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ORIGINAL ARTICLE

A novel machinability test for determining the cutting behaviour of iron-based, carbon-containing and copper-containing powder metallurgy steels (PMS)

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Abstract Parts made by powder metallurgy generally do not require subsequent machining operations. However, further machining of these sintered parts cannot be avoided in case of special, complex geometries. The goal of the research discussed in this paper is to create an easy-to-use, time-efficient and cost-efficient method to describe the secondary machining properties of iron-based, copper-containing and carbon-containing powder metallurgy steels (PMSs) in terms of the energy indicators. In order to compare the machinability of PMSs with different compositions, a new test method was developed. Considering the high importance of the turning process in the manufacturing of PMS parts, a short axial grooving test was developed. Cutting force measurements were carried out where the characteristics of the measured signal referred to the machinability of the tested materials. This newly developed test can be carried out quickly, and it can successfully be applied to characterize the energetics of PMS machining. Based on the test results, appropriate alloying element percentages could be determined.

Keywords Metal matrix composites · Machinability evaluation · Cutting force measurement · Signal processing

Abbreviations

PMS	Powder metallurgy steel
MMC	Metal matrix composite
F_c *[N]*	The average value of the main cutting force components
F_f *[N]*	The average value of the thrust (feed) cutting force components
F_p *[N]*	The average value of the passive cutting force components
$F_{c\ steepness}$	The independent variable of the fitted linear regression curve for the main cutting force component
$F_{f\ steepness}$	The independent variable of the fitted linear regression curve for the thrust (feed) cutting force component
$F_{c\ max}$ *[N]*	The maximum value of the main cutting force component
$F_{f\ max}$ *[N]*	The maximum value of the thrust (feed) cutting force component
$F_{c\ fluctuation\ max}$ *[N]*	The maximum value in the fluctuation of the main cutting force components
$F_{f\ fluctuation\ max}$ *[N]*	The maximum value in the fluctuation of the thrust (feed) cutting force components
K_c *[N/mm²]*	Specific cutting force for the longitudinal turning tests
E [Ws/mm³]	Unit power factor for the longitudinal turning tests

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1 Introduction

Powder metallurgy is a popular replication technology due to its productivity and variety of applicable material compositions. This process is mainly used in part manufacturing, e.g. for automotive industry. The main advantage of this process is that it can produce the parts directly to final size and shape by simple compacting operations. However, powder metallurgy is not a suitable technology to create complex geometries with special features such as threads, cross holes and slots. In order to create these features by compacting, additional machining operations, so-called secondary or subsequent machining (e.g. drilling, turning and tapping) need to be realized [1]. Porous materials show a particular behaviour during the cutting process as discussed in [2]. However, we can find little technical information about the methods to define and describe these characteristics.

Therefore, during our research, we focused on the energetic properties of the secondary machining of iron-based powder metallurgy steels. The energetic investigations of the cutting process include the effects of the geometry and the material properties of the machined parts. We also would like to determine the relationship between the energetic behaviour of the cutting process and the machinability of these sintered materials by changing the material compositions.

In fact, the international literature abounds in researches and experimental results about the machining of different steels and metal matrix composite (MMC) materials, as discussed in [3–6]. However, lots of these studies are restricted to the measurement of cutting force, surface roughness and tool wear [7–10] or tool life [11], and these tests require time-consuming experiments. But, there is a need for a simple, quick, easy-to-perform and easy-to-evaluate test which can provide usable results, even just to compare the investigated materials to a base material.

Currently, an increasing number of researchers' aim is to assess the machinability of different materials by using different cutting methods and cutting conditions. The problem is the fact that machinability is not a universally defined parameter but rather a concept. It is more like a property, e.g. how easy or difficult the machining of the examined part is or how problematic the forming of the part is by using a defined cutting tool [12]. According to another point of view [13], machinability describes the condition of chip removal by comparing it to the cutting conditions of an arbitrarily chosen reference material. Due to the limited amount of machinability researches focusing on turning of PMS, in this research, we referred to the machinability testing methods of conventional metallurgy steels as the points of reference.

In contrast to the metals produced by conventional alloying methods, the properties of powder metallurgy parts depend on the composition of the powder mixture, the compacting pressure and the applied sintering conditions, e.g. temperature. Investigations regarding the machinability properties of the powder metallurgy technique focus on the impact of composition and on the effect of the compacting and sintering parameters [14]. The secondary machinability properties of these materials, like chip formation or cutting forces, have only a marginal role in the powder metallurgy industry.

However, due to the increasing application range of these materials, more and more researchers investigated the machinability of MMCs. Capus [15] described the machinability of PMSs made from austenitic stainless steel powders using simple drilling and turning tests. The aim of the investigation was to examine the effect of different material compositions on tool wear. The results showed that by adding manganese sulphide (MnS) to the original material composition, a lower amount of tool wear occurred during machining. This is important because this way, the abrasive effect of the materials can be changed.

Further turning and drilling tests were carried out for aluminium-based composites by Kumar et al. [16] and Palanikumar et al. [17], respectively. Both papers include the conclusion that the levels of machining parameters can be optimized to avoid or (at least) greatly reduce the possibility of build-up edge, extend tool life and improve surface roughness without any loss of productivity. This way, besides the composition of the materials, the adjusted cutting parameters also have great influence on the result of the machining process.

Karabulut [18] investigated the effect of milling parameters on surface roughness and cutting forces using uncoated carbide inserts during the machining of AA7039/Al_2O_3 metal matrix composites. He found that the most effective control factor for the surface quality was the type of the material while feed rate and cutting speed were the most effective control factors for the cutting forces according to the ANOVA analysis.

As an alternative solution, researchers preferred the green machining of PMS materials to the machining of sintered parts [19, 20]. Machining a powder metallurgy part in its green state is a commonly used technology to produce the desired shape. This may be a reasonable choice: The stock material in its green state has moderate mechanical properties—therefore, machining is considered to be easier from the aspect of the significantly decreased cutting forces and tool wear. In the green state, the quality of the bonding between the powder grains depends on the compacting pressure and the shapes of the grains which provide the mechanical adhesion [14]. The compacted parts prove to be enduring enough to be transported, but they are also vulnerable: Their solid state is very similar to chalk, and they tend to crumble. This can cause several problems during machining—first of all, at clamping. Another disadvantage is the fact that the shrinkage (caused by the sintering after green machining) may alter the created geometry significantly.

