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Procedia Engineering 100 (2015) 1262 – 1269

Procedia Engineering

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25th DAAAM International Symposium on Intelligent Manufacturing and Automation, DAAAM 2014

The Influence of Working Environment and Cutting Conditions on Milling Nickel – Based Super Alloys with Carbide Tools

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Abstract

This article is focused on the influence of the work environment and values of cutting conditions on tool wear in machining of nickel – based super alloys. These materials are popular in the aerospace industry and in other demanding applications, due to their excellent mechanical properties. Machining of these materials brings many problems mainly due to their high strength at high temperatures, low thermal conductivity, high hardness and work hardening. Therefore it is necessary to reduce the influence of these factors on the tool, for example by changing the cutting conditions or optimization of cutting environment. The problems with the machining of these super alloys are described. The next part is focused on the experiment where the cutting process and cutting tool wear were evaluated. For the test a milling cutter with indexable inserts was used. During the test the cutting speed and feed rate was changed.

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Keywords: Cutting conditions; Tool wear; Carbide tools; Nickel based HRSA; Working environment

1. Introduction

Nowadays, productive machining of nickel - based HRSA presents a challenge. The machinability is very hard, cutting tool wear is high and the demands on the machines are high too. There are problems with the build-up edge,

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Peer-review under responsibility of DAAAM International Vienna
doi:10.1016/j.proeng.2015.01.492

micro cracks, heat affecting of the machined surface, residual stresses etc. [14] Many studies have been carried out and raise some questions about the cutting process. One of these questions is focused on the phenomenon which occurs on the tool tip, when HRSA materials with poor machinability are machined and coolant is applied. Reference [1] provides much information about the phenomenon as well as about the cutting conditions which are usable for productive machining. Authors of this reference conducted very interesting experiment which demonstrates the problems with mentioned phenomenon. Reference [5] is also focused on the cooling when the nickel based HRSA is machined. It is very comprehensive paper which offers much information about processes which occur near the cutting edge. Reference [10] gives information about machinability of HRSA taking account of tool materials which can be used for the given cutting conditions. The information from this reference was also used for designing the experiment.

2. Machinability of nickel based super - alloys

Machinability of nickel based super - alloys is extremely poor, mainly due to their low thermal conductivity, build up edge and self-hardening, which leads to high dynamic cutting forces. Due to these factors the tool wear is extremely high and increasing the tool life by minutes is an enormous success [3]. The greatest problem in machining these materials is the heat stress. An extreme heat load is applied to the tools and the plastic deformation of the cutting edge may be observed. When the cutting speed is about 30 m/min the cutting temperature can exceed 1100°C. This can lead to diffusion of carbide particles and to the weakening of the bonding strength between carbides and binder. Materials such as Inconel 718 have also high strength and hardness which leads to high flow stress of about 1-3 GPa on the tool when these materials are machined. Notch wear at the depth of cut is observed due to the hardened layer, which arises due to the extreme self-hardening of these materials. [10] Therefore it is necessary to select suitable cutting conditions with respect to the cutting material. The coatings are beneficial due to lower friction and higher thermal stability of the cutting tool. The recommended cutting speed is in tens of m/min when coated carbide tools are used. The feed rate must be selected appropriately in view of the fact that when the feed rate is too low, the time of friction on the flank of the tool is longer. Basically the increase in the time delay before opening the chip/tool interface leads to higher thermal stress. One possible way to improve the machining process is optimization of the working environment for example by using high pressure cooling.

3. Working environment – high pressure cooling

High pressure systems, where the pressure reaches hundreds of bars can ensure an increase in cutting tool life. When high-pressure cooling is used, a greater exchange of heat in the chip/tool interface is allowed than with conventional cooling. This can reduce the cutting temperature. When high-pressure cooling is used it is necessary to ensure the direction of the liquid to the interface between the chip and the tool tip as can be seen in Fig. 1 option B. There is better chip evacuation from the cutting area and lower friction between the chip and the tool face. [2] When the liquid is focused outside of the tool chip interface, great improvement in tool life cannot be expected due to thermal shocks which may lead to reduction in tool life compared to dry machining. The thermal shocks are formed as the tool is heated rapidly in the cut and after that is cooled. [13] When continuous cooling is used the thermal shock cannot be formed due to the constant flow of fluid to the interface.

