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SELF-GENERATED VIBRATIONS AND PROCESS INSTABILITY WHEN TURNING HIGH CHROMIUM WHITE CAST IRON WITH PCBN TOOLS

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The dynamic instability and related problems when turning high chromium cast iron (HCCI) with two polycrystalline cubic boron nitride (PCBN) tools in wide range of cutting speeds and feed rates were studied in the article. The tool wear mechanisms and specifics for both tools as a main criterion of appearance of process instability were investigated. In spite of the chatter-like surface of machined workpieces it was shown the dynamic stability of process by two method '0-1 test' and determination of maximum Lyapunov exponent. Taking into account the strong periodicity of process with several clear harmonics it was concluded that such process is related to self-resonant phenomena.

Keywords: high-chromium white cast iron, PCBN tools, self-generated vibrations, dynamic instability

1. INTRODUCTION

The superior wear resistance of HCCI makes these materials effective in applications in aggressive environments where varying resistances to abrasion, erosion and erosion-corrosion are required, such as those for slurry pump casings and impellers, crushers, breaker screens, gravel and dredge pumps. According to multiple studies of microstructure and properties of HCCI during last decade (Dogan Ö.N. et al., 1995, Xie G. et al., 2010, Zhou J.M. et al., 2004), its high wear resistance is attributed to a combination of hard primary and eutectic carbides of M_7C_3, where M includes Fe, Cr, and other carbide forming alloying elements, and a relatively ductile ferrous matrix. The hardness of M_7C_3 is in the range of 1200–1800 HV, which may vary with composition. Other carbides such as $M_{23}C_6$ can also be produced, depending mainly on the chemical composition and also influenced by the heat treatment.

However, in spite of the great operational value of HCCI, the material is difficult to machine, since the amount and the hardness of the microstructural carbides constituents is extremely high. The cutting process, therefore, is accompanied by the severe tool wear and tool deterioration which results in the generation of strong forced and self-excited vibrations. This applies especially to the process with heightened cutting conditions when the amplitude of vibration might be drastically increased resulting in the appearance of low-frequency vibrations, so-called 'chatter'. It is well known that the fundamental reason of the 'chatter' is the complexity of tool-workpiece interaction and chip formation process due to strongly nonlinear nature of the phenomena which are caused by and dependent on such factors as temperature-dependent plasticity, temperature- and velocity-dependent friction conditions, nonlinear stiffness of tool and machine components etc. (Wiercigroch M. et al., 2001). Two different types of chatter are usually considered in the studies (Wiercigroch M. et al., 2001, Quintana G. et al., 2011). First one is related to the regenerative effects where the systems dynamics on the current pass is dependent on the workpiece geometry from the previous one. Second type is related to the physics of cutting process and depends on the conditions in plastic deformation zones during machining, change of value and mechanism of friction effects between tool surfaces and workpiece and chips. In turn the friction conditions are determined by relative motions between tool and workpiece. In spite of the huge amount of studies considering 'chatter' in metal cutting processes anyway there is significant uncertainty in this question. In accordance with a general opinion the main indications of chatter are the strong process instability which affects the surface finish and is accompanied by large-amplitude regenerative oscillations which can be periodic, quasi-periodic or chaotic (Wiercigroch M. et al., 2001, Quintana G. et al., 2011, Stepan G. et al., 2011). The stated above implies the appearance of vibrations with increasing amplitudes and probably with variable but decreasing frequency of, at least, one of the main harmonics. On the other hand the drastic increase of amplitude is impossible, at the reasonable conditions, because of the presence of highest harmonics and high frequency chaotic vibrations which tend to suppress the high-amplitude vibrations. Thus it turns out to be impossible to recognize the chatter by most of the methods. The methods based on the analysis of trajectories in a phase space are insensitive because of the presence of a steady cycle with high spectral energy as compared to chaotic component of signal. Therefore, visually the process may be characterized as stable accepting the bad surface quality of the workpiece and appearance of relatively strong harmonic at some moment of the cutting process when one of the system's parameters reach some critical value.

The main goal of this paper is characterization of the process of machining as-cast and quenched HCCI with two different PCBN tools from the point of view of process instability. The determination of the conditions of appearance of self-generated vibrations during machining is performed by the results of wavelet and Hilbert-

Huang transforms. The specifics of tools wear mechanisms and morphology of worn tools are considered and discussed as a one of the important parameters which influences on the process stability. The parameters of surface finish were considered depending on the cutting conditions and vibrations characteristics.

2. TEST CONDITIONS

Since the hardness of HCCI is considerably above 45 HRC, the use of conventional tool materials for its machining, such as carbide or ceramic, proves impossible or/and inefficient. In presented study two grades of polycrystalline boron nitride (PCBN) tools were employed throughout the test: binderless CBN (bCBN), (ISHM, Ukraine) and standard high CBN content tool (CBN-500) (SECO Tool AB, Sweden) as a reference one. The PCBN tools were chamfered round inserts RNGN 120400S02020. The toolholder provided the side rake and back rake angels equal -6°. The workpiece materials were HCCI ∅70×380 mm sized bars of different chemical compositions (low and high C-Si content and related carbides) and heat treatment – as-cast and hardened. The chemical composition and some properties of considered cast irons are presented in Table 1 and 2. The cutting conditions were selected in the range: v_c = 120-160 m/min, f = 0.4 mm/rev, a_p = 1.5 mm – to study the tool wear effect (‘wear test’) and v_c = 150 m/min; f = 0.1, 0.2…0.6 mm/rev and a_p = 1.5 mm – to study the dynamic response of fresh tools (‘force test’). The data acquired during the tests for following analysis were: acceleration spectra of tool tip and force spectra effecting on the tool in three directions, characteristics of tool wear and surface quality. The signals were sampled with 120 kHz for acceleration and 1 kHz for forces, respectively.

