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DRGANIA W PROCESIE SKRAWANIA STOPU TYTANU

VIBRATIONS IN CUTTING PROCESS OF TITANIUM ALLOY

Praca przedstawia wyniki badań eksperymentalnych procesu skrawania stopu tytanu Ti6Al4V. W eksperymencie mierzono siły skrawania oraz przemieszczenia przedmiotu obrabianego podczas skrawania z różnymi głębokościami. Następnie, zarejestrowane sygnały przeanalizowano metodą współrzędnych opóźnionych, stosowaną do badania zjawisk nieliniowych, otrzymując mapy Poincare i wykresy rekurencyjne. Wyniki tych badań pozwoliły na identyfikację rodzaju drgań i dobór odpowiednich parametrów skrawania. W ostatniej części pracy wyniki badań skrawania stopu tytanu porównano z wynikami otrzymanymi dla klasycznej i kwasoodpornej stali.

Słowa kluczowe*: stopy aluminium, proces skrawania, dynamika skrawania.*

This work presents experimental investigations of cutting process in which the titanium alloy (Ti6Al4V) is cut. During the experiment the cutting forces and displacements of the workpiece are measured as a function of the cutting depth. The obtained signals are analysed using methods useful for nonlinear phenomena that is the method of delay coordinates, Poincare maps and recurrence plots. The results let us identify kind of vibrations and select the most proper cutting parameter. Finally, the results of titanium alloy cutting are compared with outcomes of classical and stainless steel machining.

Keywords*: titanium alloys, cutting process, dynamics of cutting.*

1. Introduction

Titanium alloys belong to so called superalloys which have high strength combined with high heat resistance and corrosion as well. Therefore titanium alloys are applied for extremely loaded components e.g. in civil and military aviation. The demand for a steadily growing productivity and product quality led to increasing of cutting parameters and this, in combination with their particular mechanical and physical properties can also make difficult machining. Additionally a further growth of a civil air traffic is predicted for the next years. Therefore the productivity of titanium alloy machining is one of the major challenges in production engineering [1]. Nowadays, new methods of titanium alloys cutting such as water jet cutting, laser cutting [3], plasma cutting are used especially in conditions of high part precision and short production time: [4]. Each of these modern, nonconventional means of materials processing has certain benefits, but also shortcomings that are discussed in the paper.

Beside various machining method, different kind of tools are tested. Despite, many researchers believe that alloyed cemented carbide (W–Ti/Ta)C–Co is not suitable for machining of titanium alloys. However, the result of study reported in [9] shows that the alloyed uncoated carbide (W–Ti/Ta/Nb)C–Co and alloyed CVD-coated carbide have good possibility to use in end milling of titanium alloy Ti-6242S even under extreme dry cutting condition. Authors explain it is probably due to the grain size of tools' substrate, its geometry and the class of titanium alloy Ti-6242S. Series of machining trials on the range of cutting speed between 60 and 150 m/min are conducted. These speeds can be treated as a traditional because high speed cutting refers to cutting speeds which are about five to ten times higher. Characteristics of cutting forces obtained for alloy Ti6Al4V at cutting speed up to 700 m/min are reported in [1]. Results received from different scientific institutes exhibit meaningful differences depending on a tool geometry and coatings.

A comparison of titanium alloys Ti6Al4V and Ti555.3 machinability for a traditional turning process is presented in [2]. The specific cutting force and specific feed force, tool wear, chip morphology, rake face and cutting edge after machining were analysed. The outcomes reveal that although the cutting force decreases versus cutting speed (up to 90 m/min), tool wear measured as a flank wear area considerably grows for higher cutting speeds. Nevertheless from point of view of final product user, the surface roughness seems to be a very important factor. Such investigations are talked over in [10]. A comprehensive review of machinability of titanium alloys is presented in [6]. The paper points out the main problems associated with the machining of titanium alloys as well as tool wear and the mechanism responsible for tool failure. It is found that the straight tungsten carbide cutting tools maintain their superiority in most machining processes, while CVD coated carbides and ceramics come out not to be such a good tool. As a major cause of a rapid tool wear, high cutting temperature is indicated whereas, the low modulus of elasticity of titanium alloys is a principal reason of chatter during machining.

During high speed cutting, it is important to understand the chip formation mechanism. Therefore paper [12] describes the effect of different influential variables including the tool chip angle, cutting velocity, chip thickness and also the structure of Inconel 718 and Ti6Al4V on chip formation and cutting forces. The experimental examination is completed with temperature measurements. For the cutting speed from 5 m/s to 80 m/s the specific cutting force behaves in a classical way, that means the force falls down when the cutting speed is higher regardless of the a clearance angle.

An interesting and novel solution to improve productivity of titanium and nickel alloys cutting is developed in [18]. Authors introduced diamond tool with forced cooling system that is efficient for high speed machining.

Most of published paper concerning cutting of titanium alloys have pure experimentally nature but there are such of them in which a mathematical model is developed, e.g. tool life mathematical model for end milling is discussed in [8]. The theoretical results are compared to experimental ones with a positive effect. The tool life models show that the cutting speed is the main factors on the tool life, followed by the feed and axial depth of cut. Increase many of these three cutting variables leads to reduction of tool life.

On the basis of above literature one can conclude that scientific papers mainly exhibit results of force measurements during cutting under different, conventional and high speed conditions. This paper goes further because outcomes of titanium alloy Ti6Al4V turning is compared to stainless (EZ6NCT25) and ordinary (C45) steel and then a new method of time series analysis is proposed.

