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**FACULTY OF MECHANICAL ENGINEERING**
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# Analysis and improvement of the subsequent machinability of iron-based powder metallurgy materials

PhD Thesis Booklet

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*The opinions of the referees and the material recorded at the defense will be available for viewing later at the Dean's Office of the Faculty of Mechanical Engineering of the Budapest University of Technology and Economics.*

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# 1. INTRODUCTION TO THE RESEARCH TOPIC AND OBJECTIVES

Nowadays there is a growing need for replication technologies which are able to produce parts in mass production with high dimensional and form accuracy. The technology of powder metallurgy can be a possible solution for these demands. The technology can produce simple or complex parts with high accuracy in mass production. Furthermore, it is possible to produce alloys that cannot be produced by any other technologies.

The raw materials of this technology primarily include metal powders, but sometimes other powder mixtures can also be used. The first step of the production is the powder-making process; after that the powder mixtures are prepared according to the customer’s demands. During the preparation of the powder mixtures alloying elements are added to the base mixture in order to modify the mechanical properties of the materials. The next step is the compacting process. During this process the powder mixture is compacted in a rigid die with the demanded shape applying high loads. Finally, the compacted pre-parts are heat-treated (this is the so called sintering process). During sintering the powder particles are linked and the parts receive the final mechanical properties. The alloying processes also occur during the sintering process. The sintered parts can directly be used for further applications.

The disadvantage of this technology is that the size and shape of the compacted parts are limited. For example, threads, cross-holes, slots cannot be produced directly by the compacting and sintering processes. Another issue is that the production costs of these features can be extreme high. For this reason, subsequent machining operations are needed, such as the drilling, turning and milling operations of the compacted and sintered powder metallurgy parts.

According to industrial results [1], 60 % of the parts made by powder metallurgy require some kind of subsequent machining operation, which obviously justifies the detailed investigation of this research area. The machinability investigations of different metals have essential importance in the production planning. These investigations present regularly emerging demands due to the technological classification of the newly developed sintered materials.

Machinability is not a universal definition. It is a rather complex concept that expresses how easy or difficult it is to cut the investigated material with given cutting tools and technological parameters. Normally, properties of the machined surfaces, tool life, the magnitude of the cutting force components, the form of the machined chips forms and the machining costs are included in the machinability. Until now there are no known test methods those can express these complex properties of the materials numerically, or even compare them to a reference material.

Based on these considerations the aims of my researches are the following:

- The comparison of the mechanical and machinability properties of iron-based sintered metals with different material compositions,
- To develop sintered steels with more advantageous subsequent machining properties by modifying the original material compositions,
- Investigate the effects of the material composition changes on the powder metallurgy production technology so that the original manufacturing technology of the sintered parts is not effected negatively,
- Investigate the mechanical properties of the sintered metals made from the modified material compositions so that the applicability of the sintered parts on their original field of use is not effected negatively,
- Carrying out machinability tests and make technological recommendations in order to improve the subsequent machining properties at given cutting conditions.

## 2. BACKGROUND AND METHODS OF RESEARCH

Customers usually require sintered parts with given mechanical properties. These properties can be influenced by modifying the process parameters (material composition, compact density and sintering conditions) of the powder metallurgy technology [2, 3]. During the subsequent machining operations these final products will be machined. This way, the technology of the subsequent machining operations must be adapted to the mechanical properties of the sintered parts.

Various problems occur during these subsequent machining operations. As a result of the different material compositions, a lot of different materials can be created and must be machined ranging from the highly abrasive materials to the soft materials. As a result of the porous structure of the sintered material, interrupted cutting conditions always occur on the micro level during machining. Using emulsion for cooling is not recommended as the emulsion liquid could remain in the surface pore system of the materials and cause considerable corrosion. In the case of some materials considerable amount of burr may occur during machining [1].

On the industrial field drilling and turning are mainly the operations used as subsequent machining operations, but milling operations are also being applied more widely. As a result international literature also focuses on these operations.

Researchers [4] prefer to develop new alloying elements with which more preferable machinability properties can be reached. In most cases this means MnS, MnX or other extra alloying elements with own codes. However, reaching the same behavior by changing the ratio of the original material compositions of the powder mixtures has not or just slightly been investigated yet.

A number of machinability tests have been developed based on drilling operations [5]. The point of these tests is to determine the number of through holes those can be drilled in the investigated material until tool breakage under specific cutting conditions. These tests can easily be carried out, but they do not take the quality of the used cutting tools and the changing of the cutting parameters into consideration.

