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Machining of M390 Microclean® and M398 Mircoclean® PM Steels – The Comparison of Cutting Forces and Surface Roughness

Jozef Majerík (0000-0002-6577-1987), Juraj Majerský (0000-0003-2342-0852), Henrieta Chochlíková (0000-0003-4938-129X), Igor Barényi (0000-0002-9296-600X), Jana Escherová (0000-0002-4203-2495)[1], Mária Kubasáková (0000-0003-2908-3439)
Faculty of special technology, Alexander Dubcek University of Trencin. Ku kyselke 469, 911 06 Trencin. Slo-vakia.
jozef.majerik@tnuni.sk, juraj.majersky@wittmann-group.sk

Article deals with comparison of cutting forces and surface roughness between materials produced by powder metallurgy - M390 and M398 Microclean® from producer, company Böhler. Main interest is the analysis and comparison of the cutting forces and surface roughness after the processing by cutting inserts with DNMG and WNMG geometry, radius 0.4 and 0.8 mm, after hard turning at the same process parameters for both materials and all four types of cutting inserts. The comparative studies were carried out for cutting forces and surface roughness with the aiming to observe the difference between "old generation" M390 and "new generation" M398 PM Steel for future processing in production. The corelation between the cutting forces and surface roughness was investigated. The measurement results indicate that the M398 is necessary to process with higher cutting forces which are linked with higher surface roughness than for M390. It is in relation with higher contain of additive elements in M398 and carbides formed by them even that both materials are in delivered condition soft annealed, containing Ferrite instead of Martensite [1], [2]. No less significant is influence of the type of cutting insert. The WNMG geometry showed better results for processing of both materials and is more suitable for their processing as well as radius 0.8 reached superior cutting parameters and surface roughness than 0.4. The result of this experiment is the selection of the appropriate geometry of the cutting insert, together with the determination of the correct parameters for machining the investigated materials supported by the results of the experiment. Suitable combination of cutting inserts and cutting parameters can reduce the time and energy requirements to process these high-quality steels. The results of this experiment helped to fulfil the knowledge about both materials in the row of experiments which are provided to increase material properties against abrasion and wear.

Keywords: PM Steel, Cutting force, Cutting insert, Dynamometer, Surface roughness

1 Introduction

Materials M390 Microclean® and M398 Mircoclean® produced by company Böhler are powder metallurgy steels with high contain of Chromium and other additional components. (see Tab. 1 – 2) [1, 2] Both steels are dedicated mainly to plastic industry for molds and machine parts. In plastic industry machine parts must resist high wear and chemical influences. Due to contain of both materials and production by HIP (Hot Isostatic Pressing) technology, these intermetallic materials are very tough, wear and chemical resistant. Materials produced by the HIP method are well known for their minimal porosity, very precise composition control, high density, isotropic properties, very fine microstructure with small grain. [3] Minimum grain sizes and round shapes of carbides in powder steels significantly increase the values of critical stresses. [3-4] According to J.M Torralba [3] and according to practice, this method (HIP) is suitable to produce materials intended for high loads, abrasive environments, for example the defence or aerospace industries.

Both materials must withstand the abrasive environment in combination with high temperatures (up to 450 °C) which are conditions commonly used in plastic industry. Moreover, these materials are used in food industry for food processing machines, especially for cutting devices and knives. It places high demands on materials – the compactness, toughness and resistance against wear must be enormous. In food industry the particles of materials cannot contaminate the food, otherwise it can cause harm to the person consuming the product. In plastic industry the particles of materials can cause damage of the injection molding tool surface or blocking of mold inlet system, or the destruction of the molded part later. Therefore, the difficult machining conditions were expected before the experiment.

In their article, M. Stanford and P.M. Lister [5] solved the influence of the environment on the wear of cutting tool while processing the steel. Based on their tests they recommended cooling of the cutting tool by Nitrogen – N2, or mixture of the air with majority of Nitrogen which was used as a coolant. The pressed air is not recommended because the higher contain of Oxygen causes quicker wear of the tool in comparison with other methods. Using of Nitrogen has an advantage in situations where standard liquid coolants are not suitable – for example when the chip of material would be analysed.

