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Mechanism and types of tool wear; particularities in advanced cutting materials

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ABSTRACT

Purpose: of the study was to test the applicability of different cutting tools in producing tool-making equipment and to put the emphasis on the mechanisms present in the high-speed-cutting process.
Design/methodology/approach: used are optical and SEM observation and comparative analysis of wear types at the cutting edges of the end-mill cutters.
Findings: the characteristic wear of end-mill cutters is caused by of the fact that the cutting speed is no longer the main influential factor on wear, but more likely wear is the consequence of the high-speed of the tool movements (feed rate), the tool is worn out when it can no longer generate a prescribed surface quality or assure required workpiece accuracy.
Research limitations/implications: all observed parameters, which are difficult to predict, are closely connected with the appearance of favourable wear at the tool tip of the end mill cutter.
Practical implications: results presented were also confirmed in the production environment, when dies were produced for practical use.
Originality/value: is in description of tool life in HSC, which is related to the tool wear pattern, chip shape and - particularly in advanced machining operations - the surface texture and workpiece accuracy. Optimisation of the cutting parameters in HSC is thus not made with respect to the maximum removal rate, but rather to the low level of the cutting forces and better surface quality.
Keywords: High-speed-cutting; Tool wear; Ball-end-mills

1. Introduction

For nearly a decade we have believed that the basic mechanisms of tool wear and different kinds of wear produced at the tool tip can be understood (see Shaw at [1], Luttervelt at [2]). On the basis of experimental measurements of different tool wears, and the application of proper statistical techniques, it was possible to predict the tool life and therefore the intervals of changing the tools. This was the period of intensive work on so called "data bases on machining parameters" [3,4,5]. At the same time, poor future prospects were forecast for the cutting processes because of the higher energy waste and related economical inefficiency.

However, recent developments in machine tools, computerised control, automatisation, combined with the related unforeseen improvements in the cutting materials and their protective coatings with special geometrical shapes of the tools, make such a prognosis completely invalid. Moreover, the degree of use of the machining operations has even significantly increased. New cutting materials increase the tool efficiency costs of performing machining operations, and also highly increase the reliability of the cutting and the quality of the products (see e.g. [6] for review).

All these tremendous changes present new challenges and tasks to the users of tools and researchers of the machinability problems. If we were able to predict a tool's life only on the basis of measurements of the flank and crater wear of the tool, the changeable circumstances caused by new tools and all related unknown wear appearances would demand that we consider tool wear as a collection of different kinds of wears located at the tool tip, difficult to separate in the form of ordinary locations [7].

This phenomenon is especially explicit in finish machining [8] and high-speed cutting (HSC) operations [9], where the emphasis should be placed on the reliability of the cutting process, tool life and required surface roughness The advantages of this process lie not only in the speed of machining (lower costs) but also in attaining the lower, prescribed surface roughness. This allows us to make finish machining parts by using only one machine. In such cases the necessary post-machining operation, such as grinding, is no longer required; furthermore the intermediate transport, and highly demanding operations for the subsequent fixing and positioning of the workpiece can also be avoided [10].

Therefore, the applications of HSC in different machining applications - as for example those in die machining - demand constant examination of these processes in relation to competitive approaches, in both the technological and the economical sense [11]. Further progress, and the possibilities for practical, economically justifiable implementation of the HSC processes for milling of hard steels, is closely linked to the latest development of new, highly efficient cutting tools. The multi-layer coated carbide tools which have recently appeared, offer prospects for even higher applicability of these processes. These cutting materials - for which the producers promise the same efficiency as that achieved with much more expensive PCD cutting materials, - are characterised by being considerably lower priced.

However the usage of such advanced tools makes the classical interpretations of wear mechanisms increasingly useless. The explanations of the complex wear process as separately abrasion, adhesion, diffusion or oxidation - especially when we use the tools at increasingly higher speeds - is not relevant for understanding different wear mechanisms when using recent tools [12,13]. Not only is the allowed wear at the tool tip considerably smaller here, but also the changes in wear pattern induce changeable tribological contacts [14].

