Journal of Machine Engineering, 2023, Vol. 23, No. 2, 110–122
ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)

Received: *30 March 2023* / Accepted: *26 May 2023* / Published online: *02 June 2023*

cutting process, machining,
metal cutting

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A STUDY OF LOW-FREQUENCY VIBRATION-ASSISTED BANDSAWING OF METALLIC PARTS

Sawing is often the first work step in the metal cutting production chain. Especially for larger workpieces, bandsawing is used for this purpose. Nevertheless, studies on sawing have led a niche existence in the research landscape for a long time. However, as a result of the optimization of manufacturing processes in terms of economic efficiency, bandsawing is increasingly becoming the focus of research, since there are still saving potentials here. The aim of this paper is to investigate the extent to which the bandsawing process can be influenced by active, low-frequency vibration superimposition in the feed direction. First, analogue tests were carried out and parameter combinations were determined which have a positive influence on the process. Subsequently, these parameter combinations were investigated on a real sawing machine with an excitation unit, analysing the extent to which the results from the analogue tests could be transferred to the real process.

1. INTRODUCTION

In the digitalization and automation of production processes, sawing processes have only played a subordinate role until now, although they are often the first work step in the process chain. Due to the constantly rising material cost as well as for ecological reasons, a resource-saving method of production along the entire process chain is becoming more and more important. Hence cutting processes are the focus of research works on process optimization and further development [1]. Particularly in the area of bandsawing, experience from practical application has shown great potential with regard to saving material in the saw kerf and increasing tool life.

The tools used in band saws are endless saw bands with a low inherent stability and a large number of teeth made of cemented carbide or high-speed steel. The saw band is often guided over two guide wheels and tensioned between them as well as turned by up to 90° into the working plane by means of a guiding device. The saw band can thus circulate outside the working space of the machine, allowing the machining of long workpieces. Guide elements are mounted as close as possible to the workpiece to stabilize the saw band.

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https://doi.org/10.36897/jme/166530

Due to its unsupported length, the band is relatively unresistant to torsion around its longitudinal axis in the direction of primary motion and to a perpendicular bending to the working plane, despite the pretension between the guide elements. This is particularly noticeable, when it is compared with tools for other metal cutting processes. Moreover, each individual entry of a saw tooth into the workpiece results in an impulse exciting the entire saw band to vibrate. This process is represented schematically in Fig.1. It can be seen that the depth of cut of each tooth is a function of time ($f_z(t)$) and varies with each new tooth impact. The impact itself depends on several factors such as cutting speed (v_c), feed rate (v_f), material and tool geometry.

To prevent periodic excitation and thus the development of resonance vibrations, saw bands can be designed with a varied distance between the teeth. But even in this case, the remaining vibration causes a change in the real depth of cut of the individual teeth. The susceptibility to as well as the amplitude and frequency of vibration are influenced by many factors, such as the saw band tension or the distance between the guide elements or rather the unsupported length of the saw band, and can only be predicted to a limited extent.

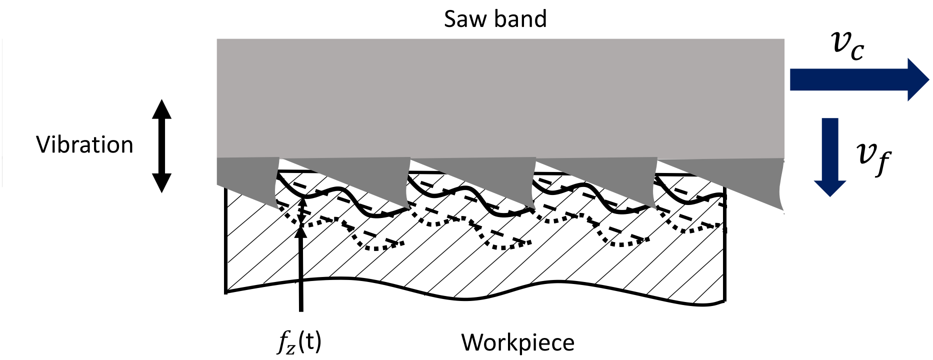

Fig. 1. Influence of tooth entry impulses and vibrations on depth of cut, inspired by [2]

This undefined form of vibration input into the sawing process is unwelcome and has negative effects on it, such as a poor surface quality and a faster tool wear. Most publications have examined the issue of vibrations arising from the process, their effects and how to reduce them. In [3], the comparison between aluminium and wood saws was discussed in terms of vibration and the transfer of recognition between the materials. Other publications have dealt with the detection of chatter effects [4, 5]. The authors of [6, 7] investigated the influence of process vibrations on material loss and the influence of the surface in the case of wood materials.

