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STEAM-PROOF MILLING OF PLANE SURFACES FROM FERRITIC-MARTENSITIC STEEL

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Abstract

Using of ferritic-martensitic steel as a construction material in power industry enables an increasing of power efficiency and a decrease of pollution. The aim of this article is to describe problems of machining ferritic-martensitic steel, depending on experimental study, for special applications – machining of dividing plane of steam turbine casing.

Key words: *milling, ferritic-martensitic steel, turbine, tool geometry*

1. INTRODUCTION

For parts of energy device used in the "creep" area are key useful properties creep resistance and resistance to hightemperature corrosion (oxidation) in the environment of water vapor. In industrialized countries (notably the U.S., Japan, EU countries as well as India and China) is devoted great attention to technological development and adoption of new brands martensitic steels based on (9-12)% Cr, modified by other elements (Mo, W, Co N, B, V). This group also includes steel X12CrMoVNb9-1 [Jandova 2006]. This steel is today best known under the tradename P91 (9% Cr - 1% Mo). It is a modified ferritic-martensitic steels microalloyed by vanadium, niobium and with controlled nitrogen content [Arivazhagan 2009].

This steel is designed for the production of forgings, castings, sheet and pipe, where their application is expected at temperatures of 550-650°C, in particular for the energy and petrochemical industries. Cast form of this steel is intended for casing of steam turbines working in steam to 600°C. Steel was developed primarily for the purpose of increasing the efficiency of thermal power plants, which are still the main source of electrical energy. Mainly for economic reasons and also requirements for reduction of harmful emissions. This can be achieved by increasing the steam parameters, ie temperature and pressure steam to enter the steam turbine from the current 540°C/18Mpa up to supercritical 610°C/30MPa. Is expected that the equipment operating under conditions when the steam temperature of 600°C and a pressure of over 26 MPa increases efficiency by up to 8% and the emission of carbon dioxide will decrease by about 20%. For the production of equipment operating in these conditions are continuously evolving progressive creep-resistant steel and corrosion like this [Saha 2003].

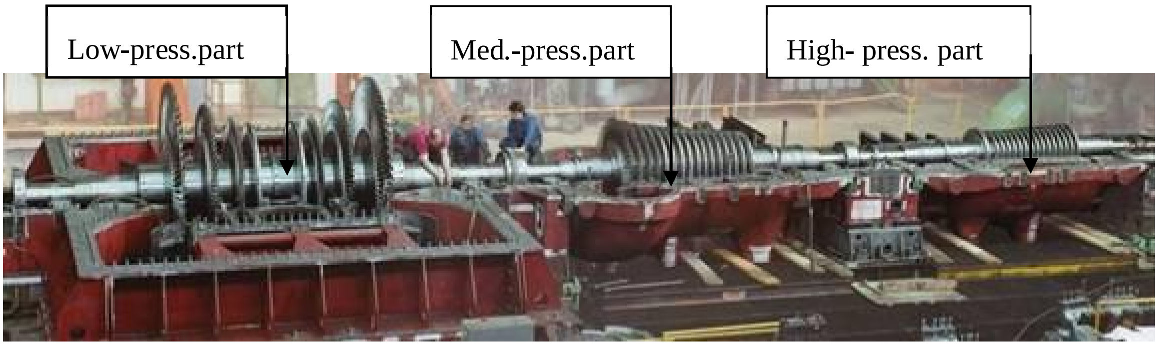

Fig. 1 Parts of the steam turbine

Knowledge of machining steel P91 almost is not available. That is a relatively new material compared to other stainless steels. It was developed as a material of pipe elements (tubes, elbows, flanges) for the energy and chemical industries. Therefore, first appeared under the name T91 (tube). Over the last few years due to its properties began to use as a structural material for steam turbine casing. However, only in a limited number compared to conventional construction materials. Therefore, there is not a lot of information about its machining. If manufacturers are forced to use it, it is very dificult to achieve the desired results, especially in terms of machined surface condition.

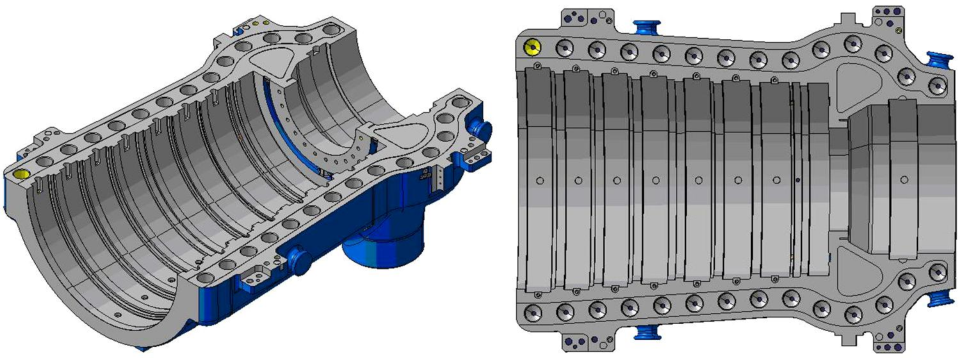

Fig. 2 Model of inner casing steam turbine

The most problematic area is the dividing plane. These turbines operate at high temperatures and pressures. Therefore, the dividing plane must be steamproof. This means that the surface must be machined to a low value of roughness and flatness. Also, tracks of the of the cutting tool are observed. Roughness can be affected by the choice of tool and cutting conditions. Significant influence on the surface roughness has geometry of the cutting tool. For example is better to choose a larger rake angle γ_o, which guarantees greater stability of cut and thus better finished surface. Another angle which affecting the roughness of the machined surface is the angle of setting of the main and minor cutting edge κ_r and κ_r '. It holds that the smaller the angle, the better the achieved value of surface roughness. Nowadays, more and more are beginning to use different finishing inserts with wiper geometry. In this case it is not necessary to deal with this angle. In terms of cutting conditions the best surfaces are achieved at higher cutting speeds, lower feed rates and lower depths of cut. Roughness of the machined surface is usually not a direct reflection of these conditions, but is rather a reflection of tool wear. Therefore cutting conditions are chosen to cause as little tool wear as possible.

