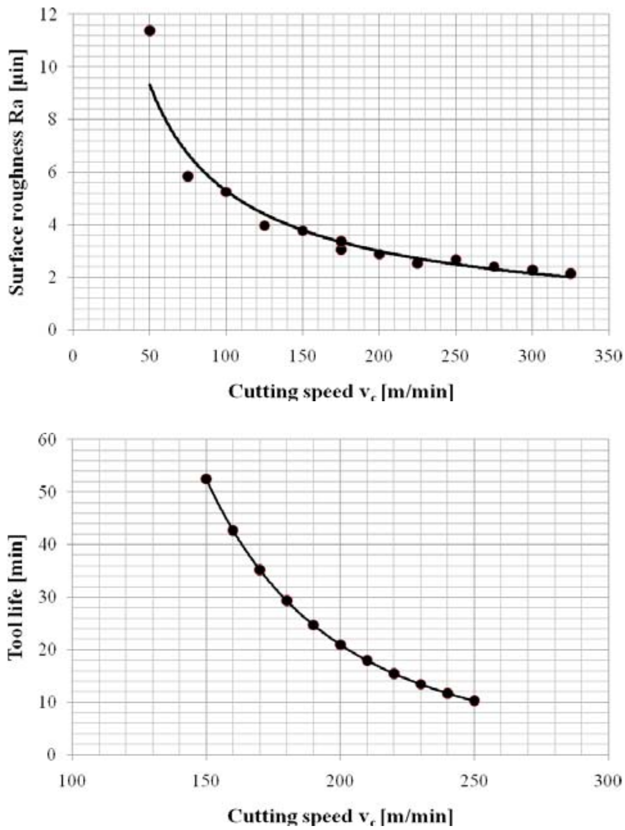

Figure 5. Surface roughness and tool life against cutting speed - turning sintered molybdenum with coated carbide tools in dry conditions.

6. CONCLUSIONS

In accordance to the considerations presented in this paper, we may draw the following conclusions.

Machinability index is an approximate value indicating the machinability of different engineering materials which can be very useful in the design of mechanical parts.

The machinability testing comparison of different materials is recommended when many of the same pieces have to be machined.

Short machinability test can be applied as a preliminary test.

Tool life equations are important for identification of machining process in optimization. Since tool life has a stochastic behavior, regression analysis and other statistical techniques should be used for data analysis in order to determine tool life equation.

The regression analysis should be done, tool life versus cutting speed, in order to determine tool life equation. The ISO standards: Tool Life Testing in Milling, Part1 - Face Milling 8688/1; Tool Life Testing in Milling, Part1 - End Milling 8688/2, and Tool Life Testing with Single Point Turning Tools 3685 are good guidelines for tool life testing.

The Integrated Machinability Testing Concept can be used both for optimization of machining process and to create machinability data bank for a factory.

Tool life of coated CBN tools is longer than uncoated CBN and ceramic tools when machining 100Cr6 hardened steel. However, the surface roughness is generally lower with uncoated CBN tools.

In spite of low stiffness of the workpiece, like slim compressor gas turbine blade, it is possible to increase tool life by approximately twenty times and to increase the cutting speed by three times when

milling titanium alloy TiAl6V4 with PCD cutter as opposed to carbide tools which are normally used for this purpose. Better results are obtained when cutting fluid is applied.
Good results are obtained by applying Laser Assisted Machining - LAM in machining Titanium alloys.
It seems that for machining nickel based alloys ceramic tools are better than CBN tools. However, machining Inconel 718 with CBN-coated carbide tool was much better than with conventional TiAlN coated carbide tool.
Both the application of laser assisted machining – LAM in machining nickel based alloys and the application of High Pressure Jet Assisted – HPJA in turning of Inconel 718 with carbide tools seem to be promising.

In accordance to our machinability testing experience dry turning of sintered molybdenum can be successful with M15 TiAlN coated carbide tool at rather high cutting speed v_c = 200 m/min with corresponding tool life of T = 20 minutes. However, in the literature the recommendation is that the cutting speed should be less than v_c = 120 m/min and copious supply of coolant should be used.

It will also be of further interest to investigate dry sintered molybdenum machining with different tool materials and different tool geometries.