Major industrial companies, like Höganas Inc., also provided suggestions about the machinability of sintered PMS materials. These companies carry out machining tests using a larger variety of compositions and cutting tools and publish machining information focused on tool wear, cutting forces, surface roughness and corrosion behaviour of the machined materials. These companies often develop and publish their own researches in the field of machinability [21–23].

2 Testing machinability

It is known that higher loads during the cutting process result in higher tool wear. This way, the energetic parameters of the cutting process can give a clear picture about the wear of the cutting edge and through this about the machinability of the investigated material [24–26].

We assume that this statement is true for the Fe–Cu–C-containing PMSs. Based on this, integrated, compact metrics representing the machinability are able to characterize the circumstances of the machining process (e.g. performance) and the wear of the cutting tool.

The effect of the material composition changes has effect on both the compacting and the mechanical properties of the sintered materials [27]. This way, it is possible to find such compositions where the compacting properties only minimally change, but the secondary machining properties of the materials are significantly improved.

However, the examination of the compacting properties' changes is not the purpose of this article; our goal is to describe the secondary machining properties better in the case of industrially used composites where the material composition has been widely modified.

For the purpose of practical application, it is expedient to create metrics that take different parameters of the investigated materials into account (such as material properties, cutting properties) at the same time.

Based on the literature studied in this paper, machinability tests are usually expensive and time-consuming due to the high number of experimental machining and the amount of data to be processed. Therefore, a more effective machinability test is necessary to be developed. First, it is crucial to decide what kind of parameters should be chosen to monitor and describe the cutting process and thus the machinability [28]. Researchers—such as Schwarzer et al. [29] and Šalak et al. [30]—apply simple cutting operations like scratching and face turning to define the machinability of the investigated materials. Their results provided a point of reference to our design of experiment. However, our aims were different concerning the evaluation method and output parameters (as described in Sect. 3).

In this study, we introduce a newly developed, time-efficient and economical testing method and an overall, informative representation about the secondary machinability of the investigated PMSs. The new 'grooving test' can provide specific information about machinability with respect to energy indicators like cutting force components and mechanical properties of the tested material. Our test is based on a face-turning operation, and it has been adjusted to be performable on lathes using conventional tools and inserts. During the establishment of the testing method, the following considerations were taken into account:

- The test should be performed in a short time.
- A minimum number of measuring instruments should be used for the data collection.
- Determination of machinability in an empirical (qualitative) way is possible.
- Machinability can be determined by using mechanical properties of the tested materials.
- For determining machinability, it is possible to create machining indexes.
- The rating of machinability can be done by relative technological parameters. In this case, the machinability of a tested material is based on the comparison to the machining properties of a chosen reference (or base) material: normalized C45 (1.1191). The difference between the cutting behaviour of PMSs and cast steels could also be determined by applying this method.

The assessment of machinability can be realized by indices those are based on the technical criteria regarding the applied machining environment.

3 Experimental procedure

3.1 Investigated materials

According to the considerations and criteria described in the previous chapters, the following aims were taken into account during the planning of the experiment:

– Development of a machining test that can give representative information about the machinability of the sintered PMSs according to energy-based indicators like cutting force components during machining.
– Improvement of the machinability of sintered PMS by changing the material composition without losing the advantageous mechanical properties.

As we focused on the energetic aspects of machinability, we measured the cutting force components; characteristics of tool life and surface roughness were left out of consideration.

The effect of the tool wear was kept under control by defining a tool wear limit. In our case, the tool wear limit was the maximum flank wear of 0.2 mm. The condition of the cutting edge was checked after every machining process by using a digital microscope. Due to the moderate time requirement of our test, there was no considerable tool wear to be observed.

Because of the geometry of the machined surface, there was no sense to make surface roughness measurements. This kind of investigation did not give additional information about the energetic behaviour of the machining process.

Due to the harmful effects of cooling-lubricant fluids, only dry machining was carried out. This is a commonly used technology to machine porous materials besides using a minimum quantity of lubrication [31]. Dry machining greatly avoids the corroding effect of the cooling fluid on the part, but the absence of lubrication causes the tool life to decrease and the cutting forces to increase significantly [32].

Iron-copper-carbon steels are the most commonly used material system in powdered metal components [33]. So, for the investigations, the NC100.24 mixture group produced by Höganäs Inc. was chosen. This type of mixture is one of the most widely used grades in the manufacturing of sintered parts [14]. Due to the irregular surface and the spongy structure of the powder particles, the basic NC100.24 has relatively high green strength, and due to its low contents of oxygen and carbon, it has good compressibility. The mechanical and technical properties of NC100.24 can be seen in Table 1, according to [14].

In order to improve the secondary machining properties of these materials, mainly additional alloying elements, e.g. MnS or MnX, are added to the basic powder mixture [22, 23]. However, our aim was to investigate whether we can reach the same effect by modifying the original material compositions of the Fe–Cu–C system without adding any other material to the basic powder mixture. This way, the original material composition of NC100.24 was changed by adding extra amounts of copper and carbon (in the form of graphite) to the basic powder mixture. Table 2 summarizes the modified compositions.

Alloying element modifications until 0.5 % C and 4 % Cu are daily applied in the industry. However, in the case of sintered parts, where high tensile strength and hardness are necessary, alloying element modifications can exceed this range. This way, modified material compositions containing more than 0.5 % C and 4 % Cu were also investigated. For the industry, quick and tangible results are needed. Due to the great extent of modifications, if we would like to create new material compositions, we can get estimations about the expected machinability behaviour of the new material compositions.

