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Paweł KAROLCZAK[1*],
Maciej KOWALSKI[1],
Marcin KASPRZAK[1]

FEED CUTTING FORCE ANALYSIS USING DISCRETE WAVELET TRANSFORM IN DRILLING OF ALUMINIUM MATRIX COMPOSITE

This paper presents an analysis of the cutting forces during the drilling of a ceramic fibre-reinforced aluminium matrix composite. The machining was carried out under dry drilling conditions and with minimum lubrication of the cutting zone. The mean values of the feed force and the ratio of this mean to the force amplitude were calculated. This result is the load stability coefficient was thus obtained. The measured force waveforms were decomposed using a discrete wavelet transform in Matlab. An approximation, which is a filtered force waveform, and a detail, i.e. the noise of the measurement, were obtained. The numerical value of noise and interference was calculated from the ratio of load stability after filtration to load stability before filtration. It was found that the use of oil mist lubrication slightly reduces the average value of the feed force during drilling of the tested composite. The interference affecting the force measurement when drilling with MQL is higher, while the type of Daubechies wavelet compactness does not affect the filtration power.

1. INTRODUCTION

Metal matrix composites (MMC), including the most commonly used ones with aluminium alloys as the matrix (AMC), are becoming increasingly important in many industries such as aerospace, automotive and military due to their properties [1]. This is directly related to the improvement in mechanical properties such as stiffness, compressive strength and hardness compared to the matrix material. Additionally, these materials maintain their properties at high temperatures [2]. The improvement in properties is a result of the due of second component of composite materials, which is a reinforcement, usually ceramic [2]. The presence of ceramic reinforcement in composites makes their machining more difficult, mainly due to increased wear of cutting blades [3].

[1] Department of Machine Tools and Mechanical Technologies, Faculty of Mechanical Engineering, Wroclaw University of Science and Technology, Wrocław
[*] E-mail: pawel.karolczak@pwr.edu.pl
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Cutting force is one of the key indicators determining the machinability of a construction materials. This is because the cutting force directly affects tool life, energy consumption and also the quality of the finished product. When drilling polymer-based composite materials, the feed force causes delamination [4, 5]. Also when drilling metal matrix composites, the cutting force plays a key role. Metallic composites (MMC) are not subject to delamination, instead the problem is to achieve high hole quality requirements regarding size, shape, surface roughness, the absence of surface and near-surface defects. In order to avoid excessive cutting blade wear and to obtain holes of satisfactory quality, diamond blades should be used. Unfortunately, their use is limited because of their high price. Another important aspect is ecology in the machining of composites. The best method of machining to reduce negative effects on human health and the environment is to use machining without coolants [6]. Despite the undoubted advantages of dry machining, such as no air, water or soil pollution, no health risks for workers and significant cost savings, in many cases it is not possible to carry out dry machining, because the heat generated during dry cutting negatively affects tool wear and the surface layer of the workpiece [7]. At the same time, excessive use of coolant leads to dangerous health and environmental problems [7]. A compromise concept is to support machining with an oil mist [8]. This solution is known as minimum-quantity lubrication (MQL) of the cutting zone. This is a method that provides the necessary lubrication by spraying a small amount of lubricant near the chip-to-tool contact [9, 10]. Also in the machining of aluminium matrix composites, it allows to reduce forces and improve the roughness of the machined surface in both turning [11], drilling [12] and milling [13].

Monitoring the machining process is a very important part of modern manufacturing. By monitoring and supervising tool condition, chip form, vibration, surface quality [14-19], the manufacture of defective products is prevented. The effectiveness of monitoring depends on the accuracy of the measurement of the physical quantity, the ability to correlate it with the supervised indicator, but also on the choice of the appropriate signal processing method to be applied according to the specific type of signal measured during the process. To achieve the desired machining efficiency, the stability of the machining system must be ensured. Under certain conditions, the dynamic nature of machining processes leads to the emergence of physical phenomena that alter the stability of the process and interfere with its monitoring [14]. Hence the need for filtering of the measured signal. In the literature, one can find research results of studies using such methods of data signal analysis, processing and filtering as: FRF (Frequency Response Function) [20], singular spectrum analysis, direct-time analysis, power spectral density, Fourier transform - fast, or short-time and wavelet transform were used [14]. The wavelet transform (WT) method is widely used in process monitoring. This method decomposes the signal into a shifted and scaled series of functions characterised on a time-frequency scale [21]. It provides good resolution in both the time and frequency domains and can extract time-domain information in different frequency bands. The continuous wavelet transform (CWT) requires a lot of computing power and is not suitable for online signal processing. The discrete wavelet transform (DWT) works faster, does not require as much computation, but cannot cope with the analysis of high-frequency signals. The packet wavelet transform (PWT) is used for such signals [14].

