Journal of Machine Engineering, Vol. 12, No. 1, 2012

band sawing, cutting forces,
condition monitoring, tool wear, chatter

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CHARACTERIZATION OF BAND SAWING BASED ON CUTTING FORCES

Band sawing is one of the most efficient methods for which in general it is known that uneven tool wear, chatter and cutting blade defects can affect cutting performance significantly. A data acquisition system was arranged on an industrial band saw machine in order to characterize the band sawing process based on measurements of forces. In this paper, the cutting force signals are analyzed in order to demonstrate important relations to workpiece and cutting blade properties. It is shown that cutting forces contain information about inhomogeneity of a cut workpiece. Signals of cutting forces also reveal important properties of blade geometry that is related to uneven blade wear. Discontinuities such as blade welding are clearly evident in force signals and it is shown that unevenness of blade backing geometry can cause a significant variation in forces due to wedging between the workpiece and a blade support. An original method for blade shape extraction from force signals is presented in detail. Paper also reports on chatter phenomena observed at specific cutting conditions. Possible solutions to the addressed problems and phenomena are discussed in the conclusion.

1. INTRODUCTION

Band sawing is one the most economical cutting processes in industrial machining due to low waste material production and low consumption of subsequent energy. It is one of the best possibilities of cutting large workpieces (more than 1 m width) hence the importance of band saw metal machining has been increasing considerably in the last twenty years. Although band sawing is an important and economical industrial process some answers to band saw machining problems have not been provided yet. In realistic industrial large-scale production of ball bearings, only one millimeter of saved material per cut at 14 million cuts per year means 14 kilometers of bars saved per year. Amount of extra material removed by subsequent machining presents considerable cost and depends on surface finish of the cut and on planar accuracy (geometrical tolerance) of the machine.

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Ahmad et al. [1] reported on importance of workpiece geometry and band saw parameters on the performance of the band saw cutting process. It was shown that machine parameters and workpiece shape have a considerable effect on cutting forces and surface finish. In 2009 Sarwar et al. [2] reported on measurements of specific cutting energy for different materials and different workpiece geometries. It was shown that stainless steel, a difficult-to-machine material, has a much greater cutting energy required per volume material removed than an easy-to-cut material such as ball bearing steel. It was also shown that a blade can only receive a certain amount of energy (not specific) before wearing out and the amount is approximately the same for a difficult-to-cut and for an easy-to-cut material. It is expected that machine parameters have a significant role in wear results. Currently there are no scientific papers on methodology for optimal cutting performance of a band saw machine.

Band sawing as well as milling simultaneously engages more than one tooth in cutting hence however there are very few similarities between the two processes. Andersson et. al. [3] was the first to report on relationship between positional errors, tool wear and cutting forces in band sawing. Much more attention with regard to analysis of cutting forces was dedicated to milling and some ideas can also be implemented in the case of band sawing. In 1998 Lee et al. made statistical analysis of cutting force ratios for flank wear monitoring in precision machining with the aid of artificial neural networks [4].

Wear and failure modes during cutting of ball bearing steel were studied in 2005 by Sarwar et al. [5] where it was concluded that most of the wear on the band saw teeth is caused by abrasion of the tooth flank as well as adhesion-abrasion of the tooth tip. Predominant cause of tool failure in that case was out-of-square cutting or tapering caused by excessive tooth flank wear. Cutting forces were observed in the research and it was shown that both thrust and cutting force increase with blade wear however the rate of increase is different for each of them hence the tool wear can be monitored through cutting forces. Söderberg et al. [6] showed dependency of wear on metallurgical properties of the tool in band sawing.

Wear progresses greatly when chatter occurs during machining therefore some research in band sawing was dedicated to chatter vibrations. Theoretical lateral and torsional models for a simplified band saw were derived in 1965, 1967 and 1978 by Mote [7], Alspaugh [8] and Ulsoy [9] respectively in order to predict natural vibrations of a band saw. In 1990 Yang et al. [10] showed some methods for blade vibration suppression. Okai et al. [11] and Le-Ngoc et al. [12] reported on self-induced vibrations and connected process parameters to wash-boarding phenomena in band saw cutting of wood. Wash-boarding was first reported in 2003 on cutting aluminum workpieces by Gendraud et al. [13]. Other cutting phenomena like tooth chipping was also reported on sawing steel by Chandrashekaran et al. in 2008 [14].