Team of authors around M. Akif Erden [6] investigated changes of properties after adding of Molybdenum to powder steel. One of main outputs was that the addition of Mo improved the hardenability of steels with the addition of Ni and Cr, and at the same time reduced its brittleness after hardening. They also found out that increasing of cutting speed will improve the surface roughness *Ra* up from 19,8 % up to 36,6 % [6, 12] According to their results, the cutting tool coating and feed rate had the biggest influence on the cutting forces *Fz* and surface roughness *Ra*. The shape of chip was mostly affected by the feed rate but without a significantly observed change in the cutting speed.

Majerík et al. [7] analysed the surface structure of M390 and M398 PM steels after hard turning from the roughness and chip point of view. Authors found out that at the specific parameters the WNMG and DNMG geometry cutting inserts with diameter 0.4 mm burned down during the machining. The feed rate as a cutting parameter had the highest effect on surface roughness, then the lower feed rate and the lower surface roughness was achieved. They recommended coolants to avoid the damage of the cutting insert together with obtaining lower surface roughness and to process material in delivered condition.

Šalak et al. [8] found during the tests of new testing apparatus for porous PM steels that the microhardness of the machined surface shows that the hardening occurs even at low machining speeds and not only at high speeds. It can be evaluated as a possible way how to prepare difficult parts from M390 and M398 and after machining, parts should be processed by the HIP [9 - 10] to get compact product without pores, what can bring savings for production and savings of very expensive material. The additional HIP brings improving of the material properties, including surface roughness, surface integrity but with possible negative influence on the corrosion resistance. [10]

Based on analysis of available articles the tests should be performed. Authors of this article continuously work on the goal to improve surface properties of material M390 and M398, especially surface integrity and following surface processing. This article brings partial result of long-term research with intermetallic materials mentioned above. After the end of the research, it is assumed that the results will be applied in industrial practice.

The paper is also a continuation of previous research by the author's team [7], which was thematically focused on surface roughness, topography, accuracy, chip formation analysis & investigation of M390 and M398 steels after hard machining, which was also the title of a previous paper published in this journal.

2 Materials and methods

Powder metallurgy PM steels Böhler M390 Microclean® (microstructure can be seen in Fig. 1) and M398 Microclean® (microstructure can be seen in Fig. 2) has a high contain of Chromium and other alloy components. (see Tab. 1-2). Chromium and other components provide special properties of both materials – especially wear and corrosion resistance. In plastic industry – the corrosion and wear are linked with the processing of plastic materials. Some types of plastic materials contain physical components for improvement of its properties, for example glass fibres and chemical components for special properties of materials, for example Sulphur or Phosphorus. These properties are linked with high temperatures (usually 220 °C – 450 °C), therefore the properties of materials resisting all these conditions must be unique. In addition to components, the method of production of these steels also affects the properties of the material. Powder metallurgy, especially method HIP with very fine grain powder helps to create structure of material which is close to ideal material. [11-12] The fine structure of the material consists of carbides and base matrix (Ferrite in delivered condition, Martensite after hardening), but in comparison with standard steels there are not the grain borders which can be evaluated as a material defect, but the fine grain structure is very compact and the grain borders are minimal, what eliminates the possible defects as an intergranular corrosion or cracks.

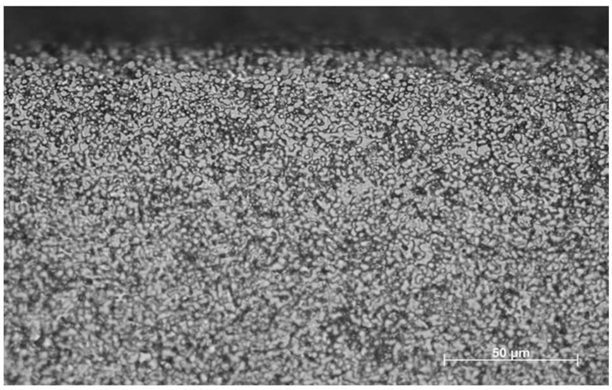


Fig. 1 *LM microstructure of experimental steel M390*

Tab. 1 *Comparison of the chemical composition of M390 material (wt. %) [1], [7]*