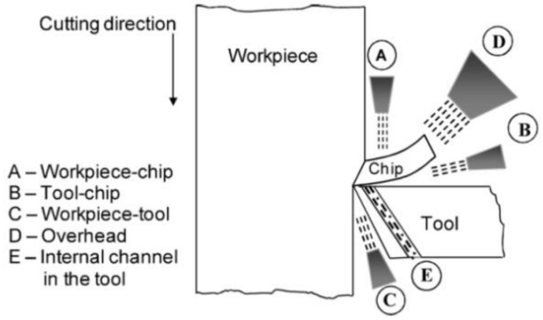

Fig. 1. Basic direction of coolant applications taken from [2].

Routing liquid to the top of the chip (Fig.1. option D - overhead) leads to vaporization of the liquid in the zone of primary plastic deformation. This phenomenon leads to blocking of further flow of cold fluid – this leads to reduction of the cooling effect. [2] It may be stated that the internal geometry of the jet is very important in terms of the coherence and kinetic power of the water jet. [12]

When high-pressure cooling is used, it is necessary to find the optimum cutting conditions, mainly in terms of the ratio between cutting speed and coolant pressure. This ratio is important in terms of the erosive action of pressurized fluid on the cutting tool and because there exists a specific value of the critical pressure. When the critical pressure is achieved, the tool chip interface temperature does not decrease and is almost the same when the pressure is increased. Increasing the pressure above the critical level can lead to greater wear of the tool as already stated by erosive action of the fluid on the tool. [1, 4, 5]. In Fig. 2 can be seen the result of the experiment, which confirms this idea. However there is a question why the tool life increases as the cutting speed increases from 20 m/min to 30 m/min when the pressure is 203 bars. It could be caused by an inappropriately low tool working temperature. Below this temperature the cutting tool is more brittle and could be more easily damaged.

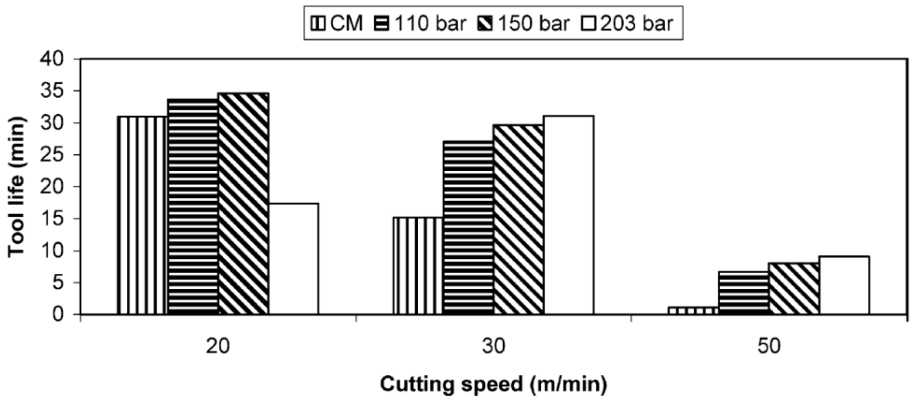

Fig. 2. Tool life - machining of INCONEL 718 at various coolant pressures at feed rate of 0.3 mm/rev - taken from [1].

The fact that increasing the pressure to above a certain level does not reduce the temperature may be attributed to the critical heat flux [5]. Boiling of water is characterized by four stages with different rates of heat transfer. The first stage is characterized by free convection with a relatively small coefficient of heat transfer. The second stage is characterized by formation of vapor bubbles. The movement of bubbles in the liquid produces an intensive mixing of the liquid (two phases). This leads to increasing of heat exchange to the maximum which is determined by critical heat flux. After that stage transition boiling occurs, where the heat exchange is decreased. The last stage is characterized by the lowest heat exchange between the liquid and the hot surface caused by a cushion of steam, which prevents effective heat transfer.

As the pressure is increased to the critical pressure, it seems that there is a more intense flushing of the places where the transition boiling has been, when the pressure of cooling medium was lower. This leads to changing of the transition boiling to nucleate boiling.

