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MEASURING THE DYNAMIC TWISTING BEHAVIOUR OF SAW BLADES IN THE KERF DURING THE SAWING PROCESS

Vibrations may occur in all kinds of production processes. Particularly the kinematics of band saws with their thin and unstable structure of the saw blade causes high vibrations, which generate, on the one hand, a high acoustic level. On the other hand, the impact can be seen as grooves on the surface of the workpiece. To optimize the sawing process, the vibration behaviour of the saw blades is investigated by experiment on a test band saw with a contactless measuring system during the sawing process of steel. The focus here is on the twisting of the saw blade in the kerf. The sawing parameters of cutting speed and feed rate are varied here in a wide range to examine the stability of the process and the occurring displacement of the saw blade. The results of this investigation indicate that the saw blade in the kerf shows a characteristic behaviour, which is subject to the cutting parameters. It is obvious that the performance of the process depends not only on the cutting process but also on the tensile state of the saw blade affected by the design of the saw frame, the saw blade guides and the saw blade tension. The results obtained are able to support future developments and identify an optimization potential for the sawing process.

1. INTRODUCTION

The performance of metal band saws depends not only on the input power of the machine but also on the behaviour of the tool, i.e. the saw blade. The major challenge for a stable process is to balance cutting force and feed rate to achieve a vibration stimulation of the saw blade during cutting. The problem here is the thin und unstable structure of the saw blade, which is only pre-stressed in cutting direction and guided by two saw blade guides on both sides of the workpiece. Depending on the workpiece dimensions, the free length between the two saw blade guides leads to an indefinite vibration behaviour, especially in unstable process conditions. The vibration behaviour of the saw blade results in a low quality of the workpiece surface as well as the twisting of the saw blade in the kerf. The more the saw blade twists in the kerf the greater the occurring cut deviation gets. Thus the cutting losses on the workpiece and the wear of the tool increase. In the following, this

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twisting behaviour of the saw blade in the kerf is investigated with a contactless measuring system integrated in a test band saw.

The fundamentals of cutting with band saws are briefly explained below to understand the conditions during the cutting process. The bandsawing process is classified into horizontal and vertical band sawing. This investigation is focused on horizontal band saws, which are standard in the modern metalworking industry. The saw blade is pre-stressed between the two wheels, one of which is powered, and then twisted by the saw blade guides towards the cutting plane, as shown in Fig. 1. The whole saw frame is moved downwards through the workpiece at feed rate [1].

The twisting angle for typical horizontal band saws is up to 90 degrees. This twisting induces a stress state in the cross-section, which has a great influence on the sawing process and the tool life of the saw blades. In addition, the manufacturing tolerances for the sawing process are higher and the maximum feed rate is reduced.

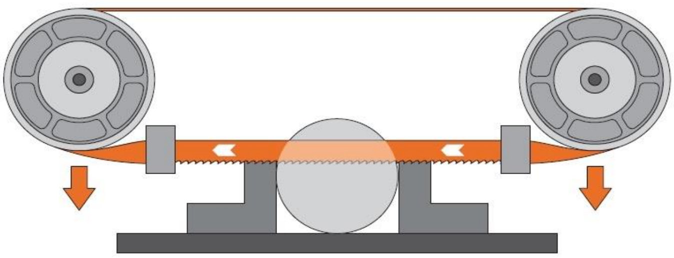

Fig. 1. Principle of horizontal bandsawing [1]

The saw band geometry is specially designed for a slight vibrational response. Hence the tooth distance varies along the entire length of the saw band, but there are alternating segments with a specific tooth distance. For example, a saw band has a variable tooth pitch of three to four teeth per inch (TPI). That means that there are three TPI in one segment and four TPI in the next segment. This is why the frequency of the tooth impact onto the workpiece changes from segment to segment and the vibrational response is reduced [2]. Especially resonances of the system are avoided. A further measure is the setting of the teeth. Thus single teeth are inflected out of the saw blade axis to the left and to the right in a certain sequence. This helps to prevent a jamming of the saw blade in the kerf, but the cutting width is increased.

To understand the conditions in the kerf during sawing, a model for the resultant force F is explained using a single saw tooth. In Fig. 2, the direction of the sawing parameters of cutting speed v_c and feed rate v_f and the resultant force F is shown [3]. The resultant force F is a vectorial addition of the three components of cutting force F_c, feed force F_v and passive force F_p. The effective direction of the cutting force and the feed force works in the opposite direction of the saw band movement. The passive force F_p is perpendicular to the plane formed by the cutting force F_c and the feed force F_v. The direction of the passive force F_p alternates with regard to the tooth impact, but the theoretical average of the passive force is about zero due to the setting of the teeth.