Chemical content of M390 according to Microcelan® and spectral analysis measurement							
Component	C	Si	Mn	Cr	Mo	V	W
Content % Böhler	1.9	0.7	0.3	20.0	1.0	4.0	0.6
Content % Spectro	1.98	1.19	0.38	20.37	0.85	4.02	0.33

Tab. 2 *Comparison of the chemical composition of M398 material (wt. %) [2], [7]*

Chemical content of M398 according to Böhler Microcelan® and spectral analysis measurement							
Component	C	Si	Mn	Cr	Mo	V	W
Content % Böhler	2.7	0.5	0.5	20.0	1.0	7.2	0.7
Content % Spectro	2.65	0.55	0.51	20.09	1.0	7.1	0.43

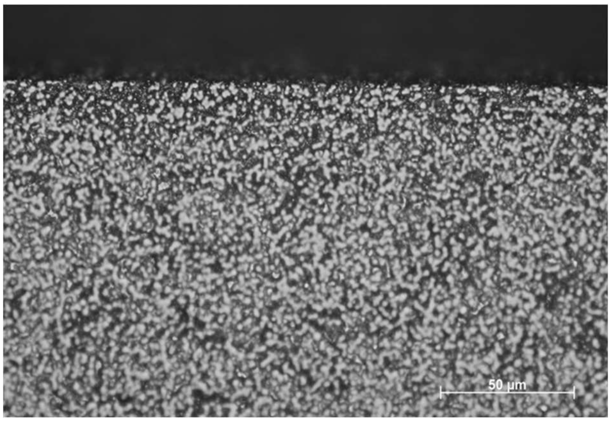


Fig. 2 *LM microstructure of experimental steel M398*

For machining were chosen cutting inserts from company DORMERPRAMET - types DNMG 110408E-NMR, DNMG 110404E-M, WNMG 080408E-NF T9315 and WNMG 080404E-NF T9315. The cutting inserts were recommended directly by supplier DORMERPRAMET. Both types of cutting inserts (selected geometry WNMG of cutting insert as an example for visualization) was selected with radius r_ε = 0.8 mm (can be seen in Fig. 4a, b observed by SEM and Fig. 5a, b observed by LSCM miroscopy) and also with 0.4 mm.

Experiment was provided in the laboratory of Faculty of mechanical engineering VUT Brno, Czech Republic. The experimental device contained turning machine SV 18 RD with electronic regulation of rpm, Dynamometer Kistler 9257B connected to multichannel load amplifier Kistler 5070 (see in Fig. 3) and computer with application DynoWave. After each turning process the surface roughness was measured by the device TR 100 (also can be seen in Fig. 3). All parameters and measurements were recorded to prepared excel sheets.