Table 1 Properties of the investigated powder mixture

Powder grade	Apparent density, g/cm^3	Flow s/50 g	Approx. particle size range, μm	C %	Green density, g/cm^3	Green strength, N/mm^2
NC100.24	2.45	31	20–180	<0.01	7.02	54

Table 2 The modified powder compositions

Material composition NC100.24	Additional carbon *v/v* %	Additional copper *v/v* %
Original	–	–
+0.5 % C + 2 % Cu	0.5	2
+0.5 % C + 4 % Cu	0.5	4
+0.5 % C + 8 % Cu	0.5	8
+0.2 % C + 2 % Cu	0.2	2
+0.8 % C + 2 % Cu	0.8	2
+1.0 % C + 2 % Cu	1.0	2
+1.5 % C + 2 % Cu	1.5	2

3.2 Experimental background of testing

Using the original NC100.24 and the specified new compositions, solid cylinders were compacted with a diameter of 39 mm. The density of the test parts after the compacting process was 6.6 g/cm^3, the sintering temperature was 1120 °C, and the duration of sintering was 30 min in all cases.

The cutting experiments were carried out on a Hembrug Slantbed Mikroturn 50 high precision CNC lathe developed especially for hard machining. A Kistler 9752A piezoelectric dynamometer with a Kistler 5019 charge amplifier was applied to measure the force components. Data acquisition was realized by a National Instruments 6024E DAQ Card data acquisition system. The sampling frequency was set to 1 kHz for every grooving test.

Two types of machinability investigations were carried out. First, we realized our new grooving test, and after that, in order to verify the reliability of the results, conventional longitudinal turning tests were executed as reference measurements. The used cutting parameters for the grooving test can be found in Table 3.

The simplicity of the test justifies that we used only one set of parameters for the grooving process. The cutting speed values for iron-based sintered metals are normally in the range of 120–220 m/min, and the feed rate value is between 0.05 and 0.3 mm/rev [1]. Due to the available geometry (diameter) of the test specimens and the limited maximum revolution of the used lathe machine, the cutting speed was set to 150 m/min. Based on [1], as our aim was to make a test that can be used generally for a wide range of iron-based sintered metals, the feed rate was set to 0.1 mm/rev. The limit for the depth of

Table 3 Cutting parameters for the grooving test

Experimental method	Cutting speed, m/min	Feed rate, mm/rev	Depth of cut, mm
Grooving	150	0.1	0.5

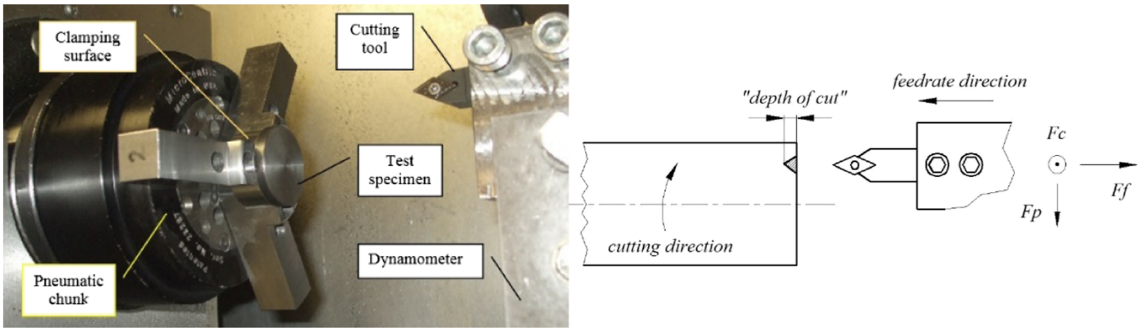


Fig. 1 The measurement arrangement in the case of the grooving test

cut value was the geometry of the used insert. Higher depth of cut values increases the risk of tool breakage.

The investigations were repeated with these cutting parameters by using different grooving diameters (25, 30 and 34 mm). In the article, the measured values and the evaluation represents the results of the tests performed near the grooving diameter of 34 mm. In the case of other grooving diameters, the evaluation results did not show significant differences. During the reference longitudinal turning measurements, we applied three different cutting speed, feed rate and depth of cut levels.

The measurement arrangements for the grooving tests can be seen in Fig. 1.

For the reference longitudinal turning measurements, the same measuring environment was used as shown in Fig. 2.

Before executing these tests, it was necessary to machine a proper clamping surface on the test specimens due to the different levels of shrinkage of the test parts after the sintering process. Furthermore, before the grooving operations, we made proper flat surfaces on the front face of the test specimens in order to avoid the effect of the radial run out of the machined surface.

The significant parameters of the used cutting tools are collected in Table 4.

We used a 'V'-form insert for the grooving investigations instead of using typical grooving inserts. Because of the geometry of the insert used, the cross section of the removed chips, thereby the cutting force components were continuously changed during the machining process. This way, a dedicated force value belongs to each moment of the material removing process. The novelty of the proposed machinability test is that it is based on non-steady-state conditions during the material removing process. Furthermore, due to the irrelevant scale of cutting speed variance along the cutting edge, the difference of speed does not have to be taken into account.

The machined surfaces after the grooving and longitudinal turning tests can be seen in Fig. 3.

The additions of different alloying elements to the original powder mixture have effect on both the production of the PM parts and machinability. For this reason, in order to get some information about the mechanical properties of the modified materials, we measured the HV30 hardness values of the test specimens with a KB Prüftechnik DKD-K hardness testing machine. Based on the statistical reliability of longitudinal turning tests, we took the results of our previous studies concerning these materials [34, 35] into consideration and used them for validating the results of the new grooving test.

4 Results and discussion

In order to illustrate the methodology of the grooving test better, a flowchart was made, that can be seen at Fig. 4. The detailed interpretations of each step are included in this section.

