UDK 621.937 ISSN 1580-2949
Original scientific article/Izvirni znanstveni članek MTAEC9, 46(6)601(2012)

INFLUENCE OF MATERIAL PROPERTIES ON THE MACHINABILITY IN FACE MILLING

VPLIV LASTNOSTI MATERIALA NA OBDELOVALNOST PRI ČELNEM REZKANJU

Milenko Sekulić[1], Miodrag Hadžistević[1], Marin Gostimirović[1], Renata Turisova[2], Vlastimir Pejić[3]

[1]Faculty of Technical Sciences, Trg D. Obradovića 6, 21000 Novi Sad, Serbia
[2]Faculty of Engineering, Nemcovej 32, 042 00 Kosice, Slovakia
[3]Faculty of Engineering, Vojvode Misica 61, 74000 Doboj, Bosnia and Herzegovina
miodrags@uns.ac.rs

Prejem rokopisa – received: 2012-04-19; sprejem za objavo – accepted for publication: 2012-06-11

A workpiece material and its mechanical properties, chemical composition and microstructure have a significant influence on the material machinability in machining, i.e., on the machining-process output properties: productivity, machined surface quality and machining accuracy. Machinability improves when equal conditions are achieved: long tool life, increased productivity, better machined surface quality, lower forces and cutting temperatures, as well as favourable chip type. Cutting-process planning requires reliable cutting-force estimates, which can be currently obtained only from process-dependent machinability databases. This paper described research in the field of cutting forces in the face milling of eight different materials: steels C45 and C60, gray irons GJL150 and GJL200, silumine AlSi12Cu.00, copper EK2-Cu.00, bronze CuSn12.01 and brass CuZn40Pb.05. The results showed that the hardness, tensile-strength values, chemical composition and microstructure of a workpiece material have a significant influence on the main cutting force, and thereby on the cutting energy in machining.

Keywords: material machinability, the main cutting force, face milling

Material obdelovanca in njegove mehanske lastnosti, kemična sestava in mikrostruktura pomembno vplivajo na obdelovalnost materiala pri obdelavi ter na zmogljivosti procesa obdelave, kot so: produktivnost, kakovost obdelane površine in natančnost obdelave. Obdelovalnost se izboljša, če so zagotovljeni enaki pogoji. To omogoča dolgo trajnostno dobo orodja, večjo produktivnost, boljšo kakovost obdelane površine, manjše sile in nižje temperature pri rezanju ter ugodno obliko ostružkov. Načrtovanje rezalnega procesa zahteva zanesljivo oceno sil pri rezanju, kar je sedaj mogoče doseči le z bazami podatkov procesno odvisne obdelovalnosti. Članek obravnava raziskavo na področju sil pri čelnem rezkanju osmih različnih materialov: jekel C45 in C60, sivih litin GJL150 in GJL200, silumina AlSi12Cu.00, bakra EK2-Cu.00, brona CuSn12.01 in medenine CuZn40Pb.05. Rezultati so pokazali, da imajo trdota, natezna trdnost, kemična sestava in mikrostruktura materiala obdelovanca pomemben vpliv na sile pri rezanju in s tem na rezalno energijo pri obdelavi.

Ključne besede: obdelovalnost materiala, glavna sila rezanja, čelno rezkanje

1 INTRODUCTION

Material machinability in machining is the key issue in the cutting-process technology, considering the fact that there is a large number of parameters influencing it (workpiece material, tool material and geometry, cutting fluid, machining-system stability, machining types, cutting conditions).[1,2] The technological properties of a process, like the economy, accuracy and machined surface quality, are largely dependent on the efficiency in solving the problem of material machinability. There are several criteria for evaluating the machinability and the most used ones are the following: tool life (influencing the machining time and the production costs), cutting forces (influencing energy consumption), cutting temperatures (influencing tool wear), machined surface quality and chip shape.[3,4]

In practise, no two materials that are subject to machining can behave alike when being cut with the same tool, at the same cutting speed and feed rates, using the same machine, and working under similar conditions. In machining, diverse materials under constant machining conditions and diverse cutting forces owe their origins to the different physical and chemical properties of a workpiece material. The properties of workpiece materials that may affect machinability are: microstructure, grain size, heat treatment, chemical composition, fabrication, hardness, yield strength and tensile strength as well as physical properties such as the modulus of elasticity, thermal conductivity, thermal expansion, and work hardening.[5]