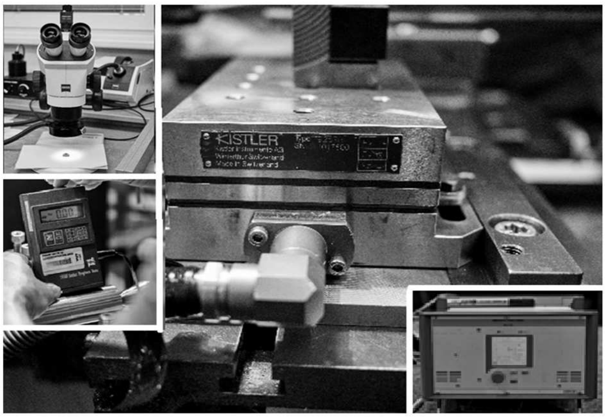
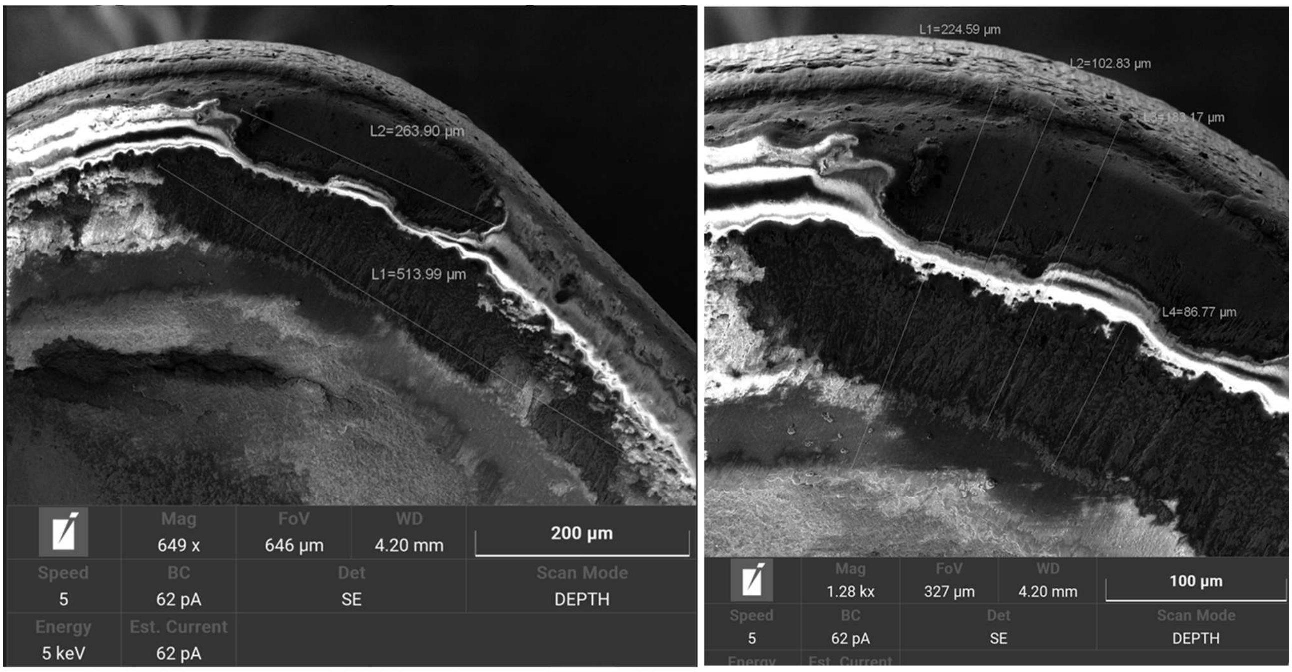


Fig. 3 *Cutting forces measurement while M390 and M398 turning & surface roughness/cutting inserts wear experimental setup*

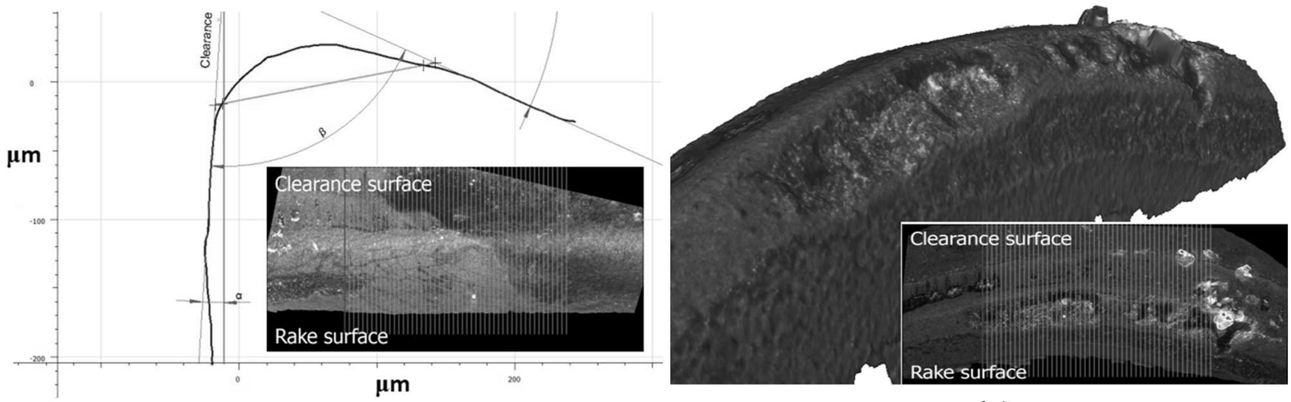
After each cutting process the surface was measured by surface roughness measuring device TR100 Surface Roughness Tester. (also, partialy can be seen in Fig. 3) The cutting parameters were chosen, analogous as a cutting inserts based on former experiment. [7] The difference was the selecting of one value for each machining parameter – cutting speed v_c = 225 m.min^{-1}, feed rate f=0.2 mm.rev^{-1}, depth of cut a_p = 1 mm.

