Application of Discrete Wavelet Transform to Analysis of Cutting Forces in Turning of Composites based on Aluminium Alloys Reinforced with Al₂O₃ Fibres

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This paper presents the results of experimental tests of the turning of an aluminium composite reinforced with Al₂O₃ fibres. The tests were carried out using three cutting tools with no cutting fluid and in minimum quantity lubrication (MQL) conditions. The cutting forces were measured. For further analyses the main force component was selected. Its mean values and amplitudes were calculated. Then the registered traces were filtered with Daubechies wavelets. Load constancy factors for the filtered off signals were calculated and compared with the factors calculated from the unfiltered signals. On the basis of this comparison, the level of disturbances and noise during the turning of the aluminium composites was assessed and the effect of the machining conditions on the size of the disturbances was determined. It has been found that the discrete wavelet transform can be a tool aiding the monitoring of the turning of composites.

Keywords: *aluminium composite materials, cutting force, discrete wavelet transform, load constancy, measurement disturbance*

1. INTRODUCTION

The interest in and demand for composite materials based on a metal (especially aluminium) matrix has been growing for the last 30 years. This is mainly owing to the high strength/weight ratio of such materials. Moreover, composites have numerous characteristics which distinguish them from other materials. The cha–racteristics include: hardness, corrosion resistance, wear resistance and thermal resistance. Thanks to their greater hardness than that of the matrix material, aluminium composites are regarded to be more difficult to machine than the matrix alone because of the blade wear index [1-3]. Another major index of material machinability is the cutting force. Hence, its precise determination, disturbance- and noise-free measurement and the forecasting of its values are major research topics in the world, particularly with regard to novel machined materials such as composites.

Composite materials based on lightweight metal matrix are usually reinforced with hard ceramics in the form of fibres or particles. This reinforcement increases the material's hardness, but significantly shortens cutting tool life. Therefore the selection of proper machining parameters and tools, ensuring optimal output at high quality of the machined elements and satisfactory blade life, is very important. This is difficult in the case of this type of materials. For example, the use of wiper tool inserts significantly reduces surface roughness, but at the same time these inserts wear out much quicker [4].

Moreover, cutting parameters differently affect the main machinability indices. When feed rate is increased, blade life decreases while roughness increases, whereas cutting speed reduces roughness, but significantly shortens tool life [5]. Feed rate has the strongest effect on roughness. The adverse effect of this parameter can be minimized through additions to the machined material, e.g. a graphene addition to composites reinforced with carbon nanotubes. A graphene addition also increases the cutting forces. From the cutting parameters the depth of cut most strongly affects the cutting force value [6]. Machinability and the material separation process can be improved through the use of special cutting inserts with textured surfaces. The texturing consists in making a large number of microholes in the insert's rake face. The holes are filled with grease. The machining can be additionally aided with other cutting fluid feeding methods. Such cutting inserts can not only reduce the surface roughness of composites after turning, but also reduce power demand and extend blade life [7]. The form and amount of reinforcement have a major bearing on the machinability of composites. The volumetric amount of reinforcement in the composite and the diameter of the particles or fibres have the strongest effect on the wear of polycrystalline diamond blades. Blade life decreases as the amount and dimensions of the reinforcement increase [8]. Optimal machining conditions can be selected on the basis of experimental tests. For this purpose a proper test plan, possibly covering all the factors involved, should be prepared. Such tests were presented in [9]. It appears from them that feed rate has the strongest effect on surface roughness in the turning of a hybrid aluminium composite containing aluminium oxide (Al_2O_3) as the primary reinforcement and molybdenum disulphide (MoS_2) as the secondary reinforcement. The cutting force increases with the rate of feed. It was found that minimal

cutting force values can be obtained at a higher cutting speed, a low feed rate and a small depth of cut. The tests showed that the specific cutting pressure (SCP) increases at a low cutting speed and a higher feed rate. This is due to the fact the material machined under these parameters is subjected to a lower strain rate. Also other factors, such as the cutting temperature and the lubrication method, affect the SCP value. In [10] it was observed that at a higher cutting speed the matrix finds it more difficult to deform and the tool rather tears out and shears reinforcement than pulls it out of the matrix. At the same time as the cutting speed increases, the cutting force and the feed force decrease. The decrease in the cutting force with increasing cutting speed is ascribed to the higher temperature in the shear plane area, which leads to a reduction in the shear strength of the machined material [11]. These results have been corroborated by many other experimental studies. Moreover, the cutting forces increase as the reinforcement fraction in the composite is increased. The forces can be reduced using self-lubricating reinforcements and selecting polycrystalline diamond for the tools [12, 13].

Research is being conducted, the aim of which is to replace either the machining other technologies, e.g. Laser treatment [14]. Because alternative techniques also have their disadvantages, solutions in machining are looked that composites machinability is improved. Machinability can be improved, in comparison with dry machining, using minimum quantity lubrication (MQL). In [15] it was shown that the use of MQL in the machining of aluminium alloy 6026-T9 significantly improves the quality of the machined surface. Moreover, it was found that tool flank wear advancement in the MQL environment is relatively slow in comparison with dry machining. The positive effect of MQL is also observed in the machining of aluminium composites. Machining in the oil mist lubrication environment facilitates the reduction of the generated forces and tool wear since a lubricant, even if fed in small amounts and in the form of mist, helps to reduce heat and friction [16].

Composite materials are regarded as poorly machinable, but they are the main material group used in aviation where the quality and safety requirements are very high. Hence, it is necessary to very closely monitor the process of manufacturing elements from composites, comprehensively analyse the machinability indices and measure the quality of the products. There are many methods of monitoring, analysing and forecasting the machining process. The forecasting of the cutting force in the milling of aluminium alloy 6060-T6 was presented in [17]. Two methods of predicting cutting force values: the Altintas method and the RLS method were used there. The results yielded by the two methods were compared with experimentally determined cutting forces. The simulated forces yielded by the RLS method were in good agreement with the experimental forces. But the peak forces and the valleys simulated using the Altintas method did not agree with the experimentally determined forces. This shows that the forecasting method should be well matched to the specific case. Prediction of the cutting forces through the cutting orthogonal coefficients identification are

shown in [18]. The fast Fourier transform (FFT) and the wavelet transform are used to monitor the machining process. An example here is research [19] in which the Fourier transform and the continuous wavelet transform were used to detect blade wear, including cutting edge nicks. The proposed FFT method can supply information on when the blade will wear out and enable tool chipping detection. In comparison with it the wavelet transform seems to be more effective in detecting the precise moment when the cutting edge begins to nick. Also chip formation and workpiece rectilinearity loss can be effectively monitored [20]. Daubechies wavelets were used in the considered paper. Moreover, in order to eliminate the influence of cutting conditions the load variation coefficient was calculated as a ratio of the force amplitude to the force mean value. The wavelet transform is used as a tool aiding the machining process monitoring via the acoustic emission signal. An example here is study [21] where acoustic emission was used to diagnose blade wear during milling. The acoustic emission signal was filtered by means of the wavelet distribution and the further analysis was carried out using the Fourier transform. Also in [22] tool wear was monitored via the acoustic emission signal which was then filtered and factorized by means of the wavelet transform. Acoustic emission and the wavelet transform combined were used to forecast and monitor the intensity of build up edge during the turning of stainless steel in [22]. The fast Fourier transform and the wavelet transform were used to detect blade wear in [23]. It was shown that a multiresolution analysis of the feed force can be used to detect cutting process time-frequency characteristics which cause blade wear. It was found that it is critical to determine the multiresolution parameter, i.e. the level of wavelet decomposition. The wavelet transform was found to be more useful than the Fourier transform as the signal analysis proceeded sevenfold faster. A hybrid analysis of machining effects was presented in [24], where the Fourier transform was combined with the discrete wavelet transform and the discrete Shearlet transform to forecast the surface roughness of milled elements. The results reported there show that each of the methods can quite accurately forecast the values of parameters Ra, Rz and Rq. But only the hybrid approach enables truly precise prediction. Wavelet analysis can be used to detect unexpected irregularities in the turning process and take online decisions on workpiece surface quality acceptability [25]. In the aforementioned paper Daubechies wavelet 6 in the five-level distribution of cutting force components was used to estimate roughness standard deviation Ra. The wavelet method was found to be an ideal procedure for processing cutting force signals online and monitoring surface finish in real time. This kind of analysis was deemed very precise and reliable at low costs of analytical calculations and with no need to use other types of signals or static process parameters such as cutting conditions or tool geometry. Also any anomalies during drilling can be detected via the discrete wavelet transform both offline and online [26]. In [27, 28] wavelet analysis was used to monitor cutting forces in the machining of composites. All the literature