The use of the wavelet transform has increased significantly in recent years. It is used to monitor the durability and condition of mechanical structures [22]. It is a tool for processing signals that are the basis for monitoring e.g. tool condition [23] and detecting surface quality [14] in machining, for detecting the onset of wear of ceramic inserts based on the profile of the workpiece [24], or for separating build-up formation (BUE) signals from tool wear signals for real-time monitoring of BUE height when turning AISI 304 stainless steel [25]. Also in the analysis of the machining effects of composites and material stacks, the wavelet transform performs very well. It is used, for example, to monitor the cutting force during the machining of carbon fibre-reinforced polymer (CFRP) composites [26], or to analyse the quality of holes drilled in material stacks [27]. The wavelet transform is an excellent tool for decomposing the cutting force signal, resulting in a force waveform without distortion or noise for both turning [28] and milling [29]. Once the force measurement signal has been decomposed into force and noise using the wavelet transform, the effects of cutting conditions in force measurements can be eliminated by comparisons of the amplitude to the static value of the force [28] or by applying a load stability coefficient [30, 31]. There is a lack of publications in the literature demonstrating the feasibility of using a wavelet transform to monitor and filter the components of cutting force in drilling. Therefore, such studies have been undertaken. In addition, they are an extension of the studies presented in papers [30, 31] on turning.

2. TEST CONDITIONS AND FORCES ANALYSIS ALGORITHM

A metal matrix composite reinforced with ceramic fibres was tested. The matrix was a cast aluminium alloy with the designation EN AC-43330 (AlSi9Mg). The Saffil fibres used as reinforcement in the test material are one of the most commonly used materials for reinforcing metal matrix composites. They belong to the group of high-strength materials, as they are characterised by good heat resistance, high tensile strength and high elastic modulus. They consist of 96% aluminium oxide and 4% silicon oxide. Their excellent strength properties (Table 1) result in the tested composite having an increased hardness – by about 50% and tensile strength by 60% and a higher yield strength by 40%, compared to the matrix material.

Table 1. Properties of Al_2O_3 fibres [32]

Density [g/cm^3]	Tensile strength [GPa]	Compressive strength [GPa]	E-modulus [GPa]	G-modulus [GPa]	Durability up to temperature [^{0}C]
3.7	1.8	6.9	300	122	1600

Drilling tests were carried out using a Csepel RF 50/1250 radial drilling machine. The holes were drilled with a solid carbide, coated drill bit, designation 6537 VHM TiAlN, which had a diameter of 9.9 mm. Three cutting speeds were used: v_c = 11, 22 and 44 m/min and four feeds: f = 0.05, 0.075, 0.112 and 0.17 mm/rev. The feed component of the cutting force was measured during drilling using a measuring track. The main component of the track was a Kistler piezoelectric force gauge, designation 9257A. The measured electrical signal was amplified with 5011 amplifiers, manufactured by the same company as the actuator. Signal acquisition was performed with a Tektronix TDS 5054B oscilloscope. The tests were carried out under dry drilling conditions and with minimum cutting zone lubrication (MQL). The oil mist, as a mixture of oil and air, was created by the Accu-Lube Minibooster. It was externally fed through a single nozzle placed close to the drill bit and the hole entrance. The operating pressure of the air was 7 bar and the fluid flow rate was 180 ml/h. An oil with the designation Lb 5000 was used to create the oil mist. This oil can be used for medium to heavy machining of all materials. It is biodegradable non-toxic and odourless. It has no chlorine, sulphur, phenyl, nitrite or biocide additives. The flash point of this oil is 190°C, the freezing point is 5°C.

The average value of the cutting force components is only an indication of the level of resistance to material separation and the overall level of load on the cutting edge. It is possible to tell how much load the blade is under by knowing how dynamic the force changes are. Load stability or dynamic load coefficients are used for such an assessment. The analysis was carried out according to the methodology shown in Fig. 1.