However, it is possible that the transition boiling or the film boiling near the surface close to the cutting edge cannot be changed to nucleate boiling, and neither by increasing the pressure to above the critical pressure. It can be attributed to the critical point of the water (about 374°C, 220 bars). When the critical point is exceeded, there is no way to get the two phases which are required for effective heat transfer. The replacement of the hot liquid from the surface is not effective due to the small space. The high pressure, together with the high temperature can cause the mentioned critical point to be exceeded, as can be seen in Fig 3.

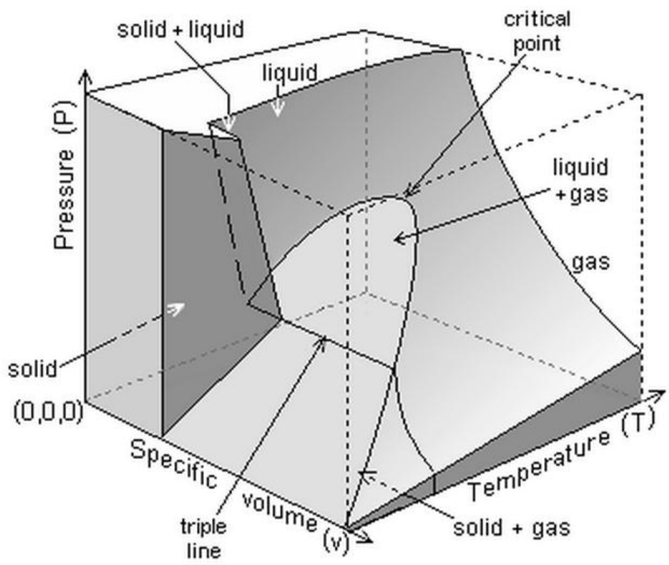

Fig. 3. Phase diagram of water taken from [6].

The next important factor which affects effective cooling is the depth of cut. For easier chip removal a thin chip is better, which can be removed more easily. But due to the self-hardening for example of the Inconell 718 the depth of cut must not be too small. When the depth of cut is relatively small the heat generated is smaller. When the cooling medium reaches the chip/tool interface there is short film boiling and in a short time it changes to nucleate boiling when the heat transfer is effective. However, when a greater depth of cut is used, the heat generation is higher and the film boiling takes longer. This leads to film boiling. [4]

4. Description of experiment

The main task of this experiment is to determine suitable cutting conditions for milling Nimonic 80A, when a coolant pressure of 40 bars is used. For comparing the constant time in cut 12.8 min was selected. The variants of cutting speed were tested at the first time, see Tab.1. Next, three variants of feed rate were tested, see Tab. 1. The VB_B wear was monitored and width was also measured. When notch wear was observed it was measured and stated too.

Tab. 1. Cutting conditions.

1. a_p= 0.5 mm; f_t= 0.21 mm/t	v_{c1} [m/min]	v_{c2} [m/min]	v_{c3} [m/min]	v_{c4} [m/min]
	10	20	30	40
2. a_p= 0.5 mm; v_c= 40 mm/t	f_{t1} [mm/t]	f_{t2} [mm/t]	f_{t3} [mm/t]	
	0.21	0.4	0.6	

For the tests we used a milling cutter with diameter 50 mm and round cutting inserts from sintered carbide with special thin coating, see Fig 4b, and milling center DMG/Mori Seiki DMU 65 monoBLOCK, see Fig 4a.

Fig. 4. (a) DMG/Mori Seiki UmB 65 [7]; (b) Milling cutter ∅50 [8].

The first measuring was carried out on the optical microscope Multicheck PC 500, see Fig. 5 (a). Special software for evaluating cutting tool wear was used. It may be stated that the precision of this measuring is not as good as measuring with high resolution 3D measuring systems such as Infinite Focus system by Alicona in our case Fig. 5 (b) which is used for demonstration of the difference in precision between these systems.