presented above shows that it is possible, and sometimes necessary, to use advanced signal analyses, including the wavelet transform, to properly monitor or analyse the cutting process. This applies to such kinds of machining as turning, milling and drilling and to various machined materials, including composites based on a lightweight metal matrix.

The analysis of cutting forces is important from the viewpoint of the durability of tools and machine tools, the quality of manufactured elements and production efficiency. The measurement of forces is characterized by significant noise, which makes it difficult to analyze the forces and cutting resistance objectively. Therefore, proper filtration of the force measurement is required. The literature offers proposals for various methods of cutting force analysis and filtration methods.

The analyses presented in the literature are often highly complex and complicated. Their application, especially during machining, can be troublesome. The common feature of online and offline analyses is that force signal can be decomposed into components. The main method of discharging the signal of forces and its filtration is Fourier and wavelet analysis. Fourier analysis is limited to the frequency domain only, treating the signal as a periodic signal. Since the force signal may be non-periodic, the authors decided to use discrete wavelet analysis to decompose the signal obtained from cutting force measurements into the signal strictly relating to the force and into disturbances. This paper presents an algorithm for the analysis of cutting forces on the basis of the wavelet transform and the load constancy factor being the reverse of the load variability coefficient described in [20]. The use of this coefficient in addition to the value of the average force is very important because it gives additional information about the cutting forces, especially the amplitude.

2. TESTING CONDITIONS

A composite whose matrix was complex casting alloy AlSi9Mg and its reinforcement were Saffil ceramic fibres was subjected to tests. The chemical composition of the material's matrix is presented in table 1. Owing to its silicon content, the matrix is characterized by lo–wered hot brittleness. This alloy is also characterized by good resistance to corrosion and to the action of sea water. It is very well weldable and castable. It is classified as a readily machinable material [29]. The fibres being the reinforcement in the tested material are one of the most popular materials used for reinforcing aluminium composite materials [30]. They consist of 96-97% of Al_2O_3 and 3-4% of SiO_2 [31]. They are cla–ssified as high-strength materials as they are characterized by high temperature resistance, high tensile strength and a high E-modulus [32]. The properties of Saffil fibres are shown in table 2. Their values are approximate and can differ depending on many factors, e.g. the manufacturing technology.

The tested material was produced using squeeze casting in the Institute of Machines Technology and Automation at Wrocław University of Science and Technology. The process was divided into two stages. First, a ceramic block was made out of Saffil fibres.

Then the block was infiltrated with liquid metal [29]. Thanks to the excellent properties of Saffil fibres and the use of a proper method of producing them, a com–posite material characterized by very good properties (in comparison with the matrix material) was obtained [27]. The Brinell hardness (HB) of the material increases by 50%, tensile strength Rm by as much as 60% and offset yield point R0.2 by 40% relative to aluminium alloy AlSi9Mg.

The increased indices may indicate an increase in specific cutting resistance. At the same time plasticity and elongation decreased which can signi–ficantly reduce edge buildup intensity. In general, due to the different properties than those of the matrix material the character and values of the cutting force components must be different than in the case of aluminium alloy machining. The cutting forces can be also affected by the composite's other peculiar properties, such as: its four times greater abrasion resistance and lower thermal expansion than that of the matrix. The properties of the aluminium composite material reinforced with Saffil fibres are compiled in table 3. The metallurgical polished section of the tested material is shown in fig. 1.

Table 1. Chemical composition of alloy AlSi9Mg [33].

AlSi9Mg	Elemental concentration [%]						
	Si	Cu	Mg	Mn	Fe	Ti	Zn
	9.5	<0.05	0.35	<0.1	<0.18	0.15	<0.07

Table 2. Properties of Al₂O₃ fibres [33]

Density [g/cm³]	Tensile strength [GPa]	Compressive strength [GPa]
3.7	1.8	6.9
E-modulus [GPa]	G-modulus [GPa]	Durability up to temperature [C]
300	122	1600

Table 3. Selected properties of tested material [34, 35].

Tested material	Properties			
	R_m, MPa	$R_{0.2}$, MPa	HB	α.,1/K
	240-260	160-170	105-115	12-20

Turning tests were carried out on a CNC TUR 560 MN engine lathe (fig. 2). An STGCR 2020K–16 turning tool and cutting inserts made of uncoated cemented carbide TCGX16T304 – Al H10, diamond coated carbide TCGX16T304 – Al 1810 and polycrystalline diamond TCMW 16T3 04F – CD10 were used. The cutting parameters typical of both roughing and finishing, i.e. vc = 150, 450 and 900 m/min, f = 0.08, 0.13 and 0.27 mm/turn, were adopted. The depth of cut was ap = 0.5 mm. The machining tests were carried out in dry cutting conditions and at minimum quantity lubrication (MQL) with oil mist. A MiniBooster MB II HDC feeder made by Accu-Lube (fig. 3) was used to produce oil mist.

Oil mist was supplied via two hoses to the tool flank and rake face (fig. 4). Oil LB 5000 (based on fatty oil) recommended for aluminium machining was used. The oil is nontoxic and environmentally safe.
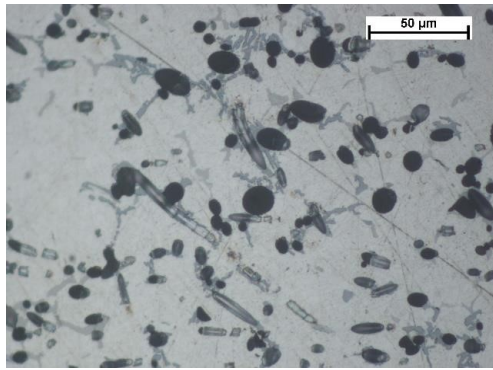
Figure 1. Polished section of investigated material.

Figure 2. NC lathe used in tests.
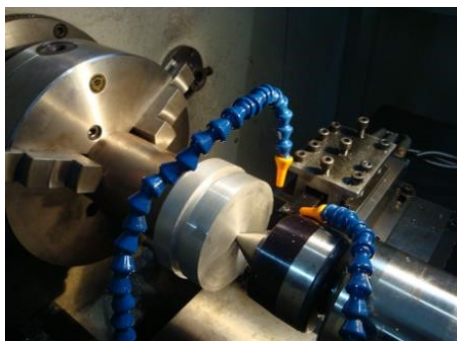

Figure 3. Oil mist producing device.