Based on turning operations the machinability properties are mainly investigated by the measuring of the cutting force components. The point of these tests is that the effects of the material composition directly appear in the evolving cutting force components. Another advantage of the turning tests is the simple evaluation of the measured force components [6].

As a result of the complexity of the milling operations, the surface quality of the machined surfaces is mainly investigated. Researchers also often create models for predicting the surface quality for the machining processes [7].

Another trend is the green machining. This means that powder metallurgy parts are machined after the compacting, but before the sintering process. The results of these researches are promising, but the poor mechanical properties (e.g. tensile strength) of the machined parts and the dimensional changes after the sintering process cause further problems.

In the case of the iron-based sintered metals the Fe-Cu-C system is used the most widely. Standardized material compositions are used within this material system according to the ISO 5755 standard. These material compositions are regulated by the MPIF Standard 35 in the United States and by the DIN 30910 standard in Europe.

Some example for these standardized material compositions can be found in Table 1.

Table 1: Standardized material compositions

| *Material group* | *Material composition %* | | | | *Density* | *Porosity* | *Hardness* | *Tensile strength* |
|---|---|---|---|---|---|---|---|---|
| | *C* | *Cu* | *Fe* | *Other* | *g/cm$^3$* | *$\Delta v/v \times 100$ %* | *HB* | *N/mm$^2$* |
| **Sint C00 (Plane iron)** | <0,3 | <0,1 | Bal. | 2 | 6,4 – 6,8 | 15±2,5 | >35 | 130 |
| **Sint C01 (Iron-Carbon)** | 0,3-0,6 | <0,1 | Bal. | 2 | 6,4 – 6,8 | 15±2,5 | >70 | 260 |
| **Sint C11 (Iron-Copper-Carbon)** | 0,4-1,5 | 1,5 | Bal. | 2 | 6,4 – 6,8 | 15±2,5 | >80 | 320 |
| **Sint D11 (Iron-Copper-Carbon)** | 0,4-1,5 | 1,5 | Bal. | 2 | 6,8 – 7,2 | 10±2.5 | >95 | 400 |

During my research, at the beginning I took the Sint C11 and Sint D11 material group into consideration. Two plane iron powder mixtures (NC100.24 and PMX), one pre-alloyed powder mixture (Distaloy AE) and one stainless steel powder mixture (410L) were investigated. The main characteristics of these powder mixtures can be found in Table 2.

Table 2: Characteristics of the investigated powder mixtures

| *Material group* | *Apparent density* g/cm$^3$ | *Average particle size* $\mu m$ | *Main alloying elements* % | *Compact density* g/cm$^3$ |
|---|---|---|---|---|
| *NC 100.24* | 2,45 | 45 – 180 | < 0,01% C | 6,1 – 7,1 |
| *PMX* | 3,1 | 180 – 212 | < 0,01% C | 6,1 – 7,1 |
| *Distaloy AE* | 3,05 | 50 – 200 | 1,5% Cu, 4% Ni, 0,5% Mo | 6,7 – 7,3 |
| *410L* | 3,3 | 75 – 100 | 12% Cr | 6,2 – 6,8 |

According to my research plan, the original copper and carbon content of each material group was modified. Carbon is a basic alloying element in the case of powder metallurgy (in the form of graphite). As a result of the carbon content modifications the material structure of the materials change, and both the hardness and tensile strength of the materials increase. Copper also should be added to the base powder mixture in powder form. At the industrially used sintering temperature (1120°C) the copper melts and forms a transient liquid phase (the melting point of copper is 1083 °C). As the result of the capillary effect this transient liquid phase penetrates the pore system of the material.

During sintering the liquid copper is rapidly distributed in the iron matrix. Diffusion bonding is generated between the iron powder particles.

As copper is a substitutial alloying element, the diffusion process consumes more time, but the diffusion provides better connection between the powder particles, and as a result the strength of the material also increase.

I modified the copper and carbon content within the material groups listed in Table 2. I carried out modifications to an extent which resulted in compositions those are rarely used on the industrial field. In the case of industrial applications fast and reliable results are neccessary. The reason of the extensive material composition changes is that if there is a need for a new sintered material where the characteristics are unknown we need to provide information – or estimations – regarding the mechanical and subsequent machining properties. The exact material composition changes can be found in Table 3.