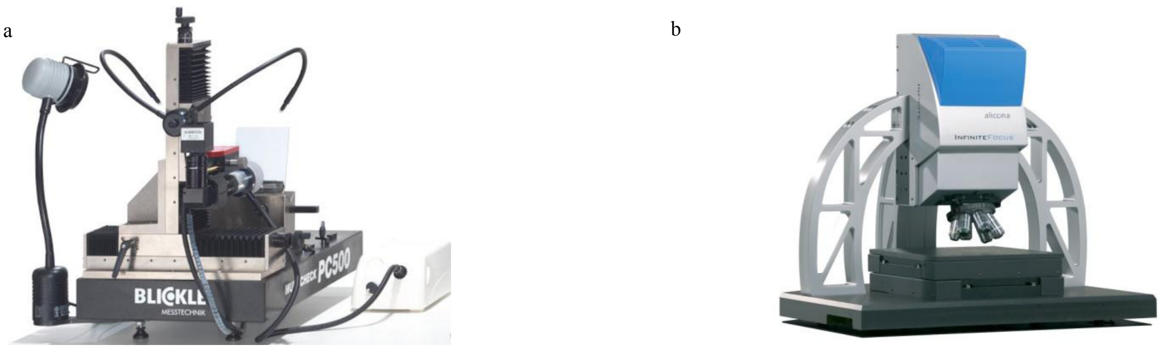

Fig. 5.(a) Multicheck 500 [9]; (b) Infinite Focus [11].

5. Evaluation of the tool wear – optical microscope

The test was carried out using four inserts. Fig 6(a) shows the influence of the cutting speed on tool wear VB_{Bmax}. Fig 6(b) shows the influence of cutting speed on the width of the flank wear. As can be seen, the cutting speed 40 m/min creates the highest values of flank wear - the VB_{Bmax} and its width. This can be attributed to the thermal load which increases with increasing cutting speed. The VB_{Bmax} shows that the smallest tool wear is achieved when the v_c is 30 m/min. The pressure of 40 bars ensures a good cooling effect for this value of cutting speed. When the v_c is 20 m/min the flank wear seems to be narrower than with 30 m/min, but in terms of productivity (material removal Fig. 78(a).), using a cutting speed of 30 m /min is better. When the cutting speed is 10 m/min there is an increase in tool wear. This may be caused, as already mentioned, when the tool is below the optimal work temperature. The smallest tool wear can be seen on the bottom of Fig. 8 (b). There is no significant notch wear when the feed rate is 0. 21 mm/tooth and the cutting speed is between 10 – 40 m/min.

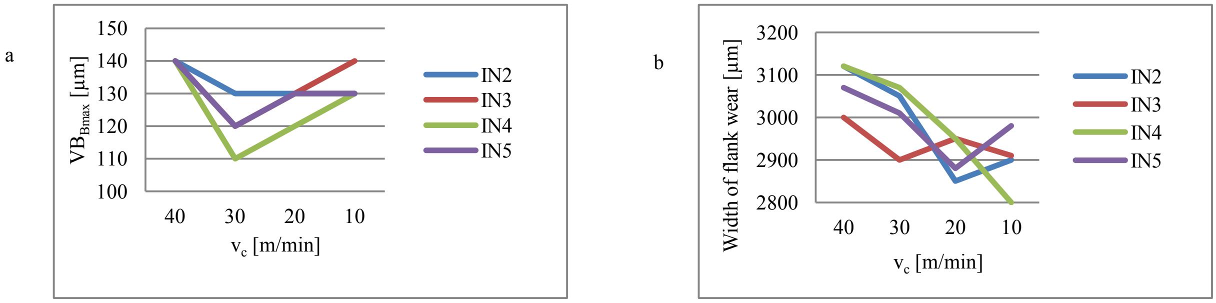

Fig. 6. (a) Influence of v_c on VB_{Bmax}; (b) Influence of v_c on width of flank wear.

The next part is focused on the influence of the feed rate on the flank wear. Fig. 7(a) shows the influences of the feed on the VB_{Bmax} and Fig. 7(b) shows influences of the feed on the width of flank wear.

It may be stated that the greatest notch wear arose when the feed rate was 0. 6 mm/tooth. The time in cut was only 3.62 min due to the great notch wear of about 180 µm. It is clear that f_t= 0. 6 mm/tooth is not advisable. The worst tool wear can be seen at the top of Fig 7(b). The tool wear with smallest VB_{Bmax} can be seen at the bottom of Fig. 7(b). A build-up edge is also created. In view of productivity the best variant of the feed rate is f_t= 0. 4 mm/tooth. As can be seen in Fig. 8 - material removal is great and significant notch wear was not observed. Feed rate f_t=0.21 mm/min shows the lowest productivity but the tool wear was small.