Figure 4. Force gauge and oil mist feeding nozzles.

The cutting forces were measured using the measuring circuit consisting of a KISTLER 9257A piezo–electric force gauge, a 5011 electric signal amplifier and a Tektronix Digital Phosphor Oscilloscope TDS 5054B (fig. 5).`

Figure 5. Signal amplifier and oscilloscope as a part of measuring circuit.

2.1 Cutting force analysis procedure

The cutting forces arising during the turning of the aluminium composite material were analysed according to the procedure presented in figure 6. The cutting forces were measured using the measuring circuit shown in fig. 4 and 5. On the basis of the measurement results mean values F of the cutting force components were calculated. For this purpose signal fragments with a constant number of points were selected. Assuming that the forces ranged from *Fmin* to *Fmax*, the maximum and minimum forces were determined for the selected signal fragments and then amplitude *Fa* of each of the cutting force component was calculated. The first stage in the analysis of the forces ended with the calculation of the load constancy factor from formula 1. This factor, being a mean value/amplitude ratio, indicates what dynamic changes in the force are and to what degree these changes can impact the tool [36]. Mathematical formulas should be centred and have to be numbered consecutively from 1 in parentheses on the far right margin of the column, as formula (1):

$$k_n = \frac{F}{F_a} \tag{1}$$

Since the cutting force signal is very noisy, which can result in force reading errors, the authors decided to filter the measurements. The aim was to remove the noise generated by machine tool motor operation and machine tool vibrations or coming from the surround. The filtration was carried out in MATLAB using its wavelet analysis module. Wavelet analysis was chosen because of its many advantages. Similarly, as in Fourier analysis, in wavelet analysis the examined signal is divided into wavelets. However, unlike in Fourier

analysis, where the signal is divided into sinusoidal waves with different frequencies, here the signal is divided into shifted and rescaled versions of the original wavelet. When one compares a sinusoidal wave diagram and exemplary wavelet diagrams one can notice that sharply varying signals (the cutting force signal is such a signal) can be analysed in more detail by means of irregular wavelets. Wavelet analysis makes it possible to detect certain properties of the analysed signal which can pass undetected by other signal analysis techniques, e.g. higher derivative discontinuity or similarity of signal fragments. Wavelet analysis also makes it possible to compress and denoise the signal without considerably degrading it. Discrete wavelet analysis, in which the raw signal if filtered twice through a high-pass filter (a wavelet) and a low-pass filter (a scaling function), is used to remove noise from the signal. As a result, two traces: 1) the denoised signal and 2) the noise are obtained. The obtained detail can be further filtered at the next decomposition levels until a signal completely free of noise is obtained.
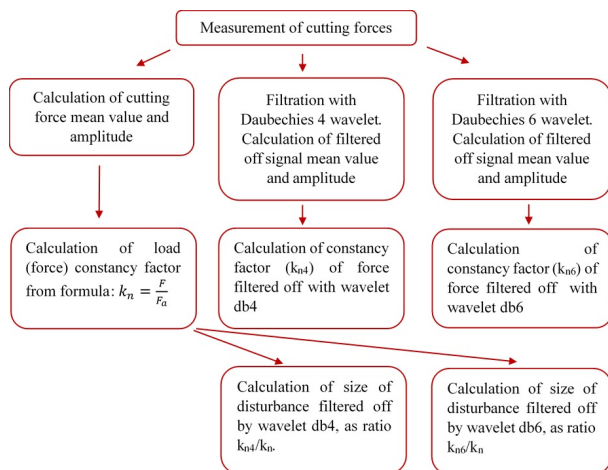

Figure 6. Cutting force analysis procedure.

A crucial point in the analysis is the choice of a wavelet. Its shape should most closely resemble the shape of the analysed signal. Two Daubechies wavelets were selected for the analysis of the cutting forces in the turning of the composites. The wavelets belong to the family of compactly supported orthogonal wavelets. It is the compactness of their support and their quite uncomplicated form which are their biggest advantages. Wavelet Daubechies 4 (less compact) and wavelet Daubechies 6 (more compact) were selected for the analysis. The choice of the two wavelets was dictated by different character (compactness) of the force traces during machining at a high feed rate and a low feed rate, respectively. The chosen wavelets are shown in fig. 7. Subsequently fragments of the cutting force traces were analysed in MATLAB. Noise-free force traces and noise were obtained. Then, similarly as in the case of the raw measurements, mean values, amplitudes and load constancy factors were calculated. Finally, the ratio of the load factor of the force filtered by each of the wavelets to the load constancy factor of the force calculated from the raw measurement was calculated. An increase in load constancy indicates that disturbances have been filtered off and removed by the

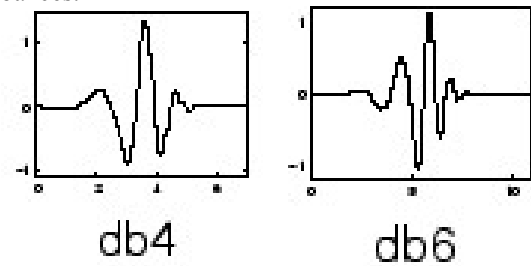particular wavelets. Thus the degree of factor kn increase can be indicative of the size of noise and disturbances.

Figure 7. Wavelets used in analyses Daubechies 4 (db4); and Daubechies 6 (db6) [37].

3. TEST RESULTS AND DISCUSSION

Selected results of filtration by means of wavelet Daubechies 4 are presented in figs. 8 and 9. The figures show the forces occurring in the turning of the com–posite with cutting insert CD10 at v_c= 150 m/min and f=0.27 mm/turn. The first trace from top (s) represents the measured cutting force. The middle trace (a1) represents the cutting force filtered off by the wavelet. Trace d1 represents the noise (measurement distur–bances) filtered off by the wavelet. MATLAB can cal–culate the mean values and amplitudes of the raw force measurement, the analysed signal and the trace after filtration. Using the calculated data the load constancy (force Fc) factors and the size of disturbances were determined on the basis of the filtered off signal constancy factor and the unfiltered signal constancy factor.
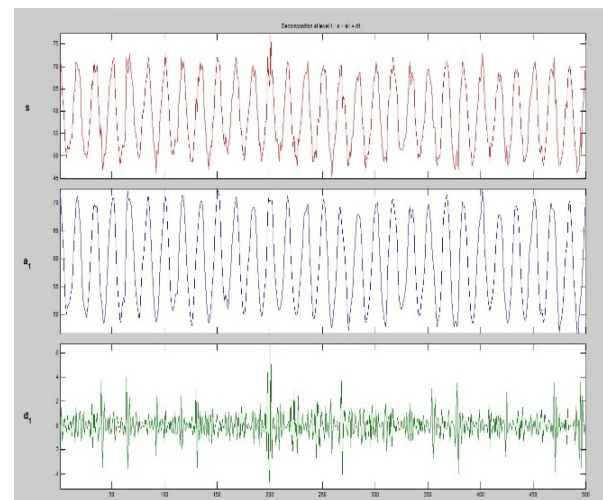

Figure 8. Images obtained from wavelet analysis – forces after dry turning with diamond insert CD10 at v_c= 150 m/min and f=0.27 mm/turn.