A defined input of vibration can, however, be beneficial for the process. This has already been shown in studies on other production processes, in which it has been possible to specifically influence metal cutting processes by means of an active, specific vibration excitation at defined frequency and amplitude values as well as vibration directions.

In general, a manufacturing process in which vibration is superimposed with a frequency between 0.1 and 80 kHz and an amplitude between 1 and 200 μm is called vibration-assisted machining (VAM) [8, 9]. The vibration can be applied to the workpiece or tool [9]. These processes can be divided into two basic categories [9, 10]:

- resonant systems (Frequency greater than 20 kHz and displacement less than 6 μm),
- non-resonant systems (Frequency between 1 kHz and 40 kHz).

In addition, VAM processes can be classified by the type of movement, such as one-dimensional tool tip movements (small reciprocations) or two-dimensional movements like elliptical movements [8]. VAM processes with one-dimensional movements are the most common ones.

The superimposition is intended to influence the mechanisms of chip formation and thus to positively influence the forces, better cooling and lubrication through periodic relief or gap formation. Lower forces, temperatures and a reduction of stresses are supposed to improve the tool life. In some processes, the surfaces and burr formation can also be positively influenced [9–12].

Low-frequency vibration-assisted machining is used to control the tool engagement and retraction mechanism around the path of the tool centre point [13]. This allows the chip form to be controlled by varying the thickness and cutting time [9, 13].

Littmann et al. [14] were the first to analyse the influences of ultrasound on the friction of contact surfaces in general. In [15], the general principles and methods of tool design for machining processes with ultrasound were described.

While in [16, 17] the effects of vibration excitation in deep-hole drilling and boring were investigated, Chen et al. [18] examined the positive effect of a vibration superimposition on the ploughing force during the machining of Ti6Al4V.

With regard to bandsawing, however, no research can be found on the subject of active vibration superimposition. Compared with the other known processes, the major differences include the more unstable tool and the smaller depth of cut per tooth, which is often less than or equal to the cutting edge radius. This results in a chip formation that can be described as a combination of ploughing and the forming of a kind of built-up edge, which fills the gap at the cutting edge radius [19]. If the real depth of cut is too small, a so-called ploughing occurs. Here the material is predominantly elastically deformed until one of the subsequent saw teeth penetrates deep enough into the material to cut it off. In the case of an active vibration excitation of the sawing process, the amplitude can only be relatively low due to the small depth of cut per tooth. Also taking account of the unstable tool and the vibrations resulting from the process, it can be concluded that a specific, active excitation is difficult.

The aim of this publication is to investigate the extent to which a specific, active low-frequency vibration superimposition (vibration-assisted sawing) in the feed direction of the saw blade can also achieve positive results, like a better surface quality or reduced forces. For this purpose, combinations of frequency and amplitude with a positive effect on the cutting process were first determined by means of analogue test. As analogue test, a bound orthogonal cut was chosen with tightly clamped single-tooth and multiple-tooth samples respectively, made out of commercial saw bands. In this way, the effects from the unstable tool were to be suppressed in the first step. In the tests, for example, chip formation was analysed using a high-speed camera, and the resultant forces arising were determined. Then supplementary tests were carried out with comparable samples by means of a grooving test on a lathe in order to gain knowledge about the tool life. These grooving tests here were recessing tests in interrupted cutting [20]. Finally, preliminary results from the established parameter combinations were applied to a band saw. All tests were carried out with a steel material.

2. TEST SET-UP AND DESIGN OF EXPERIMENTS

In order to be able to separately examine the basic effects of external influences, tests were at first carried out on analogue test stands. Various processes were taken into consideration, as the respective test stands were optimized for different analyses. In each case, the same set-up was used here for the excitation so that its features, such as frequency response function and natural frequencies, remained the same. It consisted of a piezo actuator, type P-216K040 by Physik Instrumente PI, moving the pilot carriage with the test tools. The actual movement of the tools was measured here with an eddy current sensor. The set-up and its components are shown in Fig. 2a.

Mainly carbide-tipped saw band segments were used as test tools, which are presented in Fig. 2b. For the test tools, the width of cut (w_c) was 1.8 mm and the main cutting edge of the selected teeth was 1.5 mm wide (w_{ce}). The recommended depth of cut for the test tools was approximately 6-8 µm per tooth. For the experiments presented in this paper, the feed per tooth (f_z) was always 8 µm. The vibration amplitudes u studied were 0, 50, 100, 150 and 200% of this value (u = 0, 4, 8, 12 and 16 µm).