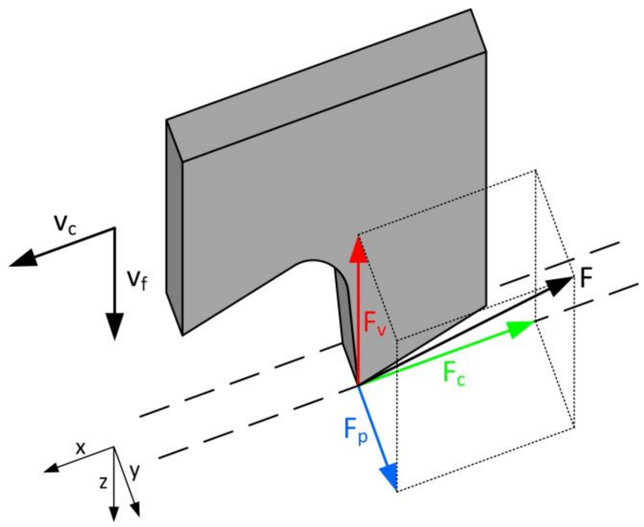

Fig. 2. Model of the resultant force *F* and the orthogonal components [4]

For the simulation of the process forces during sawing, an analytical force model was implemented by using the cutting force theory of Kienzle and Victor [3]. Figure 3 presents the results for a sawing process of steel 11SMn30+C with a diameter of 60 mm at a cutting speed of 70 m/min and a feed rate of 70 mm/min.

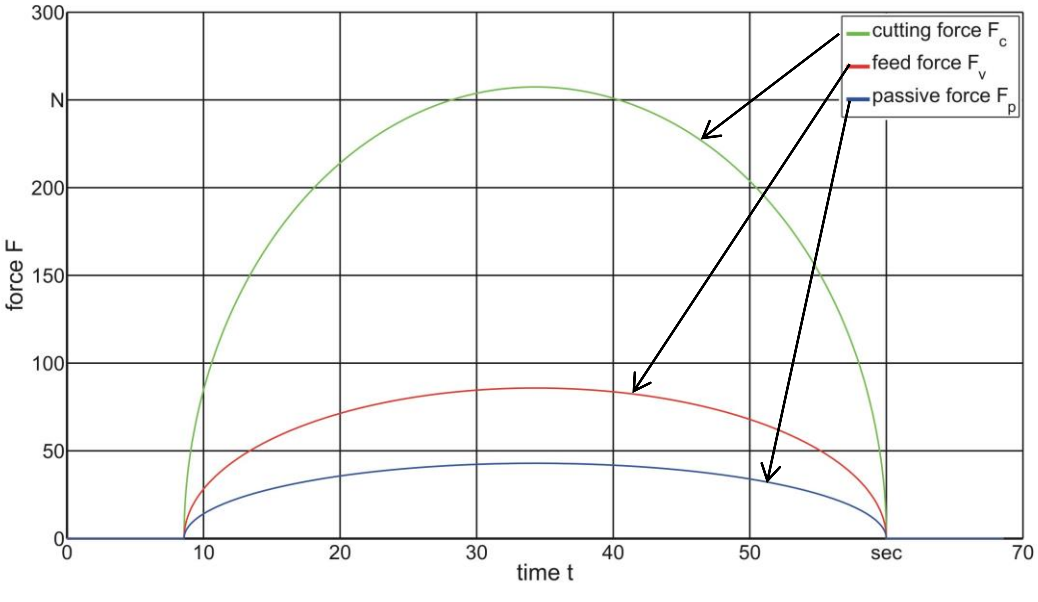

Fig. 3. Results of the analytic force calculation for sawing a round profile with a diameter of 60 mm (cutting speed 70 m/min, feed rate 70 mm/min) [4]

The characteristics of the forces are subjected to the geometry of the workpiece. The reason for that is the dependence of the cutting forces on the engagement length of the saw blade with the workpiece. This means that the cutting forces increase to a maximum value with rising contact length. After the maximum contact length is reached, the forces decrease until the end of the sawing process, as shown above for a round profile. For a rectangular workpiece, the characteristics of the forces rapidly increase at the beginning, then remain constant during sawing and rapidly decrease at the end of the cutting process. Only for the passive force the simulated behaviour is not correct. Due to the setting of the teeth, the average of the passive force during the sawing process must be zero because of the alternating effective direction of the force on the teeth. This shows the limitation of the analytical force calculation for the sawing process [4].

2. TEST BAND SAW AND MEASURING EQUIPMENT

The tests were performed on a horizontal band saw with an input power of 3 kW. For the measurement of the cutting forces, a specially designed three-component dynamometer was integrated into the workpiece clamping system of the test band saw. This dynamometer is able to measure the three orthogonal components of the resultant force F: the cutting force F_c in opposite direction of the cutting direction, the feed force F_v against the feed direction and the passive force F_p as the resulting vector vertical to the cutting plane. To decouple the forces from the structure of the machine, the workpiece is mechanically clamped onto the dynamometer as shown in Fig. 4. With this double-sided clamping system it is also possible to measure the reacting clamping forces in the clamping jaw [4].