Table 1 Chemical composition of HCCI (% wt)

	Fe	**C**	**Si**	Mn	S	P	**Cr**	Ni	Ti	Mo	Cu
Low Si content	70.55	**2.71**	**0.8**	0.34	0.012	0.019	**25.3**	0.11	0.004	0.02	0.047
High Si content	69.2	**2.95**	**1.47**	0.35	0.015	0.022	**25.7**	0.12	0.004	0.02	0.056

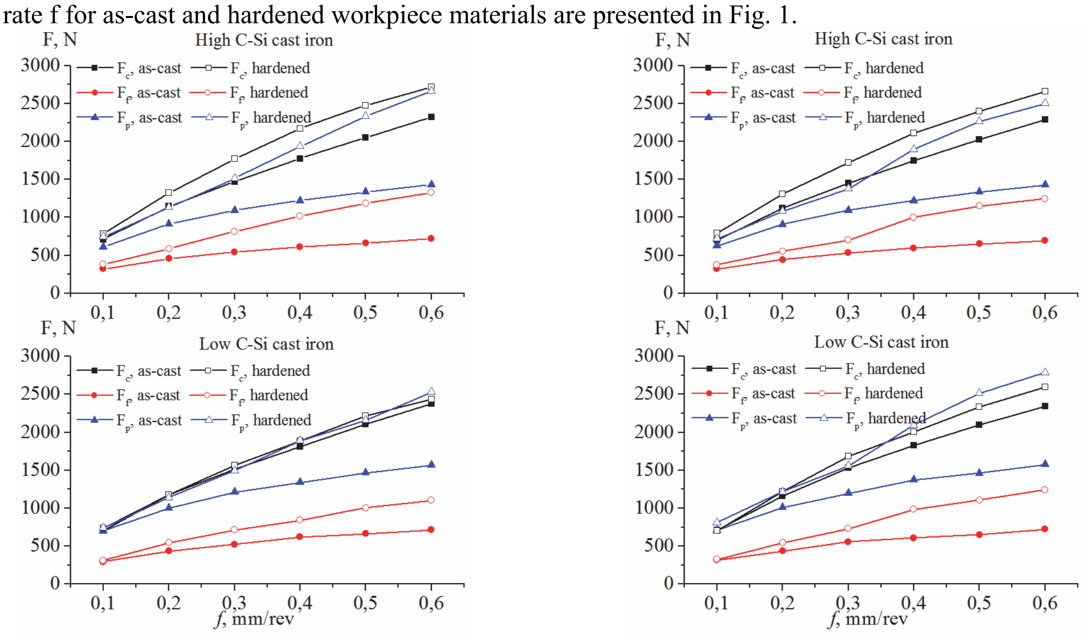
Table 2 Hardness of dominant phases of HCCI after different thermal treatments

Thermal treatment	Low C-Si content, phases	Hardness, GPa	High C-Si content, phases	Hardness, GPa
As-cast	Austenite	4.40	Primary Carbides	13.79
	Martensite	6.50	Eutectic Carbides	15.57
Annealed	Austenite	3.20	Primary Carbides	11.23
	-	-	Eutectic Carbides	14.57
Hardened	Martensite	6.68	Martensite	6.80
	-	-	Eutectic carbides	14.20

3. RESULTS AND DISCUSSION

3.1. Forces and accelerations

The dependencies of average values of cutting forces F for different directions (cutting, feed and passive) on feed rate f for as-cast and hardened workpiece materials are presented in Fig. 1.



a) b)

Fig. 1. Dependencies of forces F vs. feed rate when machining as-cast and hardened HCCI with BCBN (a) and HCBN (b) fresh tools

The characteristic feature of the process is a significant increase of the passive force component when machining hardened materials. Such a behavior is evidently related to both the increase of hardness of machined material and specifics of the tool geometry. The dependencies of root mean square (RMS) values of accelerations (a) have more complicated nature (see Fig. 2), as compared to previous case. It is evident the explicit demarcation all of the acceleration components for both as-cast and hardened materials for both types of HCCI. Moreover there are local maxima or abrupt change of behavior on the curves in case of machining hardened cast iron with high C-Si content at feed rate $f = 0.5$ mm/rev. It is also has to be noted that the real amplitudes of acceleration signals exceed the RMS values 2-3-folds when machining materials with low C-Si content with both tools and 3-5 times in case of HCCI with high C-Si content. Anticipating things, the presence of typical for ‘chatter’ waviness and marks on the workpieces surfaces were observed for as-cast and hardened HCCI with low C-Si content in overall the range of feed rates for both tools; as-cast and hardened HCCI with high C-Si content in the range of feed rates 0.1-0.5 mm/rev.

