EFFECT OF CUTTING SPEED AND TOOL GRADE ON MACHINABILITY OF PM STEELS DETERMINED BY FACE TURNING METHOD


Abstract

The machinability of PM steels is tested by different methods under different cutting conditions for singular cutting processes. Within this work the effect of the cutting speed and the cutting tool grade on machinability of PM steels was tested by the face turning method. Face turning tests at constant revolutions of the lathe of 900 and of 1400 rpm with coated PM HSS and hardmetal inserts on ring-shaped test pieces (∅40/18 x 14 mm) from 5 PM alloys were carried out. The number of passes as a machinability criterion conducted up to a specified cutting edge wear of the tools used for the tested alloys was determined. Microstructure of the materials in front of the cutting tool edge, morphology of the chips and the wear of the cutting tools were analysed. The different effect of the cutting speed and of the cutting tool grade on machinability of investigated alloys were observed.

Keywords: sintered steels, machinability, face turning, cutting speed, cutting tool

INTRODUCTION

Machinability is not a specific property of a material, but a mode of behavior of the material during cutting, and assessments of machinability should therefore specify the general conditions of cutting for which they have validity [1]. Machinability is in reality a manifestation of the interaction of workpiece and tool under the effect of power. The cutting conditions are well understood in wrought steel component machining, but when they are applied to the machining of PM products certain problems can arise [2].

In powder metallurgy (PM) parts production there is a great number of shapes, which are difficult or impossible to produce by pressing or to achieve specific dimensional tolerances and a high surface finish without machining [3]. At present about 40-50% of PM parts need “secondary” operation - machining [1]. Machining in powder metallurgy should be regarded also for a special processing method. This can enlarge the application area of PM parts to more sophisticated ones produced from high strength/high toughness and high wear resistance materials.

Machinability of PM materials is regarded as poor compared to that of wrought steels. The porosity and specific microstructure of each alloy are regarded for main factors deteriorating the machinability of PM steels, but their effect is not sufficiently defined as presented in a broad range in [1].
The machinability of PM parts by each machining operation is usually tested under different cutting conditions with different kinds of tools including geometry [4]. In spite of the fact that drilling and turning are the most widely used cutting methods also in machining of PM parts there are no quasi standardized test methods. The tests in turning are carried out mainly as straight turning, which does not represent all kinds of the turning operations used also in PM machining. This does not enable one to compare and to generalize the results attained by the researchers.

The object of this work is testing the effect of the cutting speed and the tool grade on machinability of PM steels of various compositions and properties by short time face turning test method.

EXPERIMENTAL PROCEDURE

Face turning test method

The face turning test method is applied for testing the lifetime of the cutting tools during turning of wrought steel [1,5-7]. In this test, turning of cylindrical, rolled standard cylindrical steel bars occurs from the surface of the center hole in a direction to the outer diameter of the test piece at constant workpiece (lathe) revolutions, feed and depth of cut. The test is finished at the cutting speed at which the tool failed totally or up to the determined critical cutting tool edge wears (VB\(_c\)). During this test, the cutting speed increases continuously towards the outer diameter of the workpiece.

This test method can be applied also in PM machining for workpieces with a smaller diameter [8], which will correspond with many ring-shaped parts such as, e.g. bushings, which are a common product in PM. Figure 1 shows a ring-shaped component (roller), commonly produced, which was used as test workpiece in this work. In such a case, after finishing the first there pass follows a new pass from the centre hole and repeated passes occur up to the total or to the critical flank wear (VB\(_c\)) as shown in Fig.2.

![Diagram](image1)

**Fig.1.** Dimensions in mm of sintered workpiece for face turning test.

![Diagram](image2)

**Fig.2.** Schematic of the short time face turning test on workpiece with smaller diameter.

This test method can represent more accurately modern production, which often involves a short series including mixed cutting cycles and operations. This is in reality the case of this face turning test method on workpieces of smaller diameter at which the cut is
interrupted after arriving at the outer diameter, and the tool is then shifted to the inner diameter with a repeated tool entry. For very short cycles below the critical time, as can be the case at this method, the tool wear can exceed the corresponding wear in continuous machining. This can be the most common case in PM machining, e.g. in turning or milling.