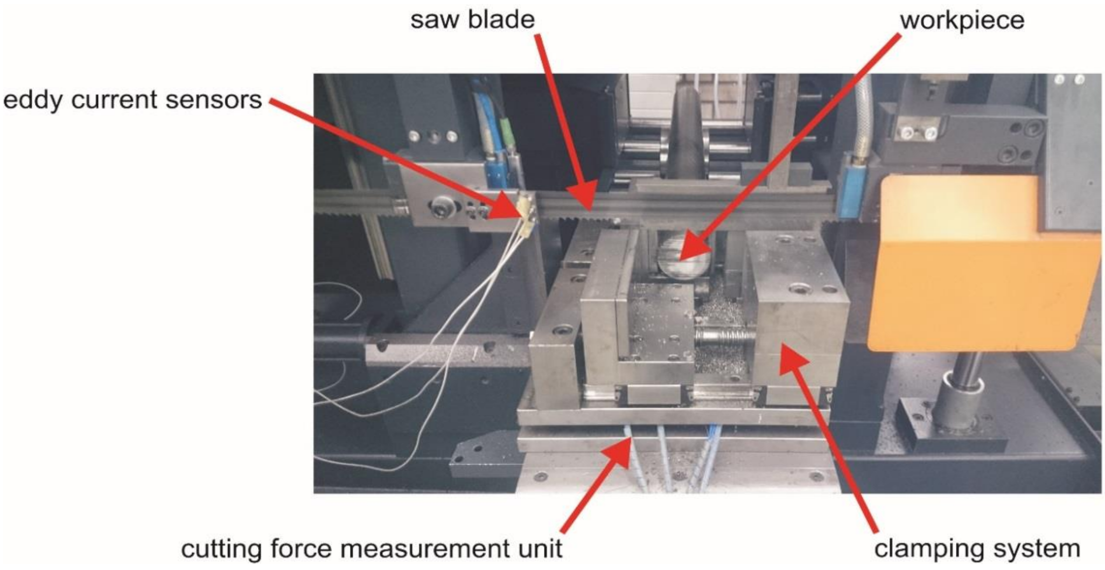

Fig. 4. Measuring system for the cutting forces and the twisting behaviour

The contactless measuring system for the twisting behaviour of the saw blade is designed with three eddy current sensors. These sensors are arranged in such a way that three vertically grouped positions can be measured over the saw blade height. The bottom position (sensor 3) is located just above the tooth depth, sensor 2 is positioned in the middle of the saw blade height, and sensor 1 is near the upper edge of the saw blade (Fig. 5). With this layout it is possible to measure the displacement over the whole saw blade height in one process at the same time. Apart from the inclination, the deformation of the saw blade can also be detected here. The sensor holder is mounted on the saw blade guides so that the sensors are moved together with the saw blade in the feed direction. The sensors were adjusted and calibrated with regard to the cutting plane with a stationary saw blade.

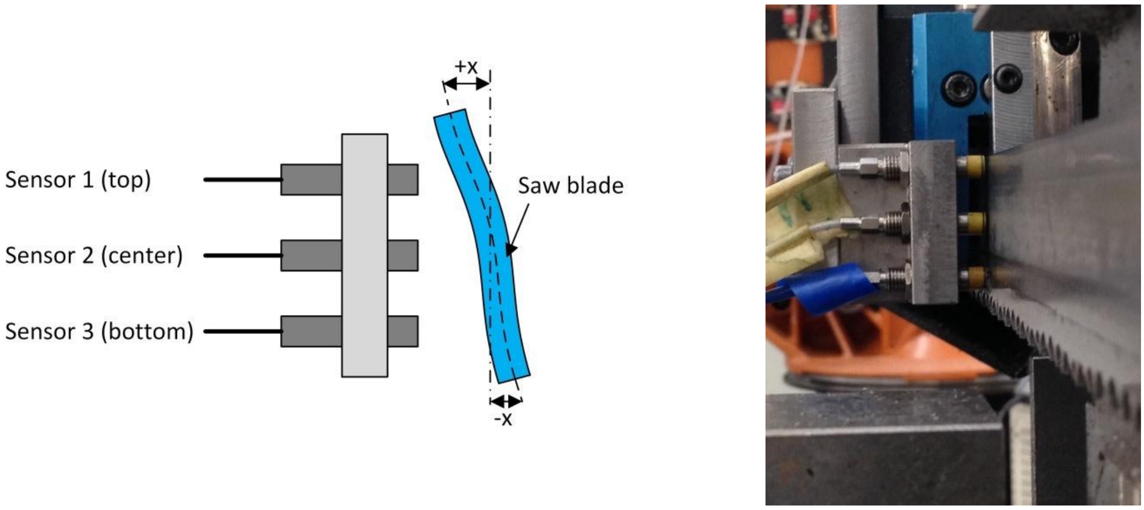

Fig. 5. Measurement principle with three eddy current sensors for the displacement of the saw blade