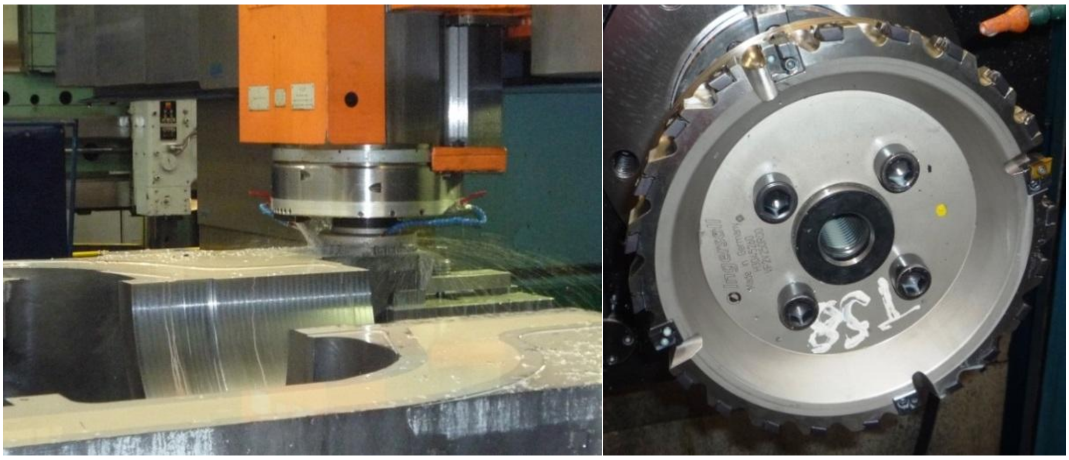

Fig. 3 Milling of dividing plane of steam turbine casing and detail of milling head (ø315 mm)

2. FINISHING MACHINING

Finishing is usually the last stage in the production chain from the perspective of machining technology. In this phase is removed the remaining less than 10% of the material allowance. After finishing operation does not follow any more. This is why it to this stage of production are too many requests. In particular, to the surface finish because the machined surface finish is final. This is particularly true in cases where the machined surface is a surface functional. Basic tasks of this phase are: 1) to remove the remaining allowance; 2) to remove traces of semi-finishing; 3) to achieve the requisite quality surface finish.

Compared to semi-finishing there is not enough, as the decisive criterion for the selection of appropriate technological conditions (tool, cutting tool, cutting conditions), only the tool life of the cutting tool, but also the quality of the machined surface. The task of this project was more productive machining dividing plane of casings of steam turbines, since milling of these planes is one of the most important and most challenging phases.

The task of the experiment was therefore: 1) selection of appropriate inserts, 2) determining the combination of cutting conditions, meeting the requirements for this stage of processing, in particular with regard to the quality of the surface finish and production efficiencies, 3) describe the problem of finishing steel P91.

The experiment was divided into two parts. The first of these was the so-called pre-experiment. His task was to select from a group of 8 selected and recommended inserts (5x coated sintered carbide, 1x uncoated sintered carbide, 2x coated cermet.) 2-3 most appropriate types of inserts that were in the next experiment deeply tested.

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3. EXPERIMENT SET UP

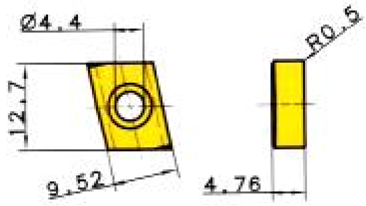
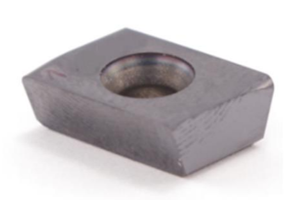
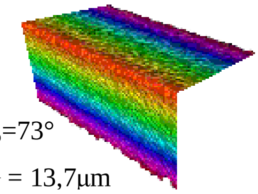
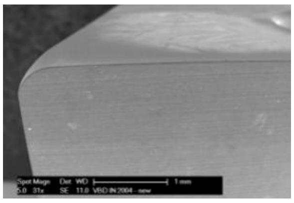
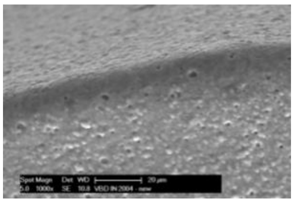
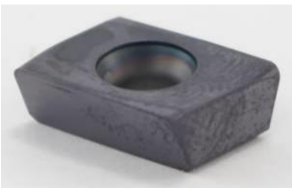
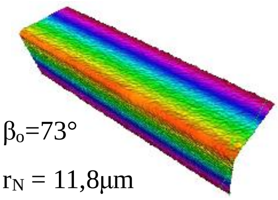
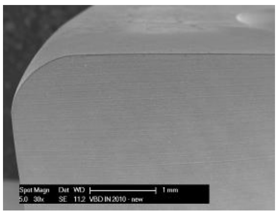
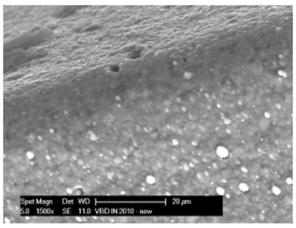
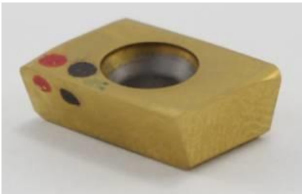
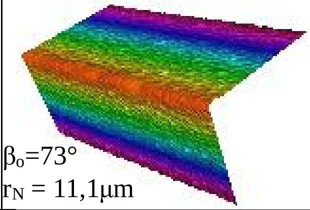
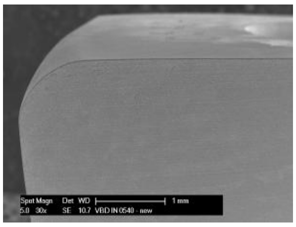
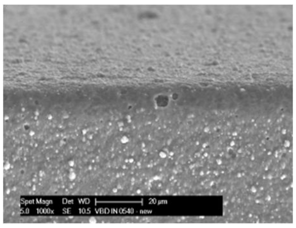


Fig. 4 Shape and size of the cutting insert

All inserts have the same shape, Fig.4. The best cutting materials for further testing were selected sintered carbides: SC-A and SC-B and SC-C. As a cutting tool was used a milling cutter with diameter of 80 mm.