2. High-Speed-Cutting, some basics

The upper limit of cutting speeds in machining with a geometrically defined cutting edge increased from 15m/min in the year 1930 to over 1000m/min after 1990. The allowed level of speeds has been always restrained by the limitation in cutting temperatures. It has been established, that the cutting speed has a distinctive relation to the cutting temperature [15]; these ascertainment help us to predict the machining technologies which assure economical production. It is argued that in the HSC machining range, the temperature on the cutting edge starts to decline again. Figure 1 shows the regions of cutting speed for milling a different workpieces [16].

What is considered to be the high speed range is a matter of different opinions; for instance, in Europe this is the velocity of cutting, where the applied cutting speeds are 100% greater than in 1990. In the USA it is rather the spindle speed, which should be higher than 10 000 rpm. Practically, we need modern cutting tool material and rigid machine tools, which assure high spindle revolutions [17]. Machine tools like these - and in the recent period also many other types - assure rational machining of hard die tools up to 60 HRc and more. All these facts have an influence on the die tool-making industry which has changed the production technologies. More and more operations usually performed by the EDM machines are being replaced by the HSC. The benefit is much greater, and production time shorter [18].

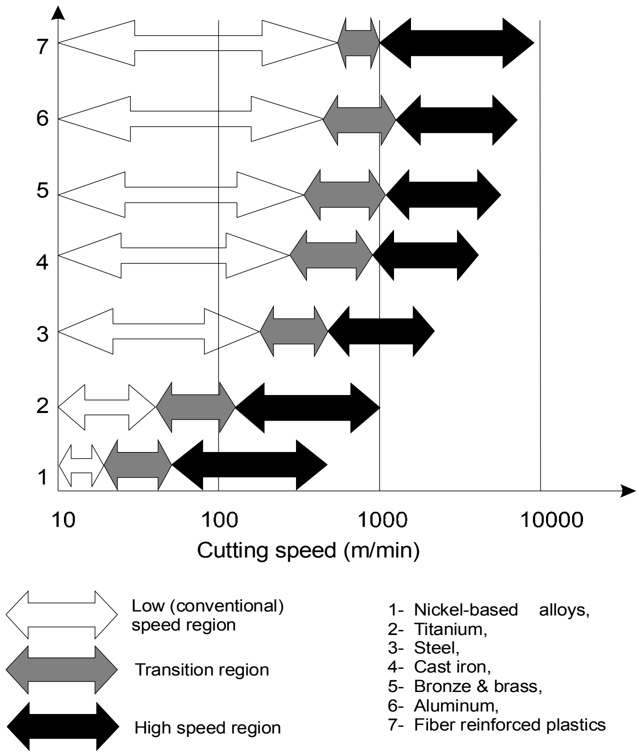

Fig. 1. Cutting speeds for milling different materials [16]

Dynamical interrelation between the machine tool characteristics and machining parameters (v_c, f, a) is directly demonstrated as the improved stability of the cutting process. The depth of cut and spindle revolutions should be chosen for such regions in which no chatter can occur. With smaller depth of cut and feed rate the cutting forces become very small; this is a precondition which ensures tolerances within the prescribed limits when thin walls are machined. There are many factors which have an influence on the allowed level of cutting speed:

- workpiece material (Al–alloys, hardened steels, composites),
- type of machining operation (turning, milling, drilling),
- machine tool (power, RPM, static/dynamic stiffness),
- cutting tool (High Speed Steel, carbide, ceramics, PCD…),
- part requirements (shape, size, stiffness, tolerances, Ra, …),
- and other considerations (chip disposal, safety, economics).

To observe all the above requirements and suggestions we must have specific technological knowledge. Some of the data can be found from the technological database and latest literature.

3. Tool-wear - ordinary pattern and recent knowledge

During the machining process, the cutting tools are loaded with the heavy forces resulting from the deformation process in chip formation and friction between the tool and workpiece. The heat generated at the deformation and friction zones overheats the tool, the chip and partially the workpiece. All the contact surfaces are usually clean and chemically very active; therefore the cutting process is connected with complex physical-chemical processes. Wear on the tool, which occurs as the consequence of such processes, is reflected as progressive wearing of particles from the tool surface.