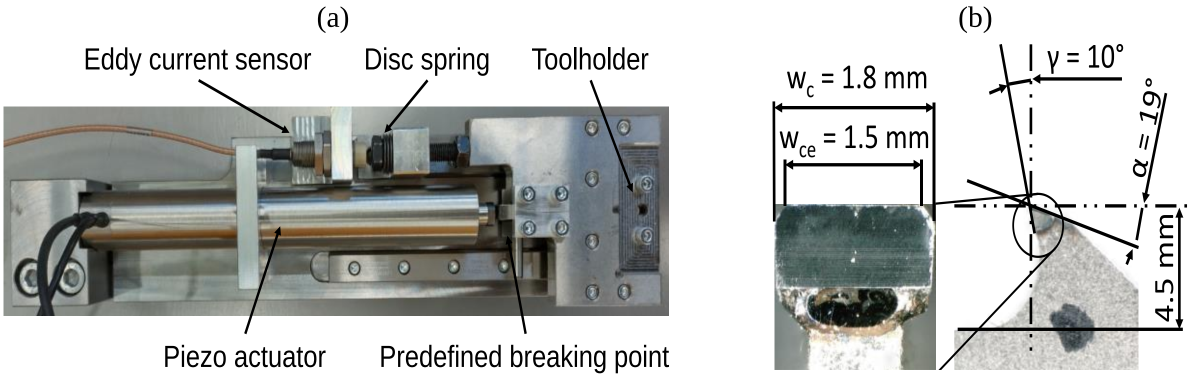

Fig. 2. (a) Experimental set-up with piezo actuator and (b) tool data [21]

Initially, experiments were carried out to determine the system response to various vibration parameters. These were carried out in free space and during cutting. Figure 3 shows the different responses of these two test set-ups. Up to a frequency of 100 Hz, the system followed the input quite well, but after that the system began to drop. By adjusting the input with the aid of the diagram, it was possible to achieve an amplitude of 16 µm up to a frequency of 400 Hz and an amplitude of 8 µm up to a frequency of 800 Hz with sufficient reserve in the system. With this information and the active measurement of the amplitude during cutting, it was possible to adjust the amplitude for each measurement in this research and verify it later. Hence, a better system response during cutting was achieved because the upward movement of the tool with the disk springs was supported by the feed force.

In all tests, 42CrMo4 was used as material and a length of cut (l) of 60 mm was sawed. Together with the defined cutting speeds, the numbers of vibrations per cut could be calculated. These are listed in Table 1, depending on frequency.

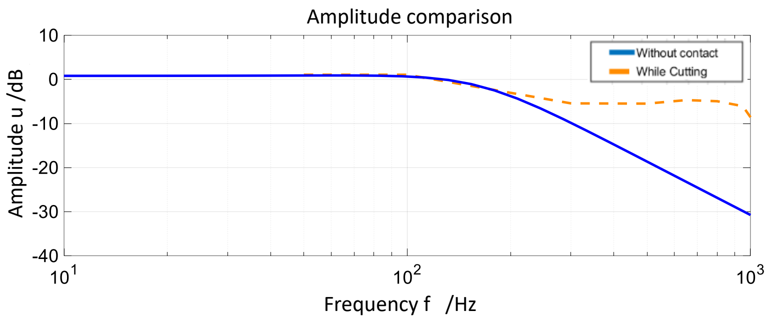

Fig. 3. Amplitude response of the system in free space/without workpiece contact and during cutting

Table 1. Numbers of vibrations depending on cutting speed v_c and frequency f

Frequency f [Hz]	v_c =60 m/min	v_c = 80 m/min	v_c = 100 m/min	v_c = 120 m/min
100	6	4.5	3.6	3
200	12	9	7.2	6
400	24	18	14.4	12
600	36	27	21.6	18
800	48	36	28.8	24

At first, bound orthogonal cutting tests were carried out to investigate the effects of the vibration superimposition during a tool pass at varying process parameters. Figure 4 shows a diagram of the test set-up and the respective effective cutting direction for positive values of speed and force, as used in the further course of the investigation. The tests were repeated three times for each parameter set.