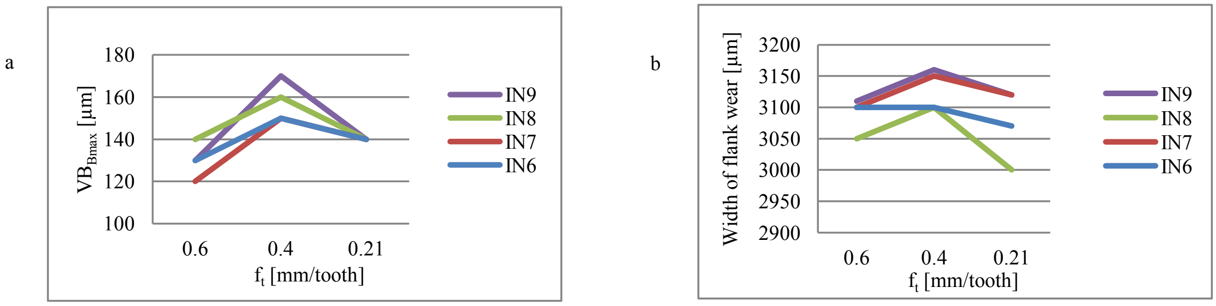

Fig. 7. (a) Influence of v_c on VB_{Bmax}; (b) Influence of f_t on width of flank wear.

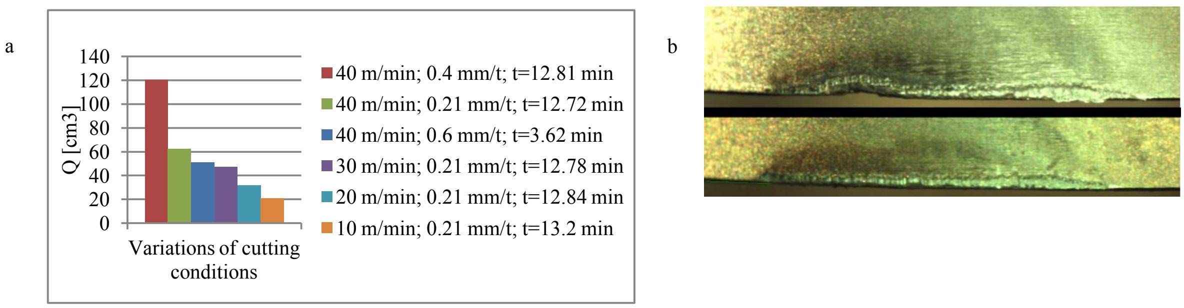

Fig. 8. (a) Material removal; (b) Flank wear v_c=40 m/min, f_t=0.6 mm/tooth; v_c= 30 m/min f_t= 0.21 mm/tooth.

6. Demonstration of the evaluation – Infinite Focus Measuremnt

The previous part describes evaluation by optical microscope. There are not as many options for tool wear measurement as with a system such as IFM. Here is only an illustrative example of evaluation by IFM. This example shows that equal rounding of the cutting edge occurs. This leads to an increase of the cutting forces, cutting temperature and to the hardening of the upper layer of the machined surface. All of these phenomena lead to increased tool wear. Fig. 9 shows the differential analysis of the short part of the unworn and worn cutting edge (cutting conditions – f_t= 0.4 mm/tooth; v_c= 40 m/min). This analysis is usable due to its clarity. Crater wear is also visible.