The criteria for a machinability evaluation (output machining-process properties) can be expressed in the functions that provide the connections among these criteria and influencing parameters. These functions are known as material-machinability functions and are determined experimentally. Cutting force is one of several parameters to be considered for a full assessment of the machinability of a workpiece material.[6] Since the face-milling process is one of the most utilized and most efficient processes, the largest number of papers and researches are about this process. The specific characteristics of the face-milling process, like a large number of teeth simultaneously cutting a material and the changeability of the cross-sectional area of a cut, have influenced the development of a large number of models for calculating the cutting-force components.[7,8] In this paper, the machinability of eight different materials was evaluated through the main cutting force in face milling. The results of testing the material machinability allow an effective and reliable management of the machining process for these materials, the modelling of the cutting forces, and a creation of a database for calculating the cutting forces.[9]

2 EXPERIMENTAL WORK

2.1 Cutting-force measurement

In face milling, the cutting forces exerted by the face-milling cutter tooth on a workpiece are changeable in time and space.[10] **Figure 1** presents the cutting-force scheme in the one-tooth face milling (the shaded area is a chip removed by one tooth per revolution).[11,12]

The main cutting force F_v can be calculated on the basis of the measured cutting forces in the x and y directions using the following equation:

$$F_v = \left[-\sin\varphi - \cos\varphi\right] \cdot \begin{bmatrix} F_x \\ F_y \end{bmatrix} \quad (1)$$

During the experiments, the cutting forces were measured using a three-force-component Kistler dynamometer (model 9257A) and also a PC-based data-acquisition system with the LabVIEW software. The experimental work was carried out at the Department of Production Engineering, the Faculty of Technical Sciences in Novi Sad. The machining was conducted on a vertical-spindle milling machine (Prvomajska FSS-GVK-3). A face-milling cutter with a Φ 80-mm diameter (Jugoalat G.707.1), cemented carbide inserts (the Sintal type P25 and type K10), the tool cutting-edge angle of $\kappa = 75°$ and the rake angle of $\gamma = 0°$ was used as a tool. All of the experiments were conducted with one insert without a coolant, except for the machining silumine where, due to the chip particles getting stuck in the cutting-edge area, petroleum was used.

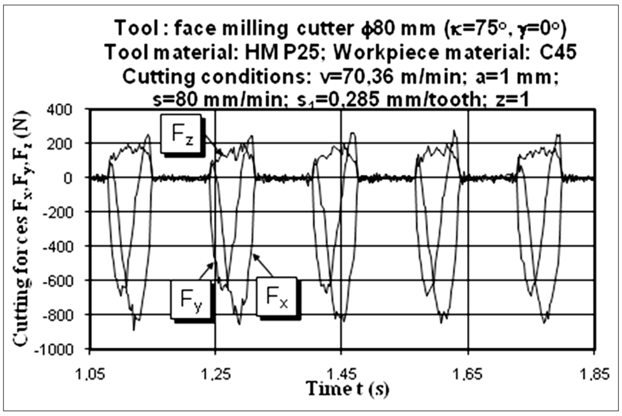

Figure 2: Cutting forces for five revolutions of the cutter
Slika 2: Sile rezanja pri petih obratih rezala

A typical cutting-force signal acting on the cutter in the x, y and z directions during the face milling is presented in **Figure 2**. The average value of the cutting forces F_x and F_y was obtained with the cutting forces for five revolutions of the cutter.[13]

2.2 Materials and cutting conditions

Eight different machinability materials have been used as workpiece materials, **Table 1**. The chemical testing of the steels and silumin were made in the factory Motins in Novi Sad; gray irons were tested in Livnica in Prijepolje; copper, bronze and brass were tested in the company Novkabel from Novi Sad.

The chemical compositions of the investigated materials are shown in **Table 1**. Experiment conditions and research into the mechanical properties of the materials are summarized in **Table 2**. The selection of the cutting conditions are closely connected to the cutting tool and workpiece materials (s_1 – feed per tooth, a – depth of a cut and v – cutting speed).