Table 3: The material composition changes

| ***Material composition*** | ***Additional carbon (C)*** *weight %* | ***Additional copper (Cu)*** *weight %* |
|---|---|---|
| ***NC 100.24*** | - | - |
| ***NC 100.24*** | *0,5* | *2* |
| ***NC 100.24*** | *0,5* | *4* |
| ***NC 100.24*** | *0,5* | *8* |
| ***NC 100.24*** | *0,2* | *2* |
| ***NC 100.24*** | *0,8* | *2* |
| ***NC 100.24*** | *1,0* | *2* |
| ***NC 100.24*** | *1,5* | *2* |
| ***PMX*** | - | - |
| ***Distaloy AE*** | *0,5* | - |
| ***410L*** | - | *2* |
| ***410L*** | - | *4* |

# 3. SUMMARY OF THE RESEARCH WORK

After the material composition changes the first step was to carry out compacting tests in order to determine the compacting behavior of the new powder mixtures. The aim of the compacting tests was to record the compacting curves those are essential to set the compacting machines. For the investigations a 200 tons (1961,33 kN) hydraulic press machine was used which was and currently is at the BUTE Department of Material Sciences and Technology. The press machine was equipped with piezo-electric force and length measurement systems, this way the forces occurring during the compacting and ejecting process and the travel of the compacting punch could also be measured. Solid cylinders with the diameter of 32,5 mm were compacted as test specimens. Before every compacting test the compacting punch and the rigid die was carefully adjusted by hand in order to prevent the tool breakage. From the powder mixtures listed in Table 3. solid cylinders with the same weight of 100 g were compacted. During the tests 8 ton/cm$^2$ compacting pressure and 7 mm/sec compacting speed were set which are the values generally used by the industry. After the tests I drew the compacting diagrams for each powder mixture. An example for these diagrams - in the case of plain iron powder groups - can be seen at Fig. 1.

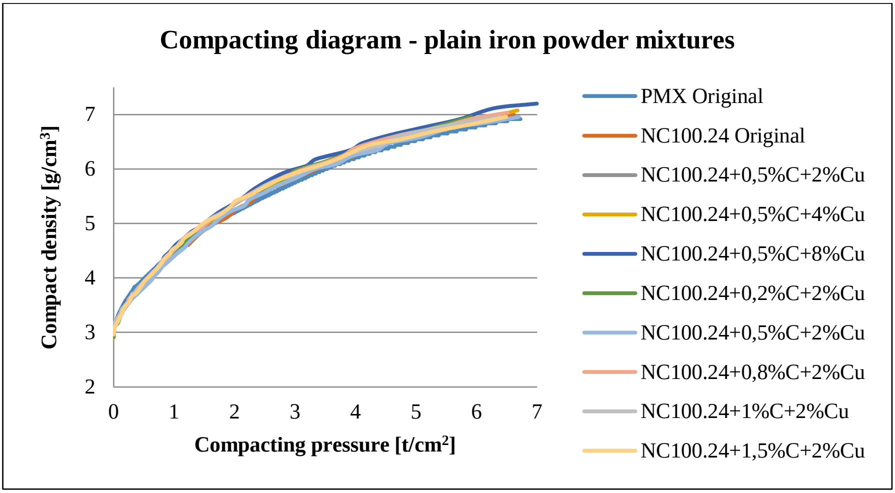


Fig. 1: Compacting diagrams for the plain iron powder groups

Based on the results of the compacting tests it can be established that the material composition changes have no effect on the compacting behavior of the powder mixtures. Differences could only be noticed in the case of the ejecting diagram. However, in the case of the modified powder mixtures smaller ejecting forces raised compared to the original mixtures. This is important as smaller ejecting forces result in smaller tool loads and tool wear. My [M1 and M2] publications are related to the results of these investigations.

As the next step destructive material tests were carried out. The aim of these investigations was to determine if there are any differences between the mechanical properties of the new sintered steels and the standardized ones. Mechanical properties are important because they influence the usage of the finished product at the final area of application. Tensile strength tests (according to the MSZ EN ISO 2740:2010 Standard) and impact tests (according to the MSZ EN ISO 25754:1995 Standard) were carried out at the laboratory of the BUTE Department of Material sciences and Engineering. Standardized test specimens were used for this investigation according to the ISO 2740 and MSZ EN 25754 Standards. This required the planning and manufacturing of an individual compacting tool. During the investigations the mechanical properties of the specific compact density range (6,0 – 7,0 g/cm$^3$) were under focus. This way, only two powder mixtures were investigated. According to the test results I could conclude that the mechanical properties of the new sintered steels did not differ from the standardized values. This way they can be used at the original area of use without any restrictions. My [M3] publication is related to the results of these investigations.