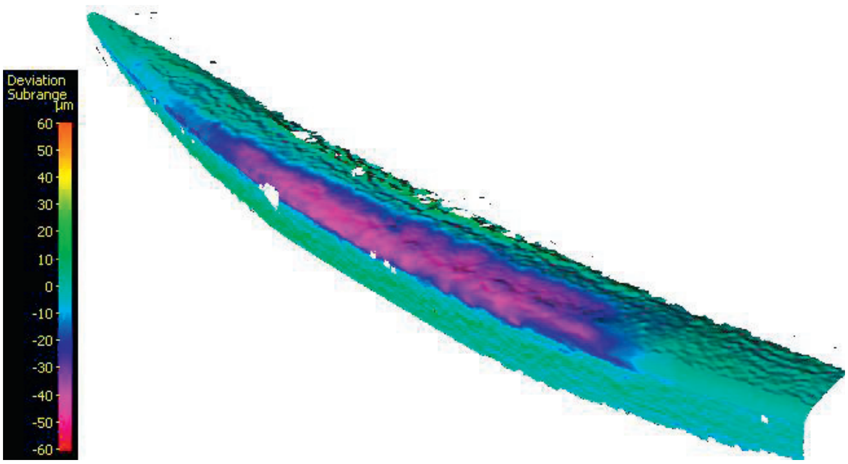

Fig. 9. Differential analysis of the cutting edge.

The 2D module, which can show the section of the cutting edge, is also good for monitoring the tool wear with high precision in the given places. The changes of the tool geometry can be also detected. An example is shown in Fig. 10.

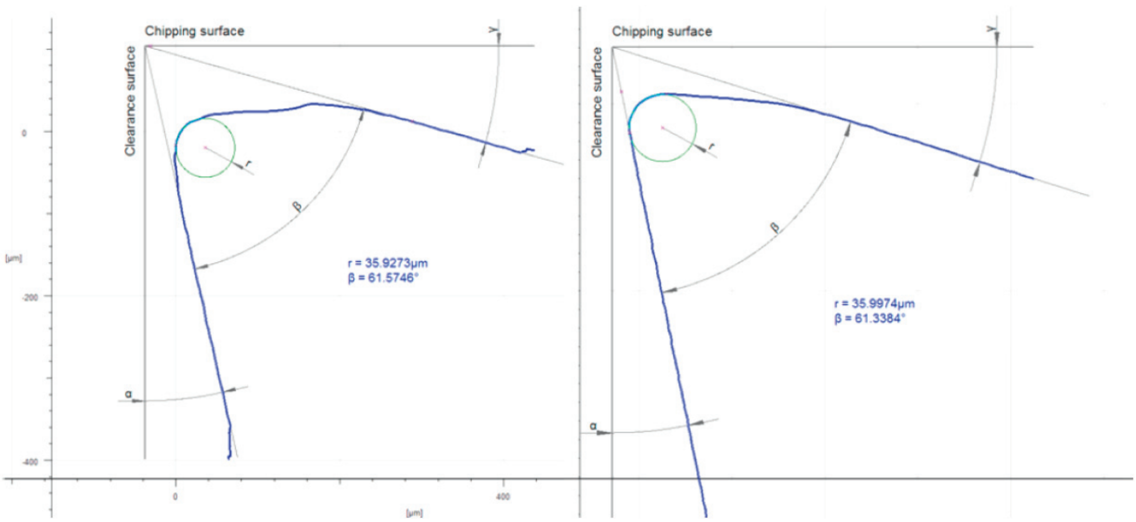

Fig. 10. 2D measurement - worn and unworn cutting edge.

The 2D measurement shows high flank wear but the 3D measurement shows that face wear is dominant. This affects the accuracy of the measurement. This issue will be investigated in the next paper.

Conclusion

The main factors which have the greatest effect on tool wear were described. The influences of the cutting environment, i.e. the pressure of coolant, was also considered and described. The experiment when the Nimonic 80 was machined with rounded inserts was proved. The experiment shows the value of the tool wear under different cutting conditions. The lowest tool wear is achieved when the cutting speed is 30 m/min and the feed rate is 0.21 mm/min. But in terms of productivity, the best option for cutting conditions is a feed rate of 0.4 mm/min and cutting speed 30 m/min. It may be stated that a different tool wear regime appears when cutting conditions are changed. Notch wear is observed when the feed rate is higher and does not appear when the feed rate is lower and the cutting speed is higher (in the tested range). It would be appropriate to investigate the phenomenon which arises at the tool tip interface. Understanding these phenomena can lead to an increase of both the cooling effect and tool life.

Acknowledgements

This paper is based upon work sponsored by project "Regionální technologický institut" no. CZ.1.05/2.1.00/03.0093.