State-of-the-art in band sawing research currently addresses self-induced vibrations and recognizing effects on sawn surface. Natural frequencies that are closely related to self-induced vibrations of a moving band saw under simplified conditions can be predicted and thus chatter can be avoided or greatly reduced. Cutting forces and relations to workpiece shape and cutting parameters were reported as early as 1988 [1]. Relations of tool wear and cutting forces were reported in 2005 [5] and later in 2009 [2] measurements of specific cutting energy were suggested as tool wear monitoring application.

This paper addresses online monitoring and characterization of band sawing process based on cutting forces. Cutting forces reveal workpiece geometry, general material and blade effect in the process. Tool wear is the effect of cutting forces therefore it is important to recognize causes of the wear. In the present research a novel approach to identification of cutting force dynamics is presented and related to blade effect that correlates cutting force variations with blade geometry.

2. EXPERIMENTAL SETUP

2.1. MACHINE SETUP

Experiments were conducted on a double column PE-TRA Toolmaster 300DC band saw of 300 mm maximum cutting width capacity (Fig. 1). The blade is tensioned at approximately 2.0 kN. The speed of the blade is controlled by a frequency converter through a potentiometer on the front panel of the machine. Thrust force needed for the down feed of the blade is provided by the mass of the machine frame and down feed speed is manually regulated through a continuous valve. During cutting none of the hydraulic systems participate in the process, which assures a steady and continuous down feed. Fig. 1 represents the multisensory experimental setup used in the research with all the electronics in the electric cabinet.

Fig. 1. Multisensory dual column band saw machine used in the research

2.2. MEASURING EQUIPMENT

The band saw was equipped with a number of sensors for a complete characterization of the band sawing process. A Kistler 9257B 3-dimensional dynamometer was mounted on cutting Tab. of the machine and charge signal was amplified by a 4-channel charge amplifier (Kistler 5019A). All sensor signals were acquired by a National Instruments NI DAQ 9188 chassis and appropriate analog input modules into a data structure with all known material, tool, lubricant and other information for further analysis. Custom software with a graphical user interface (GUI) was developed in order to acquire, present and manipulate detected signals.

2.3. WORKPIECE AND BLADE PROPERTIES

Workpiece profiles used in the present research have properties shown in Table 1. Workpieces were cut in 2-3 mm length from a 300-400 mm long bar or tube. Fig. 2 shows the workpieces after cutting.

Table 1. Workpieces' properties.

Property	Square full	Square hollow	Round full	Round hollow
Dimensions [mm]	40 × 40	40 × 40/2.5	Φ40	Φ40/27

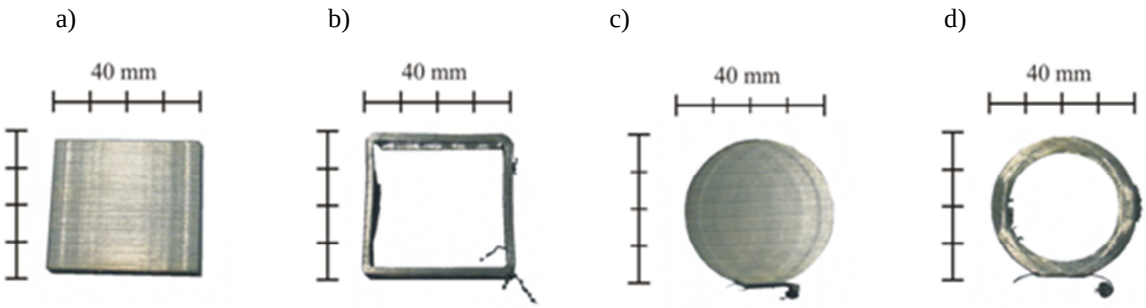

Fig. 2. Examples of workpiece cross-sections after cutting: a) Square full 40×40 mm, b) Square hollow 40×40 mm, c) Round full Φ40 mm, d) Round hollow Φ40/27 mm

Tab. 2 presents cutting blades' properties used in the experiment. The key differences between the two blades are the tooth pitch and the rake angle of the two blades. Blade 1 has a pitch of 4-6 teeth per inch while blade 2 has a pitch of 3-4 teeth per inch. Rake angle of the first blade is 11° while rake angle of the second blade is 10°.

Table 2. Blades' properties.