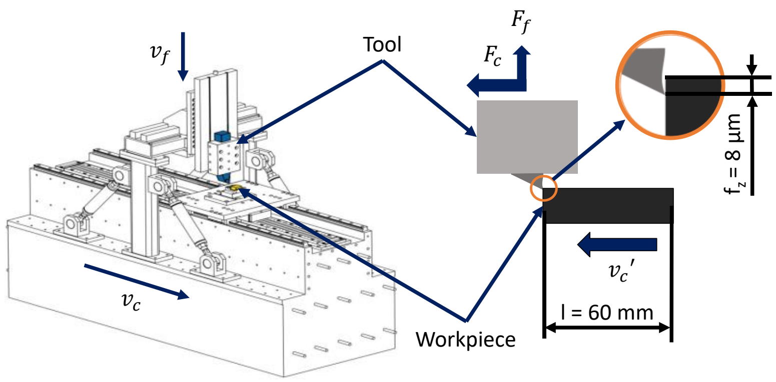

Fig. 4. Orthogonal test stand

After orthogonal cutting was used to establish parameter combinations with a positive influence on the process forces, they were examined with regard to their influence on tool life, using the so-called grooving test (according to VDI 3324). In this test, a lathe was used to carry out recessing experiments with the test tools and slotted workpieces on a lathe. A robot-assisted microscope ("Cobot" by Alicona Imaging GmbH) with a type R25 measuring head was used to directly measure the wear in the machine so that installation tolerances could be avoided.

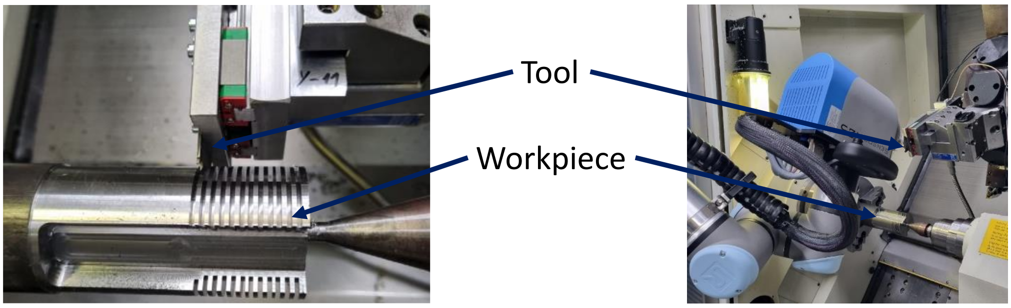

Fig. 5. Set-up of grooving test according to VDI 3324 and with the "Cobot" microscope

Finally, a band saw of the type Klaeger Pharos 300, was supplemented with an appropriate device for vibration superimposition. Figure 6 shows a diagram of the experimental set-up with the position of the actuator and sensors used. The actual movement of the excitation actuator was measured using eddy current sensors, while the movement of the saw band was established with a line laser. In the first approach, the process forces acting on the workpiece were recorded using a force measuring platform. In this experimental setup, the guide elements were approximately 330 mm apart from each other and the test workpiece was a round bar made of 42CrMo4 (1.7225) with a diameter (D_m) of 60 mm. A cutting speed of 100 m/min and a feed rate of 55 mm/min were chosen as cutting parameters. These selected values were then split up to the individual teeth with f_z of 8 μm.

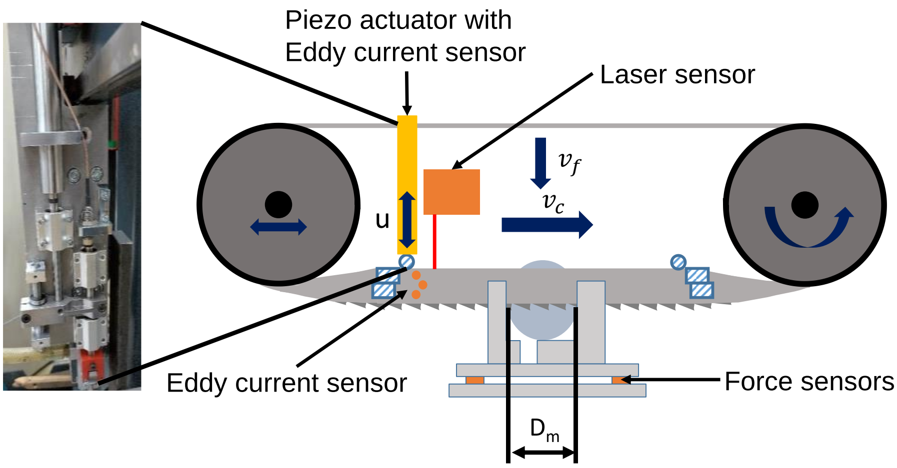

Fig. 6. Diagram of the test saw with sensors and coordinate system

During the course of the experiments, it became apparent that the great distance between the guide elements was a problem. Therefore, the force measuring device and the laser sensor were removed for the final tests. Additionally, another workpiece geometry with a diameter of 160 mm was examined to increase the length of cut. For the workpiece with a 60 mm diameter, the guide elements were 100 mm apart from each other, whereas they were 200 mm apart when the diameter was 160 mm. The cutting speed remained constant during the tests, while the two feed rates of v_f = 27 mm/min ($f_z \approx$ 4 μm) and 55 mm/min ($f_z \approx$ 8 μm) were examined. To achieve a statistical reliability, the experiments were repeated three times.