EXPERIMENTAL MATERIAL

For the preparations of the test pieces used within this work (see Fig.1), the following powder mixes/alloys without any machining aid based on Höganäs powders were used:

I Fe-0.5% C (ASC100.29 atomized iron powder),
II Fe-0.5% C (SC100.26 sponge iron powder),
III Fe-1.75% Ni-1.5% Cu-0.5% Mo-0.5% C (Distaloy SA powder),
IV Fe-4% Ni-1.5% Cu-0.5% Mo-0.3% C (Distaloy SE powder),
V Fe-4% Ni-1.5% Cu-0.5% Mo-0.5% C (Distaloy SE powder).

To the base powders, carbon (C) as natural graphite CR12 (GRAFIT a. s., Netolice) and 0.8% HW (Hoechst wax) as lubricant was added.

The test pieces were compacted in a pressing die used for a commonly produced part - roller, and sintered at 1180°C for 40 min in 70N₂/30H₂ atmosphere under industrial conditions in METALSINT a. s., Dolný Kubín.

Face turning conditions

The dry face turning test was done under the following conditions:

Constant revolutions of the lathe = of the workpiece:
1. 900 rpm; in this case the starting cutting speed \( v_c (\text{min}) \) at the diameter \( d_o (\text{min}) \) (18 mm) was of 51 m/min, and the highest one at the \( D_o (\text{max}) \) (40 mm) of 113 m/min.
2. 1400 rpm; in this case the starting cutting speed \( v_c (\text{min}) \) at the diameter \( d_o (\text{min}) \) (18 mm) was of 79 m/min, and the highest one at the \( D_o (\text{max}) \) (40 mm) of 176 m/min.

The feed - 0.1 mm/rev. and the depth of the cut - 0.2 mm was equal under both levels of revolutions of the lathe.

Two types for the cutting tools - inserts were used:
1. HIPed - PM HSS S590 (Böhler), coating TiAlN, (68 HRC, 1179 HV 0.5, 2312 HV 0.05), coded here HSS,
2. Triangular hardmetal P20 (nose radius 0.8 mm), coded here HM.

The criterion (machining criterion) was the number of passes conducted with:
1. PM HSS tools up to the cutting edge wear \( V_B = 1.3 \) or 1.4 mm,
2. HM P20 tool up to the cutting edge wear \( V_B = 0.3 \) mm (criterion for finishing operation in turning of wrought steels). The cutting edge wear was systematically measured during the cutting process as will be shown in diagrams.

The density, apparent hardness, microhardness, number of passes in dependence on the cutting edge wear, microstructure, machined surfaces, morphology of chips, and kind of wear of the inserts were determined and analyzed. There are no data about the use of the uncoated or coated HSS inserts in the turning of PM steels [1]. Some results of this work were presented in [9].

RESULTS AND DISCUSSION

Basic characteristics of the alloys used for the work pieces in testing by face turning method are listed in Tab.1.
Tab.1. Density, apparent hardness HV 10 measured as-sintered and on the cross-section of tested alloys and microhardness HV 0.025.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>I Fe-0.5C</th>
<th>II Fe-0.5C</th>
<th>III Dist. SA-0.5C</th>
<th>IV Dist. SE-0.3C</th>
<th>V Dist. SE-0.5C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g/cm³]</td>
<td>6.93</td>
<td>6.92</td>
<td>6.90</td>
<td>6.91</td>
<td>6.97</td>
</tr>
<tr>
<td>HV 10 cross-section</td>
<td>90</td>
<td>83</td>
<td>152</td>
<td>197</td>
<td>202</td>
</tr>
<tr>
<td>HV 10 surface</td>
<td>88</td>
<td>88</td>
<td>153</td>
<td>198</td>
<td>239</td>
</tr>
<tr>
<td>Microhardness</td>
<td>98-313</td>
<td>136-347</td>
<td>144-510</td>
<td>200-590</td>
<td>200-899</td>
</tr>
</tbody>
</table>

According to apparent hardness and microhardness values the microstructures of these alloys are formed by ferrite up to martensite.