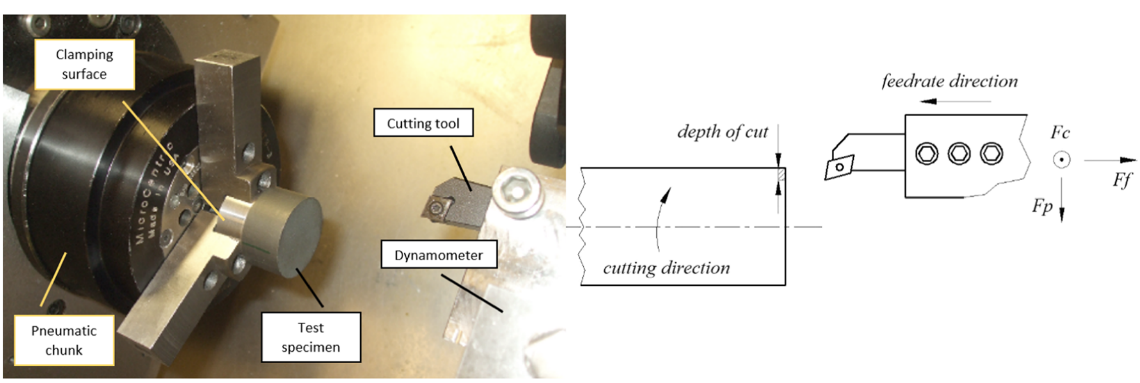


Fig. 2 The measurement arrangement in the case of longitudinal turning test

Table 4 The parameters of the used cutting tools

Experimental method	Tool holder	Insert	Cone angle ε (°)	Nose radius r_ε (mm)
Grooving test	Sandvik Coromant SDJCR1616H11	Sandvik Coromant DCMT11T304-PM	55	0.4
Turning test	Sandvik Coromant SCLCR1616H09	Sandvik Coromant CCMT09T304-PM	80	0.4

Referring to Fig. 4, the first step of the investigations was the setup of the experiments: setting the lathe machine, the machining program and the force measuring system.

The second step was the implementation of the machining tests and the data acquisition. During the grooving investigations, as mentioned above, we registered three cutting force components: the main cutting force component (F_c), the thrust force component (F_f) and the passive force component (F_p) by a LabView algorithm. Figure 5 shows one of the registered signals received from the grooving test.

In Fig. 5, the horizontal axis shows the time elapsed from the starting of the data acquisition algorithm and the vertical axis shows the recorded cutting force components.

As the data acquisition was started before machining, three different sections can be seen at Fig. 5. Section 1 is the no-load section with the noise of the measurement. Section 2 is the machining phase. Section 3 is the return phase of the cutting tool into its starting position. In the no-load zone, only the ±4 N measurement noise could be considered. When the cutting tool started to remove the material, the force components were increased until the cutting tool reached the desired depth of cut value. After that, the cutting tool was returned back into its starting position in rapid traverse movement. At this section, there was no material removing, but—because of the inertia and acceleration of the machine tool—some decreasing, false force values were measured.

In the case of the other materials, we obtained almost identical force signal tendencies without any exceptions. The only differences between the signals were the magnitude of the cutting forces and the slope of the ramps. The passive force components did not change in any case during the tests because of the symmetric geometry of the insert used. Therefore, this component was not considered during evaluation.

As the transient periods at the start and finish of the signals give fuzzy information about the material removing, only the non-transient period of the signals were taken into consideration for further evaluation. To filter the measured data, a Maple algorithm was developed. As section 1 in Fig. 5. shows, without any cutting, the force measurement system had the measurement noise value between ±4 N. The algorithm compared the measured force signals from its beginning with a 5 N of force limit. The first useful moment of our measurement (starting of section 2) was when the registered force signals exceeded this limit.

According to the used cutting parameters, the exact time of the machining—how long does it take to reach the desired depth of cut with the cutting tool—could also be calculated by the Maple algorithm. Based on the starting point of the signals and on the calculated machining time, the considered piece of the signals was cut from the measured data and saved into a new file. Apart from the effect of the applied insert's nose radius, the force signals showed linearly increasing tendency. This way, linear regression curves could be fitted onto the corresponding force components, as can be seen in Fig. 6.

In Fig. 6, the time axis shows the effective machining time of the process. The zero value on the time axis represents the first useful part of the force signals, and the last value symbolizes the last considered piece of the force signals. The scale of the time axis was not changed. Figure 6 shows all of the useful force values taken into consideration for further calculations. As—based on our previous statements—the cutting process was not carried out in a steady state and the force

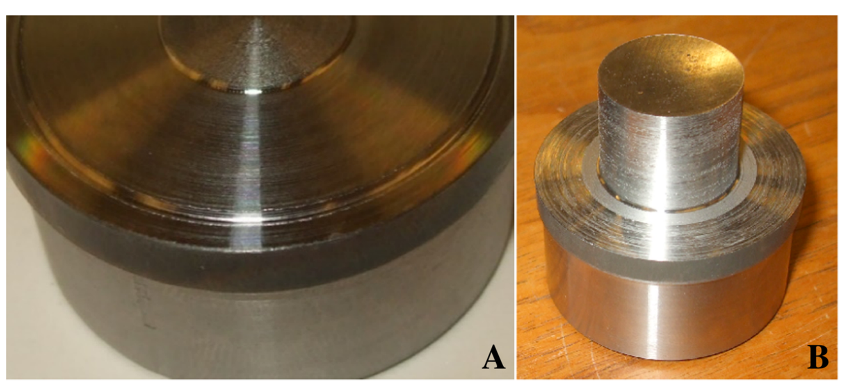


Fig. 3 The machined surfaces after the grooving (**a**) and turning test (**b**)

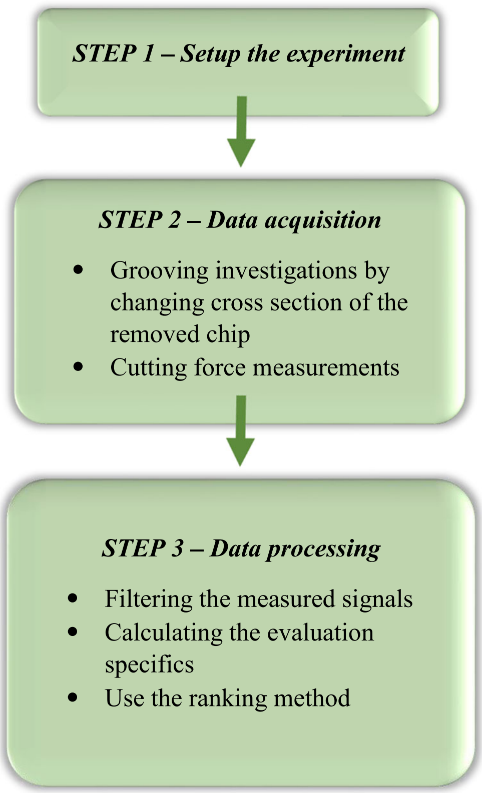


Fig. 4 The methodology of the grooving test

values continuously changed, we had the opportunity to correlate the time and force value input parameters during the evaluation.