The next step was the detailed investigation of the thermal properties of the sintered metals. During machining a significant amount of heat forms in the chip removal zone, which has a detrimental effect on the tool life. In the case of machining sintered metals cooling with emulsion is not recommended. Dry machining should be used instead which results in higher heat generation and higher tool wear. In the literature there are no information about the thermal properties of the sintered metals. In addition to this, there are no material models with which the thermal properties could be predicted during machining. For the investigations a modified Collin P200E type compacting machine was used equipped with adjustable coolable and heatable pressing parts. This machine is used for linear heat expansion measurements and is currently at the BUTE Department of Polymer Engineering. One powder mixture was investigated near two sintering temperatures (1120 and 1250 °C) and four compact density values (6,4; 6,6; 6,8 and 7,0 g/cm$^3$). According to the linear heat expansion measurement method, the heat conductivity and heat transfer coefficient of the investigated parts could be calculated compared to a reference material (in this case normalized 1.1121 steel). During measuring, a heat difference of 30°C was established between the compacting surfaces of the press machine. The generated heat values were measured at a distance of 3 mm from the edges and in the middle of the test specimens in the axis of rotation at the steady state. Thermo-couples were used for these measurements. In order to fix the thermo couples at the right places the test specimens were prepared. In order to check the validity of the measuring method the thermal properties of 1.1191 steel were also measured, which are already well-known. It can be said that the experimental setup is able to measure the thermal properties of the different sintered metals as the reference measurements gave back the thermal data of the reference 1.1191 steel. In addition to this, it can also be stated that contrary to my expectations, the thermal behavior of the sintered metals (heat conductivity and heat transfer coefficient) did not change significantly due to the effects of the different parameters of the powder metallurgy technology. The measured values are in the range of the values measured in the cases of steels made by conventional metallurgy techniques. Based on this we can say that no specific cutting condition will occur during machining as a result od the porous structure of the sintered steels. Based on the test results I could establish my first scientific statement. My [M8] publication is related to the results of these investigations.

Mechanical investigations were followed by the investigation of the subsequent machining properties. Longitudinal turning tests were carried out in order to gain basic information about the cutting properties of the original and the modified sintered steels. 34 mm high solid cylinders with the diameter of 39 mm were prepared as test specimens. The compact density was 6,6 g/cm$^3$, and the test specimens were sintered at 1120 °C for 30 minutes in a protective atmosphere. The $HV_{30}$ hardness values of the sintered parts were measured with a KB PRÜFTECHNIK DKD-K-02801 digital hardness testing machine at the BUTE Department of Material Sciences and Engineering. These measured results were also used for the evaluation of my further investigations. The longitudinal turning test were carried out at the BUTE Department of Manufacturing Sciences and Engineering. A Hembrug SLANTBED MIKROTURN 50 CNC high precision CNC lathe was used for the cutting tests. During machining the cutting force components were measured. For the force measurements a Kistler 9257A type force measuring cell, a Kistler 5019 type charge amplifier and a National Instruments 6024E data acquisition card were used. The used measuring software was a department-developed algorithm created in LabView environment. The sampling frequency was 1 kHz in all cases. My aim was to investigate the effect of the different cutting properties in a wide range from roughing operations to finishing operations. Four different cutting speed (50, 100, 150, 200 m/min), three different feedrate value (0,05; 0,1; 0,2 mm/rev) and three different depth of cut values (0,5; 0,8; 1 mm) were set using full factorial experimental design. The cutting tool consisted of a Sandvik Coromant CSCLCR1616H09 tool holder and CCMT09T304-PM inserts. The measured results were evaluated by the help of the Main Effects Plot function of the ANOVA toolbox of the Minitab v16 software. My [M4 and M5] publications are related to the results of these investigations.