**Machinability of PM steels by face turning test**

*Machinability with HSS inserts*

Figure 3 shows the relationship between the numbers of passes conducted at face turning test of tested workpieces at 900 rpm of the lathe up to the cutting edge wear VBₖ of 1.3 mm, and Fig. 4 at 1400 rpm up to the cutting edge wear VBₖ of 1.4 mm. The results show the sensitivity of the applied face turning test method, and of the cutting speed and of the tool type to very different properties of the workpieces due to their various composition, and by this heterogeneous microstructure character as documented in hardness and microhardness values (see Tab.1).

Basically, as expected, the highest machinability exhibited the Fe-0.5C alloys (50 passes at VBₖ of 0.5 mm) and significantly lower was the alloyed steels. No effect of base iron powder in the machinability of alloys I and II was observed. It is necessary to note a large difference in the machinability of Dist.SA-0.5C (50 passes at VBₖ of 1.2 mm) and of Dist.SE-0.5C (5 passes at VBₖ of 1.3 mm) which differ only in nickel content. Similar relationships were determined in drilling [1,10]. The sensitivity of HSS inserts to the carbon content in Distaloy SE was also confirmed (30 passes with 0.3% C and 5 passes with 0.5% C).

![Fig.3](image1.png)

Fig.3. Cutting edge wear of HSS inserts vs. number of passes in face turning test of alloys I-V. Cutting conditions: 900 rpm of the lathe (workpiece) (cutting speed 51-113 m/min), feed 0.1 mm/rev., depth of cut - 0.2 mm.

![Fig.4](image2.png)

Fig.4. Cutting edge wear of HSS inserts vs. number of passes in face turning test of alloys I-V. Cutting conditions: 1400 rpm of the lathe (workpiece) (cutting speed 79-176 m/min), feed 0.1 mm/rev., depth of cut - 0.2 mm.
Contrarily Figure 3 at higher cutting speed according to Fig.4, a significant difference in machinability of alloys Fe-0.5C (I, II), which differ only in base iron powder grade was demonstrated. Significantly higher machinability had the workpieces based upon sponge iron powder compared to that based on atomized iron powder. According to the course of the curve for cutting edge wear and number of conducted passes, it is possible to expect very good machinability of this material. The differences in machinability caused by the production method of the iron powder were given, e.g. also in [1,8]. This proved that the machinability of the sintered parts is still affected by starting iron powder properties, which are used also for the preparation of mixed and diffusion alloyed steels. The reasons for such behaviour in the machining of the iron powders are not sufficiently characterized. If follows from it also that the results attained must be evaluated regarding the machining method, cutting speed and cutting tool type used.

On the other hand, at a higher cutting speed minimum differences in machinability of alloys III-V were demonstrated with the consequence of significantly poorer machinability. This can be the consequence of the friction between the cutting tool and formed chip at the higher temperature formed at a higher cutting speed.

Machining at lower cutting speed with HSS insert demonstrated itself in higher sensitivity to the differences in properties of Distaloy type alloys. It shows that machinability of these alloys determined by face turning test at a lower cutting speed is higher than that at a higher cutting speed.

It was surprising that the HSS inserts used would be possible to use for longer machining time also after cutting edge wear of 1.3 or 1.4 mm. No changes in the course of the cutting process and in the surface finish were observed up to the given cutting edge wear of 1.3 and 1.4 mm.

**Machinability with HM inserts**

The machining of investigated workpieces was carried out up to the cutting edge wear of HM inserts VBc of 0.3 mm. Figure 5 shows the relationships between the cutting edge wear and number of conducted passes at 900 rpm of the lathe, and Fig.6 at 1400 rpm.

Regarding the cutting speed lower, machinability was attained by all alloys at a higher cutting speed compared to that at a lower cutting speed as was shown also in Figs.3, 4. The difference in machinability of Fe-0.5C alloys based on both iron powder grades, and also in turning with a HM tool was demonstrated. Higher machinability had the material based on sponge iron powder than the atomised one. Significantly lower differences in machinability of Distaloy type alloys compared to that conducted with HSS insert were attained regarding, in this case, cutting edge wear of 0.3 mm. The machinability of Distaloy type alloys especially of Distaloy SE according to these results can be evaluated as very poor, because at 1400 rpm only 1 pass was possible to conduct up to the cutting edge wear of 0.3 mm.