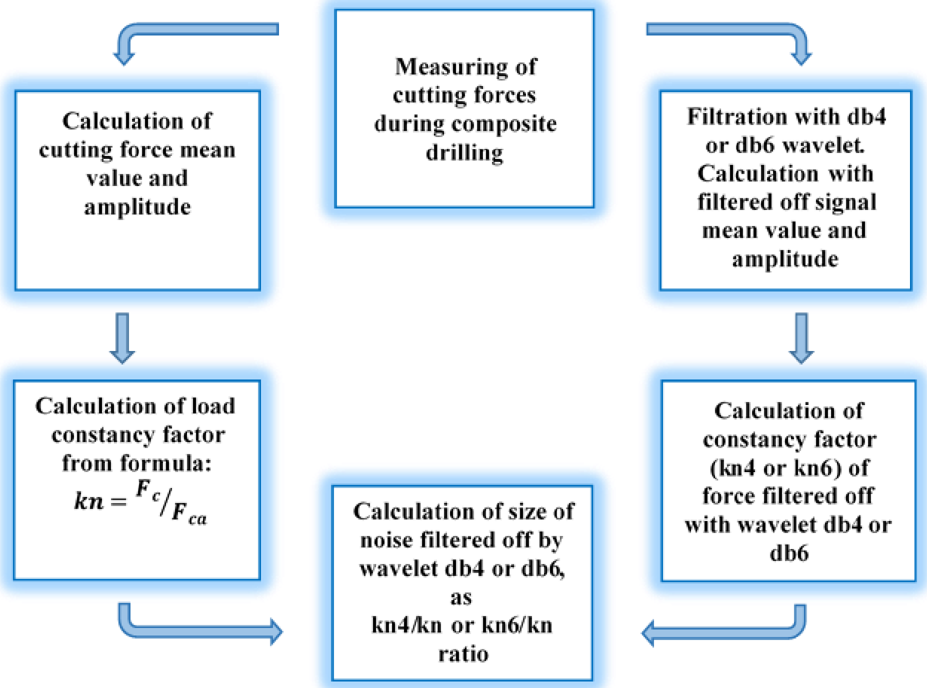

Fig. 1. Cutting force analysis algorithm

In the first step, the average value of the feed component *Ff* was calculated. Signal fragments with a fixed number of points were selected for the calculation. From this fragment, the maximum and minimum force values were determined in the next step. In order to avoid influencing the analysis of individual force peaks, 10 such values each were taken into account to determine the maximum and minimum values and averages were determined from these. In the next step, its *Fa* amplitude was calculated from the calculated maximum and minimum feed components. The load stability coefficient was then determined as the ratio between the average force and its amplitude. The measurement of cutting forces, especially when a pulsating oil mist device is in operation in addition to the machine tool, is subject to high levels of noise. High levels of noise can result in large errors in the reading of maximum, minimum and average cutting force values. Measurement filtration should therefore be carried out.

In the articles [30, 31], such filtering suggested, in the case of turning aluminium matrix composite and titanium alloy, using wavelets. Such filtering made the relationships between the load stability coefficient and the cutting parameters more logical and easier to describe with simple mathematical functions. This is the result of good wavelet filtering of noise from the measurement. This is all thanks to the properties of wavelet analysis. It allows the discovery of certain properties of the signal under study. which may be missed by other signal analysis techniques, e.g. discontinuities of higher derivatives or similarity of signal fragments. In addition. wavelet analysis also allows compression and de-noising of the signal without significant signal degradation. Discrete wavelet analysis is used to remove signal noise. in which the raw signal is filtered twice - through a high-pass filter, which is the wavelet function, and a low-pass filter, which is the scaling function. In this way, two waveforms are obtained one called approximation. is the de-noised signal and the other is the detail, i.e. noise and interference (Fig. 2).

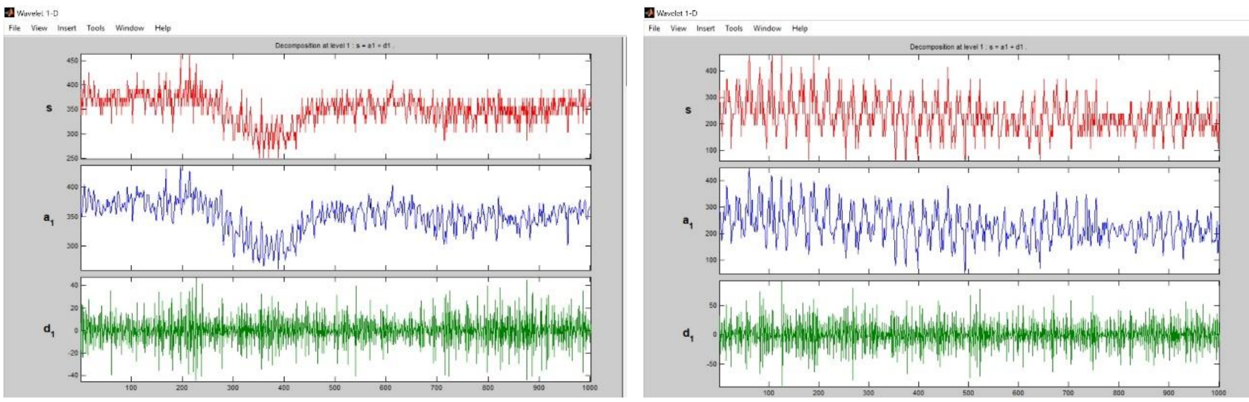

Fig. 2. Example images from wavelet analysis performed in Matlab. Red waveform (s) - measured force, blue signal (a1) – filtered force, green signal (d1) – noise

A very important step in the analysis is the selection of the wavelet. It is recommended that the shape of the mother wavelet is close to the shape of the signal being analysed, in this case the feed force. One of the most popular wavelet groups, and one with a wide range of shapes, are the wavelets of the Daubechiues family. Figure 3 shows Daubechies wavelets ordered in ascending order.

