Influence of Cutting Tool Wear when Milling Inconel 718 on Resulting Roughness

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At present, a large spectrum of cutting tools and machines is available. Therefore, cutting of difficult to cut materials seems not to be a problem which could not be solved by an appropriate choice of cutting system. This article deals with wear of cutting tool edges when milling a superalloy Inconel 718 and its direct influence on resulting roughness of a machined surface. Combinations of different cutting speeds and feeds have been performed. A criterion of flank wear amounting to VB=0.7 mm was chosen for machined material Inconel 718 and used cutting materials in combination with cutting conditions. Regarding the exacting character of the test it was necessary to use an as solid as possible machine, that is why a 3-axis CNC milling machine was chosen. All tests were performed with process liquid because of extremely high temperatures which occur.

Keywords: milling, Inconel 718, cutting speed, roughness

1 Introduction

Requirements of the industry for increasing reliability of machine parts lead to use of materials called superalloys. These materials should be both mechanically and chemically very resistant and, at the same time, their weight should be as small as possible. Machining of these difficult to machine materials containing also nickel alloys is very problematic. Properties of superalloys, which are desirable from the point of view of construction, make, on the other hand, their machinability worse [1, 2, 3].

At the most it concerns generating of extreme quantity of heat on the cutting tool edge [4, 5, 6]. For a stable machining process and a predictable course of cutting tool wear a stable, highly solid machine with a sufficient reserve of main spindle capacity is recommended. Wear occurs owing to interaction of machining system members between tool, workpiece, cutting medium and cutting conditions [7, 8, 9]. The course of chip formation and breaking plays also its role. The more imperfect this process is, the more stressed is the system, namely due to thermal effect. When milling nickel alloys, an intensive wear on tool flank occurs [10, 11, 12]. It can be divided into three basic phases. First, wear appears in the form of wear of flank surface and in the form of a partial crater wear. Then, in the second phase, which takes a substantially longer time, primary manifestations of wear are changed and have notch character. In the final phase wear of flank surface occurs in such a way that size of wear of notch character and size of wear of cutting tool point equalize. Roughness of machined surface results from edge marks of a cutting tool. Roughness depends on many factors, which also influence the course of machining, namely on cutting speeds and feed sizes [13].

2 Material Characteristics

2.1 Machined Material INCONEL 718

In order to perform experiments for establishing the influence of cutting conditions on roughness of machined surface after plane milling of nickel alloys, material Inconel 718 was chosen. In origin, the alloy was determined only for space industry and then it was applied also in civil industry. It belongs to a group of nickel based alloys, which are used in extreme conditions. Above all, they are applied for production of parts which should be extremely resistant to high temperatures and corrosion. Inconel materials are widely used in aircraft industry for production of components located in heat stressed sections of engines, gas turbines, space ships, nuclear reactors, cryogenic tanks and also in mining industry. The basic element of Inconel 718 is nickel (approx. a half of chemical composition), which determines the basic mechanical properties. It contains also a considerable quantity of chromium. The residue of material is formed by elements in less significant quantity, see Tab. 1 [14].

***Tab. 2** Chemical composition of Inconel 718 [14]*

Chemical elements involved [$w_{\%}$]							
Ni	Cr	Nb	Mo	Co	Al	Cu	Mn
50.0 – 55.0	17.0 – 21.0	4.75 – 5.5	2.8 – 3.3	1.0	0.65 – 1.15	0.2 – 0.8	0.35
Chemical elements involved [$w_{\%}$]							
Si	Ti	C	S	P	B	Fe	
0.35	0.3	0.08	0.015	0.015	0.006	Residue (18)	

2.2 Machining of Inconel 718

Material Inconel 718 belongs according to the standard ČSN ISO 513 to a group S, it means a group in which heat-resistant materials, alloys and nickel / cobalt / titanium based superalloys are ranged. The main problem occurring when milling Inconel 718 is high temperature on tool cutting edge. It occurs above all due to high contents of nickel and chromium, see Tab. 1. Therefore, a big edge wear is characteristic when milling this material. A notch wear occurs which result in breaking of indexable insert. Tools with positive geometry and an appropriately rounded edge should be used for machining in order to prevent sticking of chips on insert. The machine-tool should guarantee a sufficient torsional moment, namely when applying low cutting speeds. A further complication when machining is high ductility of Inconel 718. It achieves nearly 28% at the temperature of 800°C and thus, the edge is more stressed. The tool lives are substantially shorter than when machining usual metal materials [15,16].