3.1 Forces after turning with uncoated cemented carbide cutting inserts H10

Table 4 presents the results of measurements and analyses relating to force Fc registered during turning with an uncoated carbide insert (H10). Figure 10 shows charts of force Fc versus machining parameters, figure 11 the load constancy factors calculated for the registered course of force. Figures 12 and 13 show the disturbance and noise values after wavelet filtration.
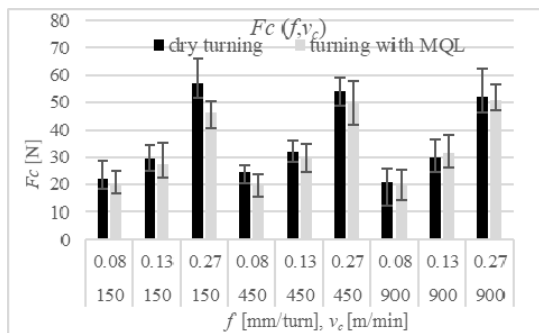
Figure 10. Cutting force *Fc* in aluminium composite turning with uncoated carbide tool.

The mean values of component Fc measured during turning with the uncoated insert change as a function of feed rate change consistently with theory. As the feed rate increases they increase from about 20N to 50-54N. No effect of cutting speed was noted due to the fact that the aluminium composite is harder than the matrix aluminium alloy. No intensive build-up edge was observed. When analysing figure 10, one can notice a slight effect of the use of oil mist. In comparison with dry machining the values of component *Fc* were found to be similar or lower. The strongest positive effect of MQL was observed during turning at cutting speed v_c=150 m/min and feed rate f=0.27 mm/turn.
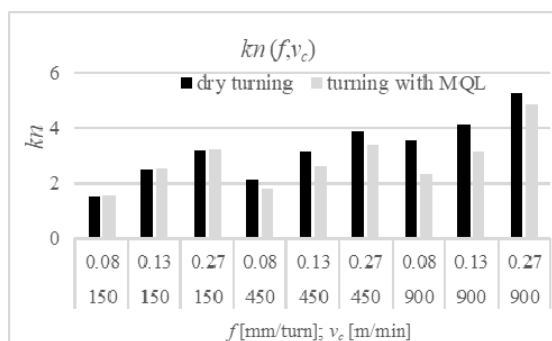

Figure 11. Constancy factor of cutting force *Fc* in aluminium composite turning with uncoated carbide tool

The course of load constancy factor versus feed rate is similar to that of force Fc. The load constancy factor value increases with feed rate. This can be due to chip breaking at the increasing feed rate. When short chips form, process stability is considerably greater, which is reflected in load stability factor values. This factor also increases slightly with cutting speed. Undoubtedly the built-up edge, forming up to the speed of 450 m/min, was a contributing factor here. It was found that even a low rate of build-up edge affects load constancy and cutting process stability. During turning at the highest speed edge build-up was no longer obser–ved, which was noticeably reflected in load constancy factor values. Minimum quantity lubrication has a very strong effect on this factor. Despite a clear reduction in chip/tool friction and in blade wear thanks to the use of MQL, the load constancy factor decreases, which is due to a considerable increase in force amplitude. The latter would increase because the oil mist feeder operated in pulses. The character of feeder operation has a bearing on machining stability, but it can also considerably disturb cutting force measurement. For this reason the cutting force measurement was subjected to wavelet filtration.
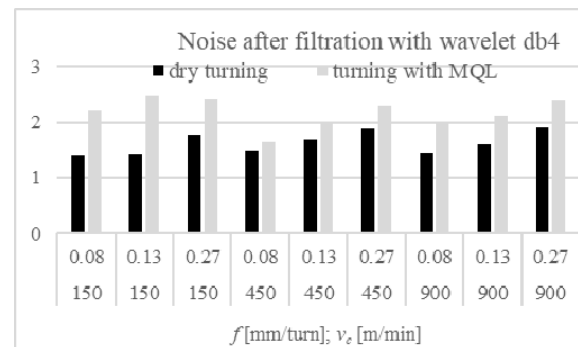

Figure 12. Noise and disturbance values in composite turning with uncoated carbide insert (H10), obtained through filtration with wavelet Daubechies 4 (db4).
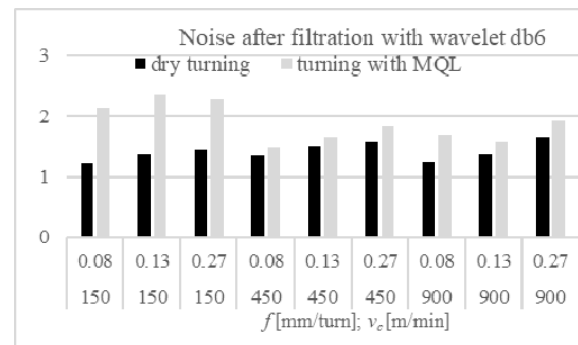

Figure 13. Noise and disturbance values in composite turning with uncoated carbide insert (H10), obtained through filtration with wavelet Daubechies 6 (db6).

After noise had been removed the constancy load factors in dry turning with the uncoated cutting insert increased by 41-90% in the case of filtration with wavelet Daubechies 4 and by 24-65% for filtration with wavelet Daubechies 6, depending on the turning parameters. In comparison with dry turning, the increase in load constancy for turning with MQL after filtration was much larger, reaching as much 146%. The disturbance and noise values change only slightly as the machining parameters increase. They were found to be considerably higher during oil mist-assisted machining. The load constancy factors after filtration for MQL-assisted turning assume values similar or higher than the ones for dry turning. They are higher by 9-72%, depending on the machining parameters, after filtration with wavelet Daubechies 4. Wavelet Daubechies 6 did not filter the signal of force Fc so strongly. After this analysis the effect of MQL on load constancy is visible only for the cutting speed of 150 m/min.

3.2 Forces after turning with diamond coated cemented carbide cutting inserts 1810

The results of measurements and analyses relating to force *Fc* registered during turning with diamond coated carbide insert (1810) are presented in table 5. Figure 14 shows, similarly as for insert H10, registered force diagrams and figure 15 shows the load constancy factor calculated for the registered traces. The disturbance values during machining with this tool are shown in figs. 16 and 17.

The geometry of insert 1810 was identical as that of insert H10. The difference stemming from the use of the diamond coating was reflected in a cutting edge nose

radius increase by 0.004mm and an increase in blade rake face roughness *Ra* by 0.02μm. It is recommended to use sharp blade geometry, such as in uncoated inserts, for the machining of soft materials. Since the composite is a material with increased hardness, coating application can only slightly change the character of the material decohesion mechanisms and so the cutting force values. The effect of coating application is evident in tool wear intensity. The reduction in coated insert wear was presented in [38].

In the case of turning with the diamond coated carbide insert, force *Fc* increases as the feed rate grows from 22N to 54N. Similarly as in machining with the uncoated insert, cutting speed does not affect the measured Fc values. Unlike in turning with insert H10, no effect of oil mist was noted. This is due to the fact that by reducing blade/chip/workpiece friction the diamond coating extends the blade's life whereby the application of oil mist does not affect so significantly the technological effects of machining.