Ever since the famous Taylor started with his tool life experiments [20] all the basic mechanisms of the tool wear process - such as the wear types which can be observed on the tool - have been intensively investigated and published. As a result of the comprehensive understanding of the tool wear appearance, the methods for wear observation and evaluation of tool-life became standardised and now serve as basic data used world-wide in the technological data-bases [21,22].

For an easier understanding of all the particularities in wear mechanism in HSC machining processes, we will firstly present an overview of what we usually denote as an ordinary tool wear. A summarised picture of the basic causes, mechanisms, types and consequences of the wear is presented in Figure 2 [23]. Tool wear is generally considered to be a result of mechanical (thermo-dynamic wear, mostly abrasion) and chemical (thermo-chemical wear, diffusion) interactions between the tool and workpiece.

If it was enough in the past to observe only the mechanical wear, and on the basis of such wear to draw conclusions about the tool life, the newly developed tool materials provide the possibility of raising the cutting speeds, which significantly increases the cutting temperature. Therefore the appearance of the chemical wear becomes more evident, especially when the speeds move into the high-speed-cutting range. Here the cutting edge locally heats to 1000 °C or even more, which enhances the diffusion and oxidation processes [24, 25].

The temperature at the contact zone might raise or exceed the level of the resistivity of the cutting materials, which results as increased crater wear, chipping of the cutting edge or even catastrophic damages to the tool tip. With high protective multi coatings, producers are also able to offer more and more efficient tools for the high-speed range, which at the same time make simple observations of the tool wear mechanisms completely unusable. Influences such as cutting parameters, tool tip geometry, machine tool or the tool tip position with regard to the workpiece surface, are factors which need to be considered for each particular case.

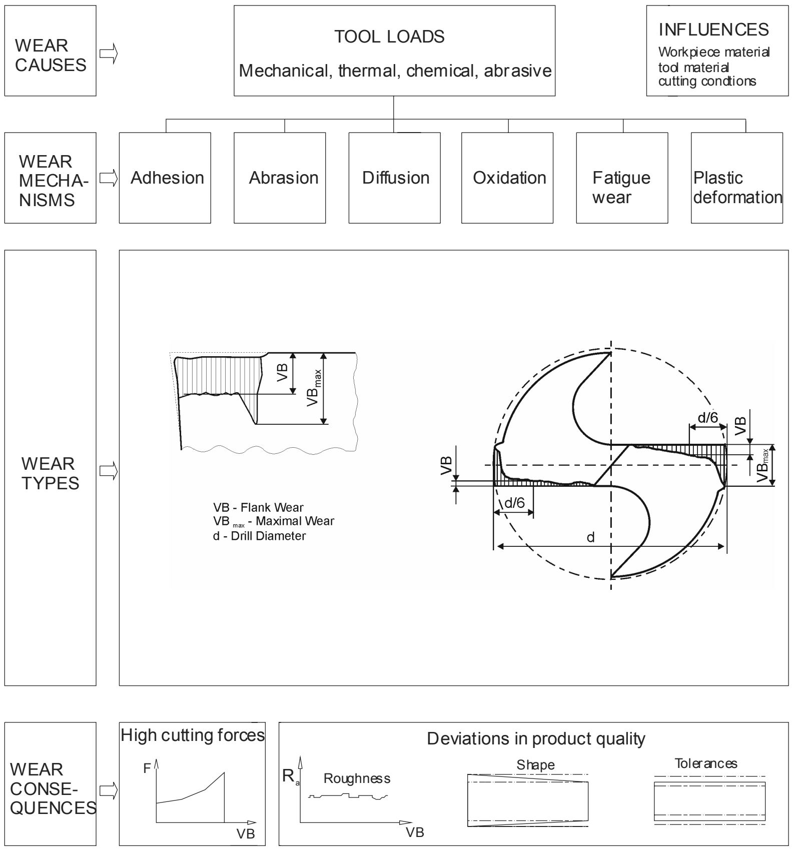

Fig. 2. An overview of the causes, mechanisms, types and consequences of the tool wear [23]

4. Tools and workpiece description for the HSC process

Tool manufacturing in using the HSC milling process requires - in addition to modern machining centres and proper CAD/CAM equipment - also qualitative tools for performing the milling operations. Contemporary cutting tools made on the basis of hard materials allow us to machine the materials with a hardness of 62 HRc. The latest developed coatings enable us to use beside the PCD and CBN cutting tools, which are very expensive, also tools made on the basis of carbides coated with multi-layer coatings.