The next step was the development of an own drilling test based on the literature. The aim of the investigations was to determine the effects of different tool materials and cooling modes on tool life and cutting force components using a tool life test (determining the number of through those can be machined until tool breakage). The test specimens were made from only one material group (PMX plain iron powders). 82x41x20 mm solid blocks were compacted to the compact density of 6,8 g/cm$^3$. The test specimens were sintered at 1120°C for 30 minutes in a protecting atmosphere. As the aim was to receive comparable results, the test was carried out in case of normalized 1.1191 steel. Three different tool materials (high speed steel without coating, coated high speed steel and cemented carbide) were used. The diameter of the twist drills was 3 mm in all cases. During machining 0,04 mm/rev feedrate and the cutting speed of 15 m/min were set in the case of the HSS tool materials. In the case of the cemented carbide tool materials these parameters were duplicated in order to make use of the better properties of the tool material. The drilling tests were performed using a Kondia B640 machining center in the laboratory of the BUTE Department of Manufacturing Sciences and Engineering. During machining the through holes were drilled according to a 8x11 raster. Besides dry machining, cooling with cold air (6 bar, -10°C) was also used. During machining the cutting force components were measured with a Kistler 9257A force sensor and a Kistler 5080 charge amplifier. The measuring software was the own software (Dynoware) of the force measuring system. The condition of the tool life was followed with a Dino-Lite AM431ZT digital microscope. The quality of the drilled holes was also checked with this after machining. To sum up the test results it can be said that cooling with cold air have a beneficial effect on the tool machining process. Using it results in longer tool life and better hole-quality. Furthermore, it can be stated that in the case of producing in small series (up to ~100 parts) HSS tools can also be used successfully. In any other cases it is recommended to use cemented carbide tool materials. My [M6, M7 and M9] publications are related to the results of these investigations.

As the next step, face milling tests were carried out in order to investigate the effect of different cutting parameters on the machined surface. The test specimens were made from one material composition (PMX plain iron powder mixture). 82x41x20 mm solid blocks were compacted to 6,8 g/cm$^3$ compact density. The test specimens were sintered at 1120 °C for 30 minutes in a protective atmosphere. As a reference measurement the whole test was executed also using normalized 1.1191 steel. The composition of the two materials are very similar, differences can be observed only in the structure and the production method. This way, the effect of the different material structures could also be determined. Face milling tests were performed using a Kondia B640 machining center in the laboratory of the BUTE Department of Manufacturing Sciences and Engineering. The cutting tool consisted of a Sumitomo AXMT123504PEERG coated carbide insert and a Sumitomo WEX2016E tool holder with the diameter of 16 mm. During machining only one cutting edge was used in order to investigate the effect of a single edge on the evolved surface quality. The condition of the cutting edge was checked with a Dino-Lite AM431ZT digital microscope. Five different cutting speeds (50, 75, 100, 125, 150 m/min), three different feed rates (0,01; 0,04 and 0,16 mm/rev) and three different depth of cut values (0,5; 1 and 2 mm) were used as cutting parameters. Besides up milling strategy, down milling strategy, dry machining and cooling with cold air was also used. After machining the surface roughness parameters (Ra and Rz) of the machined surfaces were measured with a Mitutoyo SJ-400 tactile roughness tester. Pictures of the machined surfaces were also taken with a Dino-Lite AM431ZT digital microscope in order to check if any burr was formed during machining. The test results were mainly analyzed by the Main Effects Plot function of the ANOVA toolbox of the Minitab v16 software. Based on the results it can be stated that the cold air cooling has a great effect on the machining process. The change of the surface roughness parameters depending on the machined materials and the used cooling modes can be seen in Fig. 2.

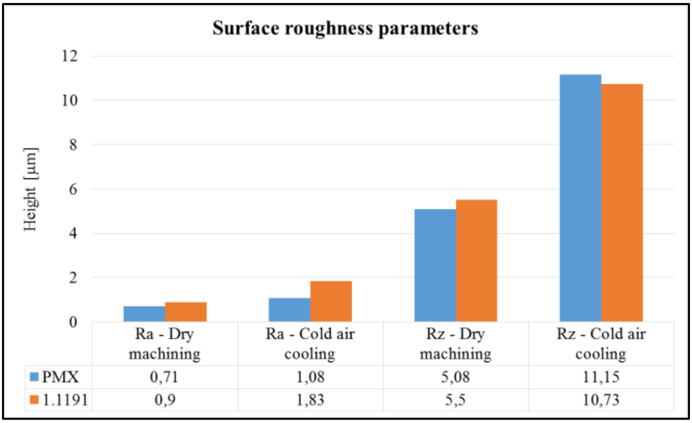


Fig. 2: Change of the surface roughness parameters depending on the cutting parameters

After evaluating the results I could draw two main conclusions:

1. Under the same cutting conditions the surface quality after machining was nearly the same in both the cases of the reference and the tested materials.
2. Contrary to my expectations cold air cooling generally has a detrimental effect on the evolved surface quality, but it increases the tool life.