2. Experimental set up and results

Experimental investigations were conducted on the experimental setup presented in fig. 1. The measurement set up is composed of the piezoelectric dynamometer Kistler 9257B, charge amplifier type 5017B and laser sensors optoNCDT 1605/2 (Micro-Epsilon Messtechnik), "sample and hold" module (SC2040) and analog-digital converter NI 6071E by National Instruments. All the signals from the dynamometer and the lasers are transmitted to the analog-digital converter, which is connected to a computer system. A workpiece used in the experiment had the same measurements and was made of titanium alloy Ti6Al4V, stainless steel EZ6NCT25 and constructional steel C45. The workpiece was cut on the lathe C11 with rotational speed of 710rpm and different cutting depth from 0.4mm to 3.0mm. The rest of technological parameters were settled (constant). The detailed description of parameters employed in the experiment is presented in tab. 1.

Theoretical investigations carried out on the basis of turning process model in which a dry friction effect plays a key role demonstrate an influence of the cutting depth on system stability and on the amplitude of vibrations during machining [15, 16]. Therefore experimental investigations here are performed for various cutting depth from 0.4mm to 3mm. The results of forces measurements are presented graphically in fig. 2 for titanium alloy Ti6Al4V, stainless steel EZ6NCT25 and constructional steel C45. The curves show the mean value of cutting forces with standard deviation as a vertical bar. Generally, forces (F_x, F_y, F_z) raise with the cutting depth what is in accordance with the classical theory although, for instance paper [12] reports some evidence about decreasing force with growing depth. The force change can be treated as a linear or almost linear that is also modelled in some papers.

It is proved that forces of titanium alloy turning are smaller than stainless steel and even than constructional steel C45 which is rather seemed to be well machinable. Looking at a displacement chart (fig. 3) which presents a standard deviation of workpiece vibrations in z direction, one can explain why the cutting forces are smaller than in case of steel cutting.

Namely, the stiffness of titanium alloy is smaller then constructional steel and therefore bigger vibrations are visible spe-

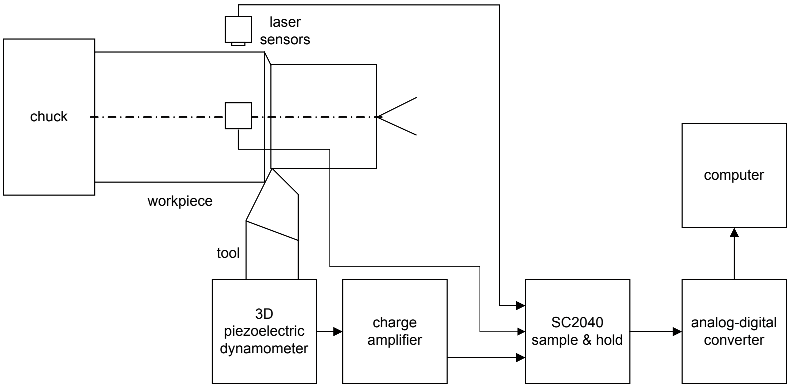

Fig. 1. Experimental set up scheme

Tab. 1. Cutting condition

No	Rotational speed [rev/min]	Feed [mm/rev]	Sampling frequency [Hz]	Tool cutting edge angle	Cutting depth [mm]
Titanium alloy					
186	710	0.25	2000	45	3.0
187	710	0.25	2000	45	2.6
190	710	0.25	2000	45	1.8
193	710	0.25	2000	45	0.9
194	710	0.25	2000	45	0.4
Constructional (ordinary) steel C45					
195	710	0.25	2000	45	2.9
196	710	0.25	2000	45	2.3
199	710	0.25	2000	45	1.7
202	710	0.25	2000	45	1.0
203	710	0.25	2000	45	0.4
Stainless steel EZ6NCT25					
204	710	0.25	2000	45	2.8
205	710	0.25	2000	45	2.3
208	710	0.25	2000	45	1.75
211	710	0.25	2000	45	1.0
212	710	0.25	2000	45	0.5