Metallographic and mechanical tests were performed at the Laboratory for Material Testing, the Department of Production Engineering, the Faculty of Technical Sciences. **Figures 3** to **10** show the microstructures of the tested materials.

Using metallographic researches it was determined that the steels C45 and C60 had a ferrite/perlite structure with clearly defined perlite lamellas, **Figures 3** and **4**.

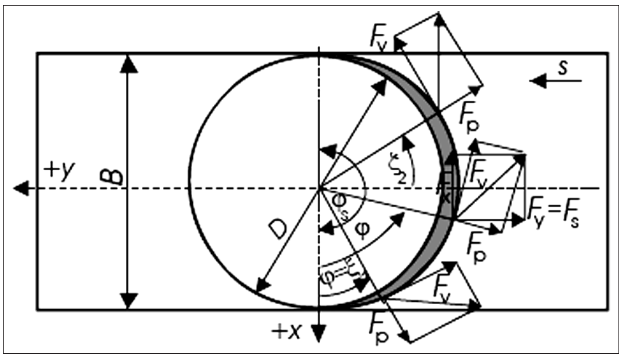

Figure 1: Scheme of cutting forces (**Figure 1** in[1])
Slika 1: Shema sil pri rezanju (**slika 1** v[1])

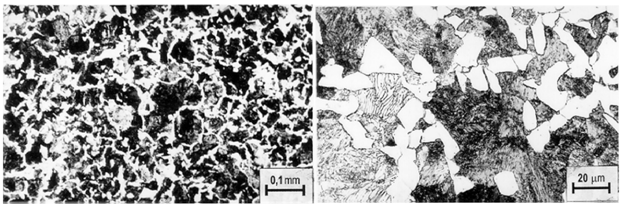

Figure 3: Microstructure of steel C45
Slika 3: Mikrostruktura jekla C45

Table 1: Chemical compositions of the materials used during the machinability test in mass fractions, *w*/%
Tabela 1: Kemična sestava materialov, uporabljenih pri preizkusu obdelovalnosti, v masnih deležih, *w*/%

Material	Chemical composition, *w*/%															
Code in EN	C	Si	Mn	S	P	Cr	Mo	Ni	Cu	V	Fe	Mg	Ag	Zn	Sn	Pb	Sb
C45	0.46	0.262	0.513	0.003	0.008	0.169		0.063	0.079	0.007							
C60	0.57	0.232	0.657	0.041	0.011	0.052	0.015	0.100	0.123	0.006							
GJL150	2.94	1.78	0.84	0.045	–	0.083	–	–	–	–	–	–					
GJL200	3.40	2.05	0.70	0.038	–	0.15	–	–	–	–	–	–					
AlSi12Cu.00	–	10.86	0.128	–	–	–	–	–	1.45	–	1.56	–					
EK2-Cu.00								0.006	99.97		0.0009		0.005	0.0074			
CuSn12.01		–			0.012			0.06	84.37		0.58			rest	11.8	0.73	0.05
CuZn40Pb.05		–	–					0.02	57.68		0.24			rest	0.19	2.47	–

Table 2: Experiment conditions and mechanical properties of the materials used during the machinability test
Tabela 2: Eksperimentalni pogoji in mehanske lastnosti materialov, uporabljenih pri preizkusu obdelovalnosti

Workpiece material Code in EN	Tensile strength R_m/MPa	Hardness HB	Cutting tool material	v/(m/min)	s_1/ (mm per tooth)	a/mm
C45	683	191	HM P25	70.36	0.285	1
C60	719	194	HM P25	70.36	0.285	1
GJL150	199	204	HM K10	70.36	0.285	1
GJL200	220	191	HM K10	70.36	0.285	1
AlSi12Cu.00	70	90	HM K10	281.48	0.281	1
EK2-Cu.00	285	82	HM K10	140.74	0.285	1
CuSn12.01	224	91	HM K10	70.36	0.285	1
CuZn40Pb.05	407	132	HM K10	113.04	0.277	1

All steel was handed out in normalized condition. The microstructure of gray iron GJL150 consisted of perlite and lamellar graphite, type A (according to ASTM), class 1 (>100 mm), equally spread all over the whole section, **Figure 5**. The test showed that the microstructure of gray iron GJL200 consisted of perlite, phosphide eutectic and lamellar graphite, type C (according to ASTM), class 1 (>100 mm), **Figure 6**.