During the evaluation of the machinability the following parameters and specifics were used:

- *The HV30 hardness values of the test specimens.*
  The hardness values often give information about the investigated materials and refer to their machinability values.
- *The steepness values of the fitted regression curve* ($F_c$steepness, $F_f$steepness)

The linear regression curves were fitted by the least square method. According to this method, the equation of the fitted line can be calculated by Eq. 1:

$$F_i\text{regression} = F_{i0} + F_i\text{steepness} \cdot t_i \tag{1}$$

where '$F_i$regression' is the predicted variable,

'F_{i0}' is the linear constant,

'$F_i$steepness' is the independent variable of $F_i$regression; in our case, it is the steepness value of the fitted line,

'i' = c, f,

't_i' is the input variable; in our case, it is the time during the machining process.

Parameter '$F_i$steepness' can be calculated by Eq. 2:

$$F_i\text{steepness} = \frac{\sum_{j=1}^{N} \left(t_i - t\right) \cdot \delta_j}{\sum_{j=1}^{N} \left(t_1 - t\right)^2} \tag{2}$$

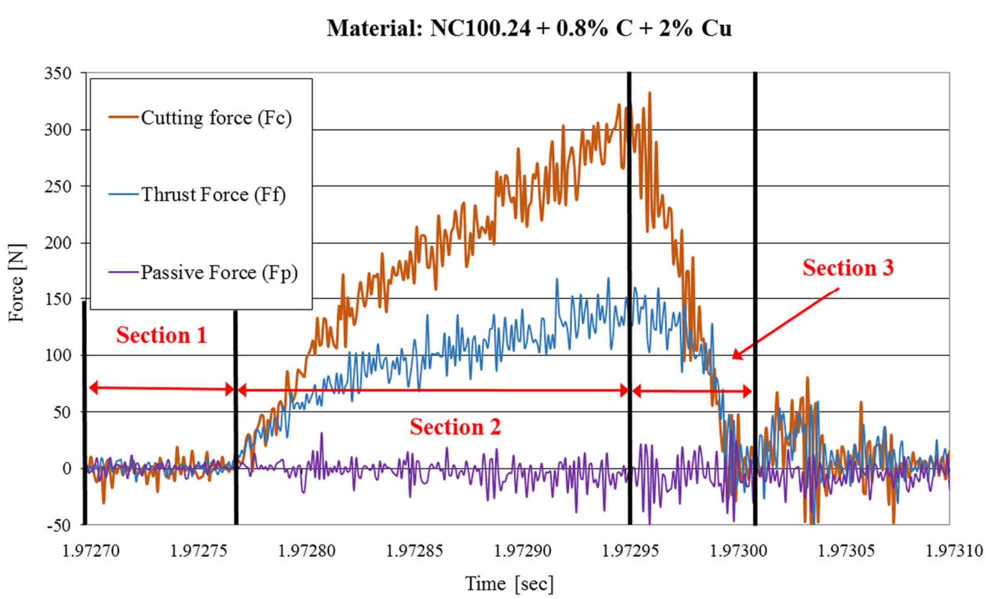
where '$F_i$steepness' is the steepness value,

't_i' are the measured input variables,

'i' = c, f,

't_i' is the average of the input variables,

Fig. 5 The registered force components during machining



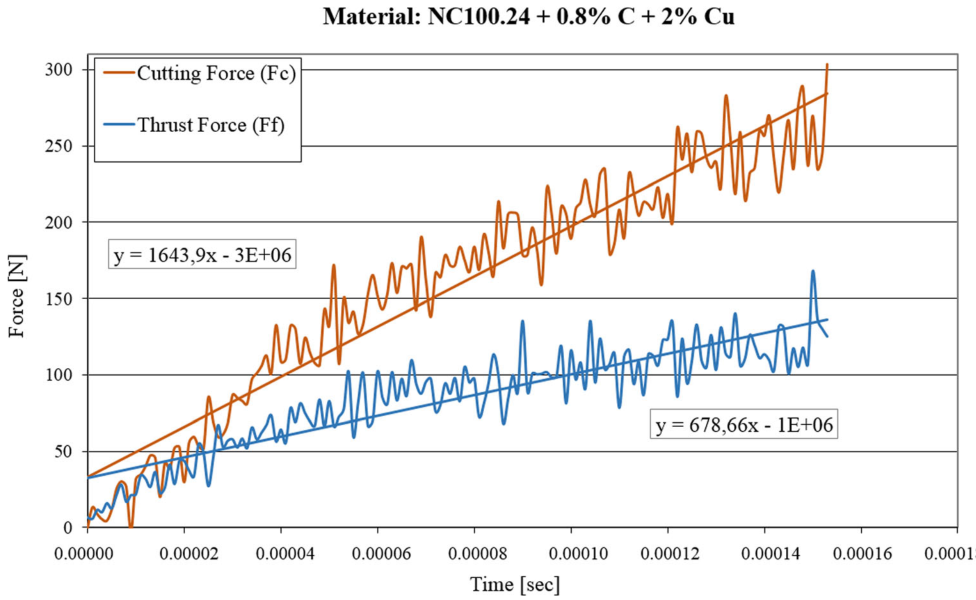


Fig. 6 The considered pieces of the signals and the linear regression curves

'δ_i' is the vertical difference of the measured variables from the fitted linear curve.

- *The ratio of the steepness values of the fitted regression curves* ($F_f$steepness/$F_c$steepness)

  The ratio of the steepness values refers to how easy or difficult the penetration of the cutting edge into the investigated material is.
- *The maximum values of the registered force components* ($F_c$max, $F_f$max)

  The maximum values of the cutting force components show how much energy is necessary for the machining process. These maximum values can be calculated based on the considered pieces of the force signals; they do not directly came from the registered signals. The maximum force components can be calculated by Eq. 3:

$$F_i\text{max} = F_{i0} + F_i\text{steepness}{\cdot}t_i \quad (3)$$

where '$F_i$max' is the maximum value of the cutting or thrust force, respectively,

'F_{i0}' is the linear constant of the fitted linear curve for the force components,

'i' = c, f,

'$F_i$steepness' is the steepness value of the appropriate linear regression curves for the force components,

't_i' is the last input variable; it is the last moment of the considered section of the signal.