Property	Blade 1	Blade 2
Manufacturer	Håkansson AB	Rix Sägen-Mehring GmbH
Type	PCVII Commander	Formula SPF
Teeth pitch [teeth/inch]	4 – 6	3 – 4
Width/thickness [mm]	34/1.1	34/1.1
Loop length [mm]	4150	4150
Rake/clearance angle [°]	11/32	10/32
Teeth material	M42	M42

2.4. TESTING PROCEDURE

Experiments were performed on four different workpieces with two blades each three times for force analysis. All cuts were performed at the same parameters. The workpiece was mounted on the Kistler 9257B dynamometer with a vice at 20 mm from the blade. Band saw drive unit was started and set to constant cutting speed v_c = 75±0.5 m/min. The down feed force is provided by the mass of the machine: Opening the down feed valve to a preset value sets the down feed which was held constant during the experiment, v_f = 1.25±0.1 mm/s. At the beginning of a cut, measurement was triggered manually from the machine control panel and the trigger signal was sent to the personal computer (PC) where data acquisition was started. During the cut, parameters (input voltage, cutting fluid, etc.) were held constant. The measurement was stopped automatically by an end switch. Described procedure provided raw data for subsequent offline analysis.

3. ANALYSIS OF CUTTING FORCES

Previous research by Ahmad [1] showed that workpiece geometry has a significant role in machining with a band saw. In the present research some new aspects of force analysis with respect to workpiece and blade geometry are reported.

3.1. WORKPIECE EFFECT

Effect of a workpiece was studied on different profiles shown in Fig. 2. Cutting force signal sampled at 2 kHz contains low frequency components that reflect a characteristic shape of a workpiece, and a superposed higher frequency component that corresponds to blade effect (described in section 3.2 An example of cutting forces - cutting component (F_x), thrust or feed component (F_z) and lateral or drift component (F_y) - is shown in Fig. 3. Force signals are presented in Fig. 3a where higher frequency component of the peak forces that appear due to blade geometry are clearly visible. The filtered low frequency component of the signal reveals geometry of the workpiece (Fig. 3b) and material inhomogeneity. The latter is clearly visible between seconds 15 and 25 where cutting forces reach a minimum. Periodical peaks can be seen on the force signals and are a result of a discrete discontinuity at the weld of the blade. They are discussed later in the section on the blade effect.

a) b)

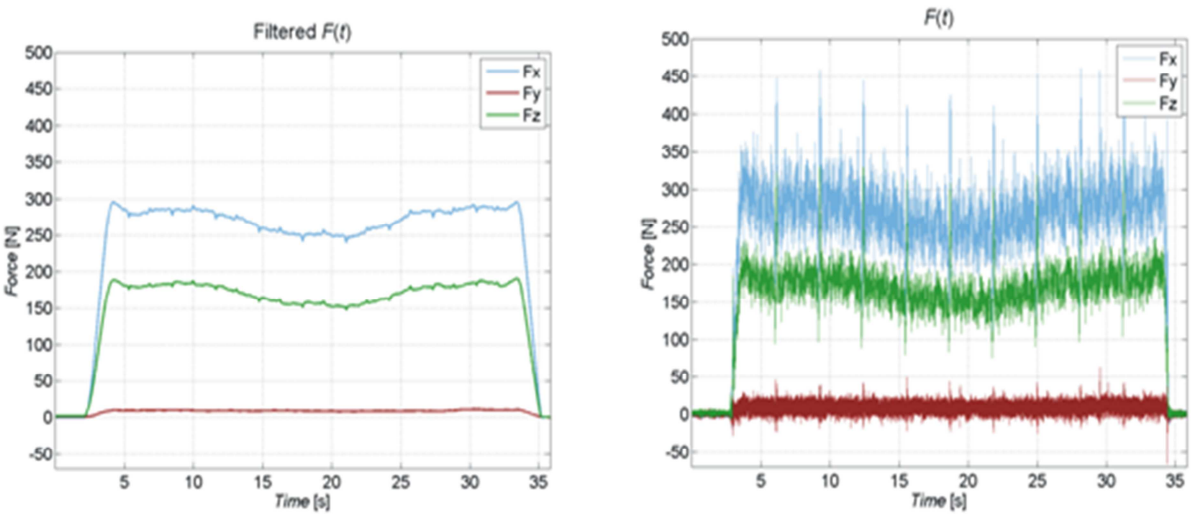

Fig. 3. Raw and filtered cutting forces on a square 40×40 profile:
a) filtered signals, b) raw signals

Fig. 4 shows examples of cutting force (F_x) signals on a rectangular full (Fig. 4a), rectangular hollow (Fig. 4b), round full (Fig. 4c) and round hollow (Fig. 4d) workpiece profiles respectively. The general shape of the signal is characteristic for each profile and depends on the width and material properties of a profile at given constant preset machine parameters. Considering that material is the same for every workpiece (except for the workpiece with inhomogeneous material), only the workpiece shape defines the general shape of a force signal.