Silumine $AlSi_{12}Cu.00$ was unmodified and consisted of differentiated needle-shaped eutectic and large needles of Al_2Cu, with large moulding porosity, **Figure 7**. The structure of electrolytic copper consisted of polygonal copper grains and a large number of annealing doubles, **Figure 8**. The inhomogeneous microstructure α of a tough solution where the isles of eutectoid (α + δ) were present, was determined with the metallographic researches of tin bronze. The porosity of the structure was noticeable, as well as its dendrite orientation, indicating that it had been obtained by casting, **Figure 9**. Brass had a microstructure α/β containing lead (light fields indicate α brass, dark fields indicate β brass), **Figure 10**.

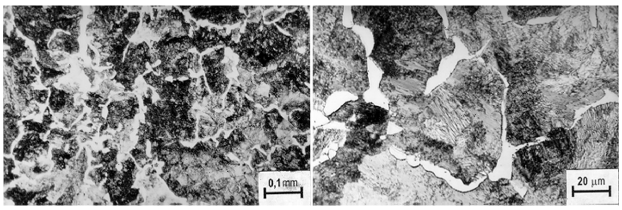

Figure 4: Microstructure of steel C60
Slika 4: Mikrostruktura jekla C60

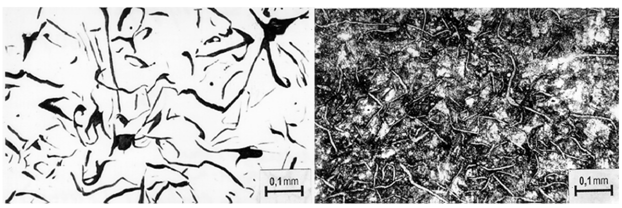

Figure 6: Microstructure of gray iron GJL200
Slika 6: Mikrostruktura sive litine GJL200

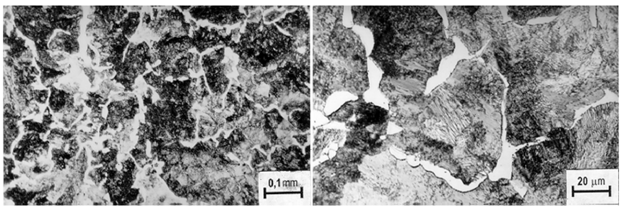

Figure 5: Microstructure of gray iron GJL150
Slika 5: Mikrostruktura sive litine GJL150

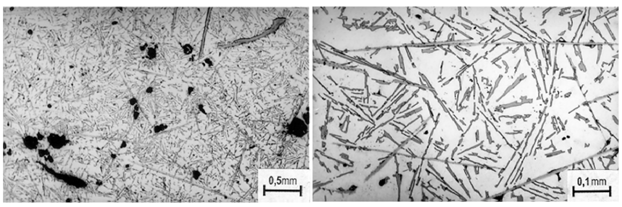

Figure 7: Microstructure of silumine AlSi12Cu.00
Slika 7: Mikrostruktura silumina AlSi12Cu.00

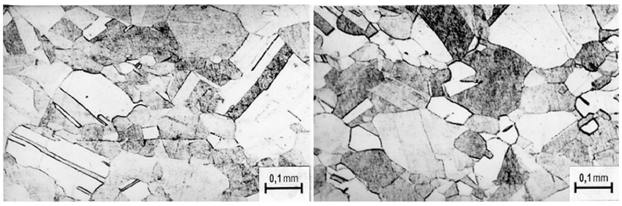

Figure 8: Microstructure of copper EK2-Cu.00
Slika 8: Mikrostruktura bakra EK2-Cu.00

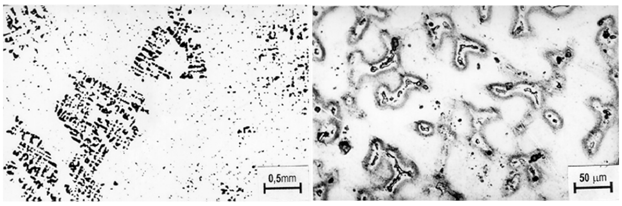

Figure 9: Microstructure of bronze CuSn12.01
Slika 9: Mikrostruktura brona CuSn12.01