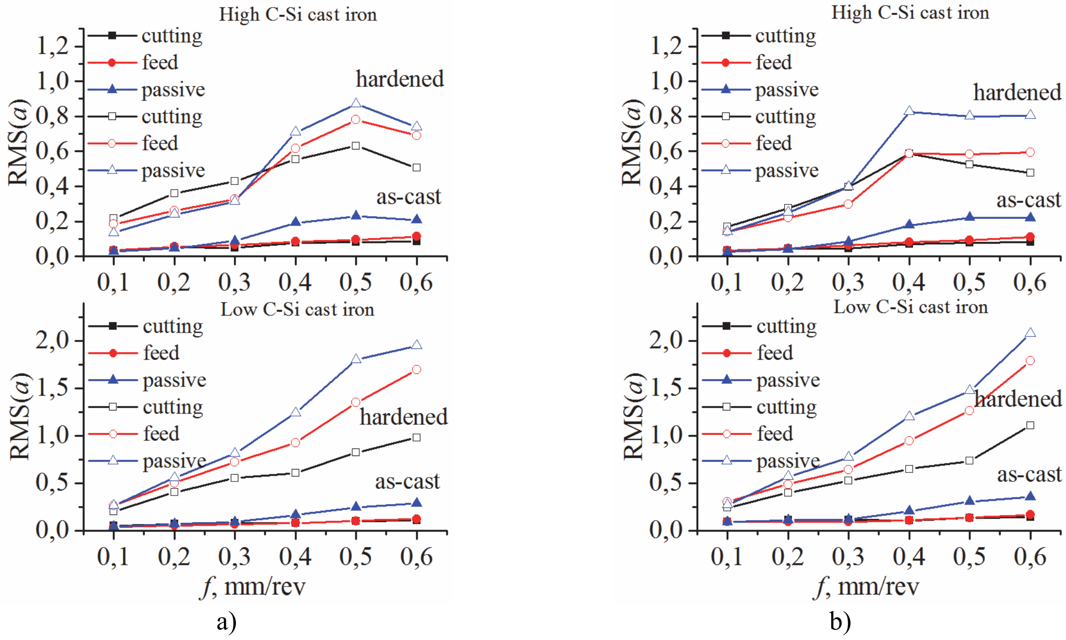


Fig. 2. Root mean square value of acceleration amplitudes RMS(a) when machining as-cast and hardened HCCI with BCBN (a) and HCBN (b) fresh tools

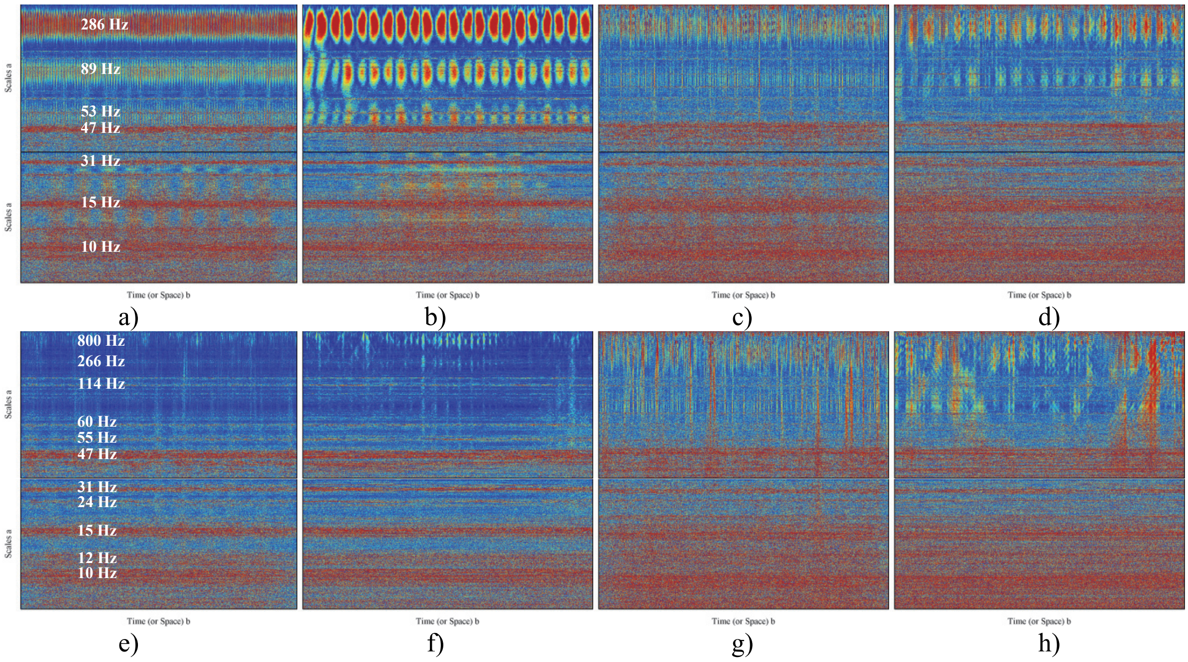


Fig. 3 Wavelet spectrograms of acceleration signal in cutting direction for **as-cast** HCCI with **low C-Si** content at different feed rates: **BCBN** tool a) 0.1 mm/rev, 5 revolutions; b) 0.5 revolutions; c) 0.6 mm/rev, 5 revolutions; d) 0.5 revolutions; **HCBN** tool e) 0.1 mm/rev, 5 revolutions; f) 0.5 revolutions; g) 0.6 mm/rev, 5 revolutions; h) 0.5 revolutions

The more detailed look on the development of the process in time during machining was done by the continuous wavelet transform. Daubechie base wavelet ‘db8’ with central frequency $\omega_0 = 0.667$ Hz was employed for analysis. The results of computation were presented as a signal power distribution $P(a, b) = |W(a, b)|^2$, where $W(a, b)$ – wavelet transform coefficients distribution, a – scale (frequency characteristic, vertical axis) and b – time (horizontal axis). The acceleration spectra for 5 and 0.5 revolutions of workpiece were analyzed at different cutting conditions. The obtained results are presented in Fig. 3 and 4 for as-cast and hardened HCCI, respectively.