These wavelets belong to the family of orthogonal wavelets with a compact carrier. It is precisely the compactness of the carrier and the rather uncomplicated form that are their greatest advantages. Daubechies wavelet 4 (less compact) and Daubechies wavelet 6 (more compact) were chosen for the analysis. The choice of the two wavelets was dictated by the different nature (compactness) of the force waveforms during high-feed and low-feed machining. Once the waveforms were selected, sections of the cutting force waveforms were analysed in Matlab. Force waveforms without noise and noise were obtained (Fig. 2). The mean values, amplitudes and load stability coefficients were then calculated, analogous to the measurement results. Finally, the ratio of the load stability coefficient of the force filtered by each wavelet to the load stability coefficient of the force calculated from the raw measurement (*kn*db4/*kn* and *kn*db6/*kn*) was calculated. The increase in load constancy indicates that the individual wavelets have filtered out and removed interference. Therefore, the degree of increase in *kn* can be indicative of the amount of noise and interference.

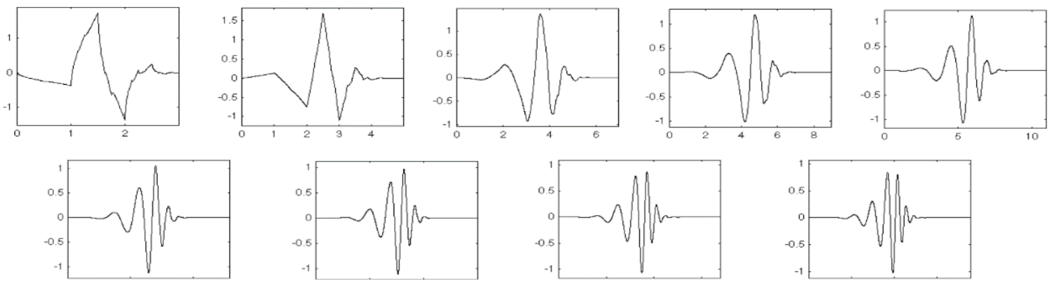

Fig. 3. Changes in the shape of the Daubechies wavelets with their increasing row

3. TEST RESULTS AND DISCUSSION

Tables 2 and 3 show the results of measurements of the feed cutting force F_f, the calculated values of the load stability coefficient kn and the values of the load stability coefficient after filtering with Daubechies wavelet 4 (db4) and Daubechies wavelet 6 (db6), as well as the amount of noise.

Table 2. Results of measurements and analyses of cutting forces generated during composite dry drilling

v_c/f (m/min)/(mm/rev)	Mean F_f (N)	*kn*	*kn* after db4 filtration	noise after db4 filtration	*kn* after db6 filtration	noise after db6 filtration
11/0.05	237.37	1.13	1.27	1.13	1.21	1.07
11/0.075	291.19	2.08	2.5	1.2	2.4	1.15
11/0.112	371.25	2.12	2.34	1.1	2.28	1.07
22/0.17	568.34	1.71	1.76	1.03	1.72	1
22/0.05	211.18	1.01	1.21	1.2	1.19	1.19
22/0.075	283.29	2.31	2.94	1.27	2.65	1.15
22/0.112	376.7	2.69	3.04	1.13	2.94	1.09
22/0.17	504.93	2.06	2.37	1.15	2.24	1.09
44/0.05	223.22	0.57	1.06	1.87	1.05	1.85
44/0.075	280.31	2	2.43	1.21	2.44	1.22
44/0.112	355.06	1.69	1.9	1.13	1.99	1.17
44/0.17	517	2.27	2.64	1.16	2.81	1.23

Figures 4–6 show the results of measurements of the mean feed force occurring when drilling composite holes and the value of the load stability coefficient as a function of feed. According to theory, the value of the force increases with increasing feed, regardless of whether it is dry or oil mist assisted drilling. No clear effect of cutting speed was observed. A slight positive effect of MQL on the value of the feed force in the drilling of the aluminium

composite under investigation was observed over the entire range of cutting parameters tested. This influence decreases with increasing cutting speed. For a cutting speed of 11 m/min, there was a reduction in the feed force value of about 11–20 per cent, for a speed of 22 m/min from 4 to 16 per cent and for a speed of 44 m/min from 3 to 17 per cent. It can also be seen that at higher feeds, the positive effect of the MQL is smaller. This can be explained by the fact that, when the performance drilling parameters are used, the lubricating and cooling effect of the oil mist is lessened, due to its hindered access to the material decohesion zone, which is related to the external mist feed used in the experiment.