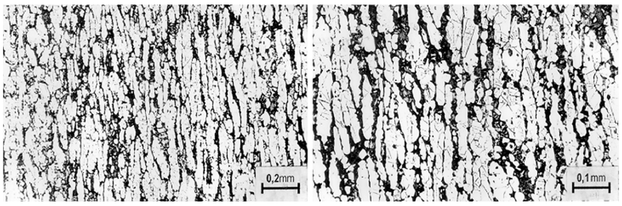

Figure 10: Microstructure of brass CuZn40Pb.05
Slika 10: Mikrostruktura medenine CuZn40Pb.05

3 RESULTS AND DISCUSSION

Figures 11 to **18** present diagrams of variations in orthogonal cutting forces and the main cutting force derived from equation (1) for the face milling of the tested materials.

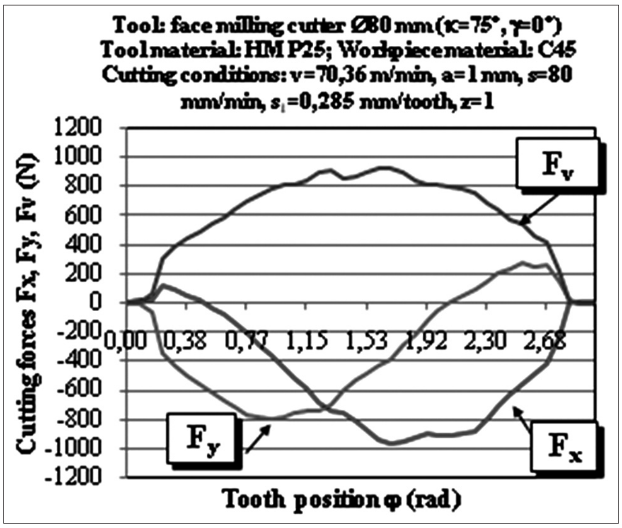

Figure 11: F_x, F_y and F_v vs. tooth position – C45
Slika 11: F_x, F_y in F_v glede na položaj zoba – C45

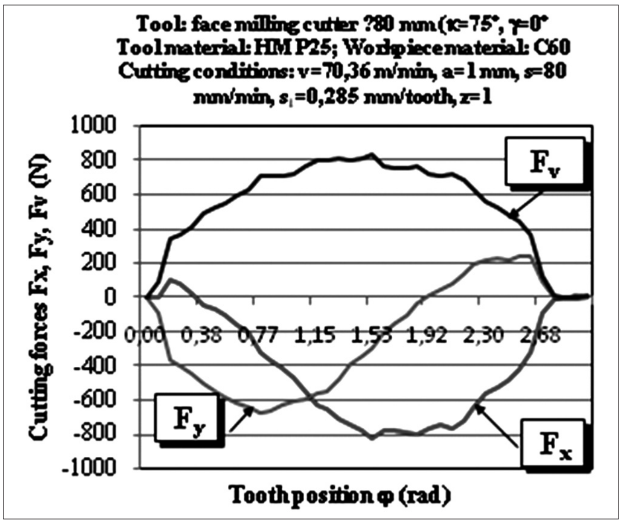

Figure 12: F_x, F_y and F_v vs. tooth position – C60
Slika 12: F_x, F_y in F_v glede na položaj zobe – C60

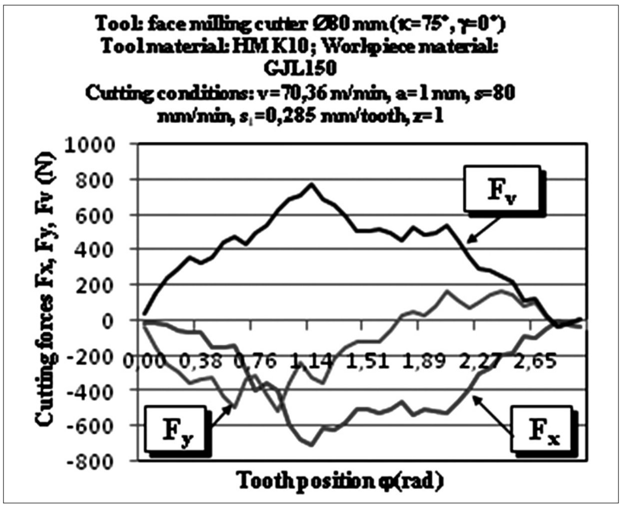

Figure 13: F_x, F_y and F_v vs. tooth position –GJL150
Slika 13: F_x, F_y in F_v glede na položaj zoba – GJL150