The measuring direction of the sensors is shown in Fig. 5. It is possible to measure the distance from the sensor to a magnetisable object by inducing eddy current up to a speed of 120 m/min. Another major benefit of using eddy current sensors is that the measuring result is not influenced by the lubricating film on the saw blade. Only the chips may produce a falsified measuring result. Hence preliminary tests were carried out to compare

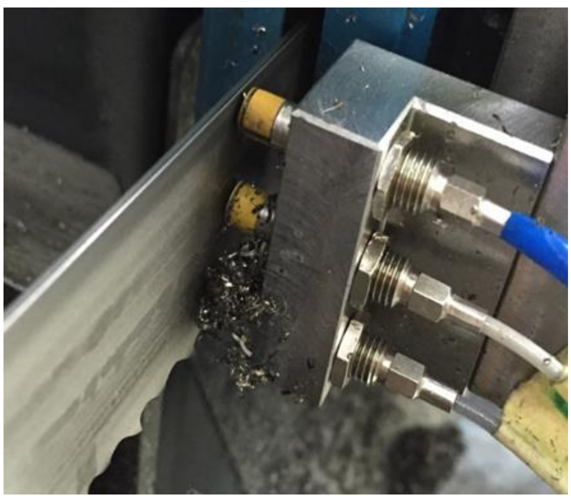

Fig. 6. Adhering chips at the sensors mounted onto the outlet side of the workpiece

the optimum position for the sensors, either on the inlet side of the workpiece or on the outlet side. The results indicated no significant differences in the measured displacement of the saw blade, but the chips adhere to the sensor on the outlet side, as shown in Fig. 6. After a while, the sensors give wrong signals because there are too many chips on the side of the sensor. For this reason the inlet side of the workpiece was chosen as measuring position for the sensors.

Another source of error can be derived from the distance between the position of the sensors and the cutting area. For the validation of this influence, several preliminary tests were performed with different sensor distances. Thus the cutting force measuring systems had to be removed from the band saw to vary the distance. The result shows no significant error due to the sensor distance as well as no different behaviour of the saw blade. The preliminary tests have demonstrated that the measurement principle is suitable to investigate the dynamic behaviour of the saw blade during cutting without any influence on the sawing process. In this investigation, the measuring setup is used to detect the behaviour of the saw blade during the cutting process for improving the bandsawing process, drawing special attention to the twisting in order to avoid a deviation of the saw blade.

3. EXPERIMENTAL INVESTIGATION AND RESULTS

The experimental tests were performed with a wide variation of the sawing parameters. Hence the cutting speed and the feed rate were not only adjusted to the recommended values for the material to be sawed but also to the extreme ranges of too high or too low parameters. This causes particularly unstable processes during sawing. The test material was 42CrMo4 alloyed steel with a diameter of 60 mm. The saw blades used were bimetallic for a standard use with three to four TPI and four to six TPI. The recommended cutting parameters for this combination of material and saw blade are a cutting speed of 80 m/min and a feed rate of 60 mm/min [5]. Due to the ductility of the 42CrMo4 material, the cutting speed shows a major influence on the wear condition of the saw blade and subsequently causes unstable processes so that the end of the tool life was reached very quickly. Fig. 7 presents the results for a sawing process with a constant cutting speed of 100 m/min and a feed rate range from 40 mm/min up to 100 mm/min. Every diagram shows the measured displacement for the three sensors throughout the process time. The start and the end of the cutting process can be clearly seen in all figures. The results show that the occurring displacement of the saw blade increases with rising feed rate. It is interesting that the directions of the measured displacement differ for the three positions of the sensors. Sensor 1 in top position near the upper edge of the saw blade always shows a positive displacement. This means that the edge of the saw blade moves towards the sensor (see schematic sketch in Fig. 5). By contrast, the displacement of the bottom position near the saw tooth shows an increasing negative displacement with growing feed rate. This is a movement away from the sensor. The measured results of the sensor in centre position are more or less between the displacement of the upper and lower positions. Another fact is that the signals show the same course of the values at the beginning of the sawing process.

Then the measured displacements drift apart. Especially the results for feed rates of 80 mm/min and 100 mm/min show a great displacement towards the end. This is confirmed by the observations made during the experiments. The sawing process is very unstable with these parameters and hence the cutting deviation was increased.

