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Quality management in development of hard coatings on cutting tools

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ABSTRACT

Purpose: In this paper, an attempt is made to establish the general model of quality management also to the field of development and introducing of hard coatings on cutting tools.
Design/methodology/approach: The conventional PVD and CVD methods have its limitations and that innovative processes are essential within the framework of an environmentally oriented quality management system. Meeting the requirements of ISO 9000 and ISO 14000 standards, the proposed model ensures the fulfilment of the basic requirements leading to the required quality of preparation processes and the quality of end products (hard coatings).
Findings: One of the main pre-requisites for successful industrial production is the use of quality coated cutting tools with defined mechanical and technological properties. Therefore, for the development and introduction of new coated cutting tool (new combination of cutting material and hard coatings), it is necessary to carry out a number of studies with the purpose to optimize the coatings composition and processing procedures, and also to test new tools in working conditions.
Research limitations/implications: The requirements from industry: produce faster, better, safety and more ecologically, force us to develop new effective tools and innovative technologies. This provides a technological challenge to the scientists and engineers and increases the importance of knowing several scientific disciplines.
Practical implications: The quality of a company's product directly affects its competitive position, profitability and credibility in the market. Quality management system must undergo a process of continuous improvement, which extends from the deployment of preventive quality assurance methods to the application of closed loop quality circuits.
Originality/value: Design of the original and structured model of quality management system for successful development, producing and involving of new coated tools in the practice.
Keywords: Thin coatings; Surface treatment; Quality management; Cutting tools

1. Introduction

The use of coated cutting tools to machine various materials now represents state-of-the-art technology. Developments in coating equipment and processes now enable us to produce a wide range of different hard nitridic and oxidic films and to deposit them on various tool substrates as monolayer, multilayer, or composite coatings. Irrespective of whether cutting tool materials are being coated, the primary concern is to control and optimise properties such as coating adhesion, coating structure, coating thickness, etc., which determine the performance of the complex composite represented by a *"coated cutting tool"* [1,2].

The present studies are of importance from two viewpoints. On the one hand, it is considered that the substrate material is important for the production of highly effective cutting tool, on the other, the performance maximum of hard coating on the different substrate is depended to precisely of the interface characteristic. The interface is analysed with regard to surface state, mechanical treatment and surface roughness [3,4].

The aim of this paper is to establish the general model of an environmentally oriented quality management in the field of development and introducing of new hard coatings on cutting tools.

2. Strategic approach in the development of hard coatings

Since the beginning of the nineteen-eighties, PVD coating has been used for large scale industrial coating of geometrically complex tools such as twist drills, reamers, taps, end mills, form tools, etc. Hard coating led to a major advance in the performance of these tools. Modern design of coated cutting tools place such high demands on the materials specified that they can very often only be met by tailoring composite materials for these specific applications. In particular, the requirements for substrate (bulk) properties, on the one hand, and tool surface properties, on the other hand, differ so much that the surfaces have to be specially treated and modified to meet the particular demands [5].

The availability of new coating systems and sophisticated coating processes enables us to understand previously unexplained phenomena relating to the performance of coated cutting materials. It is increasingly apparent that thermo-physical properties of the coatings have a substantial effect on their performance and operating parameters. The quality of coated cutting tools often depends on three main parameters, which are shown in Fig. 1 [6].

Substrate (tool) material. Unlike high speed steels, whose operating conditions are primarily restricted by their annealing resistance, hot hardness and hot wear resistance, cemented carbides, cermets or cutting ceramics are essentially limited by their toughness behaviour and their resistance to abrasion, diffusion and oxidation. One key area of interdisciplinary development work, which cannot be discussed in greater detail here, is improvement of the substrate materials.

Coating. A second key area of interdisciplinary work, which is very complex, is the sophistication of the coatings. There are a great many external and internal process variables involved. Determining the relationship between both process variables is needed in order to achieve reproducibility and high quality in coated tooling.

Interface. The study of interface problems in coating advanced tool material included the following parameters [3]:

- the surface morphology and microstructure of the substrate and the hard coating;
- the distribution of the elements at the interface;
- possible reactions between elements from the substrate and the coating.

Machinability Tests. Despite great advanced in the analysis of thin films, machinability tests are still needed to demonstrate the performance potential of hard coatings on cutting tools. The following experiments are intended to help isolate and interpret the interface characteristics between hard coating and substrate and theirs influence on the parameters in the machining process, and resulting forms and causes of tool wear.