Experiment was provided on the turning machine SV 18 RD with retrofit – added electronic speed control. The feed was automatized, altogether with its switch off. Due to the decreasing diameter of the workpiece, the machining time also decreased, which can be demonstrated on the graphs of the cutting forces, for the first and twelfth passes of the cutting tool (as can be seen in Fig. 6a, b). Cutting parameters was adjusted during the experiment because of the decreasing parameters with the goal to keep the cutting speed on the same level.



a) **b)**

Fig. 4 *a) Wear process of the rake face of the used cutting insert of geometry WNMG 080408E-NF T9315 observed by SEM microscopy (magnification 200μm)*
b) Wear process of the rake surface of the used cutting insert of geometry WNMG 080408E-NF T9315 observed by SEM microscopy (magnification 100μm)



a) **b)**

Fig. 5 *a) Wear process of the clearance and rake surface profile of the used cutting insert of geometry WNMG 080408E-NF T9315 observed by ALICONA laser scanning confocal microscopy LSCM*
b) Wear process of the 3D clearance and rake surface of the used cutting insert of geometry WNMG 080408E-NF T9315 observed by ALICONA laser scanning confocal microscopy LSCM

3 Results and discussion

Main goal of this part of continuing experiments was to increase the knowledge about machining of materials M390 and M398, especially in the part of cutting forces measurement and by that approving of information from supplier about higher wear resistance of M398 in comparison with M390. [1, 2] By the comparing of the cutting forces and surface roughness it would be possible to proceed in knowledge about the material altogether with further information for processing of M398 in practice. In comparison with previous experiment described by authors Majerík et al. [7] there was chosen only one set of parameters for all experiments and cutting inserts. The parameters were chosen based on result of previous experiment [7] and are mentioned in chapter. 2 of this article. Before the start of experiment, the expectations were the cutting forces for M398 will be higher altogether with surface roughness Ra. A demonstration of measured surface roughness profiles after turning of worse-machinable M398 steel by two different cutting insert geometries is shown in Fig. 8. All results were recorded directly at the place and surface roughness was measured just after the pass of cutting tool with appropriate cutting insert. Cutting forces were measured (the first and twelfth passes of the cutting tool with geometry WNMG 080408E-NF which are shown in Fig. 6a, b just for the predicted worse machinability and predicted higher force load during machining process) and aligned with results of surface roughness for later processing and evaluation.