In the high-speed milling operations, generally special end-mill cutters are used. Different producers have developed a variety of tool materials, made from cemented carbide and using different coatings, mainly TiAlN single-layer or TiAlN + TiN multi-layer coatings; each of their products is advertised as a highly efficient tool, but the success is differently demonstrated in practice.

In Figure 3, the dimensions and geometrical shape of the typical ball-nose milling tool with two cutting edges for HSC-machining is presented. Such an end-mill geometry is similar for all producers; however, the generations of the tools differ with respect to the coatings which can improve adhesion at the cutting edges, a fact which can provide more consistent tool life under high-loads. Micro grain carbide tools utilise the high heat resistance of the multi-layer coating, which improves the efficiency of the high-speed-cutting (speeds up to 35.000 RPM) [26].

The ball-nose mills which are also often used are those designed with more cutting edges; the main difference is demonstrated through the dimension of the ball core, which influences the toughness of the mill. Some recent researches have shown that this fact is related to the tool life of the mills. This fact further increases the importance of more comprehensive understanding of the cutting mechanisms in HSC machining.

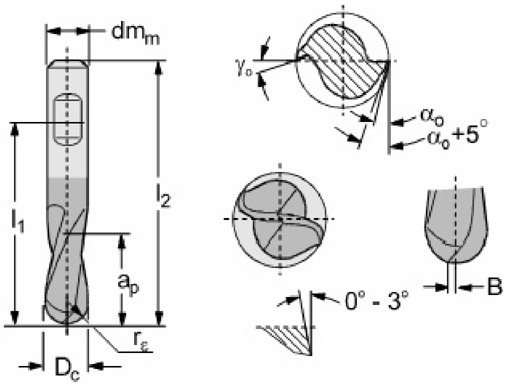

Fig. 3. Geometrical characteristics of the end-mill for HSC

A practical example with application the workpiece material (35CRMOV5 - ISO, X38CRMOV51 DIN: tool steel for hot forging of light material, grade for water cooling) with the hardness of approximately 50 HRc, used for our investigation is presented in the Figure 4. The final product is a die for forging hand tools made from aluminium; the die is in a relatively complex shape, which need to be made at three geometrical levels with engraves in the negative shape of the product.

Until now, engraves production had been performed in the classical way. The first process was the rough milling, then quenching to the hardness of 45-50 HRC, and finally subsequent EDM finishing. With the introduction of new HSC machines the EDM is now used to finish only those engraves which cannot be milled with HSC. All the machining operations were made on the milling machine with additional multiplication of spindle revolution for HSC machining.

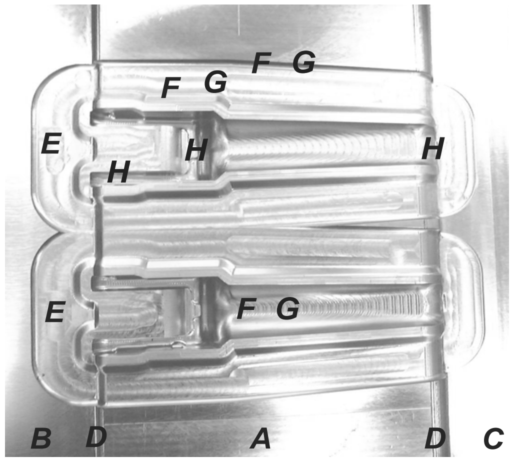

Fig. 4. An example part made with HSC machining, a die for forging hand tools made from aluminium
A - upper level of the die - rough milling, ***B*** - middle level of the die - rough milling, ***C*** - lower level of the die - rough milling, ***D*** - passages between levels - rough milling with the ball-mill Φ 6 mm, ***E*** - room for bit of the forge - rough milling with the flat-mill Φ 8 mm, ***F***- margins and side of the die - semi-roughing with the ball-mill Φ 6 mm, ***G*** - margins and side of the die - finishing with the ball-mill Φ 4 mm, ***H*** - final milling of the engraves with the ball-mills Φ 3mm, 2mm and 1 mm, maximal depth 28 mm.