For the characterisation of these parameters modern analytical techniques are used.

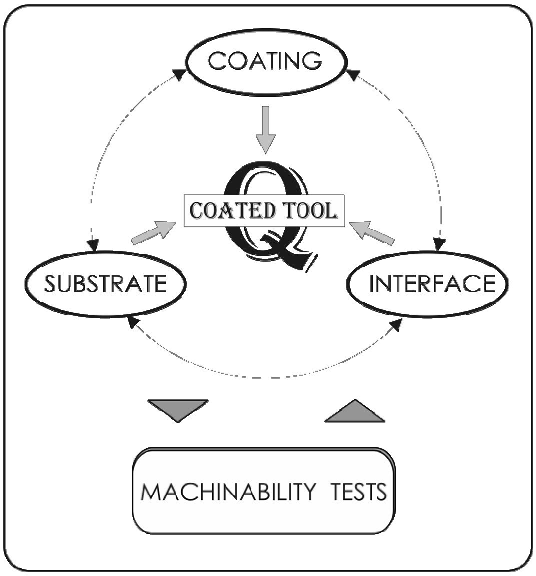

Fig. 1. The interaction of main parameters on the quality of coated cutting tools

3. Quality management in development of hard coatings

The quality of product directly affects its competitive position, profitability and credibility in the market. Thus, the major objective of quality management becomes that of achieving and maintaining the leadership in product quality and reliability. Product quality requirements should be defined for each product based on factors related to satisfying the needs and expectations of those whom the product serves.

The concept of overall total quality control system should be encompassed all of the elements of quality assurance and quality control. Some problem-solving techniques on this area include the following [7]:

- Statistical process control,
- Root cause analysis,
- Quality control circles,
- Quality improvement techniques.

Quality assurance system must undergo a process of continuous improvement, which extends from the deployment of preventive quality assurance methods to the application of closed loop quality circuits. Quality assurance methods are thus frequently effective only when they are integrated into so-call *"quality control circles"*.

Quality control circles are quality tools, which are used for achieving the above-mentioned aims and enable to transition from the quality of process to the quality of product throughout the active quality control. The principle behind systematic feedback into various levels of the *"closed loop quality circuit"* is that the use of historical data will prevent the same mistakes from being repeated, for example at the planning stage [8].

The basic elements by the establishment of the general model of quality management in the development and introducing of hard coatings on cutting tools are [2, 4]:

- Selection of the substrates and coatings,
- Preparation of hard coatings,
- Testing of hard coatings (in laboratory and workshop conditions),
- Industrial applications.

3.1. The first step of quality management

The first step in our case of quality management is selection of appropriate hard coatings (monolayer, multilayer, gradient, nanolayer, nanocomposite, CLC, DLC-coatings…) and their characterisation, which means the quantitative assessment of the relevant properties by means of physical, chemical, and technological effects. Here it is practical to distinguish between characterisation with respect to structure and composition, and characterisation with respect to the other properties.

Obviously it is not sufficient to characterise only the function and structure of a few atomic layers; the entire modified zone has to be taken into account, and the problems of the interface also have to be dealt with. In these considerations the system involving substrate-bulk material (HSS, ASP-steels, cemented carbides, cermets, Al_2O_3-based ceramic, Si_3N_4-based ceramics, CBN…), interface, surface coating or modified surface layer, and also surface, is very complex and, together, yields the system's properties which are required by the tool designer, with every part playing an important role. The complexity of the system is shown in Fig. 2 [6, 9-10].