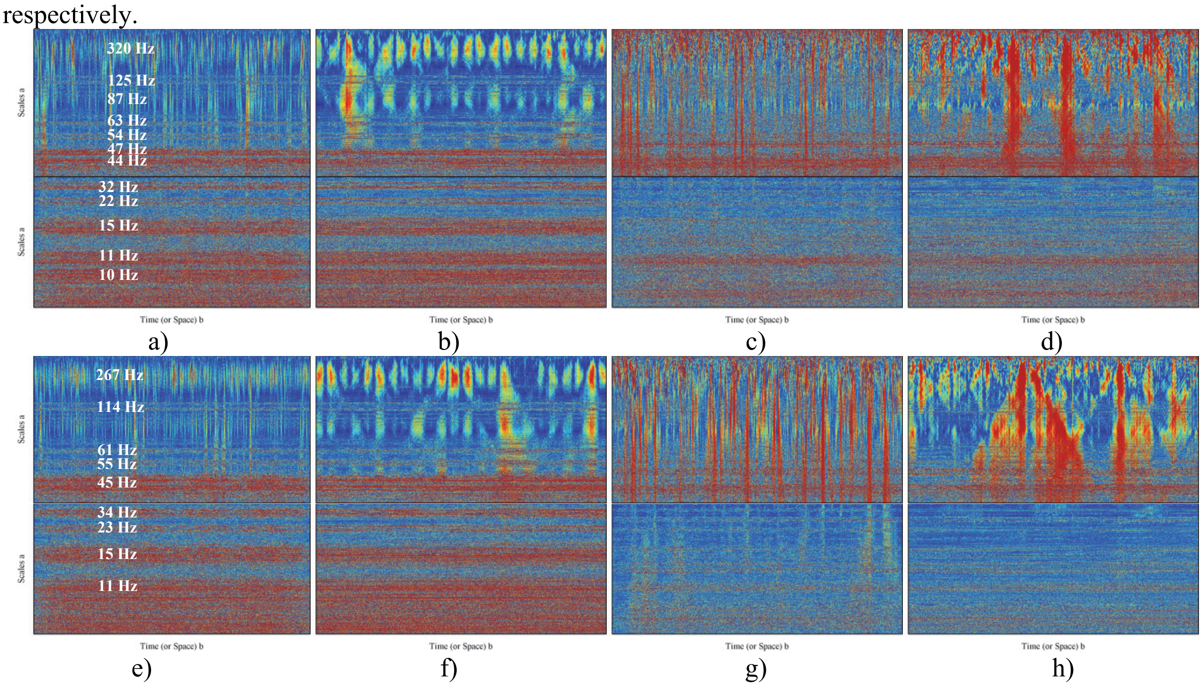


Fig. 4 Wavelet spectrograms of acceleration signal in cutting direction for **hardened** HCCI with **low C-Si** content at different feed rates: **BCBN** tool a) 0.1 mm/rev, 5 revolutions; b) 0.5 revolutions; c) 0.6 mm/rev, 5 revolutions; d) 0.5 revolutions; **HCBN** tool e) 0.1 mm/rev, 5 revolutions; f) 0.5 revolutions; g) 0.6 mm/rev, 5 revolutions; h) 0.5 revolutions

The strongest harmonics, in case of machining as-cast HCCI with BCBN tool, occurs at the frequencies 285, 89, 54, 47, 31 Hz and spindle rotation (see Fig. 3. a-d). The frequencies of generated vibrations are higher when machining with HCBN tools. It is clearly shown in Fig. 3. e-f the presence of strong harmonics, or rather excitations, with frequency around 800 Hz. The increase of feed rate up to 0.6 mm/rev causes the high-frequency oscillations (Fig. 3. c-d, g-h) for both tool grades. Though, the main difference between the mentioned processes is an explicit intermittence of oscillations both in high and low frequency ranges when cutting the BCBN tool and the presence of transitions, especially in high frequency range, in case of turning with HCBN tools.

The machining the hardened materials (see Fig. 4) has approximately the same nature as mentioned above, but the process is accompanied with much higher level of noise in wide frequency range (Fig. 4 a-b, e-f). The intermittent vibrations with strong harmonics and with modulated amplitude change into oscillations with several low-frequency harmonics with strong middle- and high-frequency noise with increase of feed rate up to 0.6 mm/rev (Fig. 4 c-d, g-h).

An ability of the concerned dynamic system “machine tool – tool – process – workpiece” to generate such the oscillations might be caused by next reasons, which could be directly or indirectly proved or studied: self-resonant phenomena, when several different machine units start to determine the system behavior; friction conditions in the contact zone between tool and workpiece, which depend on the relative speed and instant location of tool edge in relation to the workpiece surface; formation of new chemical compounds due to the high temperature and pressures in the contact zone and specifics of tool wear; tool wear (nature, mechanism and morphology of the worn edge) which most likely has self-organized nature and might be both the cause and consequence of the generated vibrations.