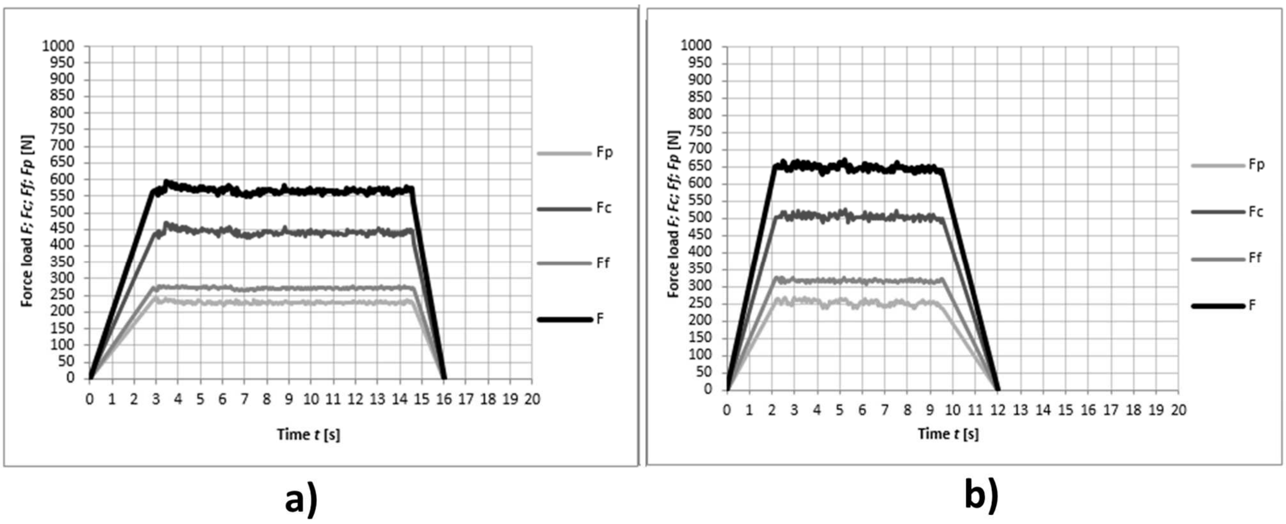


Fig. 6 *a) Graph of the dependence of cutting forces on time during experiment with cutting insert WNMG 080408E-NF for material M398 - the first pass of the cutting tool*
b) Graph of the dependence of cutting forces on time during experiment with cutting insert WNMG 080408E-NF for material M398 - the twelfth pass of the cutting tool

Based on huge number of results there was a decision to prepare a graph of average values of surface roughness for individual cutting inserts (Tab. 4), (Fig. 9) and also average values of cutting forces for individual cutting inserts (Tab. 3), (Fig. 7). Thanks to that the graphs are clear and simple with easy visible results for mutual comparison.

Tab. 3 *Average cutting force Fc for M390, M398 steels for all the types of used cutting inserts*

Cutting insert / Material		1. WNMG 080408E-NF	2. WNMG 080404E-NF	3. DNMG 110408E-NMR	4. DNMG 110404E-M
M398	*F* (N)	513.00	486.83	538.17	570.63
M390	*F* (N)	492.58	480.00	529.33	544.58

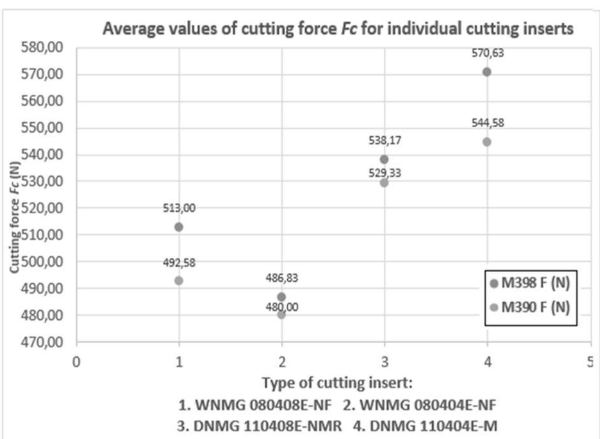


Fig. 7 *Average cutting force values for materials M390 and M398 after using all types of cutting inserts*

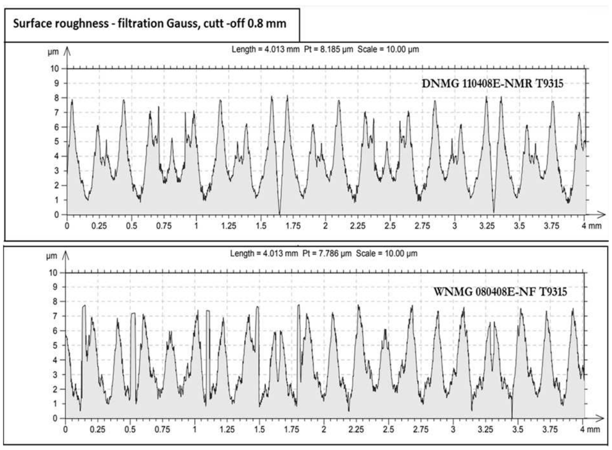


Fig. 8 *Comparison of surface roughness profiles when turning M398 PM steel with two types of cutting insert geometries*

Tab. 4 *Average values of surface roughness Ra and Rz for M390, M398 for all the types of cutting inserts*

Material \ Cutting insert		1.	2.	3.	4.
		WNMG 080408E-NF	WNMG 080404E-NF	DNMG 110408E-NMR	DNMG 110404E-M
M398	Ra (μm)	1.96	2.69	2.30	3.24
	Rz (μm)	11.07	13.09	15.70	14.37
M390	*Ra* (μm)	1.58	2.24	1.79	3.01
	Rz (μm)	9.68	11.06	11.67	12.77