Table 3 Results of measurements and analyses of cutting forces generated during composite drilling with oil mist

v_c/f (m/min)/ (mm/rev)	Mean F_f (N)	*kn*	*kn* after db4 filtration	noise after db4 filtration	*kn* after db6 filtration	noise after db6 filtration
11/0.05	191.16	1.37	1.68	1.23	1.49	1.09
11/0.075	249.97	2.04	2.89	1.41	2.74	1.34
11/0.112	333.11	2.38	2.89	1.21	2.89	1.21
22/0.17	455.68	2.17	2.92	1.34	2.7	1.24
22/0.05	179.88	1.14	1.32	1.16	1.28	1.12
22/0.075	247.79	2.36	2.99	1.27	2.68	1.13
22/0.112	317.21	2.02	3.05	1.51	3.04	1.51
22/0.17	489.76	2.8	3.42	1.22	3.52	1.26
44/0.05	186.84	1.19	1.58	1.33	1.52	1.28
44/0.075	237.34	1.7	2.63	1.55	2.63	1.55
44/0.112	340.14	2.43	2.89	1.19	2.99	1.23
44/0.17	506.15	2.23	2.91	1.31	2.97	1.34

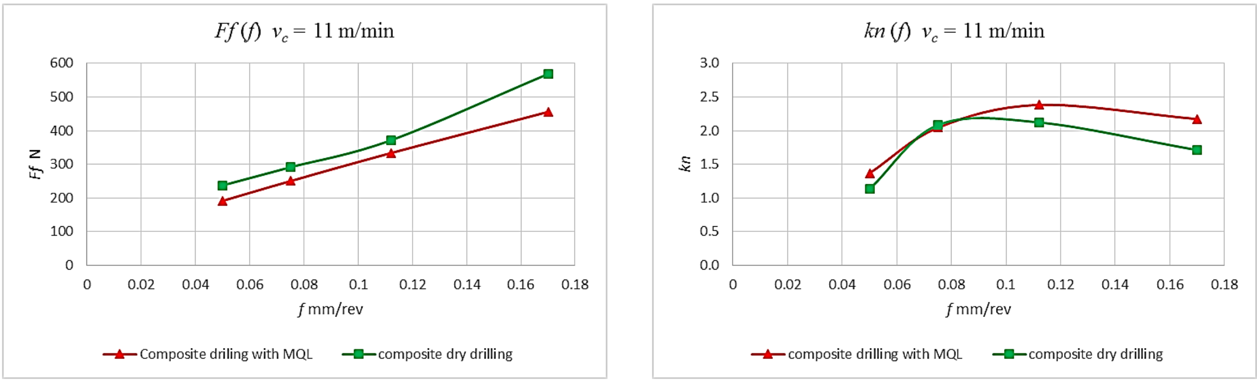

Fig. 4. Feed force and load stability coefficient measured and calculated when drilling aluminium composite at a cutting speed of 11 m/min

In the case of the load stability coefficient calculated from force measurements, the influence of cutting parameters or the use of oil mist cannot be clearly determined. Generally, its value increases as the feed rate increases. However, this is not an increase that can easily be described by a simple function. No influence of the cutting speed on the value of the *kn* factor was observed. Most surprising is the fact that the effect of minimum lubrication of the drilling zone is not noticeable. The load constancy factor takes on values that are much higher by about 100%, with to the use of oil mist when drilling at 44 m/min and a feed of 0.05

mm/rev. On the other hand, the load stability is higher during dry drilling at 22 m/min and a feed of 0.112 mm/rev. These results are different from the turning of the composite material tested [30]. In turning, a marked reduction in load constancy was observed by machining with oil mist assistance. Despite the reduction in friction, in wet machining, between chip and tool and the reduction in blade wear, the coefficient decreases as a result of the significant increase in force amplitude. It increases because the oil mist device operated in pulses. In the case of drilling, where the effectiveness of the mist must be lower because it was fed externally, at a large distance from the cutting zone, the pulsed operation of the AccuLube device should theoretically reduce the *kn* factor even further. These surprising further demonstrate the need for filtering and de-noising the feed force measurement results.

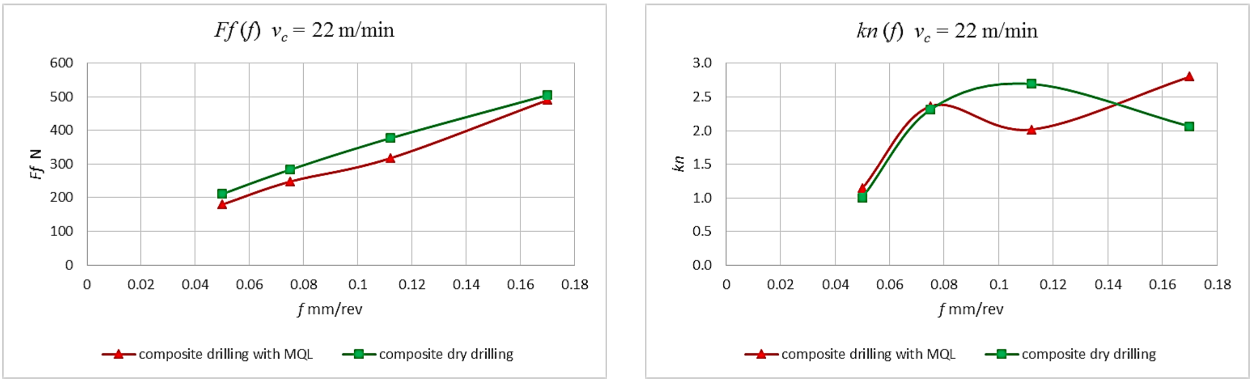

Fig. 5. Feed force and load stability coefficient measured and calculated when drilling aluminium composite at a cutting speed of 22 m/min