3. EVALUATION

In a first evaluation of the data measured, the mean values of each cutting and feed force were determined from the courses of individual cuts and recorded in diagrams, depending on the set frequency, amplitude and cutting speed. The correlations here are shown in Fig. 7 for amplitudes of 4 μm and 8 μm. The parameter combinations applied in the tests are illustrated as red points. The areas between them are linear interpolated.

The lower amplitude affected the average process forces relatively little, and the cutting speed played a more important part. The amplitude of 8 μm, however, showed a clear influence as well as an effect of the frequency in interaction with the cutting speed, which was predominantly affected here.

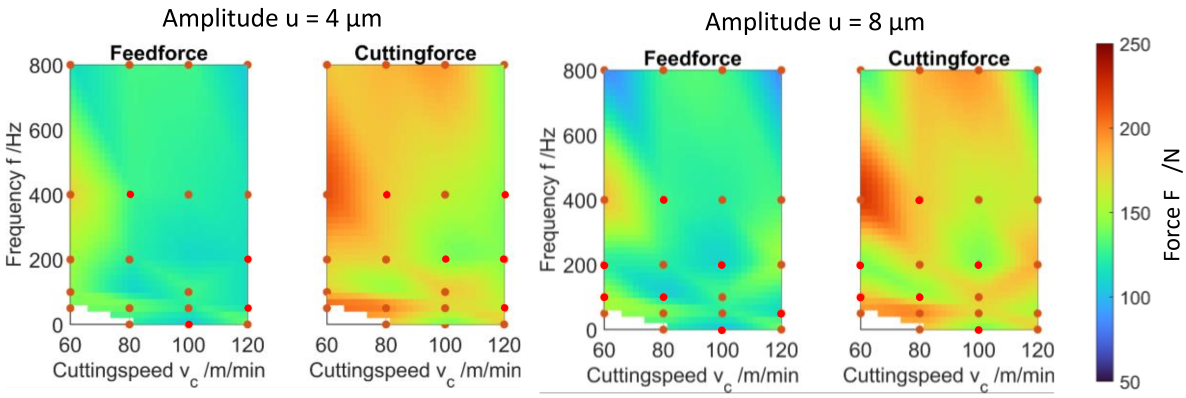

Fig. 7. Process forces at an amplitude of u = 4 μm and u = 8 μm

In the next step, the influence of amplitude and frequency was examined for constant cutting speeds. For this purpose, the lowest ($v_c = 60$ m/min, Fig. 8 left) and the highest value ($v_c = 120$ m/min, Fig. 8 right) of the previously examined correlations were analysed as examples. Since the cutting force is generally lower at higher cutting speeds, measurements with two higher amplitudes (u = 12 μm and u = 16 μm) were still added here for two frequency values (f = 200 Hz and 400 Hz). The maximum values of frequency and amplitude resulted from the system boundaries of the set-up, whereas the minimum frequency resulted from the length of cut and the wavelength. Moreover, the maximum amplitude was limited by the fact that the force at the lower reversal point became too great so that the teeth broke off.

It could be seen again that the vibrations had only little influence on the average feed force, but some influence on the average cutting force. While no real effect on forces could be achieved with the lower cutting speed and vibration-assisted sawing, the higher cutting speed showed some promising results at a higher frequency and amplitude of 8 μm.

Since v_c = 120 m/min is recommended as cutting speed for the tool in the test material, it was examined more closely here. As Fig. 2 shows influences at 200 Hz, it was selected for the following analyses. For the sake of clarity, only three amplitudes (u = 0, 8, 16 μm) were selected. The force course of individual tests was examined and illustrated here with regard to the chip form produced in each case.