<table>
<tr><th colspan="6">SC-A</th></tr>
<tr><td></td><td>
β_o=73°
r_N = 13,7μm</td><td colspan="4">High performance multigrade carbide with PVD coating with high wear resistance and high toughness. For milling of alloyed steel and cast iron at medium to high speeds. For finishing and light roughing especially in stable conditions.</td></tr>
<tr><td rowspan="6"></td><td rowspan="6"></td><td colspan="4">Composition</td></tr>
<tr><td colspan="2">Substrate</td><td colspan="2">Coating</td></tr>
<tr><td>element</td><td>[%]</td><td>element</td><td>[%]</td></tr>
<tr><td>W</td><td>85,6</td><td>Al</td><td>35,7</td></tr>
<tr><td>Co</td><td>5,8</td><td>Ti</td><td>21,65</td></tr>
<tr><td>C</td><td>8,6</td><td>N</td><td>40,25</td></tr>
<tr><th colspan="6">SC-B</th></tr>
<tr><td></td><td>
β_o=73°
r_N = 11,8μm</td><td colspan="4">Coated carbide with TiAlN coating with good wear resistance when machining cast iron and for medium to high cutting speeds. This grade is particularly suitable when it is used in a positive cutting geometry under unfavorable cutting conditions.</td></tr>
<tr><td rowspan="6"></td><td rowspan="6"></td><td colspan="4">Composition</td></tr>
<tr><td colspan="2">Substrate</td><td colspan="2">Coating</td></tr>
<tr><td>element</td><td>[%]</td><td>element</td><td>[%]</td></tr>
<tr><td>W</td><td>83</td><td>Ti</td><td>38,85</td></tr>
<tr><td>Co</td><td>5,9</td><td>Al</td><td>24,75</td></tr>
<tr><td>C</td><td>11,1</td><td>N</td><td>36,3</td></tr>
</table>

<table>
<tr><th colspan="6">SC-C</th></tr>
<tr><td></td><td>
β_o=73°
r_N = 11,1µm</td><td colspan="4"></td></tr>
<tr><td rowspan="5"></td><td rowspan="5"></td><td colspan="4">Composition</td></tr>
<tr><td colspan="2">Substrate</td><td colspan="2">Coating</td></tr>
<tr><td>element</td><td>[%]</td><td>element</td><td>[%]</td></tr>
<tr><td>W</td><td>77,5</td><td>Ti</td><td>66</td></tr>
<tr><td>Co</td><td>8</td><td>N</td><td>33</td></tr>
<tr><td></td><td></td><td>C</td><td>14,5</td><td></td><td></td></tr>
</table>

SC were tested under the conditions specified in tab.1, valid for the entire experiment. Under constant were chosen following cutting conditions: f_Z = 4.5 mm and a_P = 0.02 mm, because they are used in real machining process. If the experiment is based on the requirement to make a real machining process more productive, it is necessary to start from real cutting conditions which are used. These cutting conditions suit all tested cutting materials. Due to necessary evacuation of chip from the cut, the outside flood cooling system was used. The cutting tool was equipped with only one insert, due to the elimination of the influence of inaccuracies of size inserts or cutting tool to machined surface.

Experimental conditions	
EXPERIMENT	
Cutting mat.	SC-A, SC-B, SC-C
Type of insert	YDA323L101
v_c [m.min^{-1}]	150 - 300
f_z [mm]	3; 4,5; 6
a_p [mm]	0,02
Cooling	external flooding
number of inserts	1
Down-cut milling	

Tab. 1 Experimental cutting conditions

A combination of cutting conditions used for each of the cutting materials are shown in tab.2. These cutting conditions were chosen according to the values recommended by the manufacturer and the results of the pre-experiment. Because of the time and material intensity of experimental work could not be done fully factorial experiment. At first, the cutting materials were tested in dependence to changes in cutting speed v_C. Then the most appropriate cutting speed was determined. Then, under this cutting speed, every cutting material was also observed in dependence to changes in the value of the feed per tooth f_Z. These values were chosen as follows f_Z: 3, 4.5 and 6 mm.

SC-A					SC-B					SC-C			
f_Z [mm] / v_C [m/min]	3	4,5	6		f_Z [mm] / v_C [m/min]	3	4,5	6		f_Z [mm] / v_C [m/min]	3	4,5	6
150		X			150		X			150	X	X	X
226		X			180		X			180		X	
270	X	X	X		200	X	X	X		200		X	
300		X			226		X			226		X	

Tab. 2 Cutting conditions for used cutting materials

In case of tool life the criterion value was determined $VB_B/KB = 0.2$ mm. Another criterion was machined surface roughness of Ra = 0.8 μm and volume of removed material B = 30 cm^3. That is because the requirements for practical application states that the insert has to removed 25 cm^3. The value of B = 30 cm^3 was chosen because it ensures a 20% margin in terms of meeting the requirement. If it has been achieved by some of these values, testing was completed. With one exception was always achieved the desired volume of removed material B. Comparing it can only be done at a constant value of f_Z = 4.5 mm and cutting speed v_C = 150 and 226 m/min.