3.2. Tool wear

The tool wear morphology was investigated by 3-D optical microscope “Alicona Infinite Focus” which allows the measurement of 3-D structures of tool edges. The profiles of worn tool were extracted from the structures as respective cross-sections. The fresh tools were worn by the mentioned ‘tool wear tests’ at different cutting speeds $v_c = 120$, 140 and 160 m/min and with constant DOC $a_p = 1.5$ mm and feed rate $f = 0.4$ mm/rev. The average length of cut during the pass was $L = 200$ m. The results of measurements are presented in Fig. 6 and 7 for BCBN and HCBN tool grades respectively. Each of the picture shows three profiles of tool edge in the vicinity of maximum (top), medium (middle) and minimum (bottom) chip thickness.

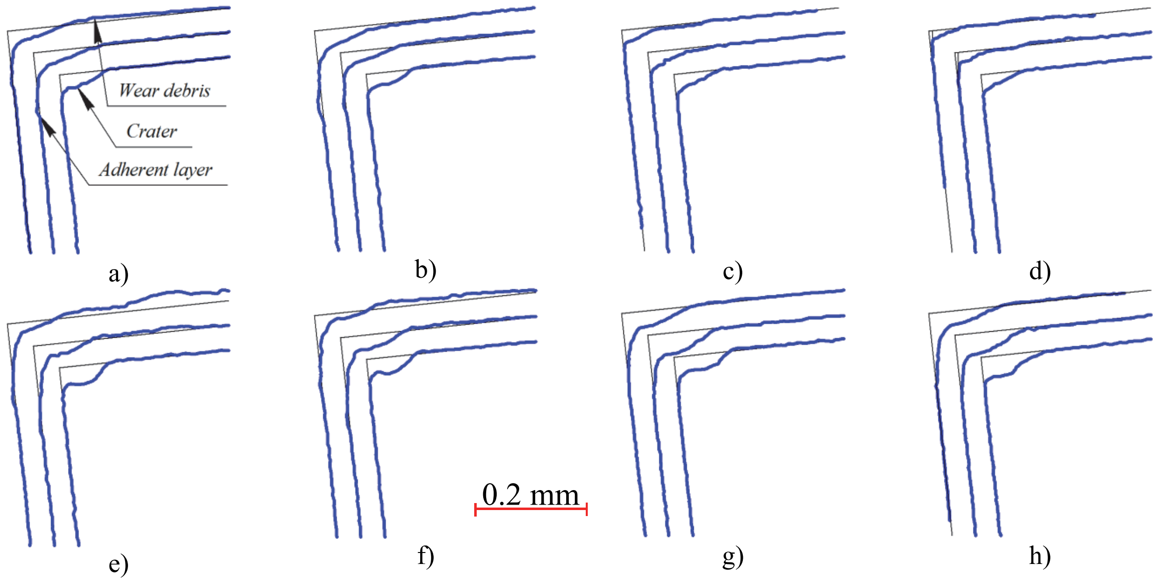


Fig. 6. Tool wear morphology when machining HCCI with **BCBN** tool at different cutting conditions: **as-cast** a) low C-Si content, v_c = 140 m/min; b) v_c = 160 m/min; c) high C-Si content, v_c = 140 m/min; d) v_c = 160 m/min; **hardened** e) low C-Si content, v_c = 120 m/min; f) v_c = 140 m/min; g) high C-Si content, v_c = 140 m/min; h) v_c = 160 m/min;