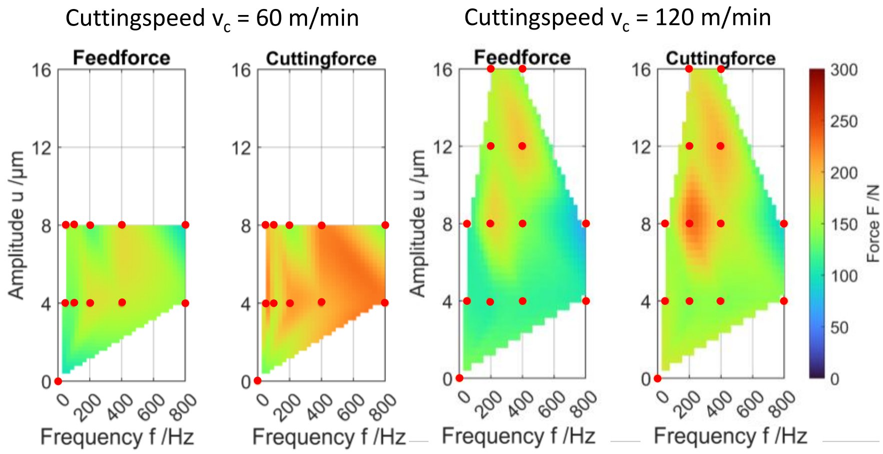

Fig. 8. Analysis of the process forces at a constant speed of v_c = 60 m/min and v_c = 120 m/min

It could be seen that the force course (Fig. 9) was relatively constant at an amplitude of 0 µm and only vibrated slightly throughout the process, in which spiral chips were formed.

Figure 9 also shows that the force *F* fluctuated between 100 N and 300 N at an amplitude of 8 µm. Owing to the vibration input, the chip thickness fluctuated and fragmented chips were formed. When the amplitude was increased further, the tooth left the material at the upper reversal points and the force decreased further so that discontinuous chips were formed (Fig. 10). The forces here in the graph were greater than 0, mainly due to the inertia of the system and some low-pass filtering of the measured data to remove noise in the analogue signal.

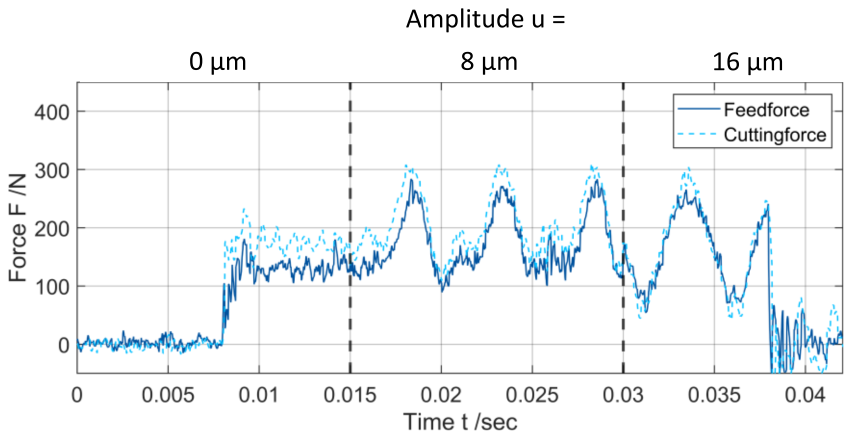

Fig. 9. Force records produced from the different measurements with v_c = 120 m/min, *f* = 200 Hz vibration frequency and varying amplitudes

Finally, the performed grooving tests were taken into consideration. Two different cutting speeds (v_c = 60 and 120 m/min) were examined here at a constant amplitude but for varying frequencies. The width of wear land (VB_B) and the cutting edge misalignment (S_v) were investigated to determine the wear. The measurements were carried out with the robot-assisted microscope system ("Cobot" by Alicona Imaging GmbH) after a path length of 50, 100, 500, 1000, 2000 m respectively.

Fig. 10. Chip form at v_c = 120 m/min, f = 200 Hz vibration frequency and varying amplitudes

Regarding tool life, there was no relevant difference between the frequencies at a cutting speed of v_c = 60 m/min (Table 2).

Table 2. Tool wear depending on frequency; v_c = 60 m/min

v_c = 60 m/min	f = 0 Hz	f = 100 Hz	f = 200 Hz
Length of cut (m)	VB_B / S_V (μm)		
1000	67.9 / 34.7	59.5 / 23.8	65.5 / 44.2
2000	126.4 / 65.1	115.2 / 92.4	132.5 / 82.8

In the tests with a cutting speed of v_c = 120 m/min, less wear could be detected at the higher frequency than in the other experiments (Table 3). However, the tests had to be stopped after a path length of about 2,000 m, because sparks were emitted during the process. This was probably due to the fact of dry cutting and the resultant heating up of the workpiece.