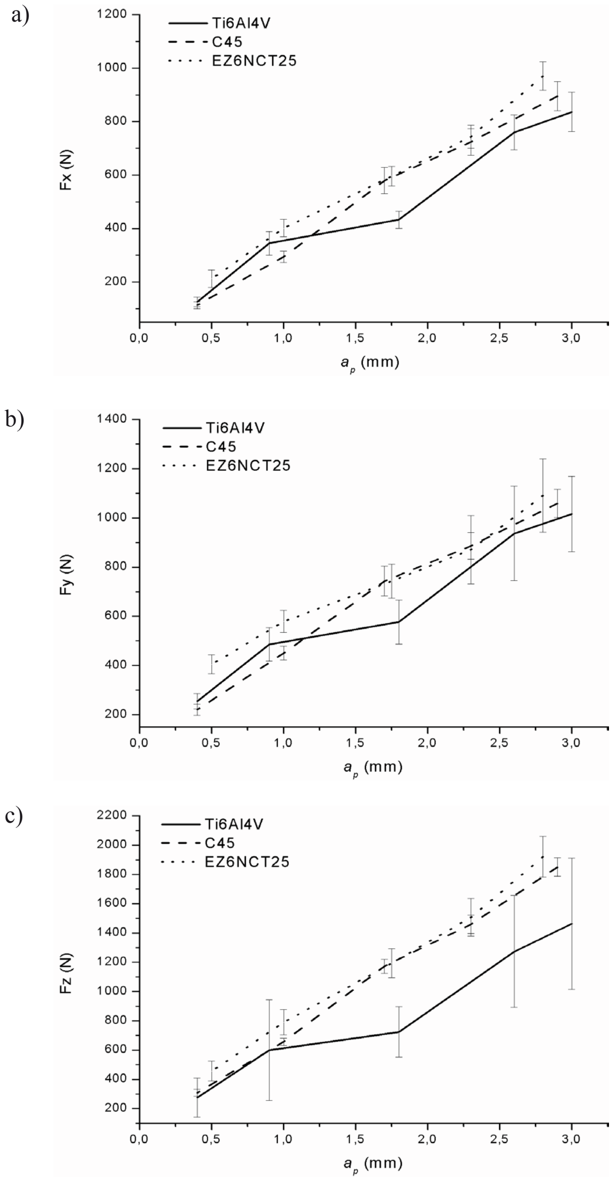

Fig. 2. Cutting forces versus cutting depth during machining titanium alloy Ti6Al4V, stainless steel EZ6NCT25 and constructional steel C45; a) feed force, b) thrust force, c) cutting force

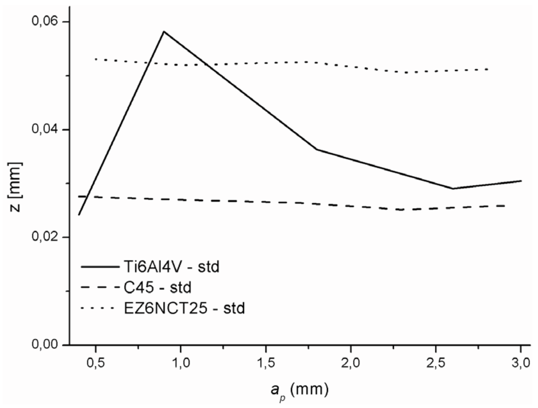

Fig. 3. Standard deviation (std) of displacement in z direction versus cutting depth

cially for the cutting depth about 0.8mm. The second reason of a rapid vibration increasing can be related to the forces jump visible in fig. 2. To sum up, very little cutting depth or bigger than some critical one can be considered as a proper cutting depth of titanium alloy. This behaviour does not exist in other materials compared.

3. Results of analysis

The outcomes of measurements recorded as time series can be analysed with many different procedures dedicated for nonlinear phenomena. Here, two methods are applied. The first, called the method of delays, is proposed in order to obtain attractors directly from time series. The second, that is a recurrence plot bases on time series as well but let us look at cutting dynamics under different angle.

The reconstruction of attractors is made with the help of Tisean package by Hegger, Kantz and Schreiber [11]. The first step in this investigation is the state space reconstruction by delay coordinates [14, 17]. A measured time series can be presented as a vector in a new space in the form:

$$x(t) = [S(t), S(t+\tau_1), ..., S(t+(w-1)\tau_1)] \qquad (1)$$

The new space is called the embedding space, the number w denotes the embedding dimension, the time τ_1 is generally referred to the time delay or lag. The time delay is taken as an integer multiple of the sampling time and is computed using the average mutual information [7], given by

$$J(\tau_1) = \sum_{S(t),S(t+\tau_1)} P(S(t), S(t+\tau_1)) \log_2 \frac{P(S(t), S(t+\tau_1))}{P(S(t))P(S(t+\tau_1))} \qquad (2)$$

where $P(S(t))$ is the probability of a measurement $S(t)$ and $P(S(t),S(t+\tau_1))$ is the join probability of measurements $S(t)$ and $S(t+\tau_1)$). The average mutual information is plotted versus the time lag and the chosen value corresponds to the first local minimum. This procedure is an equivalent of an autocorrelation function for a linear case. The embedding dimension w is obtained by the method of false neighbours based on searching w-dimensional state space in which there are no false crossing of the trajectories in the reconstructed space. Fig. 4-9 present phase space with reconstructed attractors obtained on the basis of force F_z and displacement z signals. The graphs concerning the force of titanium alloy (fig. 4) exhibit that attractors are very similar. Their shape is the same, like a set of points concentrated together but the size of attractors changes depth of cut. Considerably change is noticeable looking at fig. 5a and 5b where the attractors are reconstructed from displacement. For a_{po}=0.4mm the attractor is regular that means motion is subharmonic with period 2. As far as constructional steel C45 is considered, fig. 6 and 7 show regular motion with period 1 whereas attractors in fig. 8 and 9 differ from each other. Analysing the force only regular attractors exist but taking displacement into consideration the motion seems to be quasiperiodic for all cases.

The method of recurrence plot, used here, has been invented by Eckmann et al. [5] and is used for identification of nonlinear systems with various behaviour. Such plots are constructed by spatial proximity analysis of time series x_i. For arbitrary i and j from the interval [0,N], where N is the total number of points in given time series, a black dot is plotted on the graph if the following condition is fulfilled:

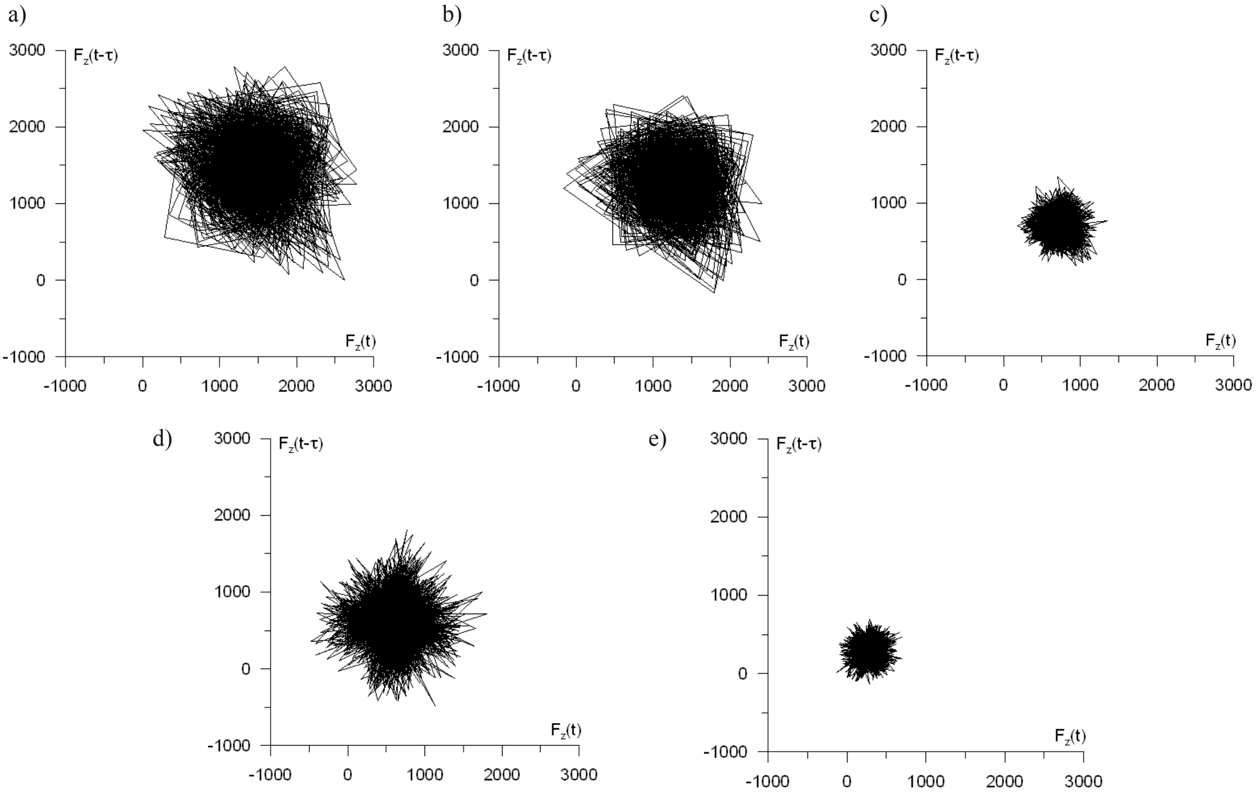

Fig. 4. Reconstructed Phase Space for Ti6Al4V from $\mathbf{F}_z$ signal a) $\mathbf{a}_p$=3mm, b) $\mathbf{a}_p$=2.6mm, c) $\mathbf{a}_p$=1.8mm, d) $\mathbf{a}_p$=0.9mm, e) $\mathbf{a}_p$=0.4mm