3 Experimental Work

The substance of the experiment was finding of such a tool which would have the most favourable results of roughness of the machined surface and, at the same time, finding of an appropriate cutting material, cutting conditions as well as geometry. Milling was carried out on a prism of Inconel 718 with basic sizes of 70x115x320mm. For particular materials of cutting tool three different cutting speeds combined with various feeds were used. For cutting materials in combination with cutting conditions and cutting geometry a flank wear amounting to VB_B = 0.7 mm was chosen for the experiment. It was chosen as the most appropriate for milling of alloy Inconel 718 by interrupted cut with use of a process medium.

For milling of nickel alloys it is recommended to use a machine which is as solid as possible. For the experiment the milling machine TOS FNG 32 CNC was used. The milling machine is equipped with control system Heidehain TNC 124 Control.

An inserted-tooth face cutter with design for 6 square inserts having rear angle of κ_r = 45° was used for the experiment, see Fig. 1.

Three inserts of square form made by manufacturers ZCCT and Sandvik were chosen. Length of cutting edge of all indexable inserts with length of 13,4 mm and recommended cutting depth from 0,5mm to 4 mm were chosen. A common geometry of these tools is characterized by a positive rake angle. Inserts differ from each other by the way and type of coat. Tools of the company ZCCT are provided with a finish having PVD technology and a SANDVIK tool is provided with a MT-CVD finish. A further difference between indexable inserts was the form of a chip-former. These differences are shown in Fig. 2.

Fig. 1 *Inserted-tooth face cutter ZCCCT FMA01-080-A27-SE12-06 [17]*

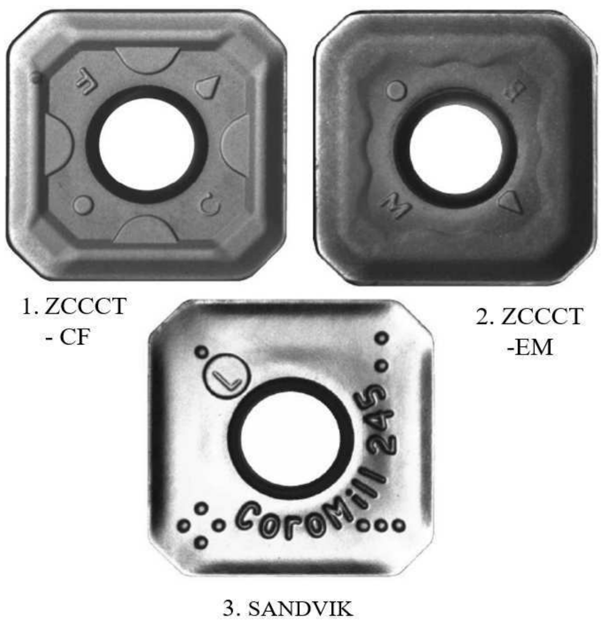

Fig. 2 *Tested indexable insert [17, 18]*

The choice of cutting conditions complied with recommendations of manufacturers of particular inserts. Cutting speeds varied from 20 m/min^{-1} to 40 m/min^{-1}. A feed per tooth was chosen from 0,1 mm to 0,25 mm. The cutting depth a_p = 1 mm was constant for the whole time of the experiment, see Tab. 1 Used milling cutter, indexable insert and cutting conditions.

Tab. 2 *Used milling cutter, cutting tool and cutting conditions*

Type of milling cutter	ZCCCT FMA01-080-A27-SE12-06						
Number	**Indexable insert**	**f_1 [mm]**	**f_2 [mm]**	**f_3 [mm]**	**v_{c1} [m·min^{-1}]**	**v_{c2} [m·min^{-1}]**	**v_{c3} [m·min^{-1}]**
1	ZCCCT SEET 12T3-CF (YBG102)	0.1	0.15	0.2	20	30	40
2	ZCCCT SEET 12T3-EM (YBG202)	0.1	0.15	0.25	20	30	40
3	SANDVIK R245-12 T3 E-ML (2040)	0.1	0.14	0.2	20	30	40