The first machining operations consist of rough milling of the die at levels marked by A, B and C. For milling passages between different levels ball-nose mills were applied, however the cutting was performed only with the flank side of the mill. For milling the inside part of the die - milling the engraves - end mills with different diameters were used; from 8 mm for rough milling to 6 mm for necessary semi-rough milling; and the final finishing using ball-nose mills diameters from 4 mm to 2 mm for milling all radius or finalizing corners.

5. Tool wear pattern in High-Speed-Cutting

In workshop production the specialists generally use cutters from different suppliers, and follow their recommendations for choosing cutting conditions and the time for changing the tool. However, for reliable assessment of the process characteristics, costs and process optimisation, the workshop testing of the cutting tools in a workshop environment is one of the necessary prerequisites.

The purpose of the study was therefore to test the applicability of different cutting tools in producing tool-making equipment. Among the different criteria for assessment of the quality of the cutters or their effectiveness, the wear appearance at the tool tip is one of the most suitable parameters.

According to the optical observation of wear types at the cutting edges of the end-mill cutters we established that two types of wear occurred in most cases: the flank wear (at the cutting edges of the mill) and central wear (at the centre of the mill). From the Figure 5, in which the SEM photographs of the cutter and both types of the wear are presented, we can establish that these types of wear cannot be easily compared with the so called ordinary wear (flank wear) of the single point turning tool or twist drill (as shown at Figure 2).

At this point we can clearly define our task; we need to define some particular wear at the cutting edges which is correlated to the total wear of the mill and which can serve as a basis for definition of the tool-life or determination of tool change interval. In this case the possibility of using some other criteria, such as surface roughness, noise, vibrations, etc., has demonstrated as the unsuitable in HSC machining.

However, the different types of wear or the magnitude of each particular wear are related to the type of the end-mill and machining process.

The wear observed at the beginning of the cutting process could be defined as deformation at the top point of the cutter. The reason lies in the low cutting speed at the centre of the cutter. This deformation increases with the number of the passes, consequently the surface roughness also increases.

In explaining these phenomena of central wear we should point out that this is not the ordinary flank wear but rather a wear which is somewhat similar. After detailed analysis of the reason causing such a problem we established that this phenomenon is caused due to influence of the feed velocity.

When the velocity (cutter linear motion along the engraves, measured in mm per minute) is too small (e.g. 3 m/min), such circumstances cause phenomena similar to the formation of built-up-edge (see also [23, 27]). Such a wearing process causes the changes in the geometrical shape of the tool-tip, consequently the whole wear of the mill and the surface roughness are increased.

On the other hand it was found that the progress of the flank wear at the cutting edges of mill can be compared to the ordinary type of wear which occurs in the drilling tools. At the beginning of the milling process the wear of the sharp edges is intensive, but after some time (e.g. 30 minutes of milling), the cutting process becomes stabilised and the surface roughness even improves. Further wear at the flank continues as usual, however it is strongly related to the wear magnitude at the centre of the mill or so called central wear.