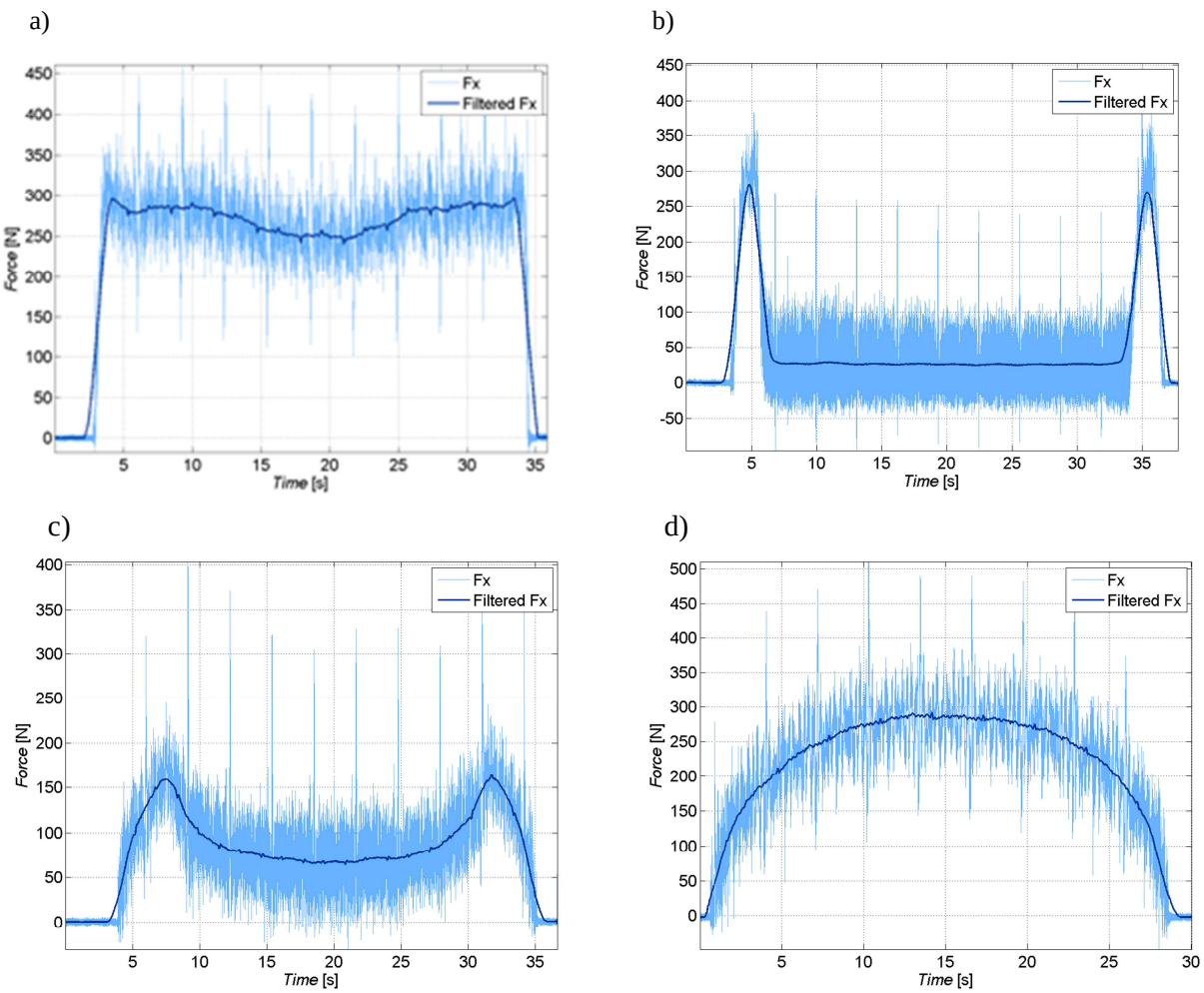

Fig. 4. Cutting force signals (F_x) of the workpieces shown in Fig. 2:
a) Square hollow 40×40 mm, b) Square full 40×40 mm, c) Round hollow □ 40/27 mm, d) Round full □40 mm