As the average values can easily be misleading, for the final conclusions I selected the settings of cutting parameters those resulted in the best surface qualities. According to this there is a parameter combination where the surface quality is acceptable and the productivity improves. It is possible to apply higher cutting speeds and feedrates than in the case of dry machining, and the tool life also increases. My [M10 and M13] publications are related to the results of these investigations. Based on the drilling and the milling tests, I could establish my second scientific statement about the effect of different cooling modes on the machining process.

After these investigations I had enough information to develop a new machinability test, which is able to characterize the secondary machining properties of sintered metals in a numerical form. The basic idea of my test was suggested by two scientific papers [8 and 9], where high-load scratching tests and face turning operations were used to assess the machinability. My test is based on grooving operations, however, it uses a non-conventional cutting edge geometry. The used cutting tool consisted of a Sandvik Coromant SDJCR1616H11 tool holder and a DCMT11T304-PM insert, which has a symmetric geometry. The novelty of my test is based on the geometry of the removed chip. During machining the cross-section of the removed chip and this way the cutting forces continuously change. Based on this the cutting force component could be indirectly related to the machining time. Furthermore, due to the symmetric geometry of the insert, the cutting speed deviation along the cutting edge was so small that I could also not take its effect into consideration during the evaluation process. Test specimens were compacted from the materials listed in Table 3. to 6,6 g/cm³ compact density with the diameter of 39 mm. The test specimens were sintered at 1120°C for 30 minutes in a protective atmosphere. In the case of the stainless materials the sintering temperature was 1240 °C. In order to collect reference results, the whole test was performed using normalized 1.1191 steel. The cutting tests were performed in the laboratory of the BUTE Department of Manufacturing Sciences and Engineering, using a high precision Hembrug SLANTBED MIKROTURN 50 CNC lathe machine. For measuring the force components a Kistler 9752A piezo electric force sensor, a Kistler 5019 charge amplifier and a National Instruments 6024E data acquisition card were used. The sampling frequency was 1 kHz in all cases. Because of the simplicity of the test, one cutting speed value (150 m/min), one feedrate value (0,1 mm/rev) and one depth of cut value (0,5 mm) were used. An example for the measured force components can be seen at Fig. 3.

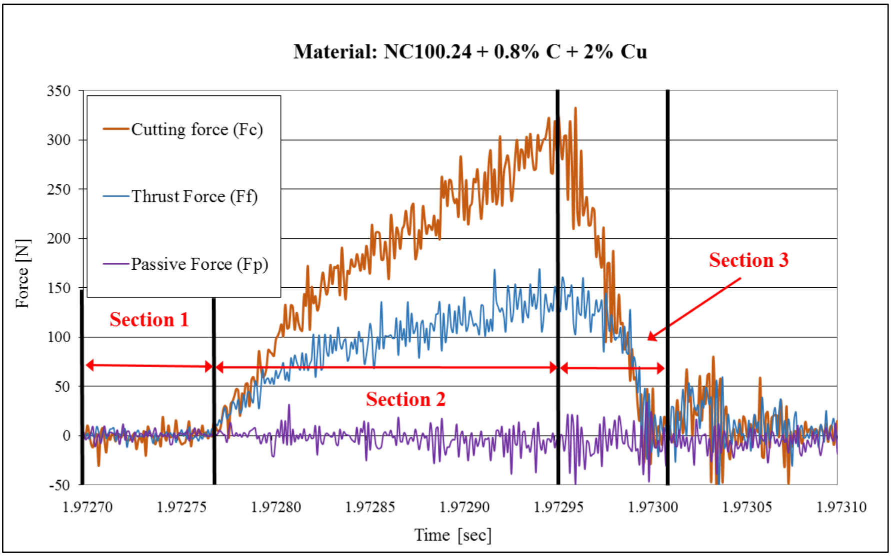


Fig. 3: Registered force components during grooving

As the test could be carried out quickly, there was no measurable tool wear during machining. During the evaluation of the measured values, only the force components of Section 2 were taken into consideration. As evaluation specifics, the $HV_{30}$ hardness values of the test specimens, the steepness values of the fitted linear regression curves onto the considered pieces of the signals, the ratios of the steepness values, the maximum values of the force components and the fluctuation values of the registered force components were taken into consideration. As no clear conclusions could be drawn from the evaluation specifics, I developed an evaluation method which took all of the evaluation specifics into consideration at the same time, weightingthem correctly. My method is based on the ranking of the evaluation specifics. First I created groups from the measured results by evaluation specifics. For the classification a ±5 % tolerance limit was considered. This means that if two values are in this tolerance field, they belong to the same group, and they get the same ranking point. During ranking groups containing the smallest values got the smallest, while groups containing the highest measured values got the highest ranking point. The evaluation specifics where more groups could be created have higher impact on the machining process. I supported this statement by the Main Effect Analyses of the evaluation specifics. After this the ranking points were summarized per material compositions. The summarized ranking points (Machinability indexes) refer to the machinability of the investigated materials. Smaller values mean better machinability.