Table 4. Measured cutting forces Fc, measurement-based load constancy factor values and after filtration with wavelets and noise values for aluminium composite turning with uncoated carbide tool.

tool	lubrication	Cutting speed v_c [m/min]	Feed rate f [mm/turn]	Mean *Fc*	Load constancy calculated from measurement	Load constancy after filtration with wavelet db4	Noise after filtration with wavelet db4	Load constancy after filtration with wavelet db6	Noise after filtration with wavelet db6
H10	dry	150	0.08	21.95	1.52	2.14	1.41	1.88	1.24
			0.13	29.52	2.50	3.58	1.43	3.43	1.37
			0.27	56.93	3.17	5.66	1.78	4.60	1.45
		450	0.08	24.48	2.13	3.21	1.51	2.88	1.35
			0.13	32.01	3.12	5.27	1.69	4.69	1.50
			0.27	54.13	3.89	7.38	1.90	6.07	1.56
		900	0.08	20.92	3.56	5.18	1.46	4.42	1.24
			0.13	30.15	4.13	6.66	1.61	5.65	1.37
			0.27	51.88	5.24	9.99	1.90	8.66	1.65
	MQL	150	0.08	19.96	1.55	3.44	2.22	3.28	2.12
			0.13	27.58	2.54	6.26	2.46	5.98	2.35
			0.27	46.06	3.23	7.83	2.42	7.36	2.28
		450	0.08	20.22	1.83	3.01	1.64	2.72	1.49
			0.13	30.34	2.62	5.18	1.97	4.32	1.65
			0.27	50.05	3.38	7.75	2.29	6.18	1.83
		900	0.08	20.44	2.32	4.65	2.00	3.90	1.68
			0.13	31.60	3.14	6.66	2.12	4.91	1.56
			0.27	50.89	4.87	11.66	2.40	9.40	1.93

Table 5. Measured cutting forces *Fc*, measurement-based load constancy factor values and after filtration with wavelets and noise values for aluminium composite turning with diamond coated carbide tool.

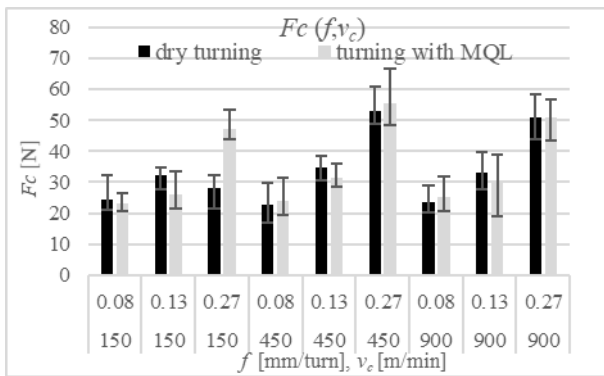| tool	lubrication	Cutting speed v_c [m/min]	Feed rate f [mm/turn]	Mean *Fc*	Load constancy calculated from measurement	Load constancy after filtra–tion with wavelet db4	Noise after filtration with wavelet db4	Load constancy after filtration with wavelet db6	Noise after filtration with wavelet db6
1810	dry	150	0.08	24.44	2.74	2.85	1.04	2.73	1.00
			0.13	32.06	2.75	3.40	1.24	3.30	1.20
			0.27	28.15	3.49	4.85	1.39	4.29	1.23
		450	0.08	22.88	2.19	2.55	1.17	2.46	1.13
			0.13	34.74	2.62	3.17	1.21	3.32	1.27
			0.27	52.90	4.16	7.40	1.78	5.82	1.40
		900	0.08	23.57	1.77	2.79	1.57	2.62	1.48
			0.13	33.11	3.19	5.27	1.65	5.21	1.63
			0.27	51.09	4.39	8.25	1.88	7.32	1.67
	MQL	150	0.08	22.97	1.51	2.51	1.66	1.99	1.32
			0.13	26.03	2.26	4.09	1.81	3.32	1.47
			0.27	47.34	3.94	7.09	1.80	5.72	1.45
		450	0.08	23.89	1.98	3.35	1.69	3.02	1.52
			0.13	31.60	3.07	5.60	1.82	5.02	1.63
			0.27	55.48	4.08	7.61	1.86	6.83	1.67
		900	0.08	25.26	2.16	3.75	1.73	3.23	1.49
			0.13	29.85	3.81	6.09	1.60	4.91	1.29
			0.27	50.83	5.00	8.35	1.67	5.70	1.14

Figure 14. Cutting force *Fc* in aluminium composite turning with diamond coated carbide tool
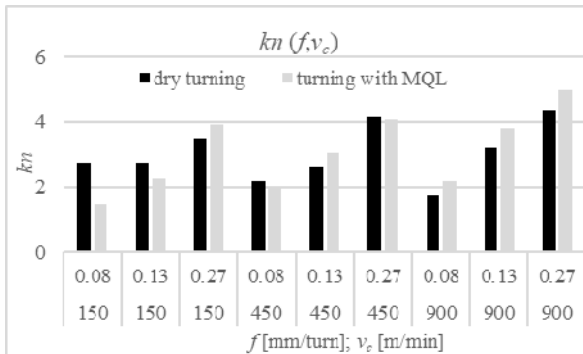

Figure 15. Constancy factor of cutting force *Fc* in aluminium composite turning with diamond coated carbide tool.

The character of changes in load constancy versus machining parameters is similar as in the case of the measured mean force. No such strong effect of MQL on *kn* as in machining with the uncoated insert was obser–ved.

Noise and disturbance values after wavelet filtration are interesting. In each of the analysed cases the use of wavelet Daubechies 4 to remove noise resulted in an increase in the load constancy factor. For dry machining this increase grows larger with the increase in feed rate and cutting speed. It is smallest (4%) at cutting speed v_c=150 m/min and feed rate *f*=0.08 mm/turn and largest at the maximum values of these parameters, amounting to 88%. Filtration with wavelet db 4 caused a large increase in the load constancy factor in the MOL-assisted turning of the composite at no substantial contribution of the machining parameters. The factor amounts to 60-86%. Completely different results were obtained from the analysis with wavelet db6. The amount of disturbance removed by this wavelet increases as dry cutting parameters increase, whereas such a correlation cannot be assumed for MQL-assisted cutting. Regardless of wavelet type, at vc= 900/min and feed rates of 0.13 and 0.27 mm/turn, disturbances during dry turning exceeded the ones calculated for MQL-assisted turning. This was not observed during turning with the uncoated insert. At the same time disturbances during MQL-assisted turning at the speeds of 150 and 450 m/min are very large and exceed the ones registered during dry machining. The noise values for MQL-assisted turning are appropriately higher than the ones for dry machining – by 65% for wavelet db4 and by 35% for wavelet db6.
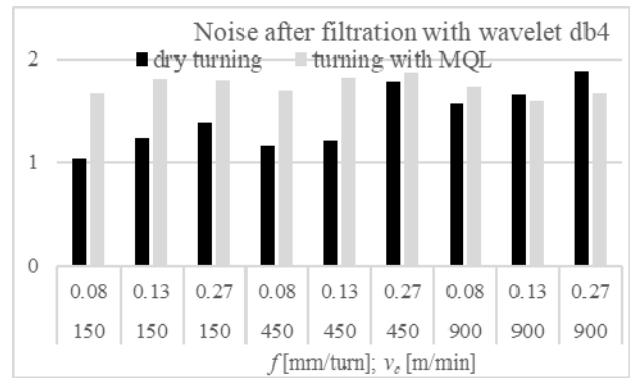

Figure 16. Noise and disturbance values in composite turning with diamond coated carbide insert (1810), obta–ined through filtration with wavelet Daubechies 4 (db4).
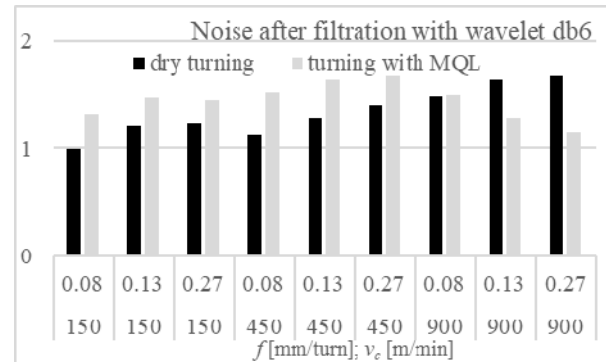

Figure 17. Noise and disturbance values in composite turning with diamond coated carbide insert (1810), obta–ined through filtration with wavelet Daubechies 6 (db6).