3.1 Measurement of cutting insert wear and of surface roughness

In this experiment flank wear of an indexable insert VB_B was measured, which was performed by means of micrometry method. For this kind of wear an appropriate microscope is necessary. A workshop microscope equipped with digital video camera with additional light was used. Interconnection between the microscope and PC was performed through programme Motic Image Plus 2.0 ML. From given variants of combinations of cutting speeds and feeds there were evaluated the results where inserts took the biggest amount of quantity of material at the given terms, thus, they obtained a required wear criterion after the biggest number of crossings. If the quantity of taken material were the same with more variants of cutting conditions, a criterion of higher productivity would decide. In Fig. 3 the course of measurement of cutting insert 3 with an achieved wear criterion is shown.

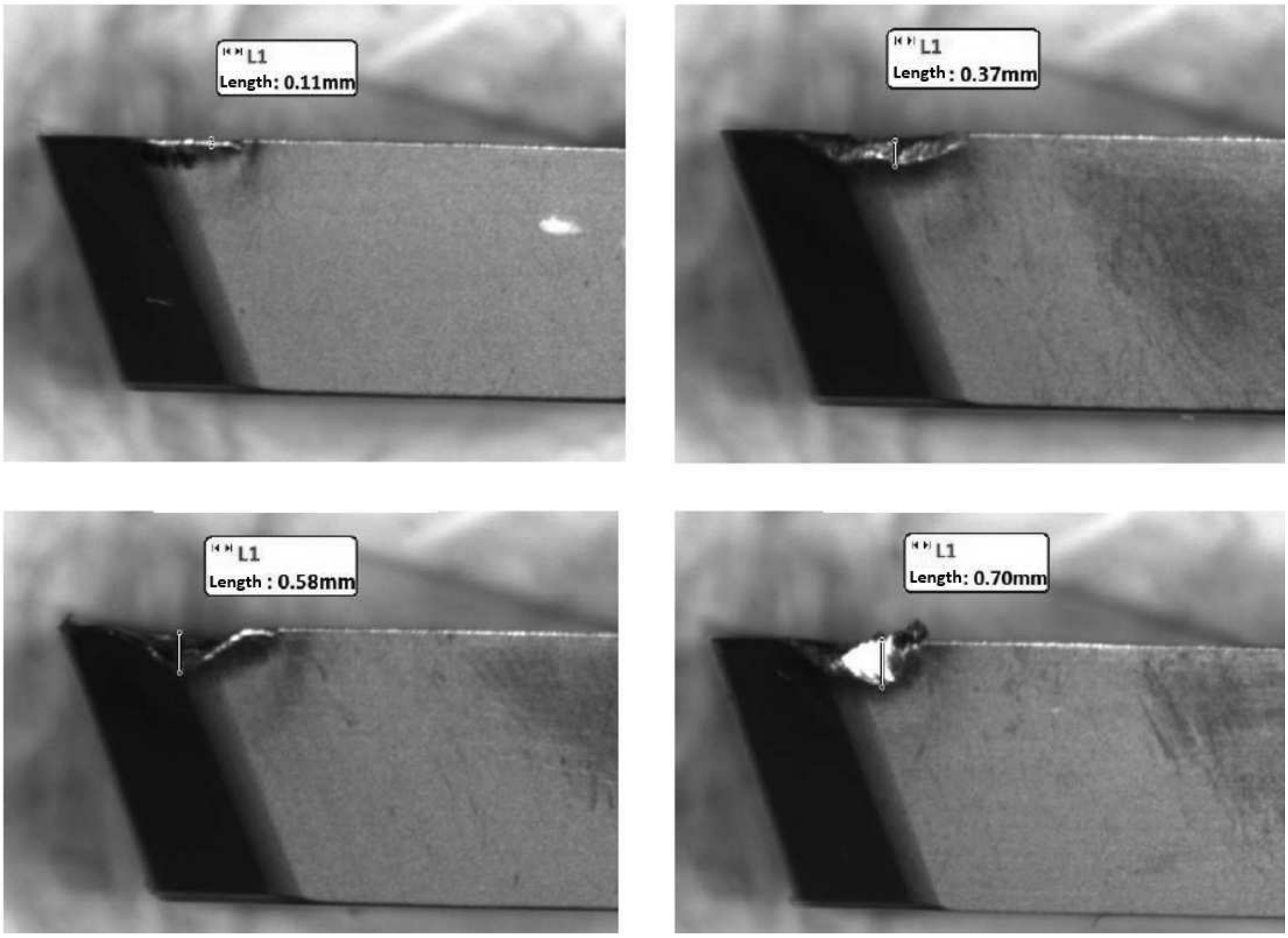

***Fig. 3** Wear course of the 3rd indexable insert*

From the given inserts an evaluation of dependence of machined surface roughness on wear was established. The choice was performed from the quantity of taken material V [cm^3] till obtaining a wear criterion of VB_B=0.7 mm. The most of material was machined at the first feed f_z = 0.1 mm and using the least cutting speed v_c = 20 $m{\cdot}min^{-1}$. These cutting inserts range from the highest quantity of taken material to the least ones in Tab. 3.

Roughness of machined surfaces was determined on the basis of average arithmetical deviation Ra. Roughness was measured by means of contact profile measuring instrument Surftest 211 made by manufacturer MITUTOYO. This roughness tester scans surface unevennesses by means of a diamond tip. Resulting roughness parameter is then shown on digital display. Roughness was measured in longitudinal direction of tool feed on the workpiece in three places. The measured values were recorded in Tab. 3.

***Tab. 3** Measured values of wear and roughness*

No. C.I.	Measure 1		Measure 2		Measure 3		Measure 4		Measure 5		Measure 6		Measure 7		Measure 8	