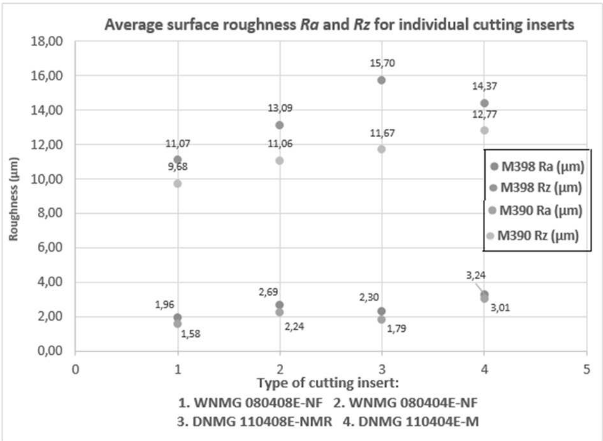


Fig. 9 *Average surface roughness Ra and Rz values for materials M390 and M398 after using all types of cutting inserts*

4 Conclusions

Based on results displayed in the graph (Fig. 7) it is possible to see that for processing of material M398 it was necessary to use higher cutting force than for M390. Similar results are visible in the graph of surface roughness (Fig. 9) where it is clearly visible that the surface roughness is higher at M398 in comparison with M390, also. The highest difference is visible for surface roughness parameter *Rz*. It can attribute this fact to several reasons, such as the use of new cutting inserts for the M398, different chip shaper, but most probable reason of this fact is higher resistance against cutting/wear of material M398. It is also the reason for higher surface roughness. Due to the higher cutting force, there is a higher load on the surface, which causes worse alignment of the marks of the cutting edge. The material holds more firmly and at machining does not cause such intensive alignment of *Rz* roughness protrusions as at M390. This is also visible when comparing the *Rz* roughness, which is significantly higher for M398 than when there is compared *Ra* roughness, which does not show that much difference in micrometres as *Rz* shows. When we compare the percentage differences, the difference in cutting force is in range from 1.42% to 4.78% (the cutting force is always higher for M398 than for M390) (see Tab. 3) (see Fig. 7). In terms of roughness, the differences are higher. For *Ra* from 7.71% to 28.29% and for *Rz* from 12.51% to 34.53%. Again, the roughness is higher for M398 than for M390 (see Tab. 4), (see Fig. 9). These results were expected based on information from material supplier [1, 2], company Böhler, but also from previous experiments provided with the same materials [7]. Even that there are some results which were not expected and brought new information to this research.

These data clearly show the M398 is worse-machinable than M390 and it will be important to correctly define the finishing operations to achieve the desired surface integrity [11, 14], suitable for processing plastic materials. The results of surface roughness *Ra* helped to confirm outputs from previous experiment.

Summary of all performed experiment is following:

- The cutting forces are higher for M398 in comparison to M390.
- The Surface roughness *Ra* and *Rz* is higher for M398 in comparison to M390.
- The higher cutting forces and surface roughness of M398 is caused by higher contain of additional components – the composition of material.
- The radius of the tool tip had influence on the surface roughness and cutting force – for the cutting inserts with the tip with radius 0.8 mm the surface roughness and cutting force were lower than for 0.4 mm.
- The WNMG geometry achieved better results in both values (lower cutting forces, lower surface roughness) for both materials (M398 and M390) in comparison with DNMG geometry. The highest difference is visible at cutting forces, where WNMG has lower value of cutting force for both – M390 and M398

than DNMG for M390 which is lower than M390.

- At the surface roughness it is possible to see correlation between the tool tip radius and surface roughness, the surface roughness for DNMG geometry is higher than for WNMG, but only in comparison of cutting inserts with the same radius (DNMG with 0.4 mm to WNMG with 0.4 mm and DNMG with 0.8 mm to WNMG with 0.8 mm). The difference between WNMG and DNMG is not so visible as for cutting force.
- WNMG cutting insert geometry is preferable for use with M390 and M398 materials than DNMG geometry.
- Based on observed results it is possible to state that the using of material M398 will bring longer lifetime of the parts than parts from M390. It can be determined on the basis of the cutting forces and the behaviour of the material during machining.
- Material processors must be careful to follow all processing conditions and achieve the desired surface integrity when switching from M390 material to M398 material, due to the possible occurrence of undesirable defects caused by higher roughness, or subsequent undesirable effects caused by different surface properties after the same type of processing with the same parameters.
- The parameters for processing M398 must be different than for M390, although not by much, but they must be adapted to a material with higher performance properties, which M398 undoubtedly is.
- Processing and obtaining the desired surface properties of products from intermetallic material M398 will probably be more energetically demanding than with M390, but this will be balanced by their quality and persistence.