Figure 4a is an example of a cutting force (F_x) signal on a full rectangular 40×40 mm workpiece. The beginning of the signal has a steep rise because the entire width of the profile is cut in a short time, that is the time of the force rising. The middle section of the signal shows gradual descend that has a minimum at approximately 20 seconds. Analysis of material hardness was performed on the cut workpiece and it was shown that the descend is a consequence of material inhomogeneity. During the production process the crust of the workpiece was cooled faster than the core thus crystal structure and subsequent hardness of the material has a gradient characteristic as shown in Fig. 5.

Figure 4b shows an example of force signal on a hollow rectangular 40×40 mm profile with wall thickness of 2.5 mm. The force has a steep rise at the beginning and the end due to the same reasons as in the full profile. In the middle of the cut (seconds 6 to 34) there is slightly more vibrations present because of the slenderness of the profile hence the workpiece has a tendency to vibrate at the frequency of the teeth entering the workpiece.

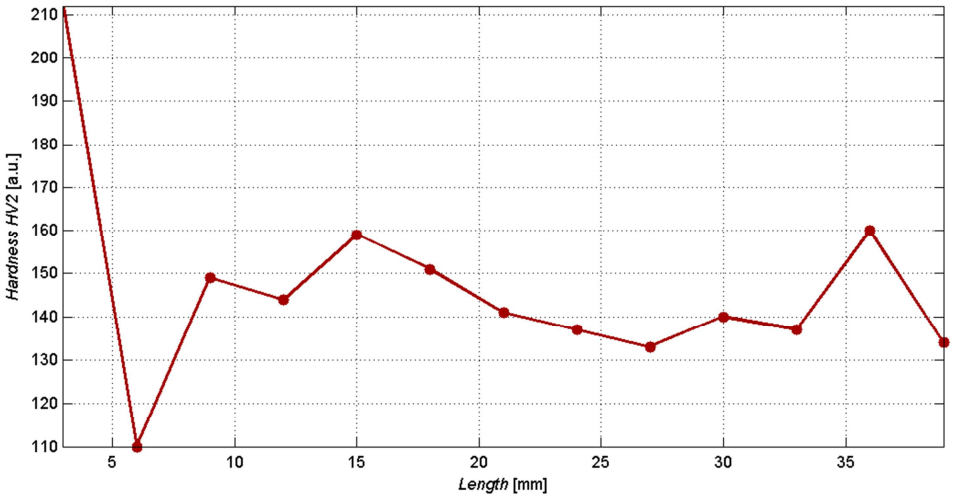

Fig. 5. Hardness profile of the 40 × 40 mm full profile

Figure 4c shows an example of force signal on a full round workpiece with a diameter of 40 mm. The force has a gradual concave low frequency component due to the workpiece shape and it reaches maximum at the maximal width of the workpiece, that is in the middle. The signal is not purely symmetrical because of the different relative angle of teeth entering the workpiece before the middle and after the middle section. Before the middle section, teeth are entering at positive angle while near the middle section (depending on the blade rake angle) the angle shifts to negative, which gives a slight increase in the cutting (X) component of the force. Asymmetry is very subtle (also depending on the width of the workpiece) but the effect of the angle of attack can affect the shape of the force profile. Fig. 6 shows relative angle of attack for the three observed instances on the round workpiece.

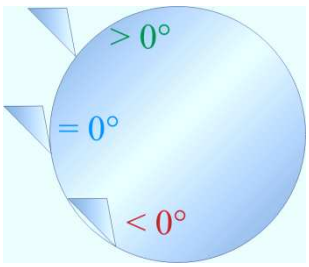

Fig. 6. Relative angle of attack between workpiece and blade with respect to height

Figure 4d is an example of a force signal on a hollow round workpiece with a 40 mm diameter. The force has a gradual rise until the maximal width of the cut that occurs at the breach of the inner wall. The vibrations are slightly higher because of the same reasons as in

the square thin walled profile (Fig. 2b). The force signal is not symmetrical due to different angles of attack with respect to height above and below the middle section. Again the point of negative-positive angle of attack change depends on the blade rake angle.