	VB_B [mm]	Ra [µm]	VB_B [mm]	Ra [µm]	VB_B [mm]	Ra [µm]	VB_B [mm]	Ra [µm]	VB_B [mm]	Ra [µm]	VB_B [mm]	Ra [µm]	VB_B [mm]	Ra [µm]	VB_B [mm]	Ra [µm]
3	0.09	0.3	0.16	0.35	0.23	0.25	0.28	0.26	0.31	0.27	0.41	0.28	0.61	0.3	0.72	0.4
2	0.2	0.25	0.28	0.3	0.28	0.3	0.3	0.32	0.35	0.28	0.4	0.32	0.6	0.35	0.71	0.4
1	0.22	0.28	0.24	0.32	0.27	0.35	0.32	0.36	0.36	0.35	0.51	0.33	0.72	0.45	-	-

3.2 Comparison of surface roughness in dependence on wear of inserts

From measured selected values a graph of dependence of machined surface roughness on tool wear, see Fig. 4, was created. At the beginning, roughness is increased with every new cutting edge. After the following measurements roughness Ra stagnates or decreases and then it creates a form of a bathtub curve. It characterizes running-in of a cutting tool, after which it achieves the best values of machined surface. Then roughness of machined surface grows together with increasing wear. The course of bathtub curve is a bit different with every cutting tool. It results from differences between particular tools (geometry form of chip-former, type and layer of applied finish). Roughness of machined surface has in the course of increase of wear of insert 3 a very similar character as other tested tools, however, when running-in, top of machined surface roughness obtains one of the highest values. Compared with a total comparison of all indexable inserts the 3rd insert obtains smaller roughness values along its whole length. Initial increase is steeper, bathtub curve begins just after the second measurement and immediately after that the least roughness of Ra = 0.25 μm is achieved.

With the first two indexable inserts a similar initial course can be seen in comparison with the 3rd insert after taking the same quantity of material. At the beginning, the 3rd cutting insert shows values of worse quality of machined surface than the other two inserts being compared. However, in the course of bathtub curve the 3rd indexable insert shows a regular increase of wear and roughness of machined surface. In doing so, it obtains the least values of both wear and roughness of machined surface after machining a concrete quantity of material.