3.1 Tool life

In case of tool life was the best results achieved with SC-A. SC-A was worn least, similary on flank and face. The worst results was achieved with SC-C. It is probably caused especially by used coating. SC-C is coated by TiN layer,while SC-A by AlTiN layer and SC-B by TiAlN layer. Primarily developed and historically oldest layer TiN reach the hardness to HV = 23 GPa. The TiAlN layers have hardness up to HV = 33GPa. They have also considerable resistance against abrasive wear. Unfortunately, TiN layers does not have so high resistance [Cselle 2006]. AlTiN layer, used on SC-A, has higher content of Al than Ti in comparison with TiAlN layer. By this achieving higher resistnece against oxidation [Jílek 2003]. AlTiN layers have proportion between Al:Ti in interval from 60:40 to 75:25 [Cselle 2006]. But, if is this proportion 60:40, AlTiN layer achieving even higher value of hardness than TiAlN [Hudeček 2009]. Therefore, on the part of tool life, SC-A was the best. Carbide SC-A also includes higher percentage of cobalt in comparison with SC-A and SC-B. Influence of cobalt content on sintered carbides characteristic is visible from next fig.5.

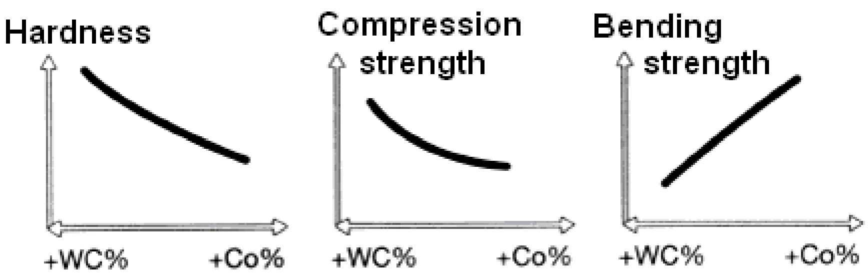


Fig. 5 Influence of Co content on properties of sintered carbide [*Příručka obrábění* 1997]

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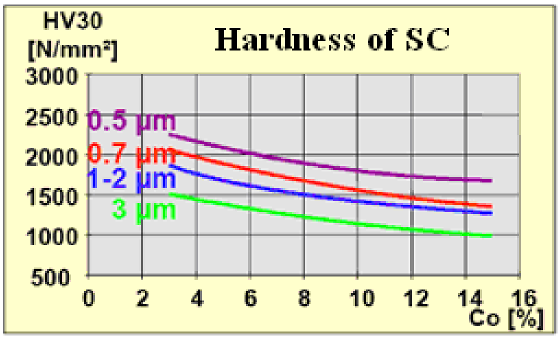


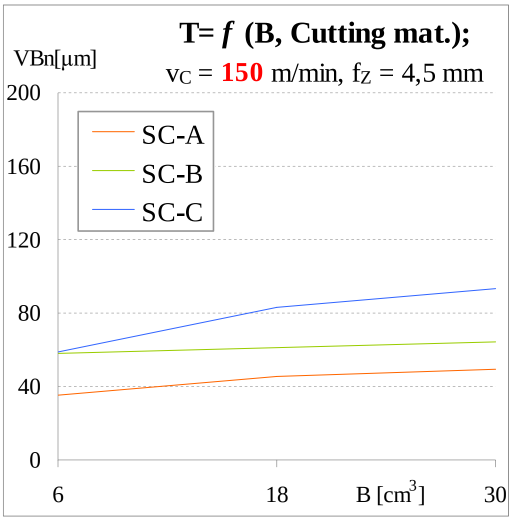
Fig.6 Effect of Co content and grain size on the hardness of sintered carbide [Kříž 2006]

Graphs in the fig.5 and fig.6 represent, that higher percentage of cobalt decreases the wear resistance of sintered carbides because of his smaller hardness and compressive strength. Comparison of positives and negatives caused by increasing of percentage of cobalt in sintered carbides is made in tab.3.

With increasing content of Co in the material	
increases	**decreases**
▪ bending strength ▪ tensile strength ▪ impact strength ▪ fatigue strength (slightly) ▪ coefficient of linear expansion	• specific weight • hardness • relative abrasion resistance • modulus of elasticity • shear modulus • compressive strength

Tab. 3 Effect of increasing Co content on the properties of sintered carbide [Humár 2008]

All inserts were more worn on cutting face. They were also more worn with increasing of cutting speed. In addition has been investigated that under monitored conditions the cutting speed v_C = 226 m/min is unsuitable for machining of this kind of steel. This value of cutting speed coincides to the area of BUE creation. This area is typical for machining of stainless steels. Size and progression of flank wear is displayed in the fig. 7. Analogous comparison, following tool wear on face of cutting edge is in the fig. 8.



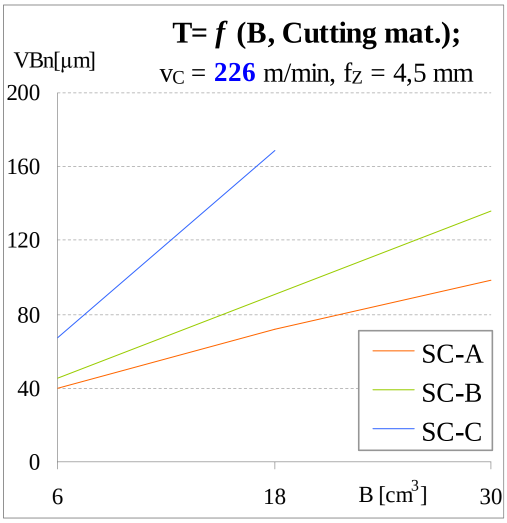
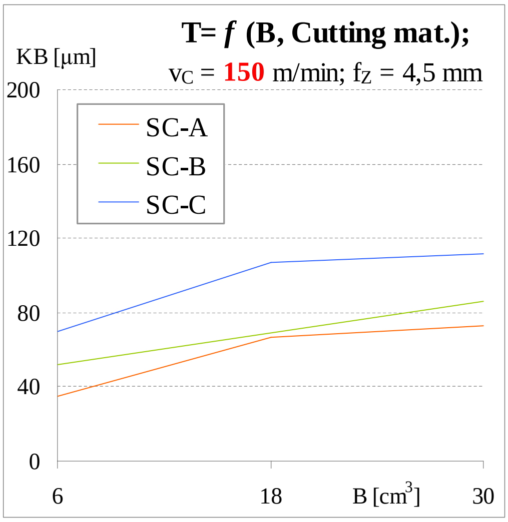