7. REFERENCES

[1] Tool Engineers Handbook, Mc Graw Hill New York, Toronto, London, 1950
[2] M.E. Merchant, Manufacturing in the 21st Century, Proc. 3rd Int. Conf. on Advanced Manufacturing Systems and Technology – AMST'93, Udine, 1993, 1-12
[3] J. Sorenson, W. Gates, Machinability of Steels, Prod. Eng., 10, 1929
[4] O.W. Boston, W.H. Oldacre, H.L. Moir, E.M. Slaughter, Machinability Data from Cold-finished and Heat-treated, SAE 1045 steel, Transactions of ASME, 28, 1906
[5] N.E. Woldman, Good and Bad Structures in Machining Steel, materials and Methods, 25, 1947
[6] E. Kuljanic, Effect of Stiffness on Tool Wear and New Tool Life Equation, Journal of Engineering for Industry, Transactions of the ASME, Ser.B, 1975, 939-944
[7] A. Henkin, The Influence of Some Physical Properties on Machinability of Metals, doctoral thesis, University of Michigan, 1962
[8] E. Kuljanic, Effect of tool life data analysis on tool life equation, Annals of the CIRP, 25/1, 1976
[9] ISO International Standard: Tool Life Testing in Milling Part 1 - Face Milling, 8688/1, Stockholm, 1985
[10] ISO International Standard: Tool Life Testing in Milling Part 2 - End Milling, 8688/2, Stockholm, 1985
[11] Testing for Face Milling, Internal Publication, CIRP, Paris, 1977
[12] Muhren, C., Eriksson, U., Skysted, F., Ravenhorst, H., Gunarsson, S., Akerstom, G., Machinability of Materials Applied in Volvo, International Conference on Advanced Manufacturing and Technology, AMST'90, Trento, Italy, 1990, 208-219
[13] Kuljanic, E., Machinability Testing for Advanced Manufacturing Systems, International Conference on Advanced Manufacturing and Technology, AMST'93, Udine, Italy, 1993, 78-89
[14] G. Byrne, D. Dornfeld, I. Inasaki, G. Kettler, W. Koenig, R. Teti, Tool Condition Monitoring (TCM) – The Status of Research and Industrial Application, Keynote Paper, Annals of thre CIRP, (1995), 44/2, 541-567
[15] J. Kundrak, B. Karpuschewski, K. Gyani, V. Bana, Accuracy of hard turning, Journal of Materials Processing Technology, 202, 2008, 328–338
[16] Y.K. Chou, C. Evans, M.M. Barash, Experimental investigation on cubic boron nitride turning of haredened AISI52100 steel, Journal of Materials Processing Technology, 134, 2003, 1-9
[17] Y.K. Chou, H. Song, Tool nose radius effects on finish hard turning, Journal of Materials Processing Technology 148, 2004, 259-268
[18] G. Poulachon, B.P. Bandyopadhyay, I.S. Jawahir, S. Pheulpin, E. Seguin, Wear behavior of CBN tools while turning various hardened steels, Wear, 256, 2004, 302-310
[19] Gabriel C. Benga, Alexandre M. Abrao, Turning of hardened 100Cr6 bearing steel with ceramic and PCBN cutting tools,Journal of Materials Processing Technology 143–144, 2003, 237–241.
[20] A.J. Oliveira, A.E. Diniz, D.J. Ursolino, Hard turning in continuous and interrupted cut with PCBN and whisker-reinforced cutting tools, Journal of Materials Processing Technology, 209, 2009, 5262–5270
[21] G.S. Galoppi, M.S. Filho, G.F. Batalha, Hard turning of tempered DIN 100Cr6 steel with coated and no coated CBN inserts, Journal of Materials Processing Technology 179, 2006, 146-153
[22] A. Attanasio, M. Gelfi, C. Giardini, C. Remino, Minimal quantity lubrication in turning: Effect on tool wear, Wear, 260, 2006, 333-338