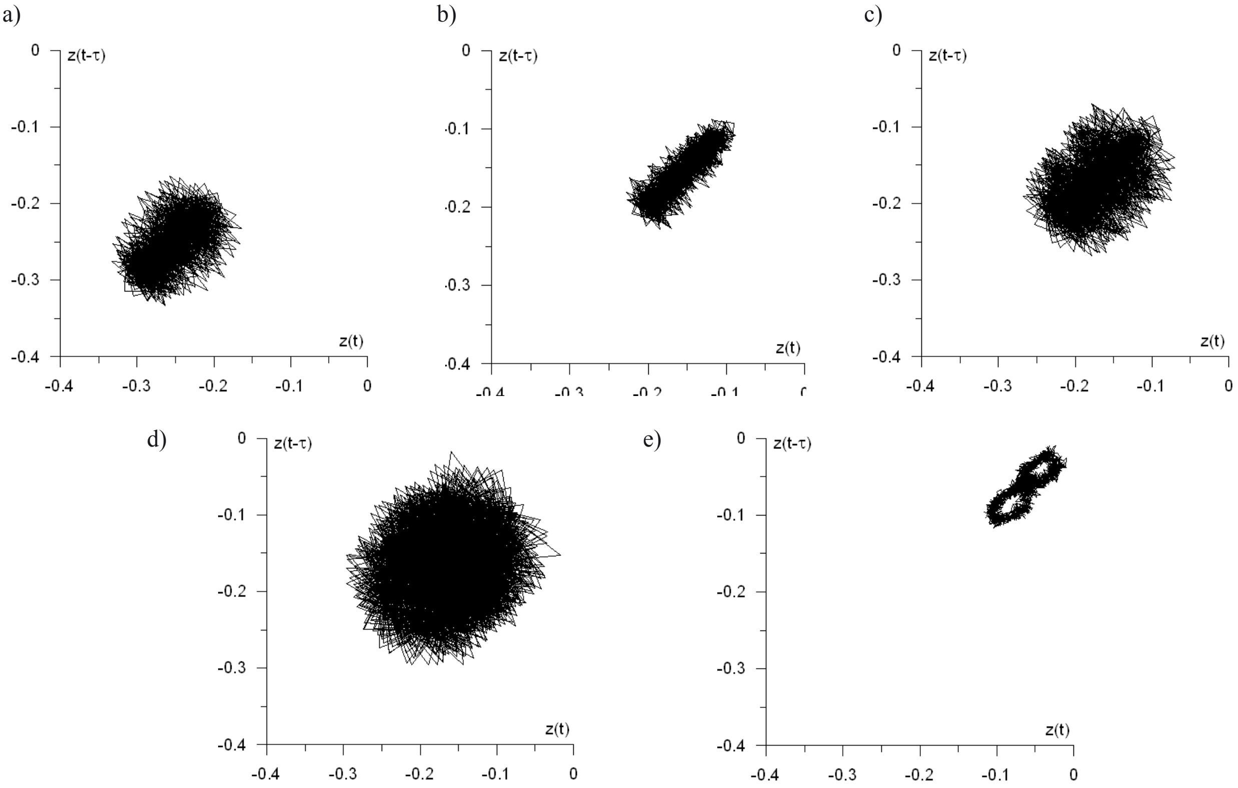

Fig. 5. Reconstructed Phase Space for Ti6Al4V from z signal a) $\mathbf{a}_p$=3mm, b) $\mathbf{a}_p$=2.6mm, c) $\mathbf{a}_p$=1.8mm, d) $\mathbf{a}_p$=0.9mm, e) $\mathbf{a}_p$=0.4mm

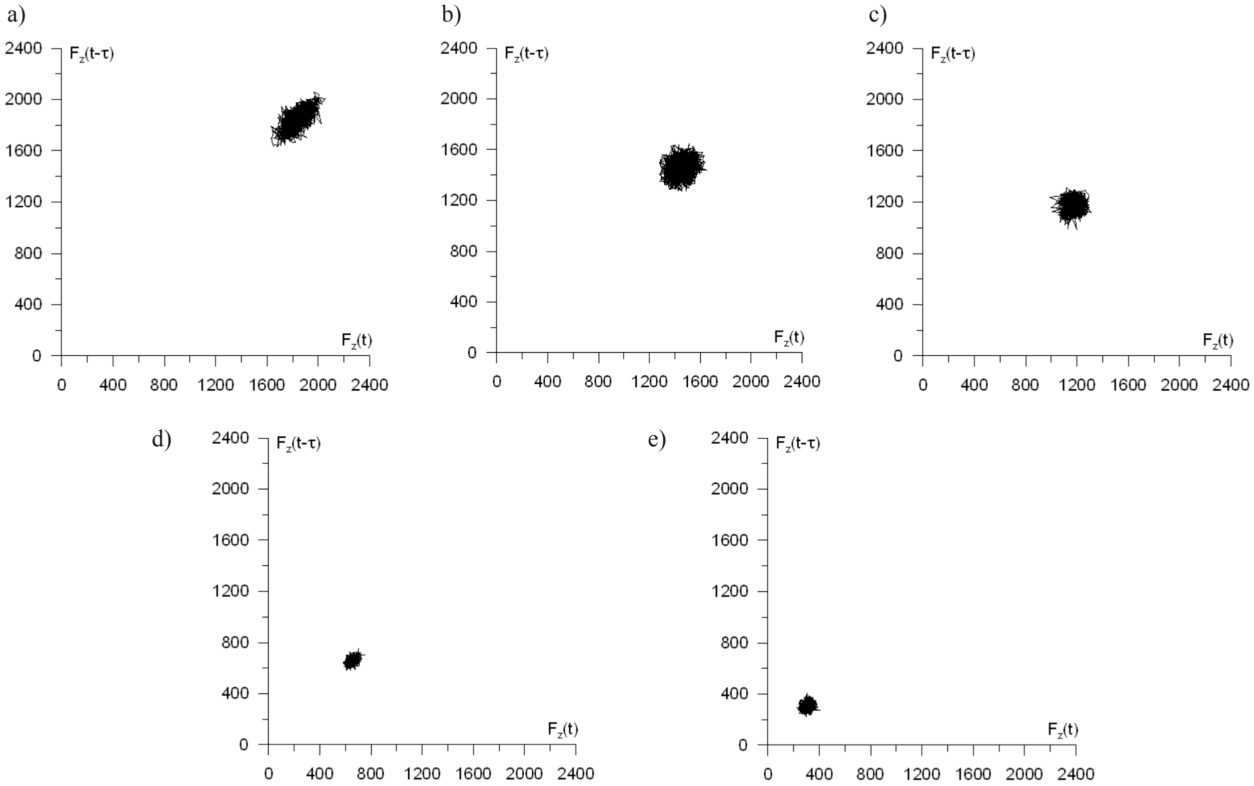

Fig. 6. Reconstructed Phase Space for steel C45 from $\mathbf{F}_z$ *signal a)* $\mathbf{a}_p$*=2.9mm, b)* $\mathbf{a}_p$*=2.3mm, c)* $\mathbf{a}_p$*=1.7mm, d)* $\mathbf{a}_p$*=1mm, e)* $\mathbf{a}_p$*=0.4mm*