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References

[1] VOESTALPINE BÖHLER EDELSTAHL GMBH & CO-KG. (2019). M390 Microclean® Plastic mould steel, In: *voestalpine Böhler Edelstahl GmbH & Co-KG. Kapfenberg.* M390EN - 01.2019

[2] VOESTALPINE BÖHLER EDELSTAHL GMBH & CO-KG. (2018). M398 Microclean® Plastic mould steel., In: *voestalpine Böhler Edelstahl GmbH & Co-KG. Kapfenberg.* M398EN - 10.2018

[3] TORRALBA, J.M., CAMPOS M. (2014). Toward high performance in Powder Metallurgy, In: *CSIC*, doi: http://dx-1doi-1org-1iy15n4gc02c3.hanproxy.cvtisr.sk/10.3989/revmetalm.017

[4] ČERNÝ, M. et al. (2012). Notch aspects of RSP steel microstructure, In: *Acta Universitatis Agriculturae et Silviculturae Mendaleianae Brunensis*, Volume LX 5, Nr. 5,

[5] STANFORD, M., LISTER, P. M., (2004). Investigation into the relationship between tool-wear and cutting environments when turning EN32 steel, In: *Emerald Group Publishing Limited*, ISSN 0036-8792, doi: 10.1108/00368790410524065

[6] AKIF ERDEN, M., et al. (2021). Investigation of microstructure, mechanical and machinability properties of Mo-added steel produced by powder metallurgy method, In: *The International Journal of Advanced Manufacturing Technology*, doi: https://doi.org/10.1007/s00170-021-07052-z

[7] MAJERÍK J. et al. (2023) Surface roughness, topography, accuracy, chip formation analysis & investigation of M390 and M398 steels after hard machining, In: *Manufacturing Technology*, Vol. 23, No. 1, ISSN 1213–2489 e-ISSN 2787–9402, DOI: 10.21062/mft.2023.015

[8] ŠALAK, A., VASILKO, K., SELECKÁ, M., DANNINGER, H. (2006). New short time face turning method for testing the machinability of PM steels. In: *Journal of Materials Processing Technology*, Vol. 176, No. 1-3, pp. 62 – 69. TTP. Elsevier. ISSN 0924-0136

[9] MEHMETI, A., LYNCH, D., PENCHEV, P., MARTINEZ RAMOS, R., VINCENT, D., MAURATH, J., WIMPENNY, D. I., ESSA,

K., DIMOV, S. (2021). The Effect of Hot Isostatic Pressing on Surface Integrity, Microstructure and Strength of Hybrid Metal Injection Moulding, and Laser-Based Powder Bed Fusion Stainless-Steel Components. In: *Applied Sciences*, Vol. 11, No. 16, Article No.7490. MDPI. ISSN 2076-341

[10] KLUCZYNSKI, J., SNIEZEK, L., GREZLAK, K., OZIEBLO, A., PERKOWSKI, K., TORZEVSKI, J., SZACHOGLUCHOWICZ, I., GOCMAN, K., WACHOWSKI, M., KANIA, B. (2020). Hot isostatic pressing influence on the mechanical properties of selectively laser-melted 316L steel. In: *Bulletin of the Polish Academy of sciences, Technical Sciences*, Vol. 68, No. 6, pp. 1413 – 1424. PAN. ISSN 2300-1917

[11] GRIFFITS, B. (2001), Manufacturing surface technology, In: *Surface integrity & functional performance Penton Press London*, ISBN 1-8571-8029-1

[12] EUROPEAN POWDER METALLURGY ASSOTIATION (2011), Introduction to Hot Isostatic Pressing Technology, *EUROPEAN POWDER METALLURGY ASSOTIATION, 2nd Edition;*

[13] DORMERPRAMET (2021), Soustružení-Turning, In: *DORMERPRAMET*, Catalogue

[14] DAVIM, J. P. (2010), Surface integrity in machining, In: *Springer-Verlag London Limited*, ISBN 978-1-84882-874-2