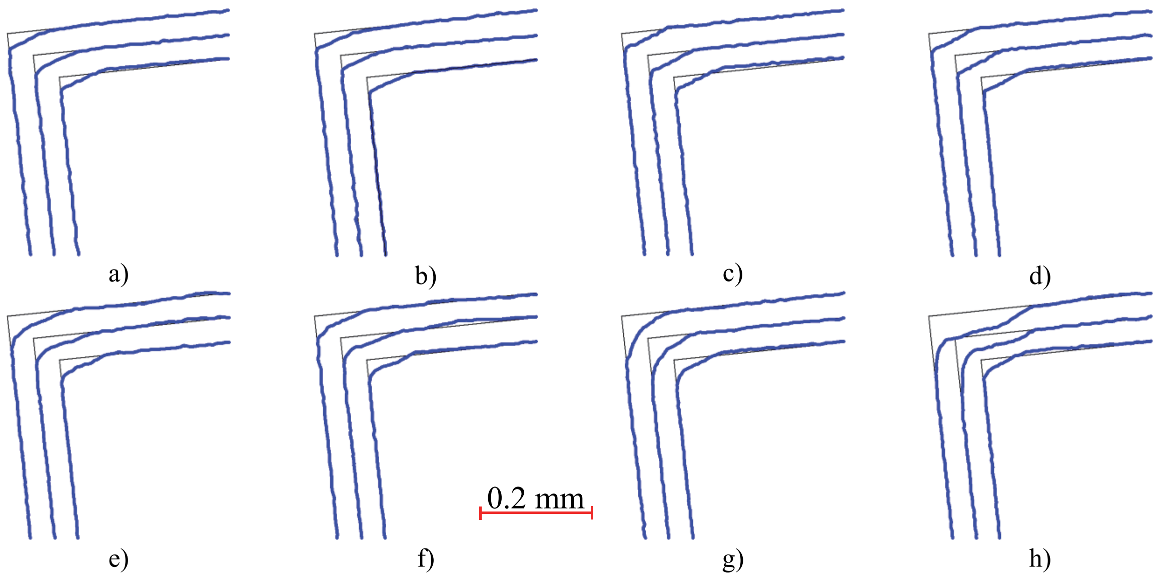


Fig. 7. Tool wear morphology when machining HCCI with **HCBN** tool at different cutting conditions: **as-cast** a) low C-Si content, v_c = 140 m/min; b) v_c = 160 m/min; c) high C-Si content, v_c = 140 m/min; d) v_c = 160 m/min; **hardened** e) low C-Si content, v_c = 140 m/min; f) v_c = 160 m/min; g) high C-Si content, v_c = 140 m/min; h) v_c = 160 m/min

The next conclusions can be done from the analysis of the obtained tool profiles:

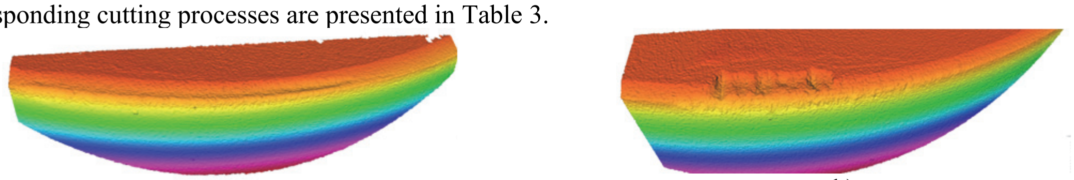
1) Both BCBN and HCBN tools were fresh when machining with cutting speed v_c = 120 m/min regardless of the test conditions. There are no flank wear lands on the worn tools but the formation of negative clearance angle was observed at some cutting conditions (Fig, 6 a, b, g-h and Fig. 7 e-h).

2) BCBN tools are much more inclined to form a chemical layer on the rake (wear debris) and flank (adherent layer) faces than HCBN ones (Fig. 6). The most suitable conditions for BCBN tools are the machining workpiece with low C-Si content at v_c = 140-160 m/min regardless of the thermal treatment (Fig. 6 a-b, e-f). The same layer can be observed for HCBN tools at higher cutting speed v_c = 160 m/min for as-cast and hardened HCCI with high C-Si content (Fig. 7 c-d, g-h) and hardened material with low C-Si content (Fig. 7 f).

3) Second big difference between two tool grades is the formation of crater on the rake face of BCBN tools in case of machining as-cast HCCI with low C-Si content and both types of hardened materials. The crater start to form at the area of the minimum chip thickness (Fig. 6 a, b, e) and grows along the cutting edge with increase of cutting speed (Fig. 6 e-h).

4) The tool wear of HCBN tools is characterized the increase of radius of cutting edge (Fig. 7). This effect is clearly seen when machining hardened HCCI (see Fig. 7 e-h). The severe tool damage was observed when cutting hardened HCCI with high C-Si content at v_c = 160 m/min. The damage is accompanied with a formation

of deep grooves with increase of tool edge radius (Fig. 7 h). In order to compare the mentioned difference in tool wear the 3-D images of worn BCBN and HCBN tools at highest cutting conditions are shown in Fig. 8. The measured cutting edge radii of worn tools at different cutting conditions with classification of effects related the corresponding cutting processes are presented in Table 3.



a) b)

Fig.8 Comparison of tool wear for different tools when machining hardened high C-Si HCCI at v_c = 160 m/min: a) BCBN; b) HCBN

Taking into account the data from Table 3 the intermittent behavior of BCBN tools as shown in Fig. 3 might be caused by the presence of the formed chemical layer on the tool surfaces which determine the friction conditions in the cutting zone. As distinct of that, the tool sharpness taken with the chamfer on the insert edge and significant increase of tool edge radius during machining leads to appearance of the high-frequency noise.

Table 3 Radius of cutting edges of worn tool

Workpiece	v_c, m/min	Radius, µm			
		BCBN	Notice	HCBN	Notice
Low C-Si as-cast	140	84	WD, AL, R, C	34	S, WD
	160	88	WD, AL, NCA, C	35	S
Low C-Si hardened	140	58	WD, AL, NCA, C	32	S
	160	72	WD, NCA, C	85	R, WD
High C-Si as-cast	140	22	S, WD	16	S
	160	26	S, WD	39	S
High C-Si hardened	140	77	R, C, NCA	216	R, NCA
	160	87	R, C, NCA, WD	157	R, G, NCA

WD – wear debris; AL – adherent layer; R – rounded; S – sharp; NCA – negative clearance angle; G – grooves; C – crater

Summarizing the mentioned above, the chatter-like behavior was clearly observed by CWT spectra as an intermittent process and can be characterized by the significant difference between amplitudes of tool vibration and their RMS value.

3.3. Specifics of generated surface and characteristics of its quality

The results of optical microscopy of obtained after machining surfaces are presented in Fig. 9. The analysis shows the synchronization of movements either between tool and workpiece or tool top and feed movements. The second way of formation of such "channels" is more feasible. The ducking of tool is more clearly visible as the feed rate increases. The results of measurements of surface roughness *Ra* are shown in Fig. 10.