Fig. 7 Dependence of tool wear (VBn) on the volume of removed material B; v_C = 150 m/min (left) and v_C = 226 m/min (right); f_Z = 4,5 mm



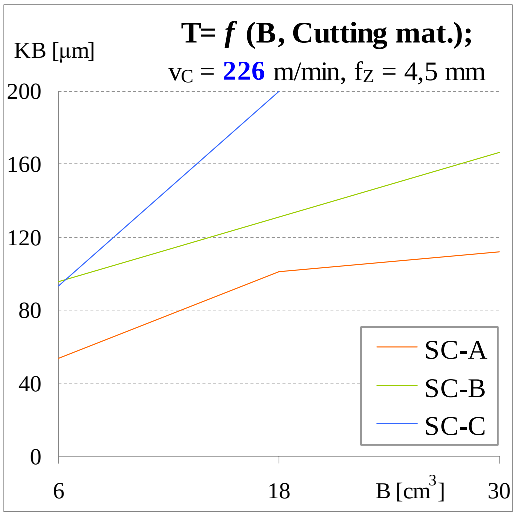


Fig. 8 Dependence of tool wear (KB) on the volume of removed material B; v_C = 150 m/min (left) and v_C = 226 m/min (right); f_Z = 4,5 mm

3.2 Roughness of machined surface

In the case of finishing machining the roughness of machined surface is the second most important criteria for the selection of the most suitable cutting material. The roughness of machined surface is very important for the dividing plane of steam body turbine. The criteria value of roughness of machined surface is Ra = 0.8µm and in the case of finishing machining the roughness of machined surface is directly dependent on the tool wear. Strictly speaking on the flank wear VB_N. Generally it is well known that roughness of machined surface is getting better with increasing cutting speed [Shao, Liu & Qu 2007; Davim 2009], it does not always have to be truth. Positive influence of increasing cutting speed on the roughness of machined surface is obtained especially in cases when there are used inserts of common construction and the main influence on the resultant roughness of machined surface has cutting conditions. In our case there were used inserts with special kind of construction, so-called "inserts with wiper geometry". The main task of these special inserts is to reach the best quality of machined surface under all kinds of cutting conditions [*Technická příručka obrábění* 2005; *Příručka obrábění* 2004]. The difference between the insert with wiper geometry and the insert of common construction can be seen in the Fig.3.

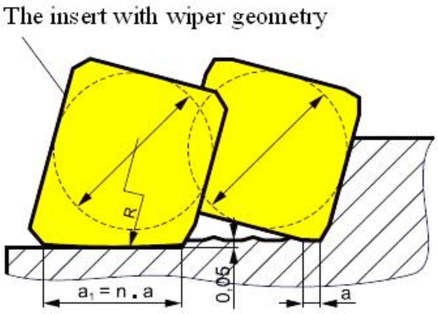


Fig. 9 Comparison of the insert with wiper geometry and the insert of common construction [*Příručka obrábění* 2004]

Roughness of machined surface is possible to evaluate by way of the whole series of parameters. These characteristics, however, have different predicative valuables about condition of machined surface eventually of its functional properties. Nowadays, still most often is used, like parameter for prescribe of roughness, its arithmetical value Ra. It is very well known this value has lower predicate capability. In following table there are compared relevancies some parameters roughness of machined surface. As you can see in tab. 4, the most suitable for classification of machined surface in light of its roughness are parameters Rt and Rz.

Functional properties	Ra, Rq	Rp	Rt, Rz	Rsk	Rku	Rsm	Wa
Contackt/ contact stifness	*		**	*	*	**	*
Fatigue strength	*	*	**		*		
Thermal conductivity	*	**				**	*
Electrical conductivity	*					*	*
Reflexivity			**				
Friction and wear	*		**	**	**	*	*
Lubrication	*	*	**	**	*		**
Mechanical sealing	*		**	**			**
Fatigue corrosion	*	*		*		*	
Assembly tolerances	*		**				**

Tab. 4 Physical/functional significance of several surface texture parameters, source (note: the two asterisks indicate a pronounced influence) [David & Paulo 2009]

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Best results were achieved identically in case of SC-A and SC-B. Surface roughness (parameter Ra) was not achieved value 0,3 µm. In addition, the surface roughness did not change depending on increasing the volume of removal material B. Type SC-C seems to be as a least convenient for cutting steel P91 from group of tested materials. In case of SC-C happened to extensive exasperation of surface roughness depending on increasing the volume of removal material B. That is unsuitable fr practical application.