The results shown in Figs.3-6 clearly demonstrate that for the machining of PM steels, in this case tested by face turning method, it is necessary to adapt the cutting speed, more advantageous a lower speed regarding lower thermal conductivity of porous material (higher temperature in the cutting zone which deteriorates the friction between the cutting tool and the formed chip) and the cutting tool grade. It is necessary to note that there are practically no published experiences with the use of HSS inserts in the turning of PM steels. The results presented also show some extent for the use of HSS tools for the turning of sintered materials compared to HM tools.
In this connection it is necessary to note that for the straight turning of sintered iron based on sponge iron powder \((\rho = 7.0 \text{ g/cm}^3)\) for an economical tool life of 15 min at a feed of 0.1 mm/rev. and depth of cut of 1 mm with HM P40 tool in [1,11], the cutting speed of 360 m/min was recommended. Similarly, for Distaloy SA-0.6C alloy under equal cutting conditions the cutting speed of 270 m/min was recommended. In our case the highest average cutting speed was \(~130\) m/min. In [1,12] for straight turning of sintered iron \((\rho = 7.1 \text{ g/cm}^3)\) for an economical tool life of 15 min with uncoated HM at a feed of 0.1 mm/rev. and depth of cut 0.5 mm the cutting speed of 120 m/min, and for turning the Distaloy AE-0.5C alloy the cutting speed of 80 m/min was recommended. These cutting speeds are within the range of those used in this work. It shows that during the time period between the data listed in [11] and in [12], demonstrated clearly was the tendency towards to turning of PM steels with lower cutting speeds. On the basis of the presented results it is possible to recommend even lower cutting speeds for turning the PM alloys with both main cutting tool grades (HSS, HM). The tool life attained in this work is hard to compare with those listed in [11,12] because the criterion is different (defined flank wear \(\rightarrow\) tool life 15 min).

**MICROSTRUCTURE**

Characteristic micrographs of tested alloys conducted through the unfinished cut after the outlet of the tool from the cut, which show the area in front of the cutting edge, are presented in Fig.7. All tested alloys had known basic characteristic microstructures according to the composition and processing procedure. In term of machining it is necessary to know the real microstructure character in the area in front of the cutting edge. According to the “interrupted cutting theory”, the schematic of which is shown e. g. in [1,13], the tool cuts the material passing one pore after another. This action of successive small impacts on the cutting edge should cause more rapid tool failure than a continuous cutting operation.

As shown in the following figures the area of material in front of the cutting edge is compressed and by this without pores. This area is much clearer as shown in Fig.7d. It means that the cut occurs in fully dense material as explained by “deformation cutting theory” [1]. The microstructure in the area after densification is also work hardened and does not correspond to the microstructure before machining. These microstructure changes of a sintered material should be regarded in machining.
Fig. 7. Optical micrographs of the cross sections through the unfinished cuts of alloys Fe-0.5C, Fe-1.75Ni-1.5Cu-0.5Mo-0.5C, Fe-4Ni-1.5Cu-0.5Mo-0.5C. a, b, c – nital etched, d – unetched.

Proof of the mentioned significant deformation of the material in front of the cutting edge is the formed chip shown in Fig.8a. Figure 8b shows the micrograph with deformed layer on the surface of the machined surface, whose knots on the surface are on the same level in Fig.8a (foregoing cut).

Fig. 8a. Section through quick-stop (braked) chip in Distaloy SA-0.5C alloy. Nital etched.
Fig. 8b. Micrograph through the machined surface in Distaloy SA-0.5C alloy. Nital etched.
**Morphology of chips**

Basically the chips formed in the machining of porous materials are short, discontinuous, and of different shape (spiral, torn) in dependence on the final microstructure and porosity of the material and the cutting conditions. Figure 9 shows the morphology of the chips formed in face turning test of selected alloys.

The morphology of the chips reflects the deformation and work hardening processes under friction between the singular microstructure constituents, and the tool, which are in progress during cutting process. It means that in the chips are “compressed”, the effects of all factors which take part in machining. The example is shown in Figs.9a, b. The morphology of the chips formed in this case in face turning test of Fe-0.5C alloys based on atomised iron powder (a) clearly differs from that formed in machining of the alloy based on sponge iron powder (b).