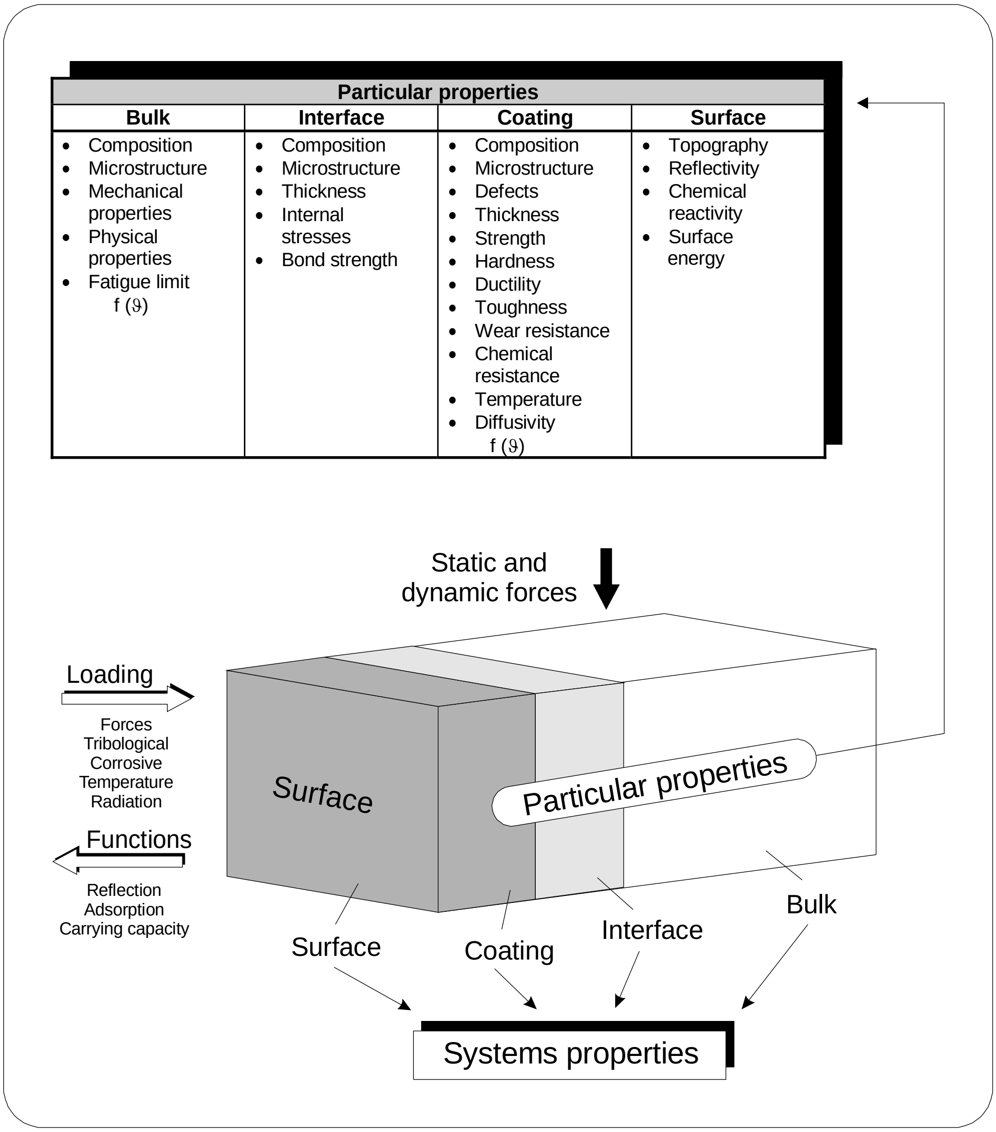

Fig. 2. System properties of a component as a result of interactions

Structure and Composition. One can use a great number of interactions to characterise a surface or a metallographic section. Feeler gauges can be used to study the surface contours, or gases and liquids to study porosity and surface energy. Notably, the interactions of a surface of coating with photons and electrons not only lead to image via light and electron microscopy, but also yield information on chemical composition, molecular structure, and binding status; by way of X-ray diffraction, knowledge of lattice parameters can be obtained [2]. The information depths (scale) of different analytical methods are different: Auger Electron Spectroscopy (AES), X-Ray Photo Spectroscopy (XPS), Secondary Ion Mass Spectroscopy (SIMS), and Ion Scattering Spectroscopy (ISS). Obviously, only the latter three methods are capable of characterising the immediate surface, EDX actually measuring the substrate (bulk) of the material. By removing the surface layer by layer via sputtering or ball-cratering [6], the surface analysis methods can be used to obtain depth profiles of surface layers, *e.g.,* showing the oxide on top of the coating, as well as the adsorbed carbon [11].