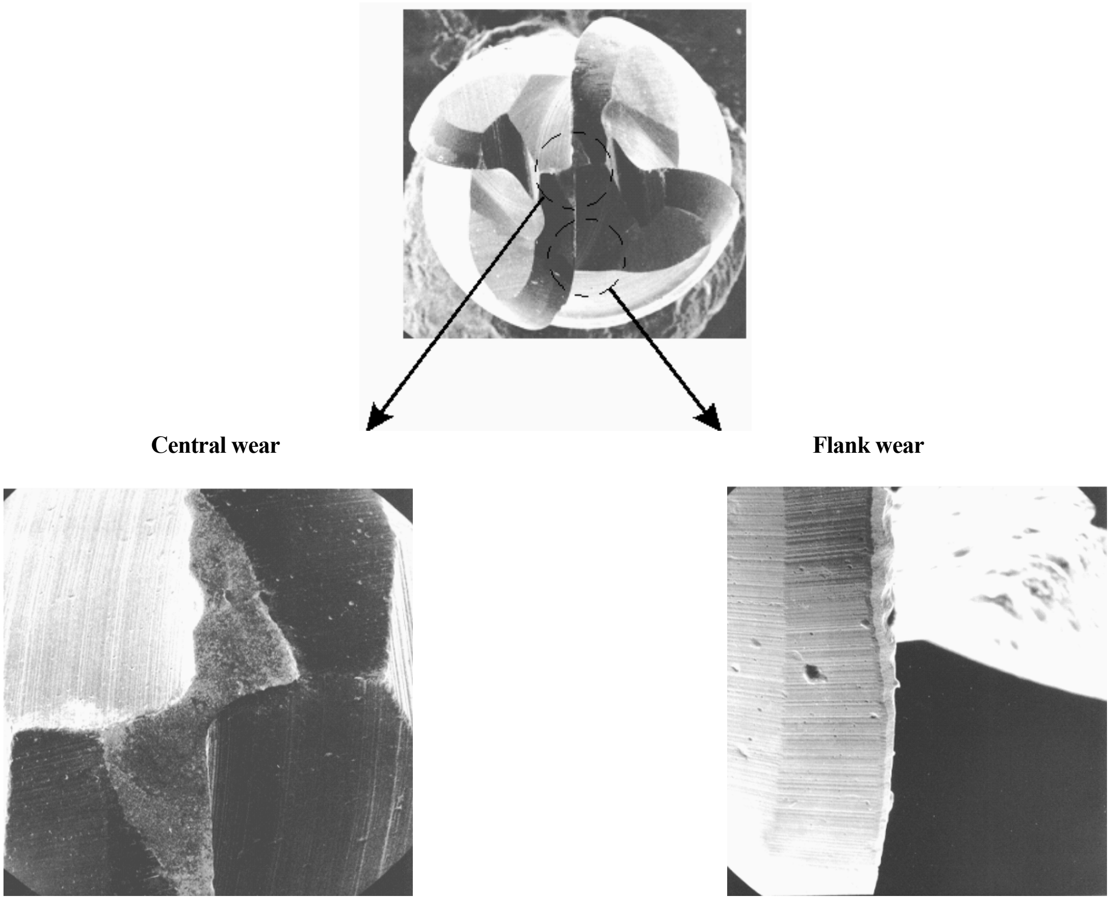

Fig. 5. Different wear types observed at the cutting edges of the end-mill (original magnification 100 times [22])