Comparison of cutting force F_x and feed force F_z reveals important information about blade wear. In order to obtain this information we define ratio of cutting forces, r_{xz} as follows,

$$r_{xz} = \frac{F_x}{F_z}. \tag{1}$$

During cutting, force ratio r_{xz} is approximately constant for arbitrary combination of cutting parameters thus the force ratio is a characteristic feature of blade wear. Fig. 7 shows that the force ratio r_{xz} is decreasing with increasing blade wear. Consequently properly filtered force ratio can be applied as a blade wear indicator.

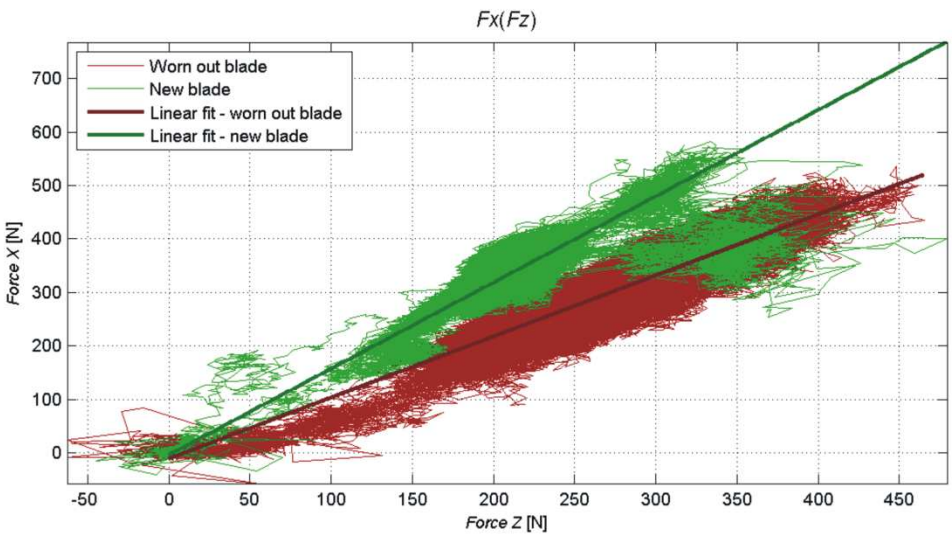

Fig. 7. Characteristic force ratio r_{xz} for tool wear on worn out and new blade

4. BLADE EFFECT

Dynamics of cutting forces has a considerable effect on blade wear since cutting forces are the cause of the blade wear. The back of any blade has a distinct waviness due to the production process of the blade itself and a distinct discontinuity usually at the blade weld.

In this section the dynamics of cutting forces is related to blade geometry and discussed with respect to blade wear.

We propose a novel procedure for the purpose of blade geometry extraction from the cutting force signals. To demonstrate the procedure, a 60×100 mm rectangular workpiece

was cut at 75.0±0.5 m/min blade speed and 1.25±0.05 mm/s average down feed speed with two different blades. The procedure for the blade geometry analysis based on cutting (F_x and thrust (F_z) forces is explained in the following steps:

1. MARKERS: Markers specify the beginning and the end of one blade pass through the workpiece. Raw force signal is smoothed with moving average filter with span of n = 100 data points in order reliably detect markers. Markers are located on the filtered cutting force signals as local maxima (shown in Fig. 8).

Profiles in Fig. 9 show that blade backing has a strong influence on the dynamics of the cutting force. At the point of the weld a large peak force is observed on both blades at the normalized thrust force magnitude of 1.27 and 1.15 for blades 1 and 2 respectively.

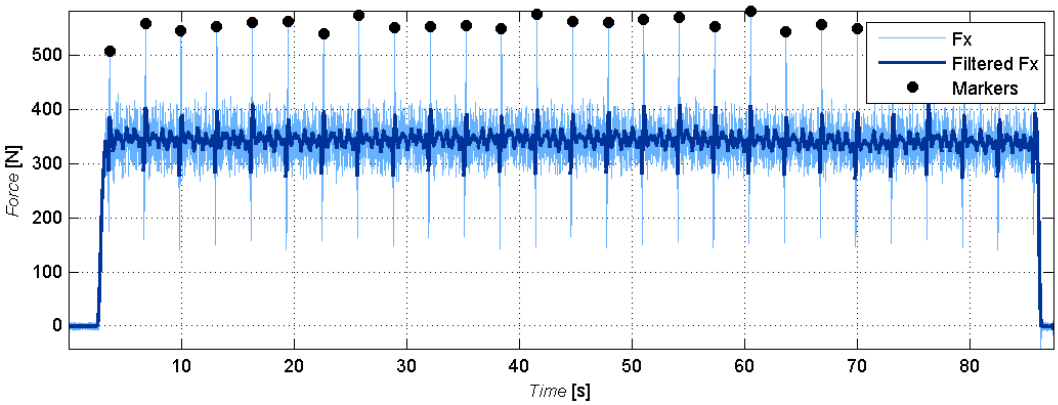

Fig. 8. Original raw cutting force signal for blade geometry characterization with markers shown