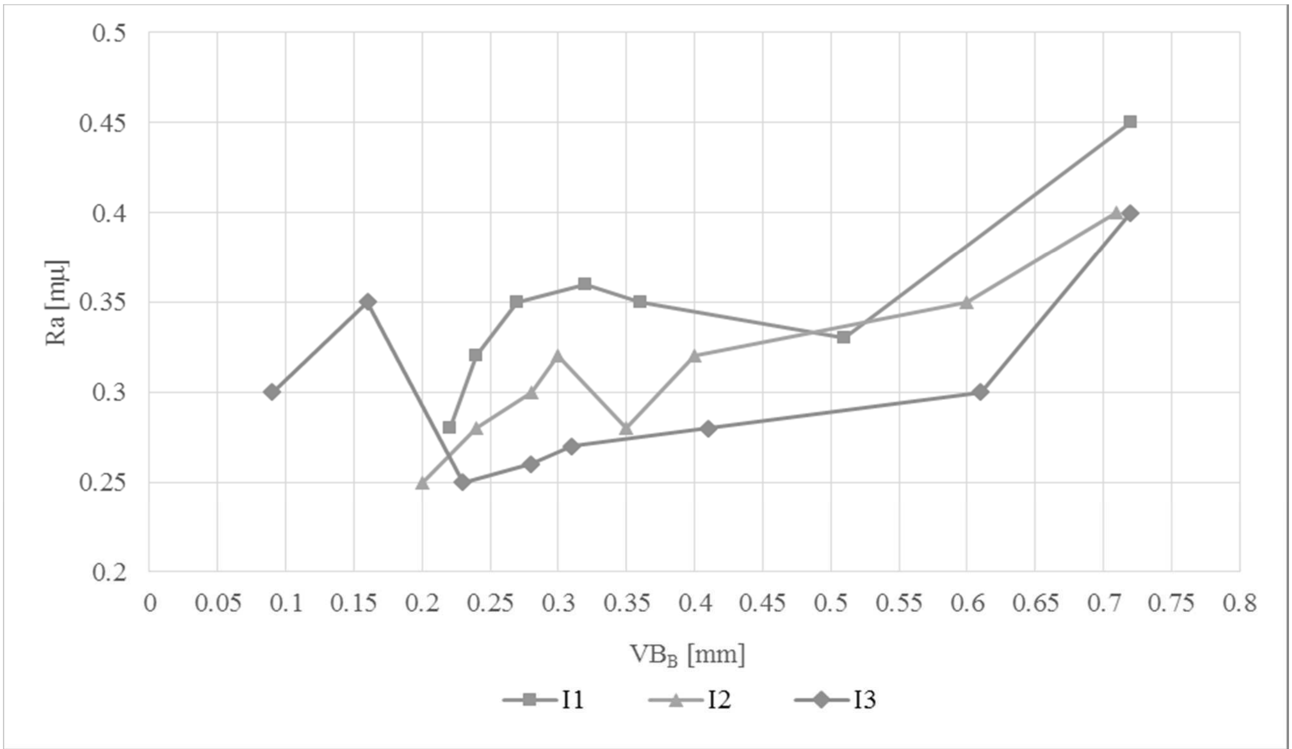

Fig. 4 *Dependence of roughness of machined surface on wear of inserts*

4 Conclusion

An always increasing share of superalloys brings questions concerning efficiency of their processing. Although all indexable inserts used were determined for machining of the group *S* according to ČSN ISO 513, a solid machine was used and only common plane surfaces were milled, it was impossible to use tools in full range of capacity given by manufacturers of these tools. It is necessary to add that tool manufacturers do not give suitability of tool using for concrete alloy Inconel, but only in general for the whole group in the scope of the standard ČSN ISO 513. Roughness of machined surfaces Ra ranges from Ra = 0,25 μm to Ra = 0,45 μm. Form of the graph of dependence of machined surface roughness on wear had the following course: First it was ascending increase of surface roughness which changed to a form of bathtub curve, where the best results of roughness parameter Ra can be seen. Having achieved higher values of wear, also roughness of machined surface grows. It is caused by wear of tool, decreasing coating surface of insert and total deterioration of cutting process.

Practically with all tested tools the least roughness of machined surface was achieved at the lowest used values of cutting speed v_f (from 20 to 30 m·min^{-1}) and feed f_z = 0,1 mm. In this way superalloys differ from machining of structural steel where increase of cutting speed leads to achieving a better quality of machined surface.

Regarding three indexable inserts tested by us, among the tested tools SANDVIK R245-12 T3 E-ML can be considered as an appropriate choice. Having achieved the best results of surface roughness and quantity of material taken up to wear VB_B = 0.7 mm.

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