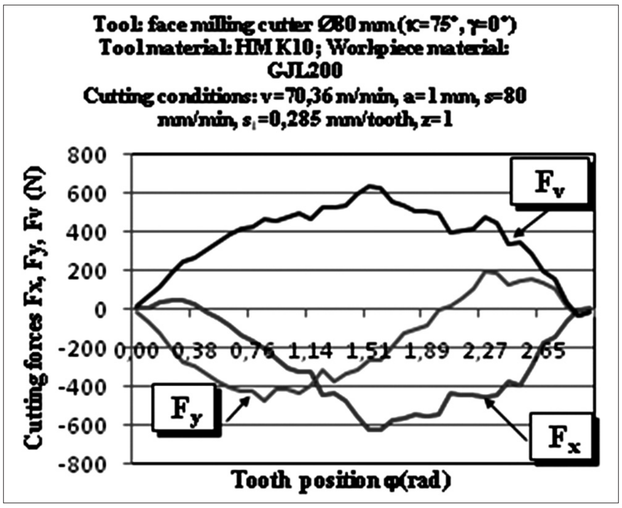

Figure 14: F_x, F_y and F_v vs. tooth position – GJL200
Slika 14: F_x, F_y in F_v glede na položaj zoba – GJL200

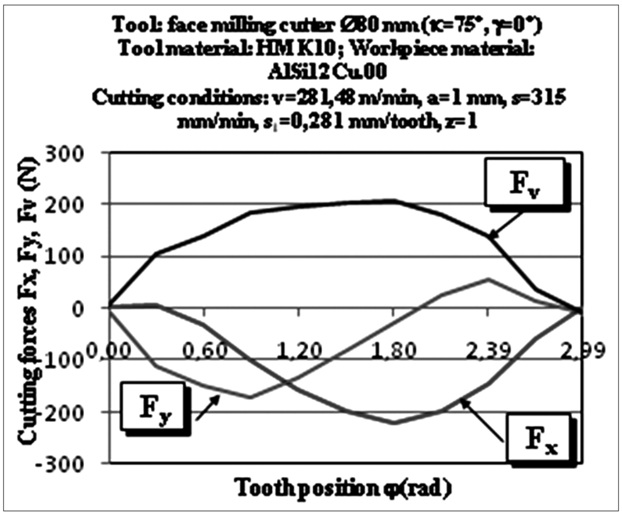

Figure 15: F_x, F_y and F_v vs. tooth position – AlSi12Cu.00
Slika 15: F_x, F_y in F_v glede na položaj zoba –AlSi12Cu.00

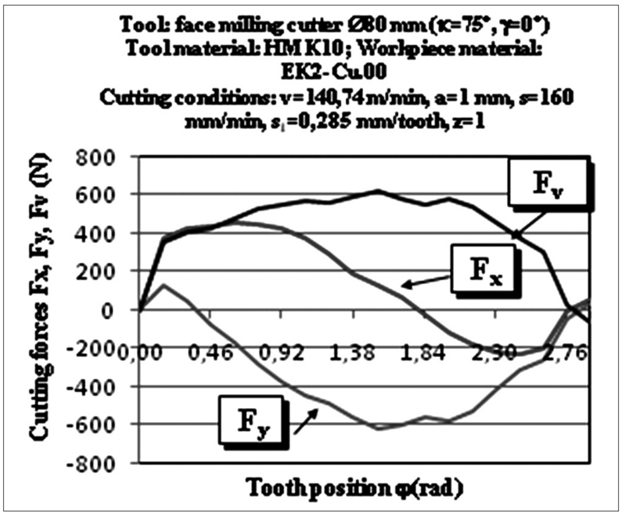

Figure 16: F_x, F_y and F_v vs. tooth position – EK2-Cu.00
Slika 16: F_x, F_y in F_v glede na položaj zoba – EK2-Cu.00