3.3 Forces after turning with polycrystalline diamond cutting inserts CD10

Finally, analyses were carried out for the tool with the polycrystalline diamond insert. Table 6 presents the results of measurements and analyses relating to force Fc registered during turning with this tool. Diagrams of the measured force are shown in figure 18, the load constancy factor in figure 19 and the disturbance values as a function of the cutting parameters are shown in figs 20 and 21.

Machining with the polycrystalline diamond insert differs from machining with the carbide inserts. Naturally, the strongest effect of blade type is visible in blade wear intensity [38]. An analysis of figs 10, 14 and 18 and the data contained in the tables shows that cutting insert CD10 generates greater forces *Fc*, especially during turning at feed rate *f*=0.27 mm/turn. Greater tool forces can be generated due to the fact that the shape of the diamond inserts rake face is different than that of the cemented carbide inserts rake face and the impact strength of diamond is lower than that of cemented carbides. Also the absence of a chip breaker on the polycrystalline diamond insert, resulting in longer chips, can affect the forces [38].

Due to longer unbroken chips the load constancy factor during turning with insert CD10 is considerably lower than during machining with the carbide inserts. The maximum load constancy factor value calculated from the measurement amounted to 2.94 while for turning with the carbide inserts it reached 5. The effect

of MQL on the value of kn was negligibly small. The absence of chip breaking is another aluminium composite cutting process disturbance. Continuous chips formed in the whole parameter range during turning with insert CD10 and at the lowest feed rate during machining with carbide. However, it was found that the disturbances filtered off by the wavelets in these cases were simply smaller. Thus one cannot assume that wavelet filtration detects this kind of disturbances.
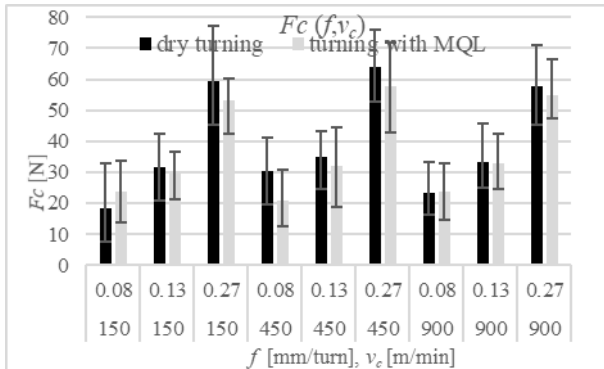

Figure 18. Cutting force Fc in aluminium composite turning with polycrystalline diamond tool

Comparing the analytical results for all the tool used one can notice some common elements. Author point out that there is very close similarity in the character of the filtered off disturbances and their changes as a function of tool type, machining parameters and the cutting zone lubrication method. However, filtration with the less compact wavelet db4 was found to be strongest regardless of machining conditions. During the experiment factors which can significantly disturb the measurement, such as build-up edge during turning at low cutting speeds, chip breaking range differences, markedly different tool wear character and intensity and the effect of MQL (especially of the character of oil mist feeder

operation), were noted. The results of the wavelet analysis show that each of the disturbances can be detected and filtered by the wavelets, but with different intensity. It has been demonstrated that the algorithm for analysing cutting forces by means of wavelet analysis is correct and one can quickly filter off disturbances in this way. However, more detailed studies are needed in order to optimally match wavelets to particular force traces.
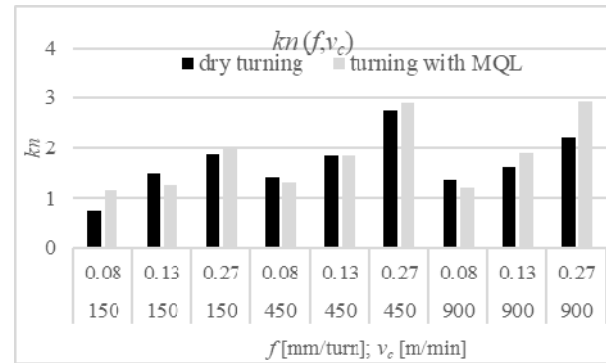

Figure 19. Constancy factor of cutting force Fc in alumi-nium composite turning with polycrystalline diamond tool.

Figure 20. Noise and disturbance values in composite turning with polycrystalline diamond insert (CD10), obta-ined through filtration with wavelet Daubechies 4 (db4).

Table 6. Measured cutting forces Fc, measurement-based load constancy factor values and after filtration with wavelets and noise values for aluminium composite turning with polycrystalline diamond tool.

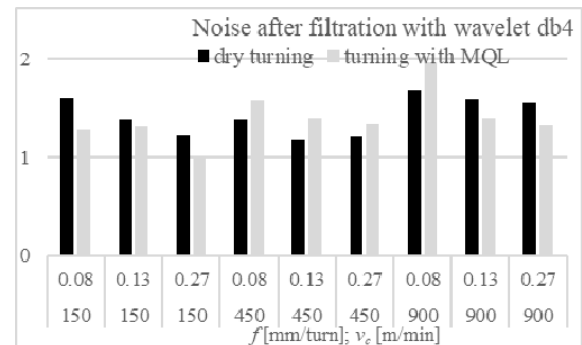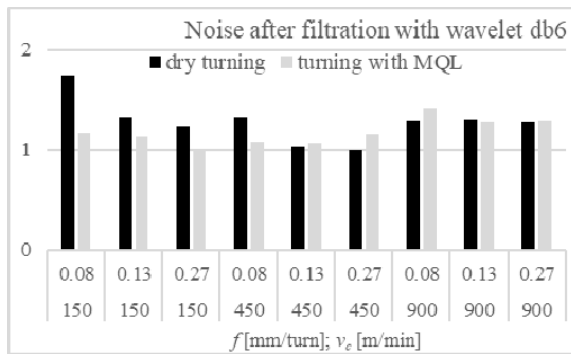| tool	Lubrication	Cutting speed v_c [m/min]	Feed rate f [mm/turn]	Mean Fc	Load constancy calculated from measurement	Load constancy after filtra-tion with wavelet db4	Noise after filtration with wavelet db4	Load constancy after filtration with wavelet db6	Noise after filtration with wavelet db6
CD10	dry	150	0.08	18.32	0.73	1.18	1.61	1.29	1.75
			0.13	31.69	1.47	2.04	1.39	1.95	1.32
			0.27	59.29	1.86	2.28	1.22	2.30	1.23
		450	0.08	30.40	1.41	1.96	1.39	1.87	1.32
			0.13	34.86	1.84	2.17	1.18	1.90	1.03
			0.27	63.84	2.75	3.32	1.21	2.74	1.00
		900	0.08	23.48	1.36	2.31	1.69	1.75	1.28
			0.13	33.26	1.61	2.56	1.59	2.10	1.30
			0.27	57.52	2.23	3.46	1.55	2.84	1.27
	MQL	150	0.08	23.67	1.15	1.48	1.28	1.34	1.16
			0.13	29.39	1.25	1.65	1.32	1.41	1.13
			0.27	53.05	1.97	1.97	1.00	1.94	0.98
		450	0.08	20.83	1.32	2.08	1.57	1.44	1.09
			0.13	32.24	1.83	2.54	1.39	1.96	1.07
			0.27	57.64	2.90	3.88	1.34	3.34	1.15
		900	0.08	23.86	1.20	2.35	1.96	1.70	1.42
			0.13	33.02	1.90	2.64	1.39	2.43	1.28
			0.27	54.81	2.94	3.92	1.33	3.79	1.29

Figure 21. Noise and disturbance values in composite turning with polycrystalline diamond insert (CD10), obta–ined through filtration with wavelet Daubechies 6 (db6).