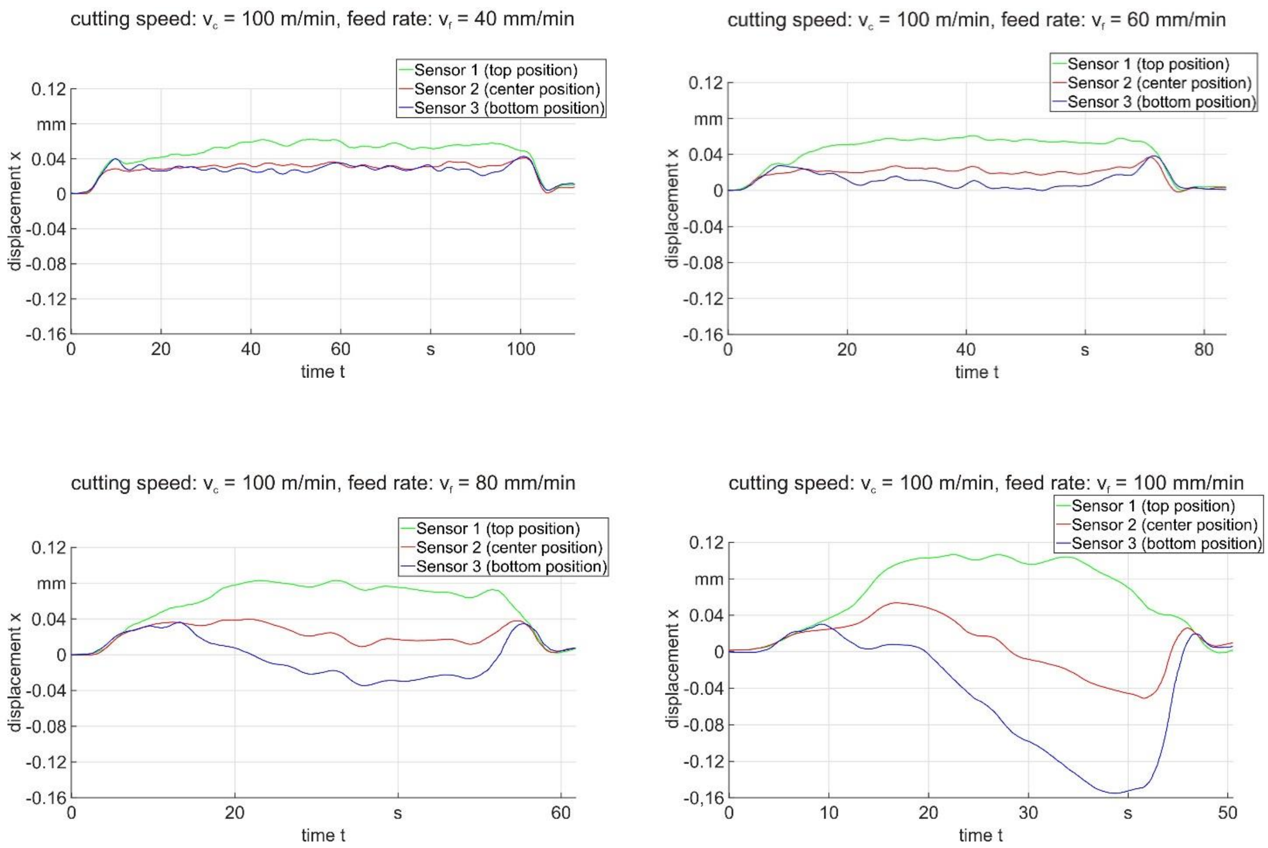

Fig. 7. Displacement of the saw blade on three positions for four different feed rates

In order to regard the twisting behaviour in accordance with the feed rate, the whole experimental data was evaluated in view of the maximum displacement values. Fig. 8 depicts the arithmetic mean of all measuring results for the maximum displacement *x* of the saw blade depending on feed rate. The diagram clearly shows that a stable process with a small displacement is possible at feed rates below 60 mm/min. With rising feed rate, the displacement greatly increases.

To illustrate the twisting behaviour in the kerf during sawing, a 3D representation of the measured results is presented in Fig. 9 for a feed rate of 100 mm/min. The diagram shows the same results as above, but the position of the sensor on the z-axis is given here in addition to the time t on the x-axis and the displacement x on the y-axis. With this presentation of the results, it is possible to understand the real movements of the saw blade during sawing. The differences in the twisting between the upper edge of the saw blade and the saw teeth can be seen especially at high feed rates, as mentioned above.