References

[1] E.O. Ezugwu, J. Bonney, Effect of high-pressure coolant supply when machining nickel-base, Inconel 718, alloy with coated carbide tools, Journal of Materials Processing Technology, Volumes 153–154, 10 November 2004, Pages 1045-1050, ISSN 0924-0136, http://dx.doi.org/10.1016/j.jmatprotec.2004.04.329.
[2] Rosemar B. da Silva, Álisson R. Machado, Emmanuel O. Ezugwu, John Bonney, Wisley F. Sales, Tool life and wear mechanisms in high speed machining of Ti–6Al–4V alloy with PCD tools under various coolant pressures, Journal of Materials Processing Technology, Volume 213, Issue 8, August 2013, Pages 1459-1464, ISSN 0924-0136, http://dx.doi.org/10.1016/j.jmatprotec.2013.03.008.
[3] Ivana Česáková, Miroslav Zetek, Vojtěch Švarc, Evaluation of Cutting Tool Parameters, Procedia Engineering, Volume 69, 2014, Pages 1105-1114, ISSN 1877-7058, http://dx.doi.org/10.1016/j.proeng.2014.03.098.
[4] M. Rahman, A. Senthil Kumar, M.R. Choudhury, Identification of Effective Zones for High Pressure Coolant in Milling, CIRP Annals - Manufacturing Technology, Volume 49, Issue 1, 2000, Pages 47-52, ISSN 0007-8506, http://dx.doi.org/10.1016/S0007-8506(07)62893-5.
[5] C. Courbon, D. Kramar, P. Krajnik, F. Pusavec, J. Rech, J. Kopac, Investigation of machining performance in high-pressure jet assisted turning of Inconel 718: An experimental study, International Journal of Machine Tools and Manufacture, Volume 49, Issue 14, November 2009, Pages 1114-1125, ISSN 0890-6955, http://dx.doi.org/10.1016/j.ijmachtools.2009.07.010.
[6] Wikipedia, Phase diagram, http://en.wikipedia.org/wiki/Talk%3APhase_diagram#mediaviewer/File:PvT_3D_plot_-_water.png, cited - 10.9.2014.
[7] Manufacturing news, Archives, http://www.mfgnewsweb.com/archives/3/2915/General-feb12/DMG--Mori-Seiki-Offers-ULTRASONIC-65-monoBLOCK-and-LASERTEC-65-Shape.aspx, cited - 10.9.2014.
[8] OSG, Products, http://www.osgtool.com/_branding/osgtool.com/images/products/Indexable_Milling.jpg.
[9] Polimet service, Multicheck PC500G2, http://www.polimetservice.ru/multicheck-pc500g2.html, cited - 9.9.2014.
[10] E.O Ezugwu, J Bonney, Y Yamane, An overview of the machinability of aeroengine alloys, Journal of Materials Processing Technology, Volume 134, Issue 2, 10 March 2003, Pages 233-253, ISSN 0924-0136, http://dx.doi.org/10.1016/S0924-0136(02)01042-7.
[11] SITEC, Systems, http://sitec.mecc.polimi.it/EN_02-01_attrezzatura.html, cited - 10.9.2014.
[12] Goikoetxea, E.; Alberdi, A.; Suarez, A.; Arleo, F. & Lamikiz, A. (2011). Numerical simulation of water jet quality for different orifice geometries, Chapter 41 in DAAAM International Scientific Book 2011, pp. 513-526, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-901509-84-1, ISSN 1726-9687, Vienna, Austria DOI: 10.2507/daaam.scibook.2011.41.
[13] Jozic, S.; Bajic, D. & Topic, S.: Flank Wear in Down and Up Milling, Annals of DAAAM for 2012 & Proceedings of the 23rd International DAAAM Symposium, ISBN 978-3-901509-91-9, ISSN 2304-1382, pp 0251 - 0254, Editor Branko Katalinic, Published by DAAAM International, Vienna, Austria, 2012.
[14] A. Devillez, G. Le Coz, S. Dominiak, D. Dudzinski, Dry machining of Inconel 718, workpiece surface integrity, Journal of Materials Processing Technology, Volume 211, Issue 10, October 2011, Pages 1590-1598, ISSN 0924-0136, http://dx.doi.org/10.1016/j.jmatprotec.2011.04.011.