Specific Properties. The properties of the surface layer or surface coating are also obtained by interactions. The interaction with a diamond pyramid or indenter yields results on the hardness of the area measured, and interactions with gases, liquids, particles, or other surfaces yield information on hot corrosion, electrolytic corrosion, erosion, or wear resistance. By measuring the hardness or Vickers ultramicrohardness and Young's modulus, the maximum load P_{max} employed during the indentation cycle was chosen, paying attention to the coating thickness, in order to eliminate possible substrate (bulk) influences in the final results, although the stress status is complex [12]. Measurements of the other properties are extremely involved due to the almost infinite number of parameters. This has resulted in a great variety of tests.

Determining wear resistance alone, which can be classified under abrasive wear, sliding wear, and rolling wear, has led to the development of a great number of tests, which all serve a particular purpose, reflecting the fact that wear resistant is a system property.

Bond Strength. The interfacial properties influence the behaviour of coatings under loading, and it is of particular interest to study the strength of the bond between coating material and substrate. Due to the thinness of coatings this task is very difficult. The tests available either use normal stresses, shear stresses, or a fracture mechanical approach:

- *The tension tests* suffer because a counter bar has to be bonded to the coating either by adhesives or by brazing. By this procedure, the coating and the interface itself might be affected and, very often, the adhesive bond is too weak to test a well-adhering coating.
- *The shear tests* suffer from the very exacting and costly sample preparation, and cannot be applied to coatings less than 100 μm thick.
- In the case of *fracture mechanical testing*, the introduction of cracks is extremely involved.

The summarising, the quantitative characterisation of bond strength has not yet been solved successfully.

Coating Thickness. The coating thickness can be measured in many different ways, depending on the properties of coating and substrate:

- Optical methods
- Removing methods
- Electromagnetic methods
- Scattering methods
- Excitation methods

Without going into detail, it can be stated that there is a thickness measuring method for any coating on any substrate, yet it is *not necessarily non-destructive.*

Non-specific Testing. So far, the characterisation methods discussed are those, which measure specific properties in a quantitative way. However, there are a great number of non-specific tests available that have evolved during the practical work on *coating/substrate* systems. Generally, they apply a very complex loading profile and yield results on bond strength, cohesive strength within a coating, bonding defects, and ductility of a coating; they will also often work very well in assessing the general quality of a coating and its bonding to the substrate. Some of them are:

- Torsion test
- Folding test
- Impact test
- Scratch test

Notably, the *scratch test* is very widely used to assess the *quality of hard coatings*, but the interpretation of results requires great experience [13,14]].

Testing under Service Conditions. Most surface-engineered components are subjected to very special and often complex loading profiles in service, which is particularly the case in corrosive aqueous and gaseous environments and for tribological applications, Fig. 3 [2,9]. In order to obtain data on the actual performance in service, the components have to be tested under closely simulated service conditions.

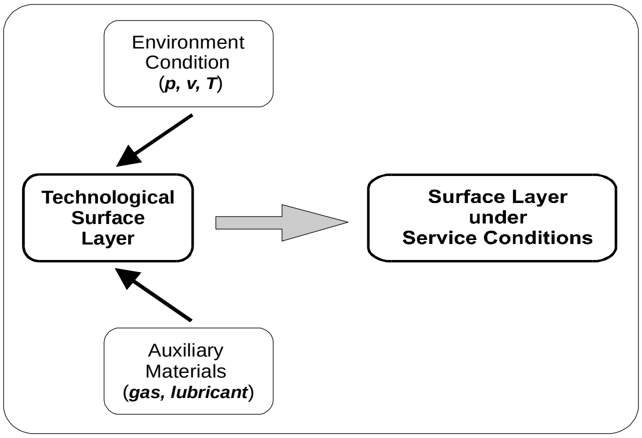

Fig. 3. Schematic display of transformation of the technological surface layer into a surface layer in service conditions

In the case of a coated cutting tool it is almost impossible to conduct direct research of events going on in the coating surface *during the cutting process itself.* What is usually done is identification of post-process changes on the coating surface (cracks, B.U.E.) and under the surface in the interface (coating delaminating, efficiency of diffusion barrier) [15].

3.2. The second step of quality management

The second step, which cannot be discussed in greater detail here, is selection and optimisation of the methods (PVD, CVD, PACVD...) of preparation of hard coatings on cutting tools for previous (in the first step) selected type of coatings.