In order to validate the results of my grooving test, the test results were compared to the results of the longitudinal turning tests. For this I selected results measured using the same cutting parameters and I used the same evaluation method as in the case of the grooving test. As a result it can be stated that although the test methods were different, they gave the same result as it can be seen at Fig. 4. Furthermore, it also could be concluded that the effects of the material composition changes were clearly shown in the machinability indexes. Using the grooving test lots of experimental time could be saved, and the effect on the material composition changes could be quantifiable, which had not been possible before. According to the results of the grooving test, I could establish my third scientific statement. My [M11 and M12] publications are related to the results of these investigations.

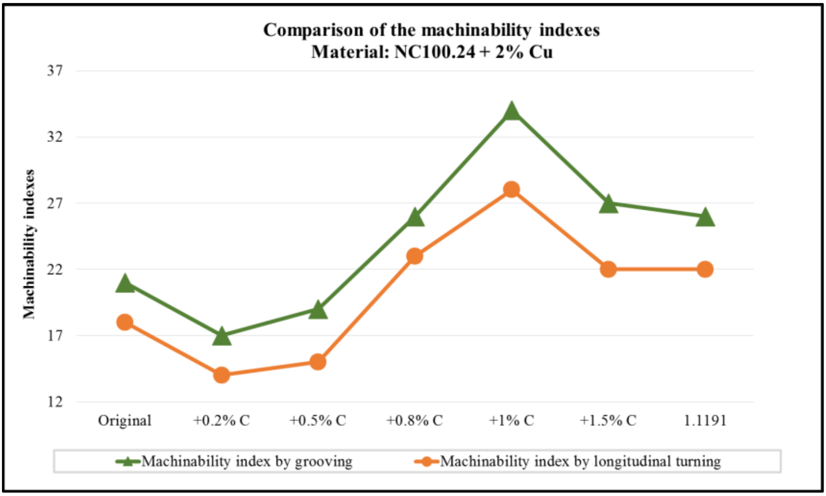


Fig. 4: Machinability indexes of the different test methods

The grooving tests were repeated using smaller modifications (copper content 3, 4, 5 weight %; carbon content 0,1;0,2 and 0,3 weight %) near globally seemingly ideal material compositions. This way the combined effect of the modification and the proper alloying element percentages could be observed. The geometry, the production properties of the test specimen and the experimental setup was the same as in case of the previous investigations. The same evaluation method was used on the measured results as in the previous case. After evaluating the test results I could establish my fourth and fifth scientific statements related to the ideal alloying element contents to improve the subsequent machining properties of sintered steels. My [M11 and M12] publications are related to the results of these investigations.

After the grooving test, a tool life test was performed in order to investigate the effect of the ideal material composition changes on tool wear. Namely, despite the low cutting forces, the modifications of the material compositions could have different effects. Face turning operations were applied to investigate the tool life. The geometry and the properties of the test specimens were the same as in the case of the second grooving test. The experiments were carried out in the laboratory of the BUTE Department of Manufacturing Sciences and Engineering using a EEN-400 type NC lathe machine. Before the machining process, through holes with the diameter of 3 mm were drilled in the test specimens in order to avoid the zero cutting speed in the axis of rotation. Tool life tests were performed using two different RPM values (1000 and 2000

1/min). Simultaneously with the changing of the machined diameter the cutting speeds were also modified (between 125 – 9,42 and 250 – 18,48 m/min). This way the effect of cutting speeds on tool life could also be considered. The feedrate value was 0,05 mm/rev and the depth of cut value was 0,5 mm in all cases. SECO CCMT09T304-F1 inserts were used for the investigations and the condition of the cutting edges were examined by a Dino-Lite AM4317T digital microscope. After the machining of a material group (which means 100 different depth of cut values), the cutting edges were also checked with an Olympus stereo microscope. In addition to this, SEM pictures from the machined surfaces were also taken. The results of the grooving test were confirmed by the tool life test. According to the grooving test ideal alloying element modifications resulted in the smallest tool wear values. In addition to this, the material composition changes had the same effect on the tool life as it could be calculated from the grooving tests. This way, the results of the tool life test also support the efficiency of the grooving test (Fig.5.).