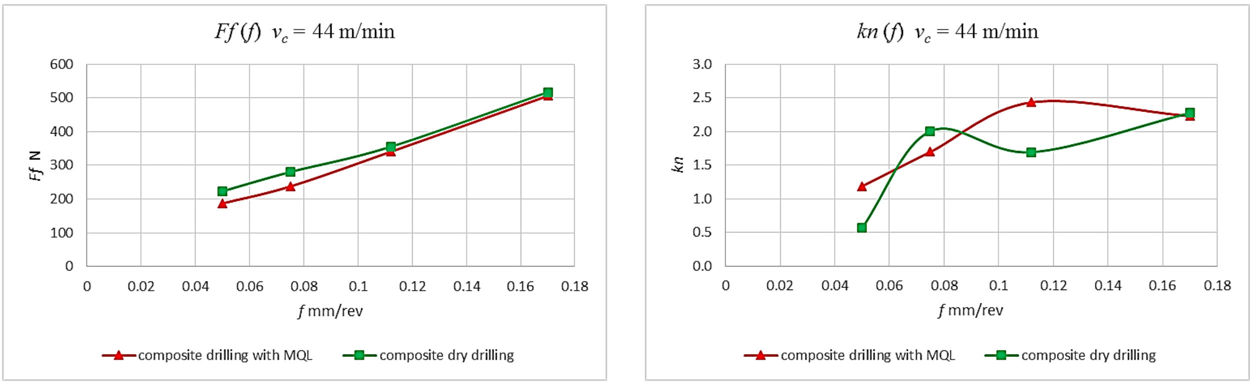

Fig. 6. Feed force and load stability coefficient measured and calculated when drilling aluminium composite at a cutting speed of 44 m/min

The graphs (Figs. 7–9) show how the application of wavelet filtering affected the values of the load stability coefficient. It is worth mentioning that the filtering mainly affects the maximum and minimum values of the cutting force and therefore its amplitude. As interference and noise are filtered out, the amplitude should be smaller and therefore the *kn* factor should have a larger value.

Analysing the figures 7–9, it is clear that after filtering out the noise, the load stability coefficient increases. The increase is significantly greater when drilling with oil mist assistance and reaches up to 50% e.g. for drilling with a speed of 22 /min and a feed of 0.112

mm/rev or with a speed of 44/min and a feed of 0.075 mm/rev. By filtering out the noise, the increase in *kn* factor when drilling with MQL is increasingly evident as the feed increases. It can also be seen that, after wavelet filtering, the *kn* values for drilling with a feed rate greater than 0.075 mm/rev take on similar values. The *kn* values as a function of feed rate after wavelet filtered are less variable and chaotic and can be described by simple functions. In the case of dry drilling, wavelet filtering did not change the nature of the relationship between *kn* coefficients and feed rate. A particularly large increase in coefficient values was noted for average feeds. In contrast to the analysis of cutting forces in composite turning [30], no large difference was found in the wavelet filtration power of db6 and db4. This indicates a different waveform, the shape of the feed force signal during drilling than of the cutting force components during turning. This is also another argument demonstrating the need to correctly select the type of wavelet for the analysis of a specific signal.

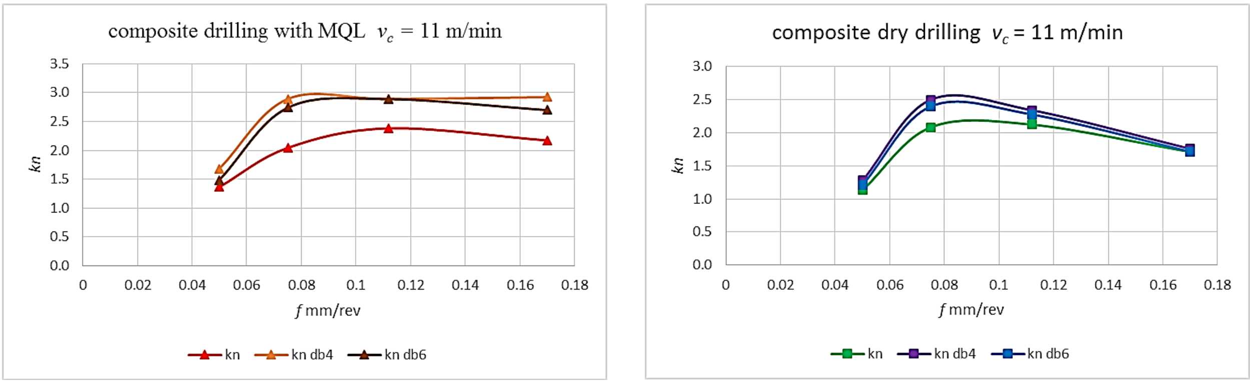

Fig. 7. *Kn* coefficient calculated from the measurements and after db4 and db6 wavelet filtration as a function of the feed. Composite drilling with cutting speed 11 m/min