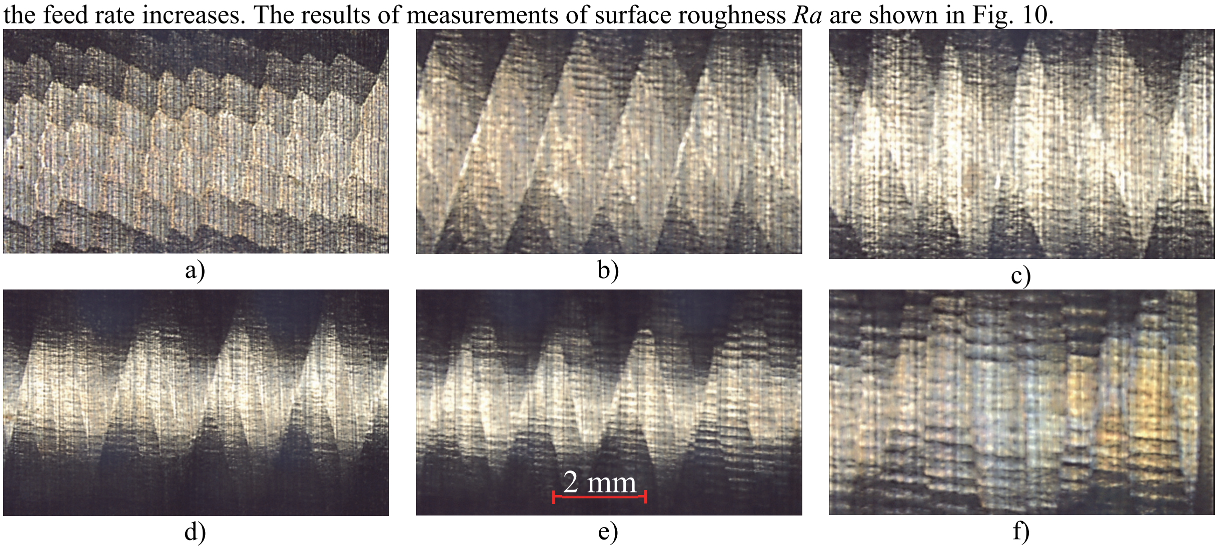
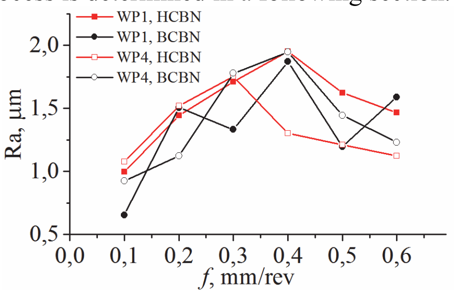
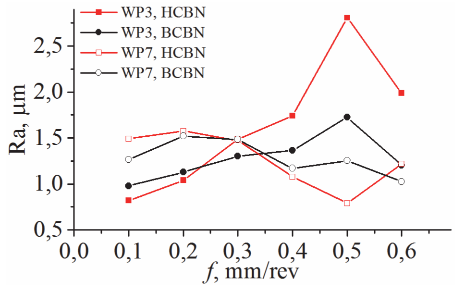


Fig. 9. Optical microscopy of generated surface after machining low C-Si content as-cast HCCI with HCBN tool: a) f = 0.1 mm/rev; b) 0.2 mm/rev; c) 0.3 mm/rev; d) 0.4 mm/rev; e) 0.5 mm/rev; f) 0.6 mm/rev

Following the definition of 'chatter', which is considered in the introduction (see above), the dynamic stability of the process is determined in a following section.



a)



b)

Fig. 10 Roughness dependency on cutting conditions, tool and workpiece materials: a) low C-Si content (WP1) and high C-Si content (WP4), as-cast; b) low C-Si content (WP3) and high C-Si content (WP7), hardened

3.4. Stability analysis

0-1 Stability test

There are many both the stability definitions and algorithms for estimation of dynamic system stability. Some of those are based on approaches of linear dynamics and compare the influence of excitation and damping components on the development of the oscillation amplitude. Archenty and Nicolescu, (2008, 2009), employing the autoregressive models, have defined instability as the condition when the effective damping coefficient approaches to zero. Another, generally accepted, approach for stability evaluation is based on the assessment of Lyapunov exponent or its spectrum. Nonlinear dynamics offers more advanced methods of stability evaluation (Gradishek et al., 1995; Berger et al., 1992) based on the analysis of fractal dimensions of trajectories in phase space or in some of its cross-sections (Poincare maps). On the other hand the vast majority of these approaches are complicated and resource consuming.
Easier method, so called “0-1 test”, was developed by Gotwald and Melbourne, (2009). The method was employed for the analysis of cutting process stability by Litak et al., (2009). Some restrictions and discussion on the method reliability are considered by Hu et al., (2005) and Gotwald and Melbourne, (2005). ‘0-1’ test is based on the asymptotic properties of a non-harmonic Brownian motion. The test calculates the spectrum of values which approach asymptotically to 0 or 1 for regular and chaotic motions, respectively. The obtained results for BCBN and HCBN tools are depicted in Figure 11.