2. SMOOTHING: Signal part that describes blade backing geometry is obtained by filtering raw force signals with a smoothing filter with a span of

$$n = f_s t = f_s \frac{l}{c}, \tag{2}$$

where n is the number of data samples in span of the moving average, f_s is the sampling frequency of the force signal measured in [Hz]. For the experiment at hand the sampling frequency was f_s = 2 kHz. Time in the equation is represented by t and is measured in seconds, length between centers of the blade supports is denoted as l and is measured in meters. During the experiment the span between the two blade supports was 0.22 m and c is the speed of the blade in meters per second (n = 350 for our experiment).

Argumentation for the selected approach is that blade acts as a wedge between the support and the workpiece thus both supports act simultaneously on the workpiece as the wedge is driven into the opening. This filtering approximately reveals blade backing geometry.

3. SEGMENTATION: Based on the locations of the markers, the smoothed force signal (step no. 2) is segmented into segments that match exactly one length of the blade.
4. NORMALIZATION: Each segment is normalized by its mean thrust force (F_z) as shown in equation 3 since the thrust force is the "cause" and the cutting force (F_x) is the "effect". Normalizing minimizes effect of material inhomogeneity thus geometry becomes more apparent.

$$f_n(x) = \frac{F_n(x)}{E[F_{zn}(x)]}; \qquad n = 1,2,\dots,N, \tag{3}$$

The symbols in Equation 3 denote:

$f_n(x)$normalized force signal with respect to blade coordinate on the n-th segment, $F_n(x)$ true force signal measured in newtons (N) on the n-th segment, $E[F_{zn}(x)]$ mean value of the thrust force signal of one period on the n-th segment, and x blade coordinate measured in millimeters ($0 \leq x \leq 4150$ mm).
N is the total number of segments and n is the index of n-th segment.

1. GEOMETRY EXTRACTION: the blade geometry is finally extracted from normalized segments by calculating the median profile. This profile corresponds to blade geometry where waviness of the profile reveals geometric variations of the blade. Overlaid normalized segments with the median profile are shown in Fig. 9.

a) b)

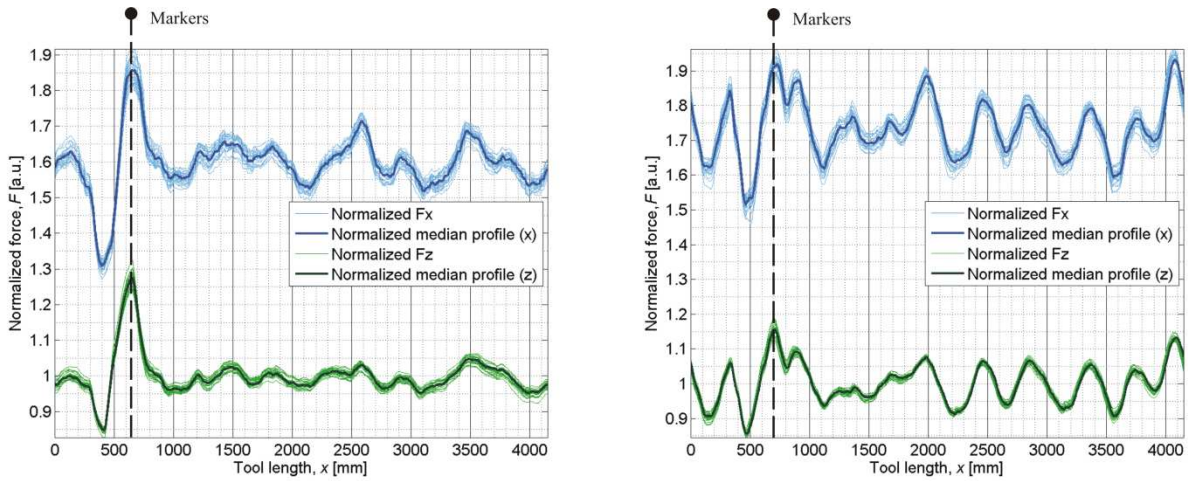

Fig. 9. Comparison of two different blades' force profiles obtained at the same cutting parameters: a) normalized geometry of blade 1, b) normalized geometry of blade 2