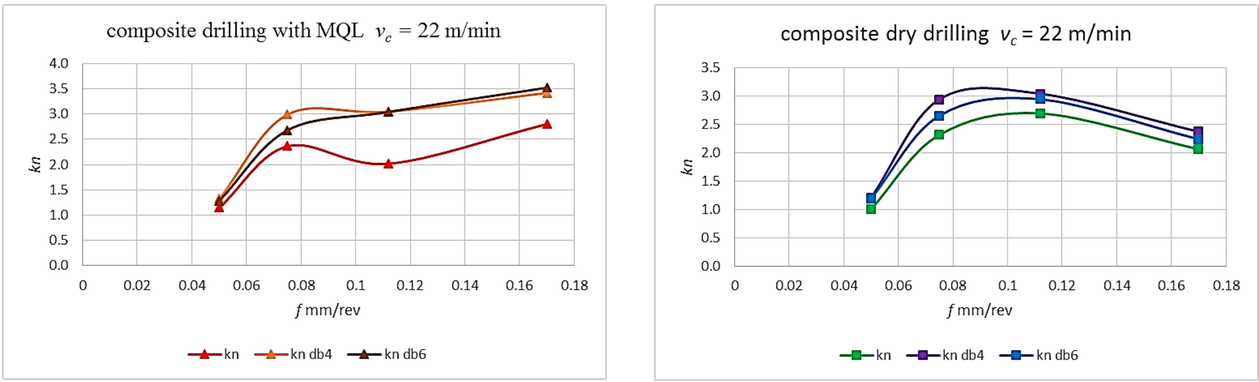

Fig. 8 *Kn* coefficient calculated from the measurements and after db4 and db6 wavelet filtration as a function of the feed. Composite drilling with cutting speed 22 m/min

As a supplement to the analyses carried out, the noise and interference values are shown in Figure 10. Larger interferences were found when machining with MQL, which is the effect of the oil mist device. The only exception is drilling with finishing parameters. In this case, the increase in *kn* values after filtration and therefore also the amount of interference during dry machining was the highest. This may be due to interference in the chip formation process and the significant difference in chip shape after dry drilling and with MQL [33]. The use of

MQL at these drilling parameters had the most beneficial effect on the length of the chips formed, and it also improved the shape of the drilled hole to the greatest extent [33]. The effect of drilling parameters on disturbance levels was not found. This indicates that the cutting process is influenced by many random factors such as inhomogeneities and defects in the workpiece material, chip flow, blade wear process, thermal changes on the machine tool its vibration and the environment on the shop floor, but also by the effectiveness of wavelet filtering in separating the force signal from interference.

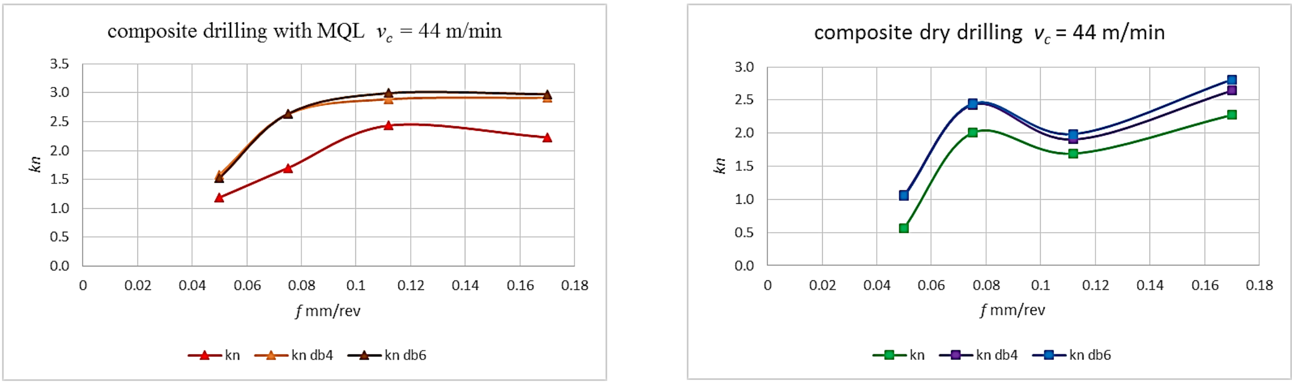

Fig. 9. *Kn* coefficient calculated from the measurements and after db4 and db6 wavelet filtration as a function of the feed. Composite drilling with cutting speed 44 m/min