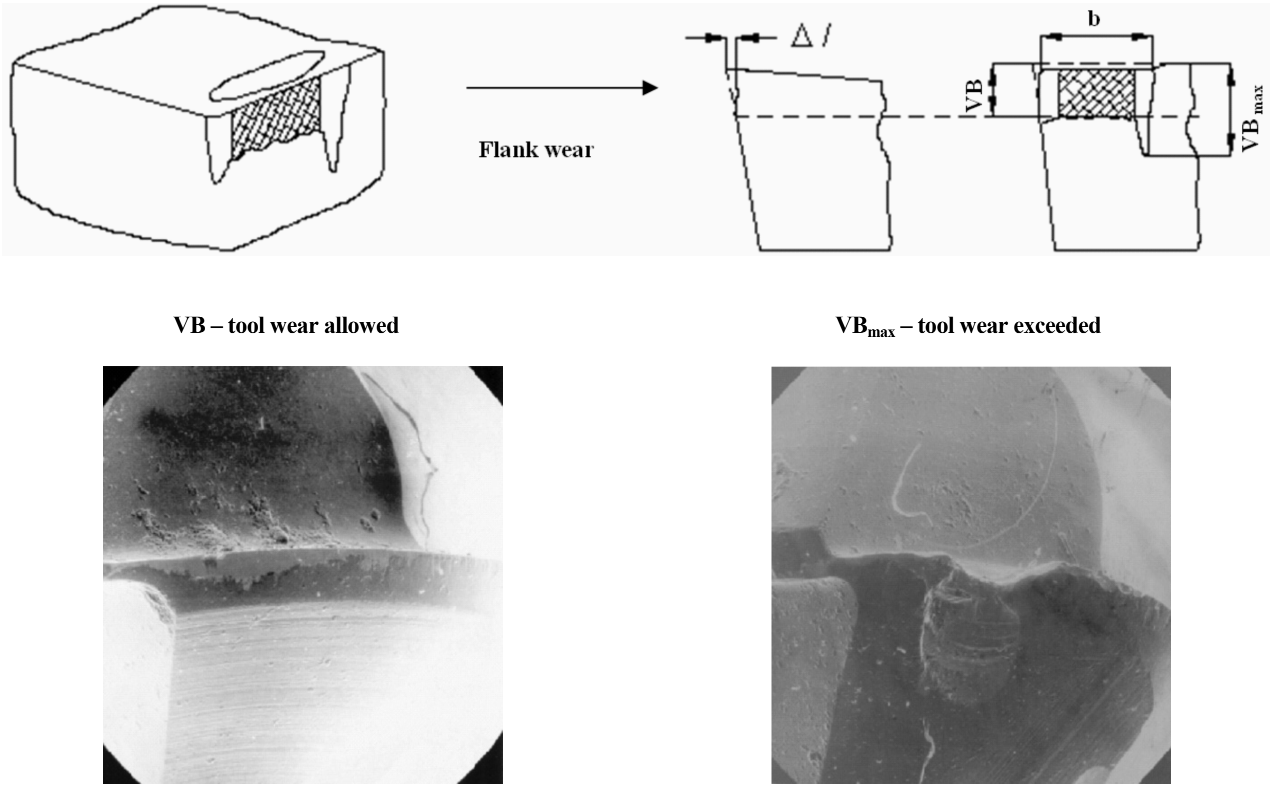

Fig. 6. Definition of the tool life criteria and damages to the tool edge when the wear criterion is exceeded.

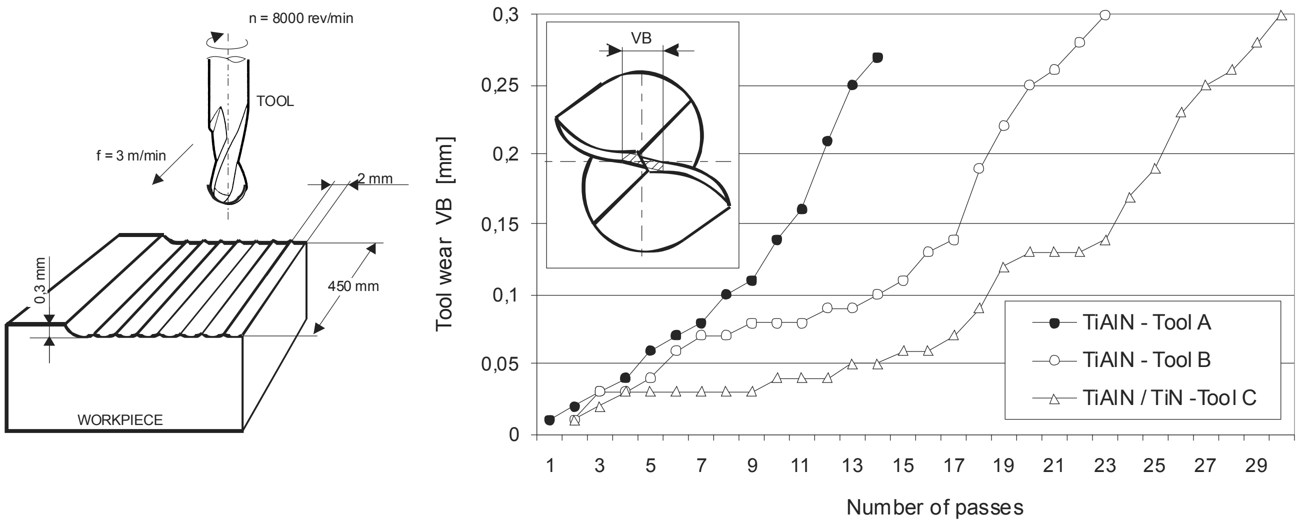

Fig. 7. Tool life diagram in using different end-mill cutters, obtained on the basis of measurements of central wear [28]