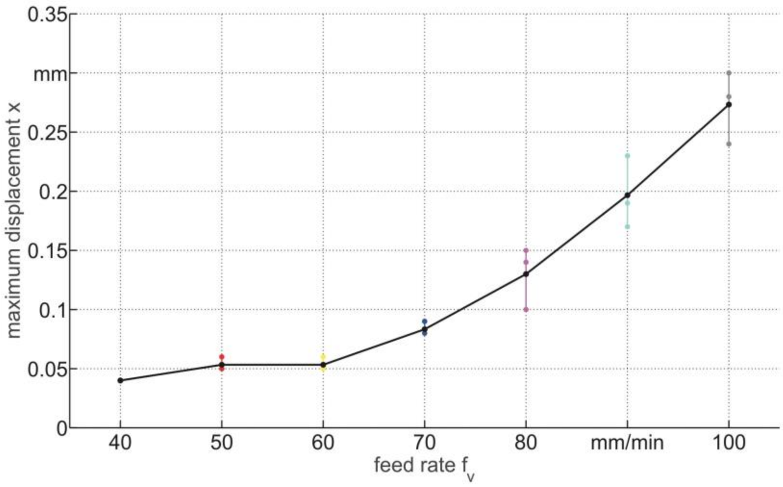

Fig. 8. Maximum displacement of the saw blade depending on feed rate

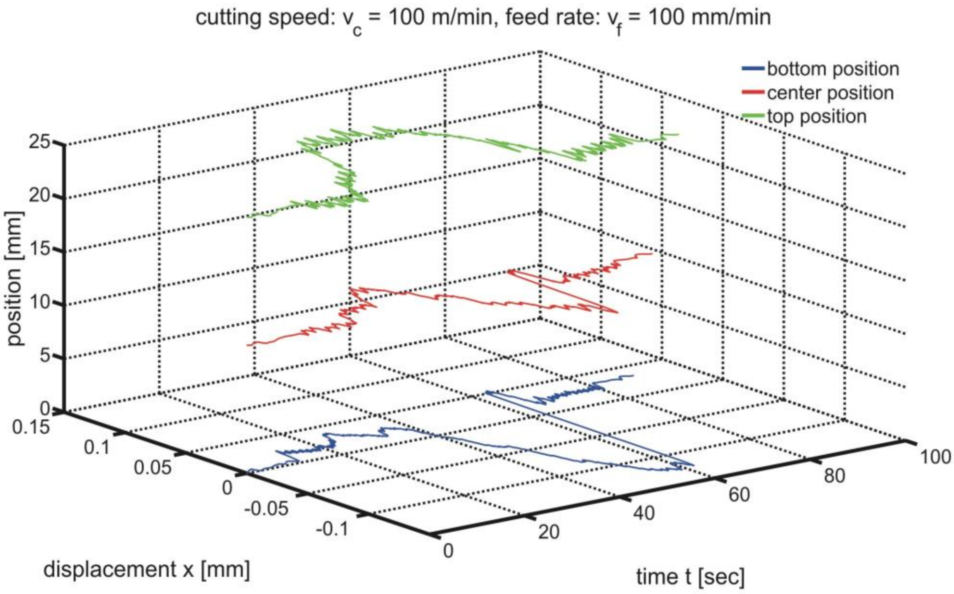

Fig. 9. Displacement of the saw blade in a 3D display

The described twisting behaviour is characteristic for the sawing process and depends on the feed rate v_f and the feed force F_v, as reflected in the results of this investigation. The influence of the cutting force F_c is negligible for the twisting behaviour, but the wear condition of the saw blade shows a direct correlation between the displacement of the saw blade and the instability of the sawing process. If the process conditions are good, the displacement of the saw blade is low and the manufacturing tolerance is less than 0.1 mm. With rising displacement of the saw blade, the cutting deviation rises and the manufacturing tolerance limit cannot be maintained any longer. Hence it can be assumed that a stable process is characterized by a maximum saw blade displacement of less than 0.1 mm. The displacement of the saw teeth is critical for this. Consequently, the position of sensor 3 near the tooth depth is relevant. For the described sawing process in this investigation, a feed rate over 80 mm/min generates an instable process as shown in the results above. As an extreme example, Fig. 10 shows a workpiece with a great cutting deviation due to a very unstable process with a great saw blade displacement. In extreme conditions, the cut follows the displacement of the saw blade and causes significant cutting losses.

Fig. 10. Side view of a workpiece with a great cutting deviation (steel grade: 42CrMo4)

Hence the evaluated correlation between the displacement and the process stability indicates the possibility to influence the process parameters during sawing to prevent a great cutting deviation. In the tests here, the process parameter of saw blade tension was held constant. But the results support the conclusion that a variation of the saw blade tension can lead to an improvement of the sawing process. Further investigations will be carried out to examine the influence of the saw blade tension on the twisting behaviour of the saw blade. In the following, a descriptive model is developed to explain this twisting behaviour.

4. MECHANICAL MODEL FOR THE TWISTING BEHAVIOUR

The results obtained indicate an explicit orientation of the twisting behaviour of the saw blade. The saw blade always twists in the same direction and that is against the twisting direction of the saw blade towards the cutting plane. The causes of this direction dependence are the saw blade tension, applied by the mechanical tensioning system, and the required rotation of the saw blade towards the working plane by the saw blade guides due to the geometry of the saw frame. Fig. 1 shows this kinematic correlation. The twisting behaviour of the saw blade in the kerf can be explained by the underlying assumption that the passive force F_p depends not only on the process forces but also on a reaction of the impact of the stress state in the cross-section. This typical stress state of the saw blade is a superposition of the saw blade tension and the twisting of the saw blade towards the working plane. The saw blade tension causes a tensile strength σ_t, whereas the twisting of the saw blade generates a torsional stress τ_T. This stress state causes an anisotropic behaviour of the saw blade in the kerf. Fig. 11 shows a tension model of the stress state in the cross-section of the saw blade. The saw blade tension force F_{BT} is applied by saw blade tension system. On the other hand, the twisting of the saw blade towards the cutting plane causes a torsional moment T, which is the reason for the torsional stress τ_T in the cross-section of the saw blade.