In the search for solutions to develop new hard coatings and improve manufacturing processes it is essential that the today's (conventional) approach be replaced by new and innovative methods, which allow us, achieve a minimum of environmental contamination in conjunction with suitable technologies providing high process stability and reliability and acceptable economic conditions. The increasing sensitivity to environmental and health issues is reflected in the increasingly stringent legislation and national and international standards. This provides a technological challenge to the scientists and engineers and increases the importance of *ecological manufacturing* as a competitive factor.

Manufacturing processes have to be developed which are not just suited to the needs of today products, but rather reach in a strategic way into the future and are suited to the products, materials and conditions with witch we will be confronted in the coming years [16].

3.3. The third step of quality management

The third step is strongly connected with quality control of hard coatings after producing and practical testing of coated tools in laboratory and workshop conditions. Quality assurance procedures have to be applied to maintain the standard achieved during development work, and need to be considered adequate for the component. These procedures are of the same nature as the ones used during the production of substrate (bulk) and can be categorized as follows:

- Process parameter control
- Random sampling
- Non-destructive testing
- Monitoring in service

Process Parameter Control. This most important of procedures deals with control of all input materials and processes used during the tool surface coating (depositing). These parameters have to be strictly controlled and maintained within specific limits in order to obtain uniform quality over a product series and periods of time. It is well known that, if a quality problem arises, the first remedial step has to be the checking of any deviations in the process parameters.

Random Sampling. The testing methods described to characterise surfaces and coatings are all used for quality assurance as well, depending on the type and purpose of the particular tool and the particular system of surface treatment:

- In the *case of small tools*, one or several samples are taken from every batch produced and tested with respect to the relevant properties.
- In the *case of larger tools (cutters)*, separate small samples are often prepared under exactly the same process conditions and then subjected to the tests selected.

In both cases, destructive and non-destructive testing methods can be used.

Special Non-destructive Testing Methods. Among them are those of particular interest that allow testing of every single piece (100 % testing). The most common one is that used in the sample visual inspection of the treated tools and categorizing them according to certain standards. Coating defects, *e.g.*, blisters, uncoated areas, and changes in colour can be detected quite easily this way. As an example: the colour of TiN coatings depends greatly on the chemistry, and a *bright golden surface* indicates the stoichiometric composition of TiN [4]. Most coating thickness measuring methods can be used for 100 % examination; the breakdown voltage is a good indicator of the density/porosity of an insulating coating.

Monitoring in Service Conditions. Quality assurance not only means assuring the production quality before delivery, but also implies that surface coatings should not fail when in use, which could often result in expensive or catastrophic side effects.

Quality control of hard coatings on tools or tool tips presents a difficult problem because the coatings are thin, mostly less than 5 μm, and coating and adhesive properties have to be excellent if the coating is not to fail during use. In Fig. 4, the relevant properties are listed together with the testing methods that can be applied. Interestingly, the scratch test, with its undefined loading profile, has to be used in order to measure the adhesive and cohesive properties. Measuring the coating thickness also presents a problem and can only be done destructively. According to the quality assurance procedures only visual inspection and feeler gauge can be used for a 100 % inspection: the other testing methods can only be applied to random samples.

3.4. Testing of coated tools

Analysis of tribo-system in cutting processes. Understanding of tribological problems, nature and characteristics of the cutting material, cooling agent and its application are of significant importance for the predictability of the tool life for a reliable production in a given application. If all parameters of the tribo-system are mutually optimally combined, it can be expected with high probability that the selected technological values with existing machinery will give an optimal product. The theory of resistance of tool is very complicated since it is necessary to know several scientific disciplines.

Fig. 5 shows a generalized system approach of analysis of the tribo-system during the cutting process, *i.e.* turning, face milling...[17]. The tribo-system that develops when using coated tools can be shown in a simplified way with a model (emphasized in Fig. 5) representing the basis for an approach in analyzing the substrate (tool)/coating/workpiece system. Substrate (3), which can be a different kind of tool, is covered by a hard coating (2) and is in contact with the workpiece (1). All the results of systematic research show that for the efficiency of the whole system the so-cold adhesive joint (5) between hard coating and substrate (tool) is of decisive importance. The quality of the joint directly defines the efficiency of hard coating in the tribological contact (4) with the workpiece.

The definition of the parameters, description of the processes and optimization possibilities of both contact spots (4 and 5) have been the subject of extensive research. Besides the regularly observed wear, change of mechanical properties and machining problems, we now encounter as important parameters also adhesion, surface physics and chemistry, film growth and epitaxy and electron metallography [18-21]. Therefore, every coated tool is also an interdisciplinary scientific problem.