The final wear can be observed as chipping of the cutting edges on the top of the cutter (see Figure 6) and the main cutting edges. As a consequence, the protective coating is damaged and the wear resistance is significantly reduced. At this characteristic point we can define the tool life. For comparison of these phenomena to the wear type of the single point turning tool, Figure 6 presents an example for determining the tool-life criteria for hard milling with a low cutting speed (e.g. 3 m/min).

As we define the tool-life criteria in HSC machining on the basis of measuring the central wear of the end-mill cutters the practical applicability of such an approach should be confirmed by using cutters from different producers. Performing the machinability tests at the practical workpiece is rather too expensive; therefore the tests were conducted on plates made from the same material as for dies (tool steel X38CrMoV5.1 hardness 50 HRc).

The characteristics of milling cutters - obtained from three different producers - made from hard-metal and coated with titanium-aluminium nitride, single or multicoated, were compared. The cutters are 6 mm in diameter and differ in their geometrical shape; the maximum speed was 8000 rev/min. By a particular pass we define a path on the plate, which the end-mill performs in 13 minutes (see Figure 7). The wear and surface roughness were measured after the cutter cut-of the whole workpiece surface.

The comparison of the cutters on the basis of the central wear is presented in Figure 7. We can establish, that the cutter with the multi-layer coating proved to be highly wear resistant and also the optimal solution. In practice, however, in some cases the appearance of central wear could be reduced or even eliminated. A typical example is when a five axis milling machine is used. With the inclination of the mill relative to the surface of the workpiece, cutting is performed rather at the cutting edges than at the centre of the mill.

However such machines are rather too expensive, and there are many examples of milling engraves when inclination of end-mill cannot be used. Here, therefore the central wear always appears and such criteria might be applied in these entire end milling problems as a basis for optimisation of the process.

6. Conclusions

Further progress, and the possibilities for practical, economically justifiable implementation of the high-speed-cutting (HSC) processes for milling of hard steels, is closely linked to the latest development of new, highly efficient cutting tools. However, the practical economic applicability of such contemporary tools is closely linked not only to the proper use of such tools but also to knowledge about the wear process at the tool tip and reliable assessment of tool life.

The characteristic wear of such tools is caused by of the fact that the cutting speed is no longer the main influential factor on wear, but more likely wear is the consequence of the high-speed of the tool movements (feed rate). In machining at high cutting speeds the tool actually slides on the workpiece surface, and the wear mechanisms are consequently different.

In high-speed-cutting of hardened steel the increased speed significantly increases the temperature at the contact zone, which even exceeds the limit of the allowed thermal stability of the cutting material. Consequently this leads to drastic reduction of the tool life. With simultaneously increasing feed rate, and speed of the deformation, the forces, heat generation and consequently the temperature at the contact zone are increased (see also [29,30].

All these processes can cause the shifting of the flank wear of the tool into crater wear, due to the higher influence of the diffusion process. Additionally, the larger cross-section of the chip causes higher cutting forces which lead more and more to the subsequent chipping of the cutting tool edges.

On the other hand, when in the HSC process the level of the feed rate is too small, the excess sliding process at the tool-tip causes the phenomena of the central wear in connection with the formation of the built-up edge; both of them are unfavourable phenomena which lower the tool life and have a negative influence on the surface roughness. Therefore the optimal feed rate is strongly related to the cutting speed.

The optimisation of the cutting parameters in HSC is thus not made with respect to the maximum removal rate, but rather to the low level of the cutting forces and better surface quality. All these parameters, which are difficult to predict, are closely connected with the appearance of favourable wear at the tool tip of the end mill cutter; these are phenomena which are discussed in the paper, and on which further research is still going on. The results presented were also confirmed in the production environment, when dies were produced for practical use. And moreover, there are some further investigations going one where our results serve as a basis for the tool improvements [30, 31].

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