4. CONCLUSIONS

The results of measurements of cutting force Fc in the turning of an aluminium composite material are pre–sented. The investigations covered a very wide range of conditions and were carried out using three different tools and nine sets of turning parameters. Dry turning and oil mist lubrication assisted turning were investi–gated. The force measurement was assumed to be subject to considerable disturbances originating from the surrounding and connected with machine tool operation, blade wear and the flow of chips on the rake face. Therefore, the authors decided to filter the force signal and assess the disturbance level on the basis of the increase in the load constancy factor due to filtration. After an analysis of the literature on the subject, the discrete wavelet transform was selected for filtration. Two wavelets out of the family Daubechies wavelets, most often used for such analyses were chosen. The analyses and their results presented in this paper show that:

- the cutting force values measured during the turning of the tested composite material change with feed rate consistently with theory; the effect of cutting speed is negligible;
- due to the blade's diamond material and geometry without a chip breaker greater cutting forces are generated than when carbide blades are used;
- since the use of oil mist results in a reduction of the values of the cutting force components by 10-25% during turning with the diamond insert it is recommended to replace dry machining with the minimum lubrication of the cutting zone;
- the load constancy factor is sensitive to the length of the forming chips – the shorter the chip, the higher values the factor assumes;
- oil mist application affects load constancy; unfortunately, the pulse-like operation of the AccuLube device for generating and feeding oil mist disturbs the turning process and decreases load constancy;
- it is possible to quickly and effectively apply the discrete wavelet transform to separate the signal coming from the measurement of the force into disturbances and the pure cutting force; wavelet filtration to a large degree removes disturbances connected with oil mist feeder operation – the increase

in the load constancy factor in the case of the forces measured during MQL-assisted machining was larger than in the case of dry machining;
- filtration with wavelet Daubechies 4 is stronger than with wavelet Daubechies 6, but one cannot categorically say that it is more precise;
- the blade used, the tool material, the blade's geometry and the presence or absence a chip breaker had a very strong effect on the values of force Fc and the level of process disturbances; also cutting speed had a major effect on the degree of disturbance; this effect can be ascribed to forming or not forming build-up edge.

The possibility of using other types of wavelets should be assessed in future research. In addition, other components of the cutting force should be analyzed. The possibility of using a discrete wavelet transform to analyze the forces in machining in which the main rotational movement is performed by the tool, i.e. milling and drilling, requires verification. It will then be possible to assess whether the analysis can be used to denoise the measurement of the cutting torque.

REFERENCES

[1] Jain P., Soni S. and Baredar P.: Review on machining of aluminium metal matrix composites, Mat. Sci. Res. India, Vol. 11, No. 2 pp. 114–120, 2014.

[2] Niknam S.A., Kouam J., Songmene V. and Balazinski M.: Dry and semi-dry turning of titanium metal matrix composites (Ti-MMCs), Procedia CIRP, Vol. 77 pp. 62–65, 2018. doi.org/10.1016/j.procir.2018.08.215

[3] Siddappa P.N., Shivakumar B.P., Yogesha K.P., Mruthunjaya M., Hanamantraygouda M.B., Raghuvir P.B. and Mathew T.M.: *Machinability study of Al- TiC metal matrix composite*, MATEC Web Conference, 2018.

[4] Schubert A. and Nestler A.: Enhancement of Surface Integrity in Turning of Particle Reinforced Aluminium Matrix Composites by Tool Design, Procedia Engineering Vol. 19, pp. 300 – 305, 2011. doi.org/10.1016/j.proeng.2011.11.116

[5] Puneet Bansal and Lokesh Upadhyay: Effect of Turning Parameters on Tool Wear, Surface Roughness and Metal Removal Rate of Alumina Reinforced Aluminium Composite, Procedia Technology, Vol. 23, pp. 304 – 310, 2016. doi.org/10.1016/j.protcy.2016.03.031

[6] Ajithkumar J.P. and Anthony Xavior M.: Cutting Force and Surface Roughness Analysis During Turning of Al 7075 Based Hybrid Composites, Procedia Manufacturing, Vol. 30, pp. 180–187, 2019. doi.org/10.1016/j.promfg.2019.02.026

[7] Devaraj S., Ramakrishna Malkapuram, and Singaravel B.: Performance analysis of micro textured cutting insert design parameters on machining of Al-MMC in turning process, International Journal of Lightweight Materials and Manufacture Vol. 4, pp. 210-217, 2021. doi.org/10.1016/j.ijlmm.2020.11.003

[8] Lane C. T, *Machining of Particulate- Reinforced Aluminium*, Fabrication of Particles Reinforced Metal Composites, International Conference, Montreal, pp. 195-201, 1999.

[9] Nataraja M., Balasubramaniana K. and Palanisamy D.: Influence of Process Parameters on CNC Turning of Aluminium Hybrid Metal Matrix Composites, Materials Today: Proceedings, Vol. 5, No. 6, pp. 14499–14506, 2018. doi.org/10.1016/j.matpr.2018.03.037

[10] Kishawy, H. A, Kannan S and Balazinski. M.: An energy- based Analytical Force Model for Orthogonal cutting of Metal Matrix Composites, CIRP Annals- Manufacturing Technology, Vol. 53, No. 1, pp. 91-94, 2004. doi.org/10.1016/S0007-8506(07)60652-0

[11] Siddesh Kumar N.G., Shiva Shankar G.S., Ganesh M.N. and Vibudha L.K.; Experimental Investigations to Study the Cutting Force and Surface Roughness during Turning of Aluminium Metal Matrix Hybrid Composites, Materials Today: Proceedings, Vol. 4, No. 9, pp. 9371–9374, 2017. doi.org/10.1016/j.matpr.2017.06.187

[12] Das D., Pradhan S.K., Sahoo A.K., Panda A., Satpathy M.P. and Samal C.: Tool wear and cutting force investigations during turning 15 wt% SiCp-Al 7075 metal matrix composite, Materials. Today:. Proceedings, Vol. 26, pp. 854–859, 2020. doi.org/10.1016/j.matpr.2020.01.053

[13] Shoba C., Ramanaiah N. and Nageswara Rao D.: Effect of reinforcement on the cutting forces while machining metal matrix composites–an experimental approach, Engineering Science and Technology, an International Journal, Vol. 18, No. 4, pp. 658-663, 2015. doi:10.1016/j.jestch.2015.03.013

[14] Gautam G.D. and Mishra D.R.: Multiple kerf quality optimization in laser cutting of BFRP composite using grey relational based genetic algorithm, FME Transactions, Vol. 48, pp. 636-650, 2020. doi:10.5937/fme2003636G