Testing methods	Property
Metallography (MET) Scanning electron microscopy (SEM)	Structure
MET SEM Feeler gauge (FG)	Topography
MET SEM FG Ball cratering	Thickness
Scratch test	Hardness
Scratch test	Adhesion Cohesion
Pin/disc Ball/disc	Friction wear

Fig. 4. Possible testing sequence for hard coatings

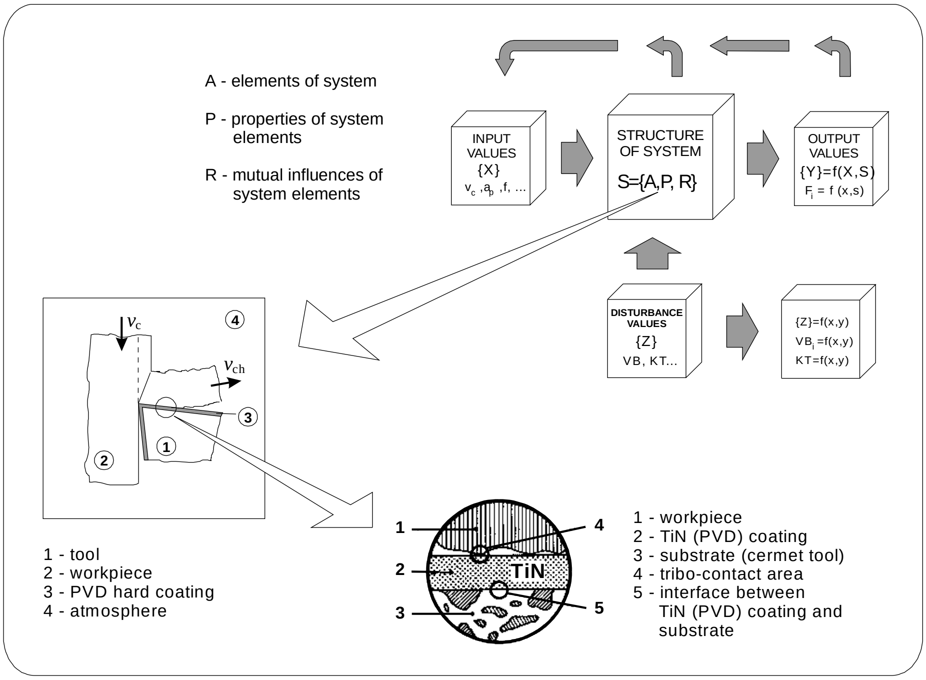

Fig. 5. Structure of tribological system in cutting process by use of coated tools (Example of monolayer TiN coating on the cermet insert)

Coated tool efficiency index. In all cases of testing tool wear, it is possible to note a marked increase in tool life of the cutting tool coated with PVD or CVD coatings, irrespective of the kind of machining procedure, either turning or milling. To be able to evaluate this effect numerically, author proposed in the past [22] a name, witch was introduced to denote this increase in the tool life of coated tools, i.e. ***"coated tool efficiency index" (CTE - index)***. It was defined as a ratio between the coated tool life time to the life time of an equal tool without coating:

$$CTE = \frac{(Tool\,life\,)_{coated\ tool}}{(Tool\,life\,)_{uncoated\ tool}} \tag{3.1}$$

In fine machining, the criterion of wear is given by VB = 0.2 mm. Thus the coated tool efficiency index would be denoted as: $\boldsymbol{CTE_{0.2}}$. Similarly, in the case of normal machining for which the wear criterion is defined by VB = 0.4 mm, the efficiency index would be denoted: $\boldsymbol{CTE_{0.4}}$.

In accordance with this definition, we defined the coated tool efficiency indexes for TiN (PVD) coated cermet tools, for the different cases as follows [2]:

- ***CTE*$_{0.2}$** = 1.48 ... by fine turning alloy steel (280 HB),
- ***CTE*$_{0.2}$** = 1.67 ... by fine turning steel Ck 45,
- ***CTE*$_{0.4}$** = 3.00 ... by turning alloy steel C 60N,
- ***CTE*$_{0.4}$** = 1.32 ... by face milling steel Ck 45.