- *The maximum values of the fluctuations in the force components* ($F_c$fluctuation$_{max}$, $F_f$fluctuation$_{max}$)

  The fluctuation in the measured cutting force values refers to the vibrations during the machining process that depend on the material compositions of the test specimens. The maximum value of the fluctuations can be calculated by Eq. 4:

$$F_i\text{fluctuation}_{max} = \max|F_i(t) - (F_{i0} + F_i\text{steepness}{\cdot}t_i)| \quad (4)$$

Table 5 The measured and calculated evaluation specifics of the grooving test

Material composition NC100.24	Hardness HV30	F_c steepness	F_f steepness	$F_{f\ steepness}$/ $F_{c\ steepness}$	$F_{c\ max}$ N	$F_{f\ max}$ N	$F_{c\ fluctuation\ max}$ N	$F_{f\ fluctuation\ max}$ N
Original	61.9	1402.2	659.1	0.470	296.8	151.3	59.5	53.2
+0.5 % C + 2 % Cu	72.6	1376.9	576.7	0.419	313.4	146.4	72.1	37.3
+0.5 % C + 4 % Cu	110.5	1526.3	611.5	0.401	316.8	135.2	48.5	27.8
+0.5 % C + 8 % Cu	111.3	1409.2	606.0	0.430	302.2	160.0	82.4	92.4
+0.2 % C + 2 % Cu	80.0	1286.2	579.9	0.451	296.8	151.8	49.1	36.6
+0.8 % C + 2 % Cu	85.0	1643.9	678.7	0.413	303.7	167.9	69.6	60.1
+1.0 % C + 2 % Cu	83.4	1729.2	711.4	0.411	342.3	188.9	113.7	79.4
+1.5 % C + 2 % Cu	91.5	1770.6	733.2	0.414	241.2	135.7	73.3	81.7
C45 (reference)	180.0	1470.6	726.7	0.494	299.8	168.9	40.2	33.1

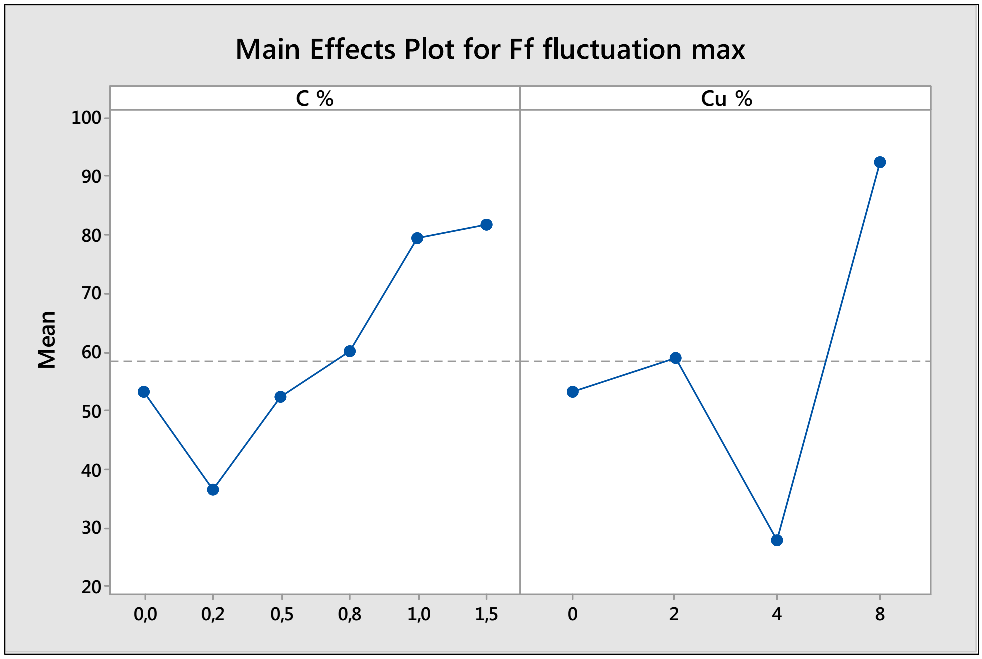


Fig. 7 Main effect plot for the grooving test

where '$F_i$fluctuation$_{max}$' is the maximum value in the fluctuation of the correspondent force components,

'i' = c, f,

'$F_i(t)$' represents the temporal change of the considered piece of the registered signal,

'$F_{i0} + F_i$steepness $\cdot\, t_i$' is the force component calculated for the same registered force component by the equation of the fitted linear curve.

With this method, we can compensate the slope and intercept of the regression line, thus making it possible to calculate the fluctuation directly.

The values of the evaluation specifics for the investigated PMSs can be seen in Table 5.

In order to investigate the effect of material composition changes on the evaluation specifics, the measured and calculated data was made by the Minitab 17 software. For these investigations, the main effect plot function of ANOVA was used. One example for the main effect plots in case of grooving tests can be seen at Fig. 7.

According to the main effect plots of ANOVA, the following evaluation specifics are the most affected by the material composition changes:

– Hardness values,
– The steepness values of the cutting force signals,
– The maximum values of the cutting force components, and
– The maximum values of the fluctuations of the cutting force components.