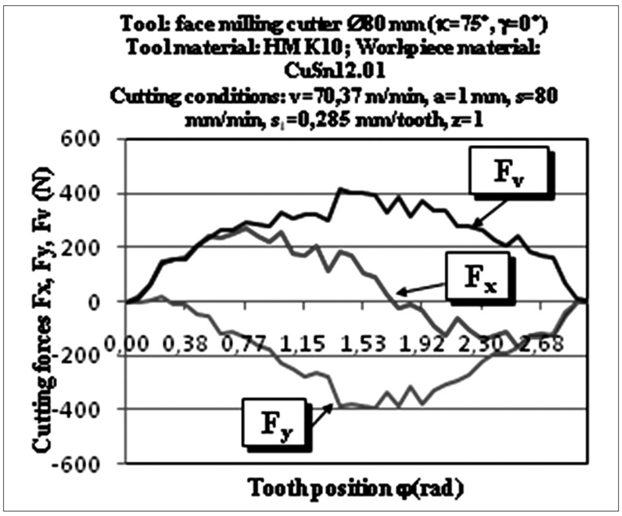

Figure 17: F_x, F_y and F_v vs. tooth position – CuSn12.01
Slika 17: F_x, F_y in F_v glede na položaj zoba –CuSn12.01

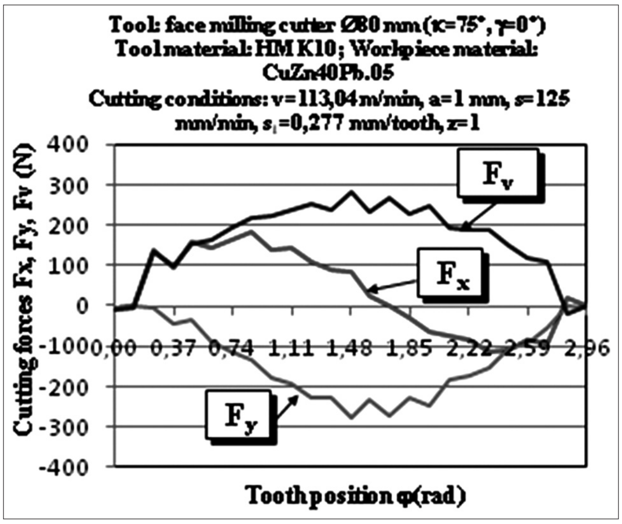

Figure 18: F_x, F_y and F_v vs. tooth position – CuZn40Pb.05
Slika 18: F_x, F_y in F_v glede na položaj zoba – CuZn40Pb.05

The results of measuring the cutting forces during the face-milling process showed that a workpiece material, with its mechanical, chemical and metallographic features, has a significant influence on their values. Mechanical characteristics (tensile strength R_m and hardness HB) have a dominant influence on the value of the main cutting force. For example, the cutting force needed to machine silumine is much lower than the force required for steels or gray mouldings.

The structure of a workpiece material also had a big influence on the value of the measured cutting forces, as well as on the result dissipation. During the cutting of steels, orthogonal forces F_x and F_y had a small dissipation, **Figures 11** and **12**. The structure of these materials was very homogenized without any noticeable micro holes and other impacts. **Figure 11** shows that the steels with a smaller percentage of sulphur (C45) are harder to be machined (a larger main cutting force is required) than the steels with a larger sulphur content (C60). This can be explained with the fact that a larger sulphur content enables the appearance of a larger number of the MnS particles that are plastically deformed during the process of the cutting machining, unlike the fragile cementite tiles in perlite. In addition to this, the presence of MnS particles shortens the contact length on the front surface of the cutting tile. The shorter contact length results in thinner chipping and a weaker cutting force.

The records of the cutting forces during the machining processes for gray tin GJL150 and GJL 200 shows a large dissipation of the experimental points, **Figures 13** and **14**. This can be explained with the presence of a large quantity of lamellar graphite in both materials (more in GJL150). The chipping is extremely short, sometimes even in the form of dust, and in that way its contact with the front surface of the cutting tile is also short, influencing the cutting forces that have smaller values than the forces required for steel machining. The fact that graphite lamellas are weak, makes the cutting forces smaller, too.