[23] CH R. Vikram Kumar, B. Ramamoorthy, Performance of coated tools during hard turning under minimum fluid application, Journal of Materials Processing Technology, 185, 2007, 210–216
[24] E.O. Ezugwu, Z.M. Wang, Titanium alloys and their machinability: a review, J. Mater. Process. Technol. 68, 1997, 262-274
[25] E.O. Ezugwu, J. Bonney, Y. Yamani, An overview of the machinability of aero-engine alloys, J. Mater. Process. Technol., 138, 2003, 233–253.
[26] S.Y. Hong, Y. Ding, W. Jeong, Friction and cutting forces in cryogenic machining of Ti–6Al–4V, International Journal of Machine Tools & Manufacture, 41, 2001, 2271–2285
[27] S.Y. Hong, I. Markus, W. Jeong, New cooling approach and tool life improvement in cryogenic machining of titanium alloy Ti-6Al-4V, International Journal of Machine Tools & Manufacture 41, 2001, 2245–2260
[28] C.H. Che-Haron, A. Jawaid, The effect of machining on surface integrity of titanium alloy Ti–6% Al–4% V, Journal of Materials Processing Technology, 166, 2005, 188–192
[29] K.A. Venugopal, S. Paul, A.B. Growth of tool wear in turning of Ti-6Al-4V alloy under cryogenic cooling, Wear 262, 2007, 1071–1078
[30] C.R. Dandekar, Y.C. Shin, J. Barnes, Machinability improvement of titanium alloy (Ti–6Al–4V) via LAM and hybrid machining, International Journal of Machine Tools & Manufacture, 50, 2010, 174–182
[31] F. Nabhani, Machining of aerospace titanium alloys, Robotics and Computer Integrated Manufacturing, 17, 2001, 99-106
[32] E. Kuljanic, M. Fioretti, L. Beltrame, F. Miani, Milling Titanium Compressor Blades with PCD Cutter, Annals of the CIRP, 47/1/1998, 61-64
[33] E.O. Ezugwu, Key improvements in the machining of difficult-to-cut aerospace superalloys, International Journal of Machine Tools & Manufacture, 45, 2005, 1353–1367
[34] R.T. Coelho, L.R. Silva, A. Braghini, A.A. Bezerra, Some effects of cutting edge preparation and geometric modifications analysis when turning INCONEL 718TM at high cutting speeds, Journal of Materials Processing Technology, 148, 2004, 147–153
[35] A. Altin, M. Nalbant, A. Taskesen, The effects of cutting speed on tool wear and tool life when machining Inconel 718 with ceramic tools, Materials and Design, 28, 2007, 2518-2522
[36] R.S. Pawade, S. Joshi, P.K. Brahmankar, M. Rahman, An investigation of cutting forces and surface damage in high-speed turning of Inconel 718, Journal of Materials Processing Technology, 192-193, 2007, 139-146
[37] R.S. Pawade, S. Joshi, P.K. Brahmankar, Effect of machining parameters and cutting edge geometry on surface integrity of high-speed turned Inconel 718, International Journal of Machine Tools & Manufacture, 48, 2008, 15–28
[38] J.P. Costes, Y. Guillet, G. Poulachon, M. Dessoly, Tool-life and wear mechanisms of CBN tools in machining of Inconel 718, International Journal of Machine Tools and Manufacture, 47, 2007, 1081-1087
[39] A. Gatto, L. Iuliano, Advanced coated ceramic tools for machining superalloys, International Journal of Machine Tools and Manufacture, 37/5, 1997, 591-605
[40] C. Ducros, V. Benevent, F. Sanchette, Deposition, characterization and machining performance of multilayer PVD coatings on cemented carbide cutting tools, Surface and Coatings Technology, 163 –164, 2003, 681–688
[41] A. Biksa, K. Yamamoto, G. Dosbaeva, S.C. Veldhuis, G.S. Fox-Rabinovich, A. Elfizy, T.Waga, L.S. Shuster, Wear behavior of adaptive nano-multilayered AlTiN/MexN PVD coatings during machining of aerospace alloys, Tribology International (in press)
[42] E. Uhlmann, J.A. Oyanedel Fuentes, M. Keunecke, Machining of high performance workpiece materials with CBN coated cutting tools, Thin Solid Films, 518, 2009, 1451–1454
[43] M. Anderson, R. Patwa, Y. C. Shin, Laser-assisted machining of Inconel 718 with an economic analysis, International Journal of Machine Tools & Manufacture, 46, 2006, 1879–1891
[44] C. Courbon, D. Kramar, P. Krajnik, F. Pusavec, J. Rech, J. Kopac, Investigation of machining performance in high-pressure jet assisted turning of Inconel 718: An experimental study, International Journal of Machine Tools & Manufacture, 49, 2009, 1114–1125
[45] ASM Metal handbooks Nr.16: Machining processes, ISBN 13: 978-0-87170-022-3, 1989