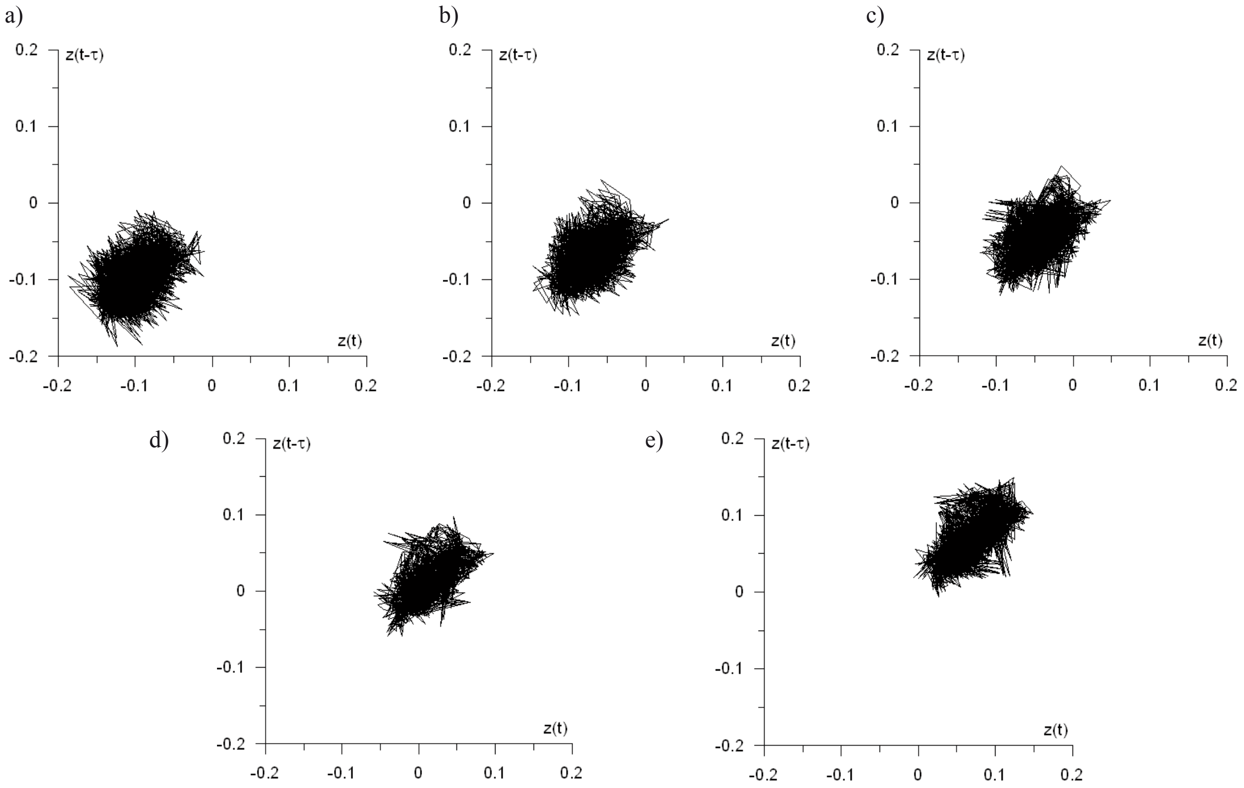

Fig. 7. Reconstructed Phase Space for steel C45 from z signal a) $\mathbf{a}_p$*=2.9mm, b)* $\mathbf{a}_p$*=2.3mm, c)* $\mathbf{a}_p$*=1.7mm, d)* $\mathbf{a}_p$*=1mm, e)* $\mathbf{a}_p$*=0.4mm*