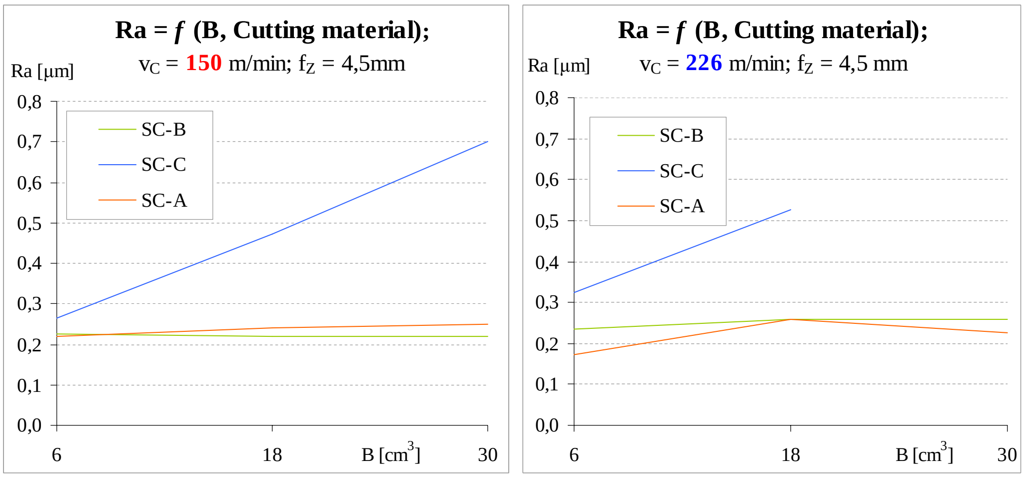

Fig. 10 Dependence of surface roughness (Ra) on the volume of removed material B; v_C = 150 m/min (left) and v_C = 226 m/min (right); f_Z = 4,5 mm

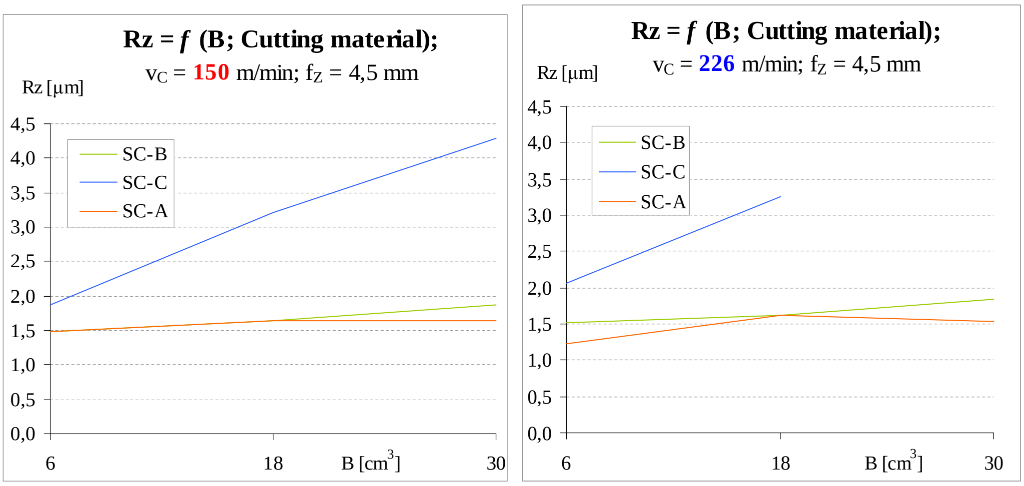

Fig. 11 Dependence of surface roughness (Rz) on the volume of removed material B; v_C = 150 m/min (left) and v_C = 226 m/min (right); f_Z = 4,5 mm

3.3 Total force load and effective cutting power

The tool life, the reliability and the productivity are influenced with magnitude of cutting forces. That can be also included total evaluation of service, for example the tool life of spindle. The lower load of cutting tool, the lower load of spindle and the lower machining input for the machine. The lower input power means the lower energy intensity of production. All of it can be seen in the total costs for service. It appears from this that it is important to use the cutting tools and the cutting conditions, which have as small as load of spindle. These cutting tools also have lower cutting forces [Řehoř 2003]. The evaluation of the force load of the cutting tool is done by watching the total force load of the cutting tool F. This value F is resultant of the values which were measured during the experimental machining.

$$F = \sqrt{F_X^2 + F_Y^2 + F_Z^2} \quad [N]$$

Where: F total force load [N]

$F_{X, Y, Z}$ components of the cutting force which were measured in axes x, y, z [N]

In term of cutting stability the increasing tool wear has negative influence on the force load of cutting process [Řehoř 2003]. That is why the cutting forces increase depending on increasing the volume of removal material. The volume of removal material is directly depending on the tool life, or the tool wear.

The lowest differences among tested types of indexable inserts are in force load point of view. But cutting force load was evaluated in initial phase of cutting process only (to the value of B = 6cm^3). That is why is not possible to conclude an absolute enclosure. The highest value of cutting force was achieved by SC-A and the lowest value of cutting force was achieved by SC-C in case of cutting speed v_C=150m/min. That is possible to explain that way, that by using v_C = 150m/min indexible inserts were worn slowly and differences among them were appeared after some time of cutting. Probably, influence of microgeometry predominated from beginning. Cutting edge radius was approximately r_N = 11 μm for SC-C and r_N = 14 μm for SC-A. Sharper cutting edge work more easily and cutting load of cutting process is also smaller. In case of SC-C by v_C = 226m/min the cutting load was influenced by higher wear of cutting edge.

By monitoring of effective cutting power is also possible to make an idea about total cutting load. The higher the cutting force, the higher the effective cutting power on spindle of machine tool.

Nowadays it is important to look at the ecological aspects of manufacturing. Energy intensity is possible to influence with correct choice of the technological conditions of the manufacturing process. Needed power for realization of the cutting process is directly proportional to absorbed energy [Koubek, Smolík & Vrhel 2010].

Effective cutting power is for machining with SC-A and SC-B almost identical. Depending on increasing the volume of removal material B, the effective cutting power increased at the most about 2% (from rated power of spindle). During initial phase of cutting process was with SC-C reached similar values of effective cutting power. However, during machining the effective cutting power increased about more than 25%. Dependences of effective cutting power on spindle for tested cutting materials are compared in fig.14.