This means that these evaluation specifics contain most of the information from the cutting process. However, we could

Table 6 The ranked evaluation specifics of the grooving test

Material composition NC100.24	Hardness HV30	$F_{c\ steepness}$	$F_{f\ steepness}$	$F_{f\ steepness}$/ $F_{c\ steepness}$	$F_{c\ max}$ N	$F_{f\ max}$ N	$F_{c\ fluctuation\ max}$ N	$F_{f\ fluctuation\ max}$ N	Machinability index
Original	1	2	3	5	2	2	3	3	21
+0.5 % C + 2 % Cu	2	2	1	3	3	2	4	2	19
+0.5 % C + 4 % Cu	4	3	2	1	3	1	2	1	17
+0.5 % C + 8 % Cu	4	2	2	3	2	3	5	6	27
+0.2 % C + 2 % Cu	3	1	1	4	2	2	2	2	17
+0.8 % C + 2 % Cu	3	4	3	2	2	4	4	4	26
+1 % C + 2 % Cu	3	5	4	2	4	5	6	5	34
+1.5 % C + 2 % Cu	5	5	4	2	1	1	4	5	27
C45 (reference)	6	3	4	5	2	4	1	1	26

Table 7 The measured and calculated evaluation specifics of the longitudinal turning test

Material composition NC100.24	Hardness HV30	K_c, N/mm^2	E, Ws/mm^3	F_c, N	F_f, N	F_p, N	F_c/ F_f
Original	61.9	2940	2.94	147.2	76.5	64.2	1.92
+0.5 % C + 2 % Cu	72.6	2760	2.76	138.5	64.8	56.7	2.14
+0.5 % C + 4 % Cu	110.5	2700	2.70	135.1	59.2	55.5	2.28
+0.5 % C + 8 % Cu	111.3	3320	3.32	166.6	55.6	48.7	3.00
+0.2 % C + 2 % Cu	80.0	2680	2.68	134.3	62.1	55.4	2.16
+0.8 % C + 2 % Cu	85.0	2980	2.98	149.4	78.4	71.3	1.91
+1 % C + 2 % Cu	83.45	3220	3.22	161.1	86.3	91.2	1.87
+1.5 % C + 2 % Cu	91.5	2940	2.94	147.2	77.5	74.6	1.90
C45 (reference)	180.0	3020	3.02	151.7	83.7	32.4	1.81

not draw unequivocal conclusions from these individual evaluation specifics. Therefore, it was necessary to develop an evaluation technique which takes all the evaluation specifics into account at the same time. This was the ranking of the evaluation specifics.

The ranking method was the following: At first, we considered the specifics of each column. For each value of a column, we defined a ±5 % tolerance interval. If another value meets this tolerance limit, this and the reference value are considered to belong to the same group; thus, they will get the same ranking point. The lowest ranking point was assigned to the group with the smallest value, and the group with the highest values got the highest ranking point. According to this ranking method, in the cases when only a few groups could be determined, the given evaluation specific had a smaller impact on the machinability. The main effect analyses established with the help of ANOVA also confirm this statement. In the case of specifics where the main effect analysis showed a great effect on the cutting process, more groups could be made and vice versa.

In order to take all of the evaluation specifics into consideration at the same time, the ranking points were summarized per line as can be seen in Table 6. The summarized ranking points (machinability indexes) refer to the machinability of the investigated materials. Smaller values mean better machinability.

As we mentioned before, we have carried out some reference machining tests in order to verify the results of the grooving tests [34]. The reference tests consisted of simple longitudinal turning operations with cutting force measurements being made during machining. With this test, we mainly investigated the effect of the cutting parameters on the machinability, but with the selection of the appropriate data collected under the same cutting parameters, it is possible to compare the results.

The turning tests had precise results about the effect of the material composition changes on the machinability properties. The only problem with the test was the relatively high time consumption of the preparation and the execution of the investigations. Executing the whole test took more than 9 h. In contrast with this, executing the newly developed grooving test took only 2 h.

In order to make the two different tests comparable to each other, in Table 7, we represent the measured and calculated evaluation specifics of the longitudinal turning test executed with the appropriate cutting parameters.

The hardness of the test specimens was the same for the longitudinal turning tests as for the grooving tests. There is an

Table 8 The ranked evaluation specifics for the longitudinal turning test

Material composition NC100.24	Hardness HV30	K_c, N/mm^2	E, Ws/mm^3	F_c, N	F_f, N	F_p, N	F_c/F_f	Machinability index
Original	1	3	2	2	4	4	2	18
+0.5 % C + 2 % Cu	2	1	1	1	3	3	3	14
+0.5 % C + 4 % Cu	4	1	1	1	2	3	4	16
+0.5 % C + 8 % Cu	4	4	5	4	1	2	5	25
+0.2 % C + 2 % Cu	3	1	1	1	2	3	3	14
+0.8 % C + 2 % Cu	3	3	3	3	4	5	2	23
+1 % C + 2 % Cu	3	4	4	4	5	6	2	28
+1.5 % C + 2 % Cu	5	2	2	2	4	5	2	22
C45 (reference)	6	3	3	3	5	1	1	22

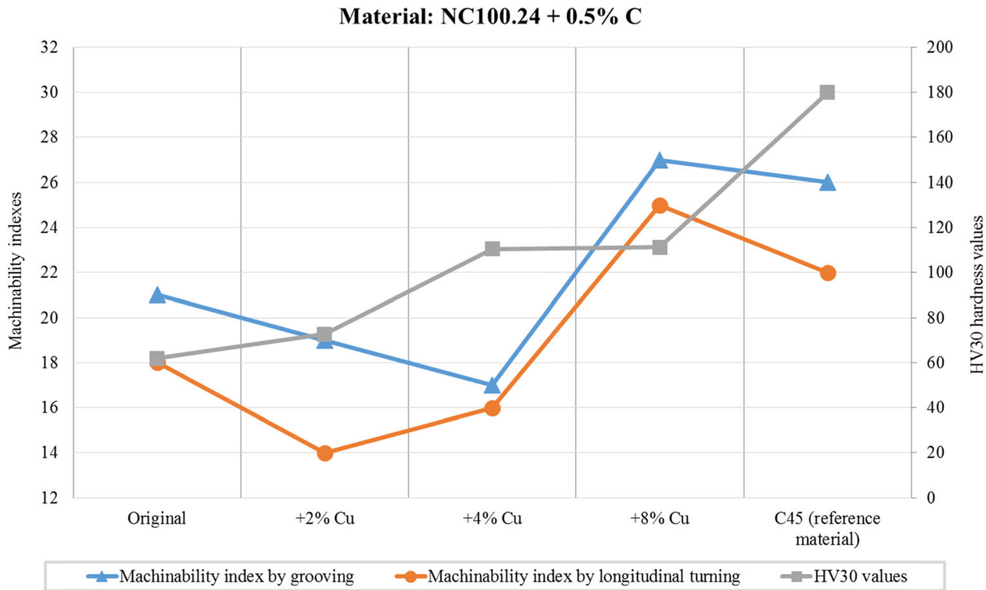


Fig. 8 The effect of the copper content modification

analogy between the calculated K_c and E values, and the $F_{c\ \mathrm{steepness}}$ and $F_{f\ \mathrm{steepness}}$ values, as they indirectly express the energy needs of removing the chip per unit. Based on the same principle, the cutting force components and the ratio of the cutting force components also could be compared for the different tests and could be used as evaluation specifics.