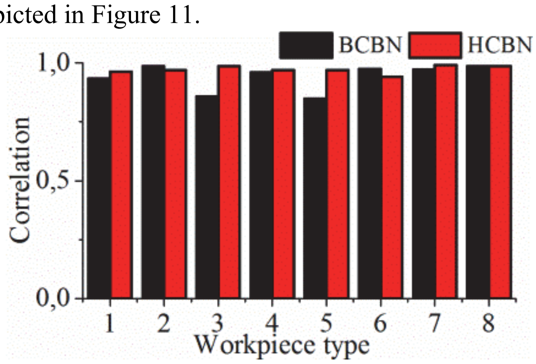


Fig. 11. 0-1 stability test for different workpiece materials: 1 – low C-Si, as-cast; 2 – low C-Si, annealed; 1 – low C-Si, hardened; 4 – high C-Si, as-cast; 4 – high C-Si, annealed; 4 – high C-Si, hardened; 4 – high C-Si, hardened; 4 – high C-Si, hardened.

Accounting the concept of ‘0-1 test’ the process is absolutely stable, or, rather, the tool tips of both tools perform regular motions. In order to verify the results, more a common characteristic for characterization of dynamic stability – Lyapunov exponent – was calculated.

Lyapunov exponent

The calculation of Lyapunov exponent for time series is not a trivial problem. One of the methods to find maximum local Lyapunov exponent is described in by A. BenSaïda and H. Litimi (2013). The results are shown in Fig. 12. The employed method considers the hypothesis that $\lambda \geq 0$ what indicates the presence of chaos or, what is the same, a divergence of trajectories follows the exponential law with positive exponent λ. Analyzing the obtained results it is evidently that the process is generally stable accepting the case when machining as-cast HCCI with high C-Si content when feed rate exceeds 0.4 mm/rev. The general tendency for all cases is the loose of dynamic stability with increase of feed rate when machining as-cast cast iron. The increase of hardness of workpiece materials results as usually in increase of stability up to the feed rate 0.6 mm/rev.
Hence the last indication of ‘chatter’, the dynamic instability, was not corroborated.

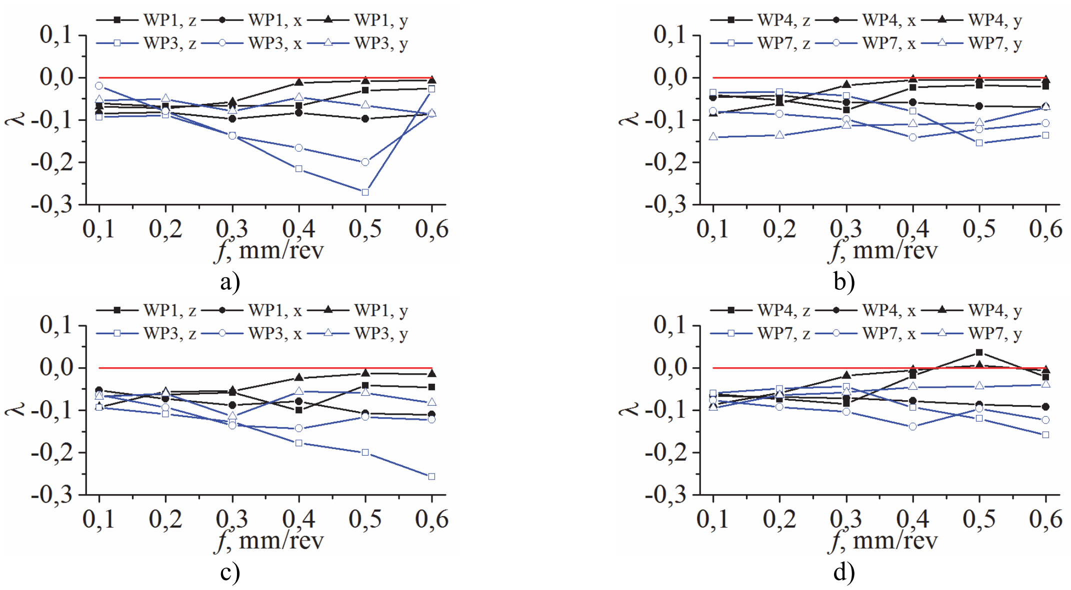


Fig. 12. Calculated maximum Lyapunov exponent (λ) for different directions (z – cutting; x – feed; y – passive): **BCBN** a) low C-Si content, as-cast (WP1) and hardened (WP3); b) high C-Si content, as-cast (WP4) and hardened (WP7); **HCBN** a) low C-Si content, as-cast (WP1) and hardened (WP3); b) high C-Si content, as-cast (WP4) and hardened (WP7)

4. CONCLUSIONS

1. It is evidently shown the chatter-like behavior of the dynamic system when machining different types of HCCI with PCBN tools: the intermittence of vibration signal, bad quality of machined surface with typical for chatter marks. On the other hand the considered process is dynamically stable what does not correspond to the conception of chatter. Taking into account the strong periodicity of the process, even in the presence of intermittence, and the synchronization of movements of parts of dynamic system it is possible to conclude that the considered case is related to self-resonant phenomenon in a several-mass dynamic system.
2. The intermittence of vibration signals is related to the specifics of tool wear formation – appearance of adherent layer on the tool surface. The presence of negative clearance angle as well as increase of tool edge radius results in the appearance of a high-frequency noise.

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