Table 3. Tool wear depending on frequency; v_c = 120 m/min

v_c = 120 m/min	f = 0 Hz	f = 100 Hz	f = 200 Hz
Length of cut (m)	VB_B / S_V (μm)		
1000	32.5 / 12.1	31.9 / 9.8	28.3 / 9.3
2000	49.8 / 29.24	45.1 / 60.5	33.7 / 12.8

Due to the unsatisfactory temperature dissipation, the tests were stopped and the wear tests were not carried out completely. But at this point, it was noticeable that the wear was lower at the higher frequency as well as that the build-up edge was smaller during these tests. Thus, a certain potential was recognizable.

After the analogue experiments were conducted, the knowledge gained was applied to the band saw and investigated in the real process.

Before starting the experiments, it was necessary to measure the straightness of the saw blade backing by means of a tactile measuring machine. The result is presented in Fig. 11 showing the waviness, which is already existing in the saw blade and sometimes greater than the desired amplitudes of the vibration superimposition. However, the wavelength was much longer than the wavelength of the vibration superimposition to be analysed (less than 10 mm).

Therefore, effects of the vibration-assisted sawing should be visible despite the waviness of the band.

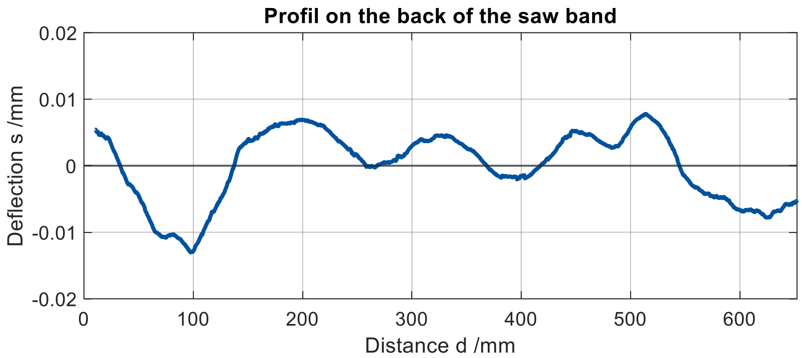

Fig. 11. Waviness of the saw band

To ensure that the desired vibration was added to the saw band, the back of the band was measured during cutting. Then the movement was analysed and compared with the movement of the piezo actuator. The orange curve in Fig. 12 shows the measured movement of the band over a short period of time. The vibration is clearly visible at the position of the laser sensor (approximately 100 mm from the material).

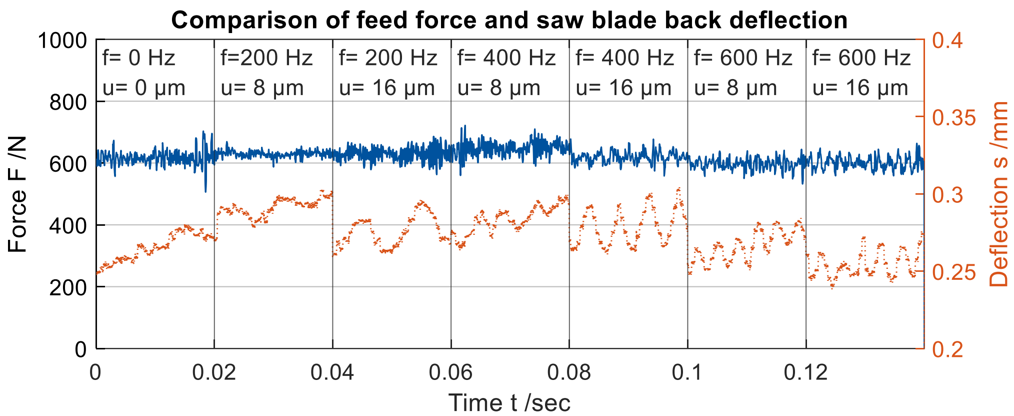

Fig. 12. Comparison of feed force and saw blade back deflection *s* with active vibration superimposition in the feed direction

The blue curve in the diagram in Fig. 12 shows the measured values for the feed force during a cutting process with the specified vibration parameters. It can be seen that the added vibrations are drowned in the noise of the vibrations by the cutting process. Thus no influence could be detected in the parameter window examined. As already established in the tests with the linear test bench, tooth breakouts were the limiting factor of the amplitudes in these tests.

The surface of the sawn samples was also measured with tactile measuring devices and optically with a focus variation measuring microscope. The results from the force measuring signals were confirmed, and no clear change of the surface could be detected as a function of an active vibration superimposition in the feed direction.