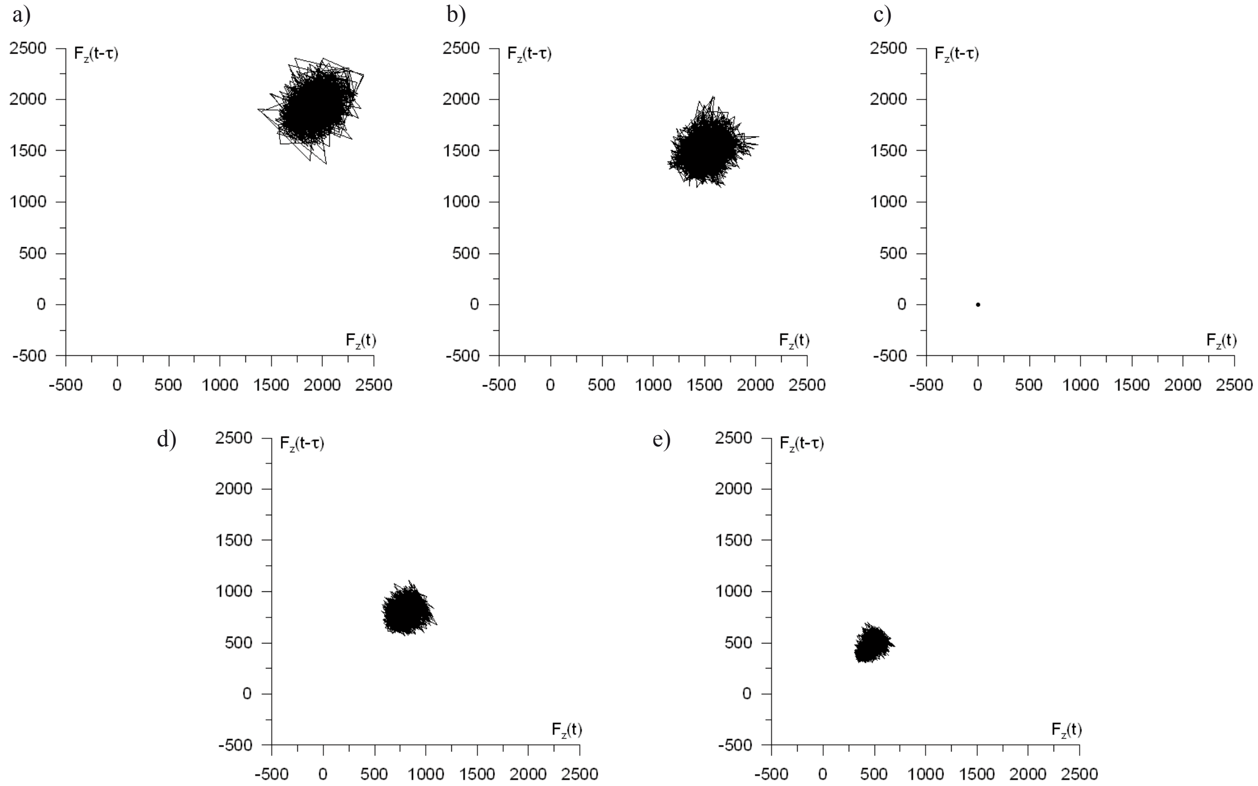

Fig. 8. Reconstructed Phase Space for EZ6NCT25 from $\mathbf{F}_z$ signal a) $\mathbf{a}_p$=2.8mm, b) $\mathbf{a}_p$=2.3mm, c) $\mathbf{a}_p$=1.7mm, d) $\mathbf{a}_p$=1mm, e) $\mathbf{a}_p$=0.5mm

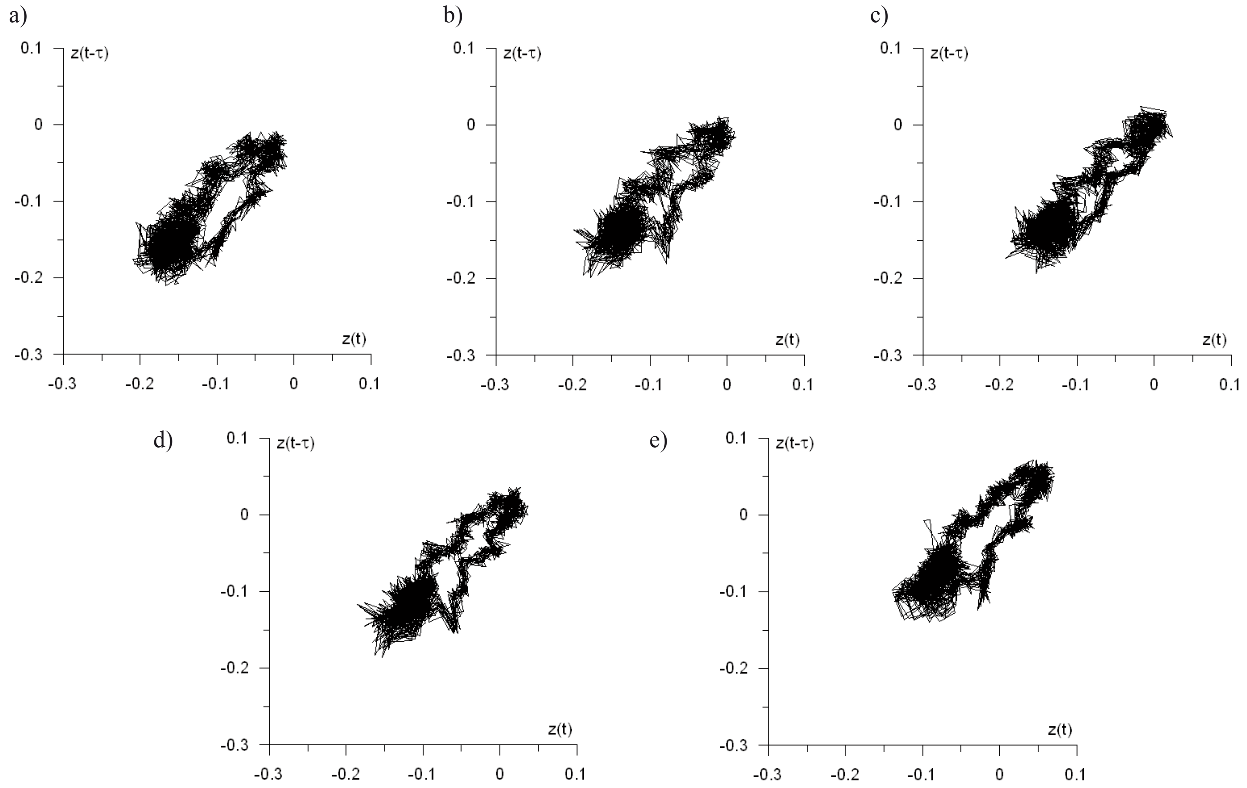

Fig. 9. Reconstructed Phase Space for EZ6NCT25 from z signal a) $\mathbf{a}_p$=2.8mm, b) $\mathbf{a}_p$=2.3mm, c) $\mathbf{a}_p$=1.7mm, d) $\mathbf{a}_p$=1mm, e) $\mathbf{a}_p$=0.5mm

$$\left|x_i - x_j\right| < \varepsilon \tag{3}$$

Note, ε is a small threshold number adjusted for each time series case separately in such a way to get a good contrast in diagram. In fact by using the above qualitative method for deterministic systems it is possible to classify the dynamics of a examined system by its characteristic patterns showing diagonal, vertical or horizontal structure of lines and stripes. The method allows to distinguish kind of motion e.g. chaotic from purely stochastic or regular behaviour. Generally, a pattern for a stochastic system is based on uniform distribution of points in the recurrence plot while a chaotic system possesses structure of lines with finite lengths [13].