The analysis of a series of examples has shown that the value of the index increases with materials difficult to machine or in more difficult working conditions (especially higher feed rate). However, this enormous increase in the ***CTE***-*index* should not mislead us: it will occur when the machining with uncoated tool is fully inefficient or in certain cases even impossible. The advantages of coatings can be exploited by using higher cutting parameters to achieve higher removal rates per unit time. Coated tools are, however, frequently also used at cutting parameters identical with or only slightly higher than those for their uncoated equivalents. Increased performance potential is then transformed into higher removal rates per tool life and not per unit time, as compared to uncoated tools.

Coated tools have achieved a high quality standard, as evidenced by the fact that more then 90 % of all indexable inserts used in turning are now coated with different PVD or CVD coatings. Use of coated tools is much less widespread in milling (interrupted cut applications), at roughly 30-35 %. The causes are to be sought in the entry and exit impacts and the associated mechanical and thermal shocks, which impose much more exacting demands on the toughness behaviour of the cutting material than on its wear resistance.

Based on the fact that today's contemporary tools market offer lot of PVD or CVD-coated cutting tools and coating systems we defined new coated tool index for comparison of the efficiency of different coated tools in the same application: ***NCTE - index***. It was defined as a ratio between the different coated tool life time, obtained with different coated tools (or coating systems) in the same cutting conditions to the life time of the tool with standard reference coating (*SRC-tool*), momentary used in the practice:

$$NCTE = \frac{(Tool\,life\,)_{coated\,tool(A)}}{(Tool\,life\,)_{SRC\_tool}} \tag{3.2}$$

Example: Turning of grey cast iron (260 HB) with uncoated Al_2O_3 + TiC ceramic inserts compare to coated ones with different PVD and CVD coatings: monolayer TiN or TiAlN, two layers TiCN + TiN, nano multilayer (TiN + multiTiAlSiN + TiN), gradient layer (TiN + TiAlSiN + AlSiTiN)… In this case ***CTE***-*index*$_{(0.2)}$ is from 1.27 to 1.80. For the TiN (PVD) coating, as standard reference coating (SRC-tool), the ***NCTE***-*index*$_{(0.2)}$ is between 0.70 and 1.00 [21,23].

3.5. From machinability tests to quality coatings on the cutting tools

Machinability tests encompass workpiece materials, cutting tools, and the cutting operations and its characterization. The considerations used in selecting and evaluating cutting tool performance and workpiece machinability. In the continuation, discussion is focused on machining tests which are still needed to demonstrate the performance potential of hard coatings on contemporary cutting tools. The latter problems will be given our full attention.

The aims of author research and development work, in past decade, were to establish the general model of improvement of cutting tools performance, above all by PVD coating, and determine the strategy to improve manufacturing processes in the way of replacing the today's (conventional) approach with new and innovative ones. New cutting tools and innovative processes (within the field of the Near-Net-Shape technology) allow us to achieve a minimum of environmental contamination (with dry or near dry cutting) in conjunction with suitable technologies providing high process stability and reliability and acceptable economic conditions. Fig. 6 shows the central part of this model.

The first step of quality management in this case was carried out by the selection and characterisation of the hard coatings, the second step dealing with selection of method (CVD or PVD) and optimization of parameters for hard coating processing. The third step, the decision for the machinability tests offers the correctness of the previous steps on one hand and provides the correct dates about the time and costs of machining on the other hand, considering the selected parameters of machining and required product quality.

4. Conclusions

One of the pre-requisites for successful production is the use of quality cutting tools with defined mechanical and technological properties. Therefore, for the development and introduction of new kind of cutting tool (cutting material or coating), it is necessary to carry out a number of studies with the purpose to optimize the substrate and coating composition, coating processing procedures, and the resulting workpiece material machinability.

In this paper author try to show the importance of improvement of cutting tool performance by PVD or CVD coatings. An attempt is made to apply the general model of quality management system based on "*closed loop quality circuits*" in development and introducing of coated cutting tools in the practice, and determine the strategy of the machinability in finish machining, where the dimensional accuracy, surface roughness and tool life are the major aspects of interest.

Stimulated by the many innovative surface technologies reaching commercial maturity last decade, the discipline of surface engineering has been seen to flourish. As a new area of engineering, its future development should be amenable to planning, through the adoption of a logical interdisciplinary approach. Such an approach will provide the manufacturing industry with many new opportunities in the design of effective cutting tools and production processes.