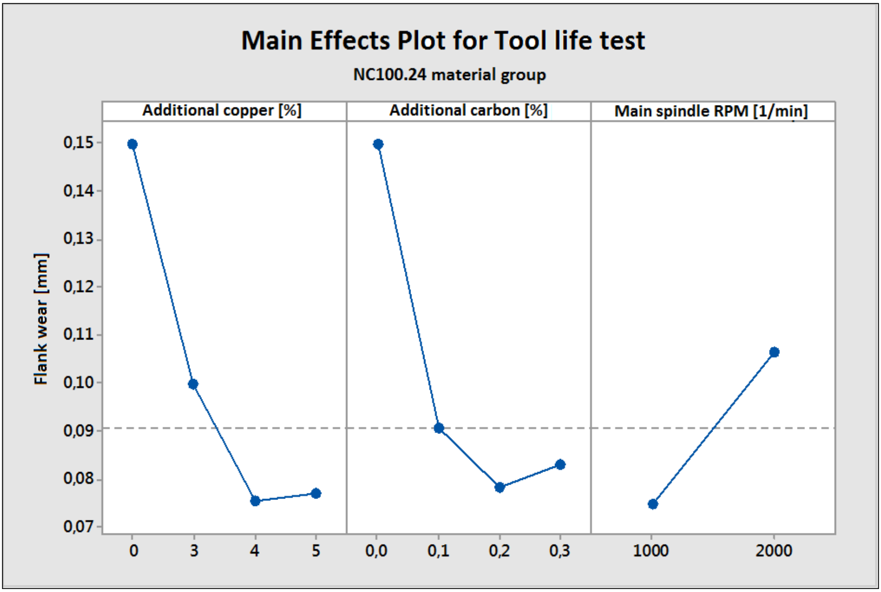


Fig.5: Results for the Tool Life Test

## 4. THESIS POINTS

Based on my previously listed mechanical and machinability investigations the following scientific statements could be established:

1. **Thesis: In the case of iron-copper-carbon-containing sintered steels belonging to the Sint C00 material group made by powder metallurgy it can be stated for the entire piece that the heat conductivity and heat transfer coefficients – playing important role in cutting processes – are independent from the compacting density and applied sintering conditions (temperature, time) during the production of the sintered parts.**

   My [M8] publication is related to the first thesis point.

2. **Thesis: In the case of iron-copper-carbon-containing sintered steels made by powder metallurgy during face milling operations cooling with high-pressurized cold air increases the surface roughness parameters (Ra and Rz), but improves the tool life. Using this method can be justified if the generated surfaces meet the demands and the tool life is the primary concern.**

   My [M6, M7, M9, M10 and M13] publications are related to the second thesis point.

3. **Thesis: In the case of iron-copper-carbon-containing sintered steels with give material composition made by powder metallurgy, quantitive determination of the subsequent machinability by turning operations based on the measured cutting force components is possible with the following procedure.**
   - **The $HV_{30}$ hardness values of the test specimens must be measured.**
   - **The main cutting force and thrust force components must be measured during the grooving operation. The investigations must be interpreted by cutting tools with symmetric geometry.**
   - **The evaluation specifics must be considered from the measured signals (steepness values of the fitted linear regression curves, the ratios of it, the maximum values of the force components and the maximum fluctuations of the force components).**

- **The measured and calculated evaluation specifics must be ranked in an ascending order considering a tolerance limit. The ranked evaluation specifics must be summarized per material. The interval of the tolerance limit depends on the value of the examine modification of material composition. Smaller values mean better machinability.**
- **The summarized number refers to the subsequent machinability of the investigated material in quantitative, numerical form taking several characteristics into consideration at the same time.**

My [M1, M2, M3, M4, M5 and M12] publications are related to the third thesis point.

4. **Thesis: In the case of iron-copper-carbon-containing sintered steels belonging to the Sint C11 material group containing 2 weight % copper made by powder metallurgy, adding 0,2 weight % carbon (in the form of graphite) to the base powder mixture improves the machinability.**
5. **Thesis: In the case of iron-copper-carbon-containing sintered steels belonging to the Sint C11 material group containing 0,5 weight % carbon made by powder metallurgy, adding 4 – 5 weight % copper to the base powder mixture improves the machinability.**

My [M11 and M12] publications are related to the fourth and fifth thesis points.

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# 6. PUBLICATIONS RELATED TO THE THESIS POINTS

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