[15] Abas M., Sayd L., Akhtar R., Khalid Q.S., Khan A.M. and Pruncu C.I.: Optimization of machining parameters of aluminium alloy 6026-T9 under MQL-assisted turning process, Journal of Materials Technology, Vol. 9, No. 5, pp. 10916–10940, 2020. doi.org/10.1016/j.jmrt.2020.07.071

[16] Kannan C, Varun Chaitanya C.H, Dwarakesh Padala, and Likithnath Reddy: Machinability studies on aluminium matrix nanocomposite under the influence of MQL, Materials Today: Proceedings, Vol. 22, pp. 1507–1516, 2020. doi.org/10.1016/j.matpr.2020.02.068

[17] Tsai M.Y., Chang S.Y., Hung J.P. and Wang C.C.: Investigation of milling cutting forces and cutting coefficient for aluminium 6060-T6, Computers and Electrical Engineering, Vol. 51, pp. 320–330, 2016. doi.org/10.1016/j.compeleceng.2015.09.016

[18] Popovic M., Tanovic L. and Ehmann K.F.: Cutting forces prediction: the experimental identification of orthogonal cutting coefficients, FME, Transactions, Vol. 45, pp. 459-467, 2017. doi: 10.5937/fmet 1704459P

[19] Lee W.K., Ratnam M.M. and Ahmad Z.A.: Detection of chipping in ceramic cutting inserts from workpiece profile during turning using fast Fourier transform (FFT) and continuous wavelet transform (CWT) Precision Engineering. Vol. 47, pp.406–423,2017, doi:10.1016/j.precisioneng.2016.09.014

[20] Somkiat Tangjitsitcharoen and Haruetai Lohasiriwat: Hybrid Monitoring of Chip Formation and Straightness in CNC Turning by Utilizing Daubechies Wavelet Transform, Procedia Manufacturing, Vol. 25, pp. 279–286, 2018. doi.org/10.1016/j.promfg.2018.06.084

[21] Pechenin V.A., Khaimovich A.I., Kondratiev A.I. and Bolotov M.A.: Method of controlling cutting tool wear based on signal analysis of acoustic emission for milling, Procedia Engineering, Vol. 176, pp. 246 – 252, 2017. doi.org/10.1016/j.proeng.2017.02.294

[22] Yassmin Seid Ahmed, Arif A.F.M. and Veldhuis S.C.: Application of the wavelet transform to acoustic emission signals for built-up edge monitoring in stainless steel machining, Measurement, Vol. 154, pp. 1074-1078, 2020. doi.org/10.1016/j.measurement.2020.107478

[23] Li W., Gonga W., Obikawa T. and Shirakashi T.: A method of recognizing tool-wear states based on a fast algorithm of wavelet transform, Journal of Materials Processing Technology, Vol.170, No.1-2, pp. 374-380, 2005. doi: 10.1016/j.jmatprotec.2005.05.018

[24] Prabhakar D.V.N., Sreenivasa Kumar M. and Gopala Krishna A.: A Novel Hybrid Transform approach with integration of Fast Fourier, Discrete Wavelet and Discrete Shearlet Transforms for prediction of surface roughness on machined surfaces, Measurement, Vol. 164, pp. 108-111, 2020. doi.org/10.1016/j.measurement.2020.108011

[25] García Plaza E. and Núñez López P.J.: Analysis of cutting force signals by wavelet packet transform for surface roughness monitoring in CNC turning, Mechanical Systems and Signal Processing, Vol. 98, pp. 634-651. 2018. doi.org/10.1016/j.ymssp.2017.05.006

[26] Eckstein M., Vrabel M. and Maňkova I.: Application of discrete wavelet decomposition in monitoring of hole-making Inconel 718, Procedia CIRP, Vol. 62, pp. 250-255, 2017. doi: 10.1016/j.procir.2016.06.023

[27] Pahuja R. and Mamidala R.: Process monitoring in milling unidirectional composite laminates through wavelet analysis of force signals, Procedia Manufacturing, Vol. 26, pp. 645-655, 2018. doi.org/10.1016/j.promfg.2018.07.075

[28] Pahuja R. and Mamidala R.: Quality monitoring in milling of unidirectional CFRP through wavelet packet transform of force signals, Procedia

Manufacturing, Vol. 48, pp. 388–399, 2020. doi.org/10.1016/j.promfg.2020.05.061

[29] Oczoś K. and Kawalec A., *Shaping of light metals*, Wydawnictwo Naukowe PWN, Warszawa, Poland 2012, (In Polish)

[30] Aybarc U., Dispinar D.: Aluminium Metal Matrix Composites with SiC, Al_2O_3 and Graphene - Review, Archives of Foundry Engineering Vol. 18, No. 2, pp. 5-10, 2018.

[31] Naplocha K.: Tribological properties of composite materials based on 7075 aluminum alloy reinforced with Al_2O_3 fibers, AFEV, Vol. 11, pp. 153-158 (In Polish).

[32] Szymczak T.: Brittle fracture of metal-ceramic composites, Composite Materials, Vol. 1, pp. 53-57, 2016 (In Polish).

[33] Naplocha K.: *Optimization of technological parameters of the manufacturing process of AK9 materials reinforced with Al_2O_3 ceramic fibers*, PhD Thesis Wrocław University of Science and Technology, Wrocław 1999, (In Polish).

[34] Naplocha K. and Samsonowicz Z.: The hardness of composite materials with increased fiber content, Composites, Vol. 1, pp. 199-202, 2001 (In Polish).

[35] Naplocha K., Samsonowicz Z.: Cracking mecha–nism of composite materials based on AlSi9Mg alloy matrix reinforced with fibers, Composites, Vol. 2, pp. 238-241, 2002 (In Polish).

[36] Cichosz P.: *Cutting tools*, WNT Warszawa, Poland 2006 (In Polish).

[37] Białasiewicz, J. *Wavelets and Approximations*; WNT, Warszawa, Poland, 2004. (In Polish).

[38] Karolczak P., Kołodziej M. and Kowalski M.: Effectiveness of diamond blades in the turning of aluminium composites. Advances in Science and Technology Research Journal, Vol. 14, No. 4, pp. 262-272, 2020, doi: 10.12913/22998624/127436

ПРИМЕНА ДИСКРЕТНЕ ТАЛАСНЕ ТРАНСФОРМАЦИЈЕ У АНАЛИЗИ СИЛА РЕЗАЊА КОД ОБРАДЕ СТРУГАЊЕМ КОМПОЗИТА НА БАЗИ ЛЕГУРА АЛУМИНИЈУМА ОЈАЧАНОГ ВЛАКНИМА Al_2O_3

П. Каролћак

Приказани су резултати експерименталних испит–ивања обраде стругањем композита на бази алуминијума ојачаног влакнима Al_2O_3. Коришћена су три резна алата у условима без течности за резање и минималне количине мазива. Мерене су силе резања. Компонента главне силе је одабрана. Израчунате су њене средње вредности и амплитуде. Снимљени трагови су филтрирани применом Добе–шијевих таласића. Фактори константности оптере–ћења за филтриране сигнале су израчунати и упоре–ђени са факторима за нефилтриране сигнале. На ос–нову поређења извршена је процена нивоа поре–мећаја и буке за време обраде и одређен је утицај услова обраде на обим поремећаја. Утврђено је да дискретна таласна трансформација може да буде од помоћи при праћењу обраде стругањем код компо–зитних материјала.