Figure 9c shows the morphology of the chips formed in the machining of Distaloy SA-0.5C alloy (significant deformation on the inner side of the chip). Figure 9d shows a view upon the side face of a chip. This is the side of the chip which was detached not cut off from the remaining workpiece material. The features of the chips can be a contribution to the investigation of the machinability of various alloys, and in this case, of Fe-C material (effect of iron powder grade) as well.

![Morphology of chips](image)

Fig.9 Morphology of the chips formed in face turning at 900 rpm with HSS tool. SEM.
The shown various morphology of the chips confirmed once more the sensitivity of the test method under cutting conditions used for the base characteristics of the workpiece material under cutting conditions used.

Cutting edge wear

Figure 10a shows the cutting edge wear (flank wear) of a HM tool formed in face turning test of all alloys, which corresponds to the abrasive wear mechanism. Figure 10b shows the singular brittle failure of the cutting edge of a HM tool which was caused, in this case, in the machining of Distaloy SE-0.5C alloy.

Figures 10c,d show the cutting wear of 2 coated HSS inserts. The attrition wear is characteristic for these. In both cases the coating was in the contact zone totally destroyed, and in spite of this the tools worked without notable problems as mentioned before. This feature was observed on all HSS tools used in these tests. It means that the carrier of the cutting ability was the HSS matrix under the undefined support of the surface coating. The cutting edge is marked by 3 arrows in Fig.10c. The flaking of the coating layer on the random failed edge shown in this figure can be the consequence of an insufficient adhesion of the coating to the matrix.

Fig.10. Cutting edge wear of HM P20 inserts (a, b) and of TiAlN coated PM HSS inserts (c, d). SEM.
The distribution, size and shape of carbides in HSS tools with TiAlN coating is shown in Fig.11a. The SEM analysis of the cross-section of the tool carried through the nose marked by a line shown in Fig.10c showed the fracture of the matrix on the nose of the tool, Fig.11b. The fracture of the cutting edge at relatively low magnification is shown in Fig.11c and the detail of the breakage, not visible due to low magnification in Fig.11c, is shown in Fig.11d. Following these results, the use especially of coated PM HSS tools in PM turning should be analysed in more detail as the damages of the cutting edges were not expected.

CONCLUSIONS

- The face turning method using common ring-shaped test specimens was presented as a new method for testing the machinability of PM steels. The sensitivity of this test method under cutting conditions investigated as to the different material characteristics and to the cutting speed and cutting tool grade was documented.
- Regarding the cutting speed ranges investigated (56 - 113 m/min at 900 rpm and 79 - 176 m/min at 1400 rpm of the lathe), higher machinability of alloys was attained in a lower cutting speed range.
- Coated PM HSS tools in the investigated range were successfully tested in face turning of PM steels up to the flank wear of 1.4 mm.
- Coated PM HSS tools exhibited higher sensitivity to the differences in properties of Distaloy type alloys compared to the iron carbon steels and hardmetal tools reversely.
• The testing with both cutting tool grades in a lower cutting speed range was more sensitive to the differences in properties of Distaloy type alloys than in properties of iron carbon steels, and vice versa in a higher cutting speed range.
• The Fe-0.5C alloy prepared on the basis of sponge iron powder exhibited under all machining conditions higher machinability compared to that prepared on the basis of atomised iron powder.
• Typical abrasive flank wear on the hardmetal tool nose was observed. On the other hand, the nose of the PM HSS inserts was face worn gradually up to the criterion $VB_c$ of 1.4 mm. Fractures on the worn cutting edges of coated PM HSS inserts at high magnification were detected.
• Significantly higher machinability exhibited the Fe-C alloys compared to the Distaloy type alloys. The Distaloy SE-0.5C alloy exhibited under all tested conditions poor, up to negligible, machinability.
• Some proofs of the “deformation cutting theory” were demonstrated. The range of deformation of the machined material in front of the cutting edge was shown in the morphology of the chips.
• The applied face turning method can be used for testing the effect of various cutting conditions including cutting tools and geometry on one selected material, or for testing the machinability of various materials under equal cutting conditions.

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