It can be concluded that cutting tool surface and surface coatings characterisation, as well as quality assurance, are very important parts of effective cutting tools development. A great variety of powerful testing methods exists both to characterise surface coatings and to ensure that the quality is adequate. Non-destructive coatings methods that can be used for 100 % testing are, however still in the development stage, and further work has to be done in this area.

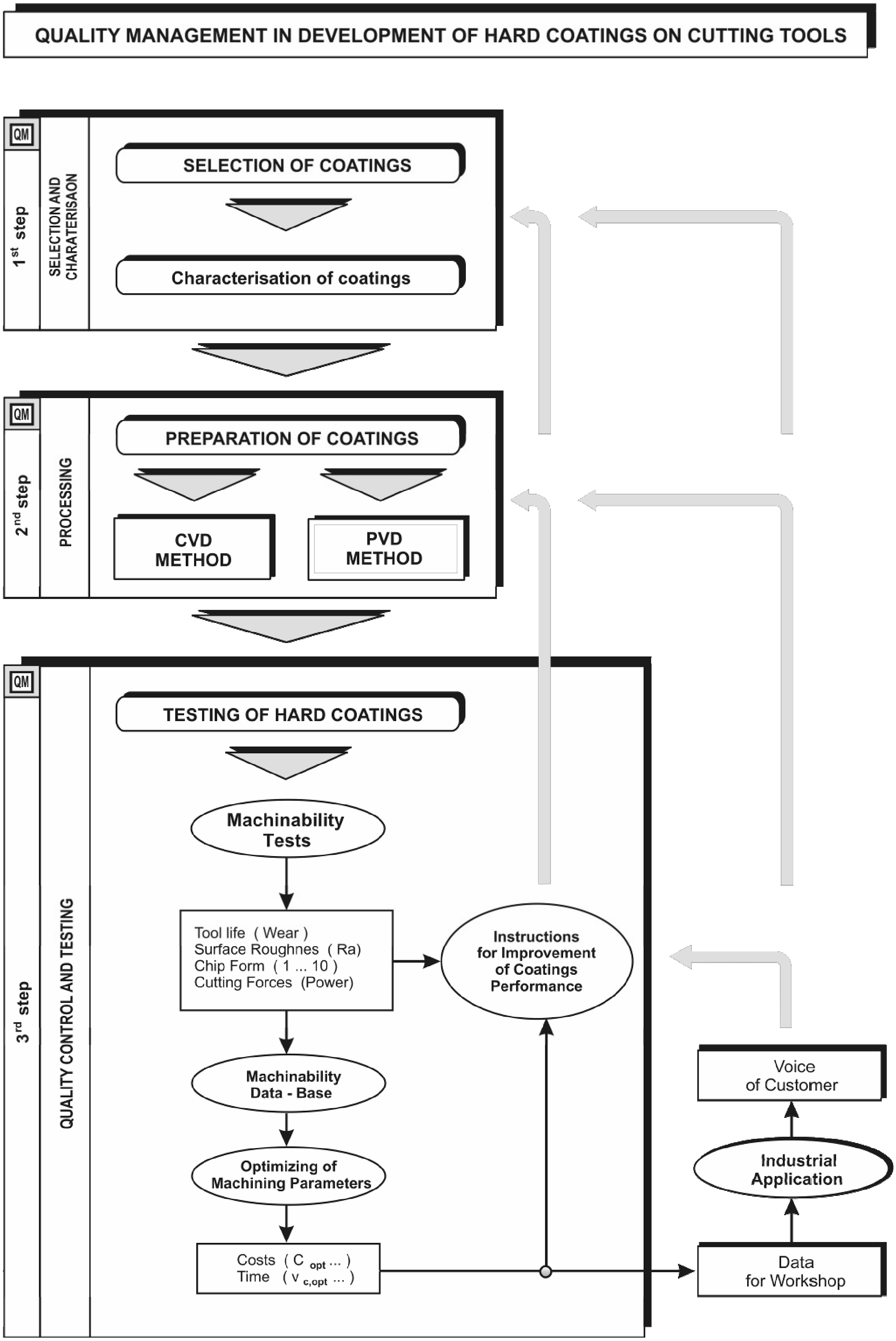

Fig. 6. General model of quality management system based on "*closed loop quality circuits*"

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