In idle mode, the stress state in the cross-section is balanced and the saw blade is in the vertical cutting plane. Only under the impact of the process forces, the reaction forces cause an imbalance and the saw blade twists. The reaction forces F_R, which influence the twisting,

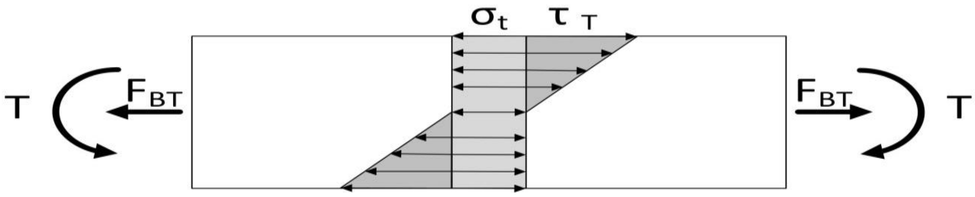

Fig. 11. Tension model of the stress state in the cross-section of the saw blade

act against the twisting direction of the saw blade towards the cutting plane as shown in Fig. 12. Simultaneously, the feed force pushes against the saw teeth and increases the twisting reaction of the saw blade. Hence the twisting behaviour is more or less linearly dependent on the feed force F_v and the feed rate v_f during the process.

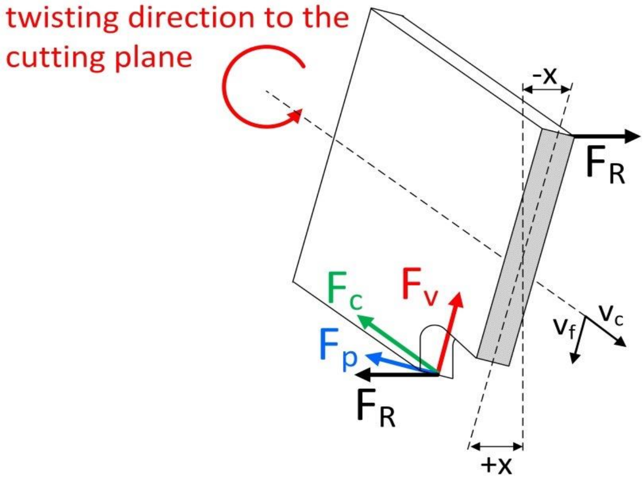

Fig. 12. Reaction forces F_R on the saw blade depending on the twisting and the feed force F_v

The reaction force F_R acts especially on the teeth in the kerf, and thus also the measured passive force F_p is increased. Hence the test results show a direction dependence of the passive force F_p. The mean passive force is theoretically about zero without any preferred direction. The conclusion of this theoretical model for the twisting behaviour is that the correlation between the occurring displacement of the saw blade and the generated passive force F_p can be used for evaluating the process stability.

5. INFLUENCE OF THE WELD SEAM

Using the described measurement principle, it is possible to investigate other effects on the sawing process. A periodical peak at a low frequency can be observed in every force measuring result. It may be supposed that the weld seam of the saw blade generates this oscillating impulse at every engagement in the kerf. The saw blade is butt-welded to an endless blade, and the weld seam is polished afterwards. Nevertheless, the area around the weld seam has different surface properties as the rest of the saw blade. This effect has not been investigated within a scientific context until today. The signals of the three eddy current sensors are measured at a high temporal resolution. An enlarged section of the signals for three different cutting speeds is shown in Fig. 13. The periodical peak can be clearly seen in all three graphs.