Figures 10, 11 and 12 represent recurrence plots which are received from the time series of displacement. Plots for titanium alloy (fig. 10) suggest that in the case of 3mm depth of cut the process is similar to regular but with rather strong stochastic component. While for a_{po}=0.4mm the motion is regular. The pattern connected with cutting of the constructional steel C45 (fig. 11) has strong stochastic background however some symptoms of regularity also exist. Considering fig. 12 which represents high level of ordering one can conclude that workpiece vibrations are regular although, main period of vibrations, which is represented by long diagonal lines, is mixed with very short period which is illustrated as black dot.

Insight in dynamics of cutting process, done together on the basis of reconstructed attractors and recurrence plots, demonstrate the kind of vibrations which is dependent on cutting depth. Thus, introducing these method of signal analysis let us look deeper on the problem of vibrations during cutting process.

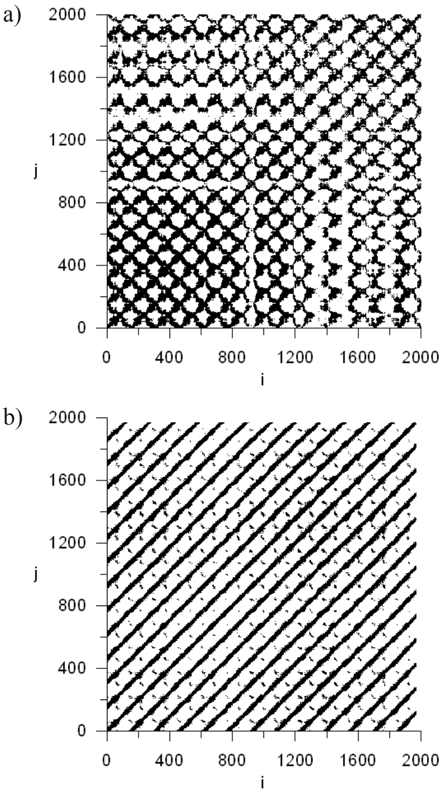

Fig. 10. Recurrence plots for titanium alloy Ti6Al4V; a) depth of cut a_p=3mm, b) a_p=0.4mm

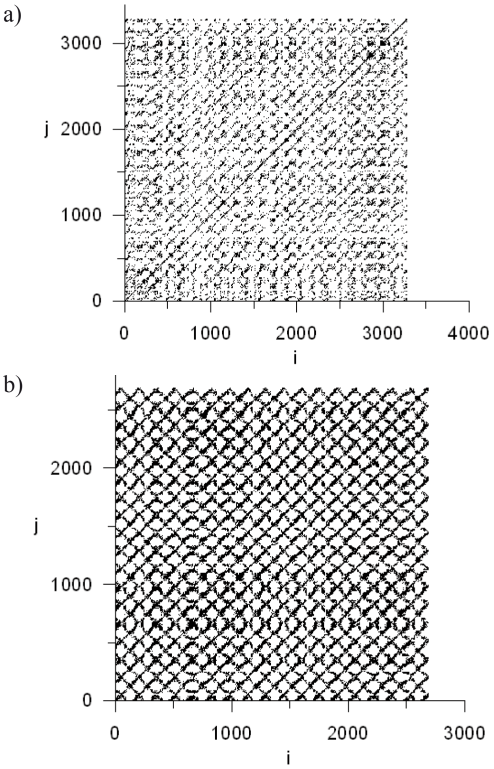

Fig. 11. Recurrence plots for constructional steel C45; a) depth of cut a_p=2.9mm, b) a_p=0.4mm

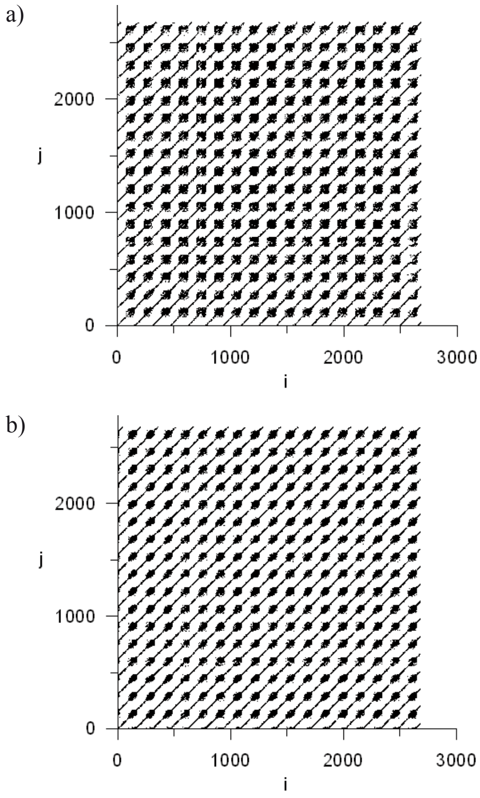

Fig. 12. Recurrence plots for stainless steel EZ6NCT25; a) depth of cut a_p=2.8mm, b) a_p=0.5mm

4. Conclusions

Cutting of titanium alloy is compared with others constructional materials. This comparison demonstrates differences between cutting forces during titanium alloy, stainless and constructional steel machining. Basically, the cutting forces grows when depth of cut increases. The level of vibrations, measured as a standard deviation of displacement is the biggest for the depth of cut 0.8mm. Noticeable jump of vibrations for titanium alloy is probably caused by friction phenomenon and low Young's modulus compared to steel. The join analysis of reconstructed attractors and recurrence plots point out at considerable influence of stochastic component specially in the signals of force. Therefore, better results are received when time series of displacement is analyzed because of smaller stochastic component. Generally, machining at small cutting depth characterizes regular vibrations that is proved by the patterns of recurrence plots. What is more, regularity is written in the nature of stainless steel cutting

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