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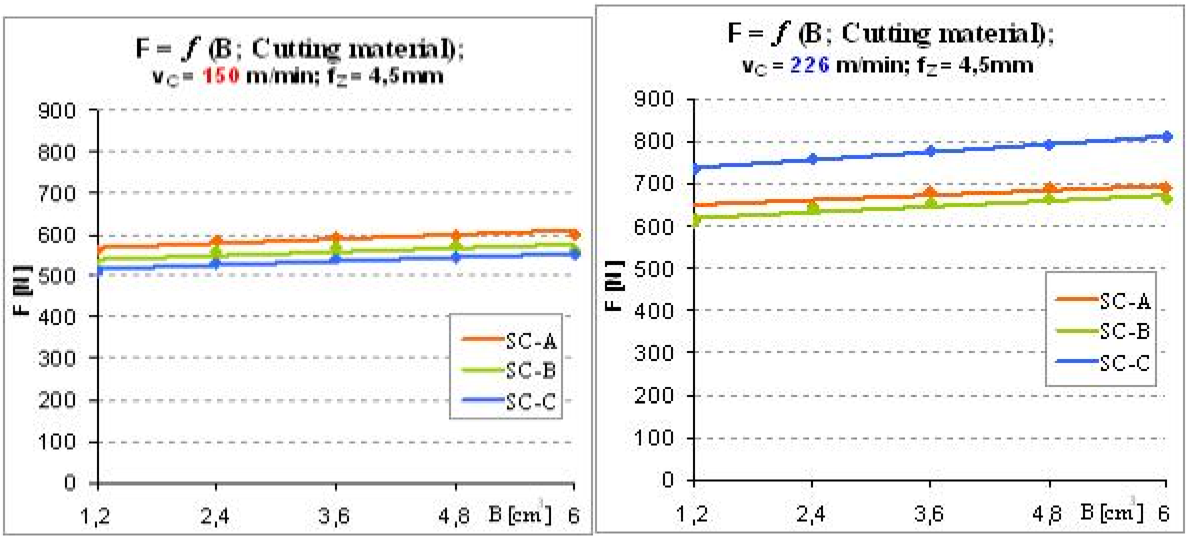

Fig. 12 Dependence of force load (F) on the volume of removed material B; v_C = 150 m/min (left) and v_C = 226 m/min (right); f_Z = 4,5 mm

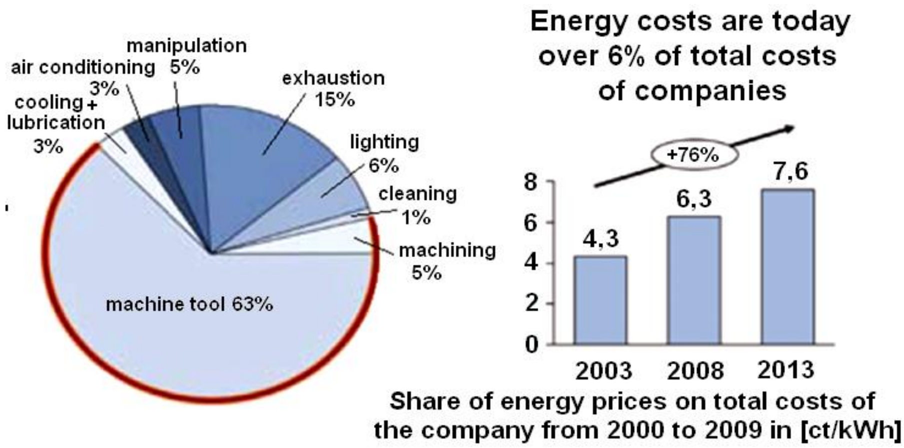

Fig. 13 Absorbed energy vs. manufacturing costs [Koubek, Smolík &Vrhel 2010]

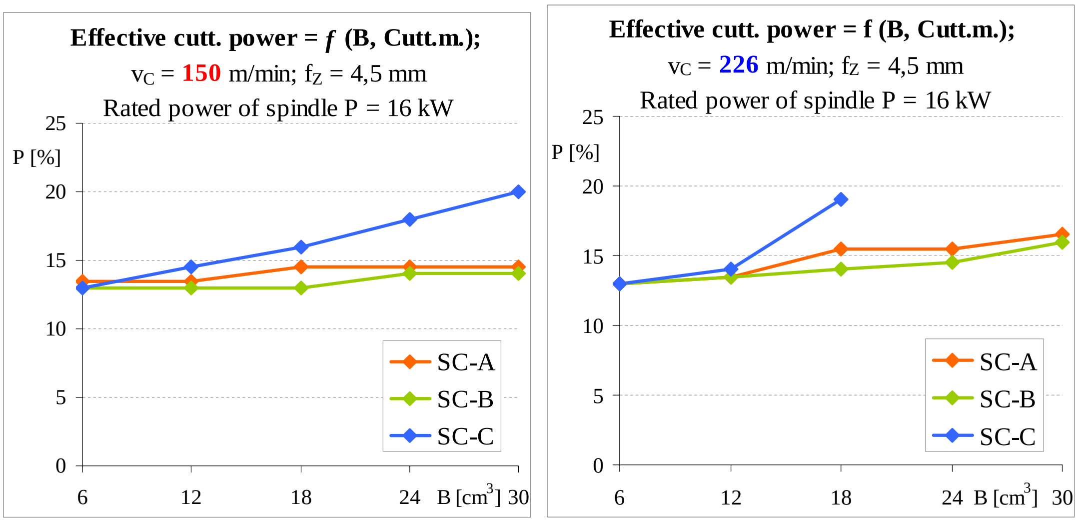

Fig. 14 Dependence of effective cutting power (Pef) on the volume of removed material B; v_C = 150 m/min (left) and v_C = 226 m/min (right); f_Z = 4,5 mm

4. CONCLUSION

It was found that when v_C = 226 m/min we come to the field of built-up edges. This is true for all tested cutting materials. This area is for machining of stainless steels typical. If there is a built-up edge effect, the cutting process becomes unstable and can not be guaranteed to meet the requirements imposed on it. For other cutting conditions requirements are met, ie. always achieve the desired amount of removed material B and prescribed machined surface roughness Ra is not exceeded. This does not mean that all cutting materials are suitable for this type of test operations. An important requirement for the machined surface is its steamproof. This is primarily dependent on the flatness of the surface finish. But more than technology affects the structure the state of machine tool. Influence to the steamproof has also a state of machined surface, especially its roughness. It is not suitable when on the one machined surface, occurs in dependence on the volume of removed material to a significant change in state of the machined surface.