As no significant influences on the cutting forces could be detected, the force measuring platform and the laser sensor was dismantled so that the guide elements of the band saw could be brought closer to the workpiece and the unsupported length of the saw blade could be minimized.

In this experimental set-up, no influence could initially be detected either. Only when the feed rate was reduced to 27 mm/min, a smoothing in certain sections of the surface showed in the case of the larger workpieces. In addition, the saw frame was lifted up during the excitation because of the greater feed and cutting forces so that only a certain proportion of the excitation was transmitted to the saw band. Due to tooth setting errors in the saw blades, a periodic surface profile was created, which was repeatedly interrupted by one outlier per saw blade revolution. The following profile (Fig. 13) was produced in the area between these outliers for samples with different vibration parameters. It could be seen that the surface became a little bit more even and flatter with increasing frequency at a maximum amplitude. One reason for this was that the saw teeth had an additional vertical cutting component due to the excitation, thus the surface was smoothed in the negative feed direction.

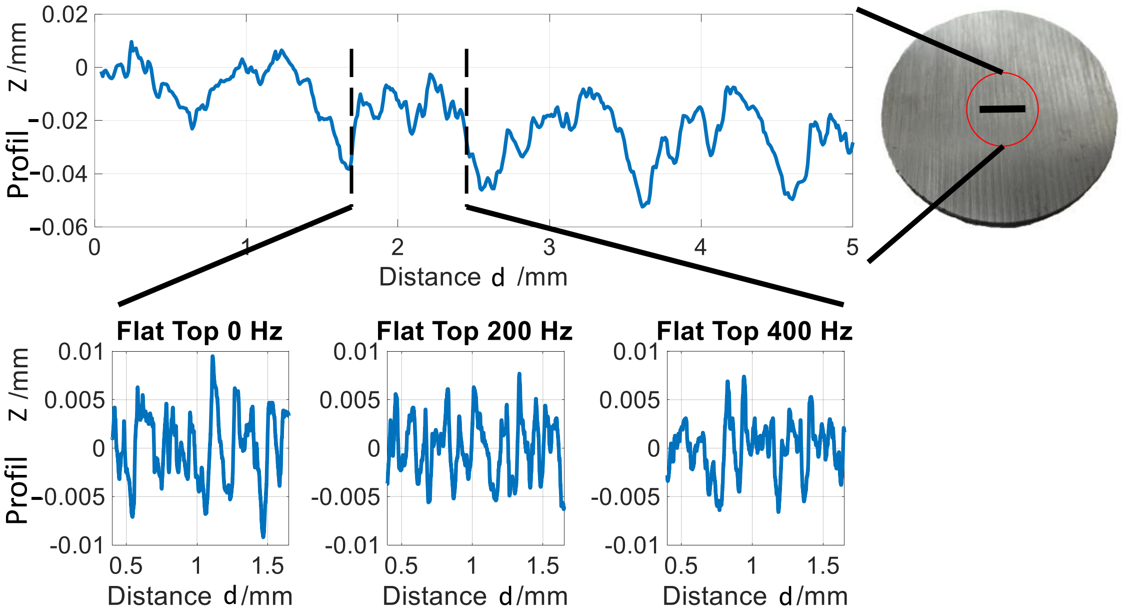

Fig. 13. Surface profile at defined sections with different excitations

4. CONCLUSION

By conducting analogue experiments, it was possible to demonstrate that vibration assistance in the feed direction had a positive effect on single-tooth samples, resulting in reduced average forces for specific parameters. At a cutting speed of 120 m/min, a reduction in forces was observed for a frequency of 800 Hz and an amplitude of 8 µm. For other parameters, however, the mean forces were greater without additional vibrations, causing the tooth to break after a few tests.

Even though the wear tests had to be stopped due to temperature problems, there was still evidence of the potential of active vibration superimposition. When applying this result to a band saw, it was found that the length of the saw band between the guide elements and the workpiece was critical. It was assumed that the unstable saw band was deformed and partially compensated for the vibration input. Additionally, it was shown that the saw frame of the used band saw was lifted up in response to the vibrations and the greater cutting forces, thereby reducing the effective amplitude between the saw band and the workpiece.

As a result, the feed rate was halved and a certain effect could be shown in particular areas of the sawn surface. However, the influence of the tooth setting error of the saw band was greater, offsetting the achieved quality improvement.

ACKNOWLEDGEMENTS

This research was supported and funded by the German Research Foundation DFG within the programme STE 1563/18-2. The authors would like to thank the DFG for this funding and the intensive technical support.

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