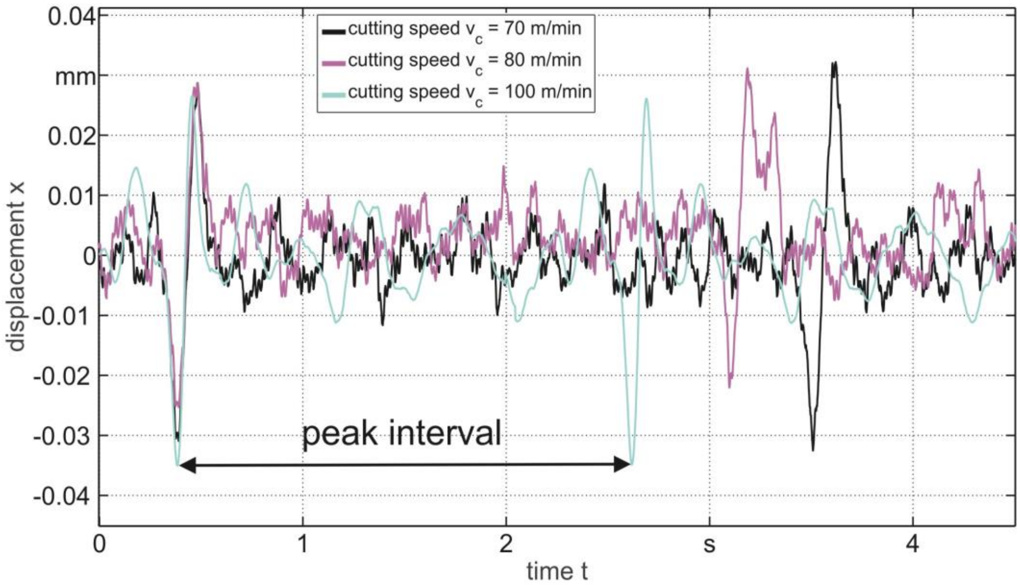

Fig. 13. Influence of the weld seam for different cutting speeds

The structure of the area around the weld seam is measured with a laser vibrometer to analyse the height differences of the weld seam in relation to the saw blade. The results correspond with the amplitude height of the peak in the sensor signal. The time interval between two peaks in the graph can be measured within the signal, as shown in Fig. 13. The cutting speed vc can be calculated with the overall length of the saw blade l in mm and the time t for a single saw blade rotation in seconds, using the following equation:

$$v_c = \frac{l \cdot 60}{t \cdot 1000} \tag{1}$$

The overall length of the saw blade is 3950 mm in these tests. For a cutting speed of 70 m/min, the time of a single saw blade rotation is 3.38 s. The measured peak interval for this cutting speed is 3.13 s. This suggests that the periodical peak is really generated by the impact of the weld seam in the kerf. The analysis of the peak interval for the different cutting speeds reveals that the time difference between one peak and the next one is equivalent to one single saw blade circulation. Table 1 shows the results of this evaluation for the signals described above.

Table 1. Comparison between the adjusted cutting speed and the measured cutting speed

adjusted cutting speed [m/min]	saw blade circulation time [s]	peak interval [s]	calculated cutting speed [m/min]	difference [%]
70 m/min	3.38 s	3.13 s	75.7 m/min	8.2 %
80 m/min	2.96 s	2.73 s	86.8 m/min	8.5 %
100 m/min	2.37 s	2.23 s	106.3 m/min	6.3 %

This effect of the weld seam in the measured signals makes it possible to compare the effective cutting speed during the process with the adjusted cutting speed in the control of the band saw. These results also enable a process-orientated monitoring of the sawing process in order to control the cutting parameters online.

6. OPTIMIZATION

Knowing the twisting behaviour of the saw blade in the kerf helps to analyse the optimization potentials for the entire sawing process and sawing machines in general. This investigation gives possible starting points for a process-orientated monitoring system for the control of band saws to optimize the cutting process. The most advantageous is the easy method for monitoring the twisting of the saw blade with a distance sensor to identify the process condition during cutting. For one thing, it is easy to integrate this type of sensor into the structure of the machine. On top of that, the quality of the signals is sufficiently precise. The main task for the design of the control is to find the correlation between the cutting forces and the displacement of the saw blade. This investigation has laid the foundations for this development. The aim of further investigations is to clarify this correlation in order to implement a reliable online prediction method for the stability of the process.

Another aim of this investigation is to further develop the analytic force calculation for the sawing process. Especially the current limits for the calculation of the passive force F_p may be overcome with the results of this investigation. Identifying the occurring displacement of the saw blade can be used to evaluate the stress state in the cross-section, and hence the reaction forces can be calculated. This result can be adapted to the formula for the passive force so that it fits into the analytical model for the cutting force simulation.

7. SUMMARY

The challenges for the optimization of manufacturing processes have to be seen alongside the effort of capturing the process data for the handling in the control system of the machine. The main task of this kind of development is particularly to find a correlation between the stability of the process and the occurring forces during cutting. To optimize the sawing process with band saws, a measuring system has been presented in this paper for analysing the twisting behaviour of the saw blade during sawing. The research results show the potential that an indirect measuring method offers for the monitoring of the process stability. Hence the displacement of the saw blade during sawing was measured with eddy current sensors at specific positions on the saw blade. It has been proven that the twisting behaviour of the saw blade directly correlates with the cutting forces, especially the feed force occurring during sawing. In addition, the supposed direction dependence of the twisting behaviour of the saw blade was confirmed. Hence a mechanical model was developed to identify the influence of the twisting on the passive force during sawing. Apart from the possibility to investigate other effects on the sawing process with the described measuring method, it was shown as an example how the weld seam influences the saw blade. This knowledge is the starting point for further investigations to develop an online monitoring system for the control system of the band saw to optimize the sawing process. Furthermore, the results are used to improve the analytic cutting force model with regard to a precise simulation of the cutting forces during sawing.

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