SC-C as compared with SC-B and SC-A does not succeed. SC-C is for finishing of steel P91 least suitable. It was to quickly worn depending on the volume of removed material. Thereby also significantly worsened progressions of monitored characteristics of the cutting process. Favored SC-A and SC-B are suitable for machining of dividing plane of steam turbine casing. Regardless of productivity, as the best solution proved to apply rather at lower speeds. Lower cutting speed means higher durability, because at lower cutting speeds the insert was less loaded and more slowly worn. Size of tool wear affects the roughness of the machined surface. The smaller the tool wear, the better the machined surface roughness. In terms of evaluation of machined surface roughness low values was achieved, and this values do not change significantly. This is due to the very design of the insert. It is a special design of insert with the so-called "Wiper" geometry. The task of such inserts is to achieve the best possible surface for all cutting conditions. The most effective value of f_Z = 4.5 mm. When f_Z = 3 mm increases the machining time, and the cutting edge is loaded with a long time. Edges are more worn out, and this will be reflected on the state of the machined surface. When f_Z = 6 mm is used, higher force load of cutting tool is achieved and it increases the power demands of the process. Value f_Z = 4.5 mm is therefore a compromise.

A very important criterion for the selection of cutting conditions is productivity. In this case, it is best to use a type of SC-A. The main reason is that the cutting material can work through their properties at higher cutting conditions, without causing degradation of quality aspects. Ability to work under these conditions is a guarantee of productivity. Insert is coated with AlTiN, which shows better performance compared with TiAlN layer on SC-B type. But the SC-B is still competitive and meets the requirements imposed on the operation.

5. DISCUSION OF RESULTS

As mentioned in the introductory part of this work, knowledge of machining steel P91 almost are not available. Therefore it is not possible to make absolute confrontation of the results with the results of other authors or other workplaces. Therefore, the results will be compared with the general findings and conclusions obtained at relatively similar applications.

When machining plays an important role the productivity and in case of the final operation, as well as state of the machined surface. The most important factor that affects the cutting process and its results is the tool life. The tool life is affected by many factors. These factors include machined materials, cutting materials, cutting tools, cutting conditions, and more. Some of these factors can not be influenced. For example, the type of workpiece material is clearly defined from the outset. Cutting conditions are also based on the nature of the operation. The choice of cutting material is dependent on the workpiece material and the manufacturer's recommendations or experiences. There may be situations where you need the suitability of the cutting material to test experimentally.

For machining steel P91, under the tested conditions are suitable coated sintered carbide inserts. With regard to the character of operations, only the large diameter milling head fitted with inserts considered. Sintered carbide substrate should contain a low percentage of cobalt. Cutting material achieves better results when coated with a suitable coating. As the most appropriate system was proved AlTiN. Effect of applied layers on tool life can be compared in the fig.15.

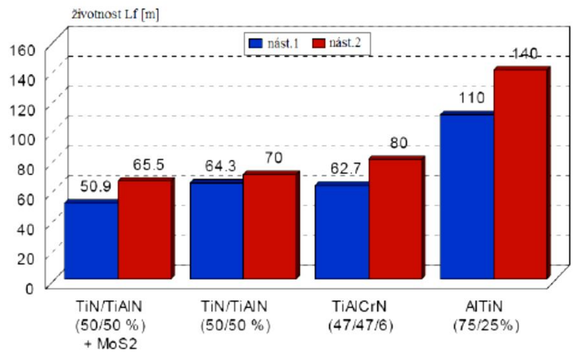

Fig. 15 Influence of coating on tool life when machining chrome-molybdenum steel [Hudeček 2009]

Another factor influencing the tool life is micro-geometry. For machining stainless steels are most suitable sharp cutting tools. It has been confirmed that to achieve the longest possible tool life the radius of curvature of the edge should be in the range r_N = 10 to 20 μm. Higher values indicate more cutting load on edge because of the larger contact between tool and workpiece material. Smaller values mean higher load due to weakening of the cutting edge.

Tool life is also affected by the cutting conditions. Mainly cutting speed and feed rate. When machining ferritic-martensitic steels for most types of materials are available areas of low and high cutting speeds. Between these areas is problematic transition area of built-up edge. Its exact location and width of the interval of cutting speed depends on many variables. In this case, the area is located around the test v_C = 226 m/min. Fig.16 shows the influence of cutting speed on the final roughness of the machined surface, just taking into account the area of built-up edges.

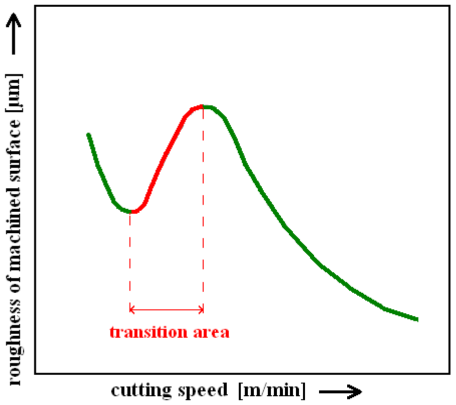

Fig. 16 Influence of the cutting speed on the roughness of machined surface [Arias 1993]

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