During the machining process of silumine AlSi12Cu.00 small cutting forces have been measured. A large tin porosity as well as the micro holes were noticed in the material structure, and, as a result, the cutting forces did not have a continuous flow. A big problem during the experiment with this material was caused by the sticking of the chippings onto the cutting-tool edge. That is why petroleum, which disables the sticking, was used during the machining process.

The main cutting force during the process of brass machining was relatively high. This can be explained with a big contact surface between the workpiece and tool because of the high plastic brass features. For this reason the chipping was thick and during the machining process the tool not only cut but also plastically deformed the working piece. Although the records from the literature say that the occurrence of the layers on the cutting-tool edge during the process of brass machining was reduced with an increase in the cutting speed to over 30 m/min, our experiment has showed something different.

It is known that brass machinability is improved with alloying. This has been proven by measuring the forces during the process of bronze and brass machining, **Figures 17** and **18**. In this case the measured cutting forces are much smaller than during the machining of pure copper, especially during the brass machining. Because of the inhomogeneous and porous bronze structure, there is a significant dissipation of the experimental points. The biphasic brass structure (α/β) also has a tendency to produce layers on the cutting-tool edge at the reduced cutting speeds.

4 CONCLUSION

This paper has discussed the dependence of material machinability on the mechanical properties, microstructure and chemical composition of a workpiece material. According to the experimental results it can be established that:

- Regarding low cutting forces, low values of hardness and tensile strength usually provide better machinability.
- Sulphur forms inclusions in steels, acting as stress raisers in the chip-formation zone and thus increasing machinability.
- Gray cast irons are frequently characterized in the literature as easily machined materials. However, the machinability of gray irons is influenced by a complex interplay of the graphite and its surrounding matrix structure, which is not well understood. The machinability of gray iron primarily depends on its composition.
- Silumine is an easy-to-cut material except for an intensive adhesion of the chip for the insert.
- Copper and copper-based alloys are easier to machine than steels. Copper is more difficult to machine than bronze, but bronze is more difficult to machine than brass.

5 REFERENCES

[1] W. Degner, H. Lutze, E. Smejkal, Spanende Formung, Theorie Berechnung Richtwerte, VEB Verlag Technik, Berlin 1989

[2] W. König, K. Essel, Spezifische Schnittkraftwerte für die Zerspanung metallischer Werkstoffe, Verlag Stahleisen M. B. H., Düsseldorf 1973

[3] E. M. Trent, Metal cutting, Butterworths & Co Ltd, London 1977

[4] M. Kronenberg, Machining Science and Aplication-Theory and Practice for Operation and Development of Machining Processes, 1st Edition, Pergamon Press, London 1966

[5] F. Mocellin, E. Melleras, W. L. Guesser, L. Boehs, J. of the Braz. Soc. of Mech. Sci&Eng, XXVI (**2004**) 1, 22–27

[6] A. Antić, D. Kovačević, D. Zeljković, B. Kosec, J. Novak Marcinčin, RMZ-Materials and Geoenvironment, 58 (**2011**) 1, 15–28

[7] F. Naundorf, Fräsen, VEB Verlag Technik, Berlin 1982

[8] H. Q. Zheng, X. P. Li, Y. S. Wong, A. Y. C. Nee, International Journal of Machine Tools & Manufacture, 39 (**1999**), 2003–2018

[9] P. Kovač, D. Rodić, V. Pucovsky, B. Savković, M. Gostimirović, Journal of Intelligent Manufacturing, doi: 10.1007/s10845-012-0623-z, 2012, 1–8

[10] M. Sekulić, P. Kovač, Journal of Machine Engineering, 8 (**2008**) 2, 65–72

[11] M. Sekulić, Z. Jurković, M. Hadžistević, M. Gostimirović, Metalurgija, 49 (**2010**) 4, 339–342

[12] M. Sekulić, M. Hadžistević, M. Gostimirović, Z. Jurković, The influence of mechanical properties of workpiece material on the main cutting force in face milling, International Symposium of Croatian Metallurgical Society, Šibenik, 2010, 213

[13] M. Sekulić, M. Gostimirović, Z. Jurković, P. Kovač, Calibration of cutting forces coefficients in face milling, Proc. of the 7th Inter. Scientific Conference on Production Engineering, Kairo, 2009, 17–18