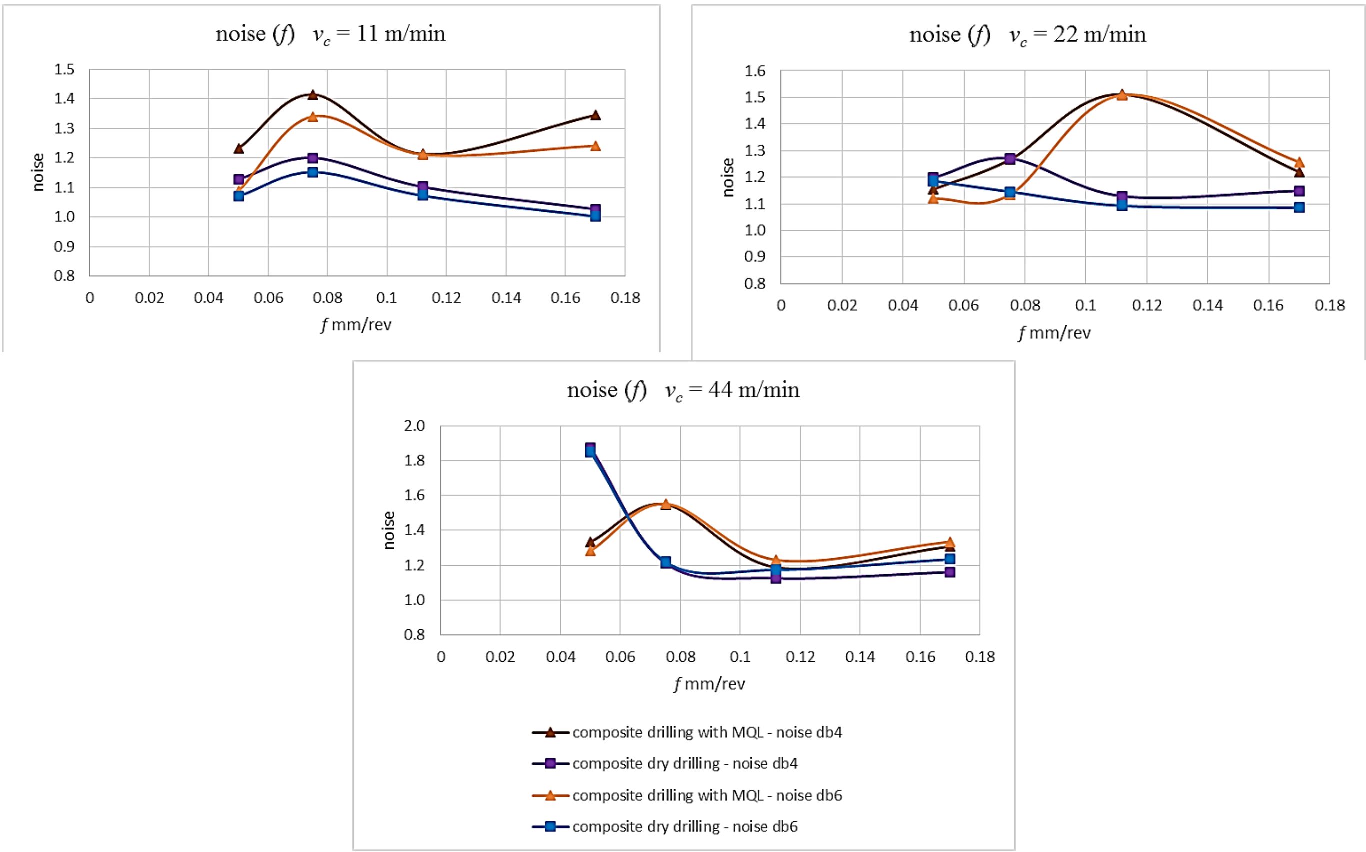

Fig. 10. Noise during composite drilling, calculated by wavelet filtering with Daubechies 4 and Daubechies waves

4. CONCLUSIONS

This paper presents the results of experimental measurements of cutting forces during the drilling of an aluminium matrix composite and an analysis of the feed force using a discrete wavelet transform. It was found that:

- the value of the feed force is significantly influenced by the use of oil mist support. It is possible to reduce its value by up to 20% compared to dry drilling,
- the change in the load stability coefficient, which is the ratio of the average force to its amplitude, changes with increasing drilling feed according to different functional relations than the average value of the feed force - this may be indicative of a large noise in the force measurement,
- the Daubechies wavelets separate the force signal in the drilling from the noise present in the measurements,
- larger levels of interference were found during drilling with oil mist, which was due to the pulsed operation of the fog machine. These pulses may have caused vibrations in the system, resulting in increased measured maximum and minimum force values.
- In contrast to the analyses of the turning forces [30, 31], no significant effect of the order of the Daubechies wavelet, and therefore the compactness of the them, was observed. This demonstrates the different nature, shape of the force signal in drilling and turning.

The results presented in this paper are the next stage of research to evaluate the applicability of the discrete wavelet transform for filtering force measurements in aerospace material machining. The next planned stage will be attempts to filter forces measured during milling of an aluminium matrix composite. The authors will also attempt to analyse the cutting force during drilling of an aluminium composite with internal oil mist supply.

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