For determining the machinability indexes of the longitudinal turning tests, we used the same ranking method. Table 8 shows the ranked machinability features and the calculated machinability indexes.

By using the same evaluation method for the different tests, the machinability indexes of the different tests could be compared in the same diagram. With the help of the machinability indexes, the effect of the different material composition changes also can be displayed. Figure 8 shows the effect of the copper content changes on the machinability properties sorted by the hardness values.

As it can be seen in Fig. 8, despite the two tests are not equivalent with each other, the reference measurements give almost the same results as the newly developed grooving test. Based on industrial results [1], the optimum value of the copper addition is between 2 and 4 %. Our results also support this statement. Establishing the exact copper percentage needs further investigations. Investigating the effect of the copper addition in smaller amounts, e.g. 2.5, 3 and 4.5 %, may provide more precise results. Based on this, it can be stated that the new test and the evaluation method are suitable to assess the machinability properties of the investigated PMSs in terms of energy indicators. Figure 8 also shows that it is possible to reach situations when both the hardness of the materials and—

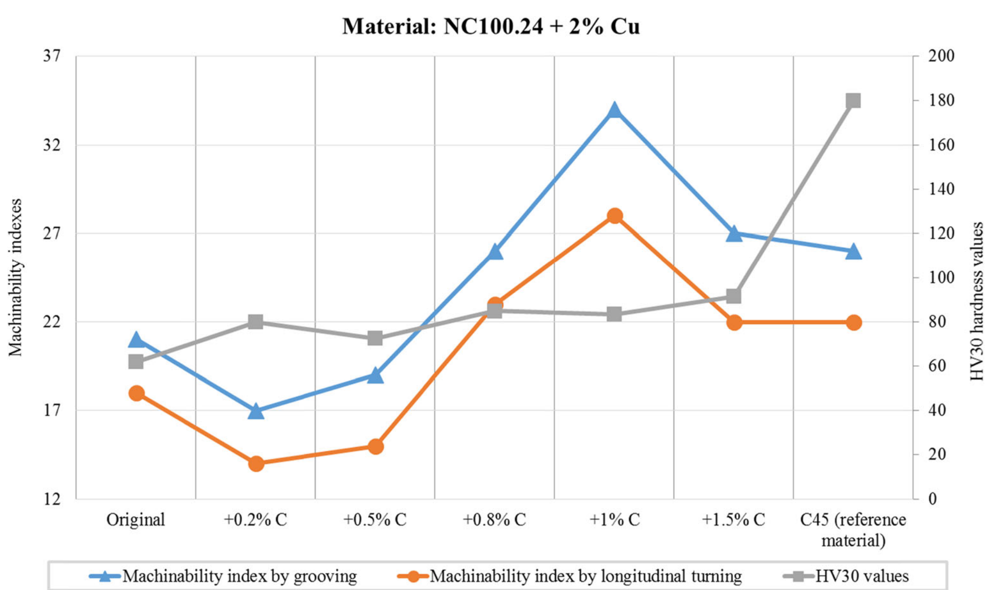


Fig. 9 The effect of the carbon content modification

through this—the mechanical and the machinability properties improve. Copper addition up to 4 % improves these features, but above this limit, the machinability properties worsen.

Figure 9 shows the effect of the carbon content changes sorted by the hardness values.

The same phenomena can be experienced in the case of the carbon addition. Up to the carbon content value of 0.2 %, both the machinability and the mechanical properties improved. However, above this value of carbon content, the machinability properties worsened. The diagram also shows that the machinability indexes of the two tests show the same trend in the case of the carbon modification.

Our aim was to develop a new, easy test which can be done quickly and which properly characterizes the energetics of the machinability of iron-based sintered metals. According to our results, the new test meets with our demand.

During the machining of a PMS with a high copper content, low cutting forces and moderate tool wear, strong vibrations raised. During the machining of a PMS having low carbon and copper content, both the cutting forces and the vibrations are acceptable. The increase of the copper content has a beneficial effect on the cutting force components but has a detrimental impact on the resulting vibrations. The increase of the carbon content has the opposite effect—high cutting forces but weak vibrations were observed.

5 Conclusions

- In the scope of this study, we developed a new test, called grooving test, which can be performed quickly and easily and is able to assess the machinability of PMSs with different material compositions in terms of energy indicators.
- The tests were performed on a high precision CNC lathe using simple grooving operations and cutting force measurements.
- Reference measurements were made in order to validate the newly developed test.
- Directly from the hardness values of the investigated materials, clear conclusions about the machinability properties of these materials could not be made.
- With the help of ANOVA, our evaluation method has been confirmed. The used evaluation method is able to compare and manage the important factors of machinability, and it gives a numerical feature wherewith the machinability of the different PMSs can be comparable.
- The grooving test provides the same, accurate results as the reference measurements, but a significant amount of experimentation time can be saved because of the shortness of the test.
- According to our test results, the secondary machining properties of iron-based sintered metals can be significantly influenced by modifying the alloying element percentages of the original material composition.
- As a rule, based on our results, copper addition increases the hardness of the materials and improves machinability up to 2–4 %. Over this limit, the machinability properties decrease.
- The same trend could be observed in the case of carbon addition. Up to 0.2 %, both the mechanical properties and the machinability behaviour improved; over this limit, the machinability properties worsened.

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Compliance with ethical standards

Conflict of interest Hereby, all of the authors declare that there are no any conflicts of interest.

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