The rest of the backing shows some effects of blade production and it appears to be quasi-periodic. This likely corresponds to milling operation on the blade production line. The blade geometry analysis shows that blade is not loaded evenly throughout the entire

length. The uneven loading results in uneven tool wear and thus early tool failure. Localized peak forces are the probable cause of excessive localized tool wear.

5. CHATTER

Beside the blade effect that results in increased local tool wear, a chatter effect was also observed at specific cutting conditions. Band sawing the 40×40 mm square hollow profile revealed a window of very high force oscillations which are related to self-induced vibrations. Fig. 10a shows the corresponding force signal F_x and its spectrogram. Chatter is clearly evident between seconds 2.8 and 4.9 on force diagram ($F(t)$) and force spectrogram ($PSD(f,t)$). Power spectral density (PSD) of the force signal is emphasized at some characteristic frequencies only when chatter occurs (Fig. 10).

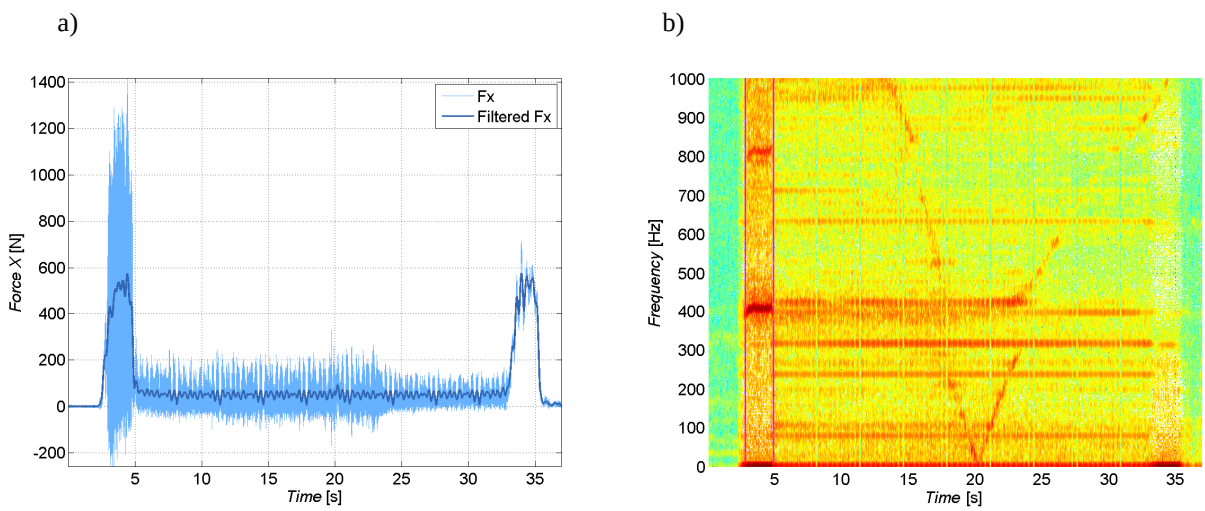

Fig. 10. Cutting force signal (F_x) and corresponding spectrogram indicating chatter on a 40×40 mm hollow profile: a) Force signal on a 40×40 mm square hollow profile, b) Force spectrogram shows some emphasized frequencies

Preliminary experiments showed that the chatter phenomena are even more evident in sound signals acquired by a microphone attached near the workpiece, therefore future work will be directed toward multisensory chatter detection methods.

6. CONCLUSIONS

In our research characteristic force signals were observed for different shapes of workpieces and some material inhomogeneity was observed on a 40×40 mm square profile.

Correlations between force variations and blade geometry were observed therefore we propose a novel method for extraction of geometry of the blade based on analysis of band saw cutting forces. The method consists of several signal processing steps, including detection of blade markers, smoothing, segmentation, normalization and blade geometry extraction. The result of the proposed procedure reveals blade geometry where waviness of the extracted force profile corresponds to geometric variations of the blade.

The large force variations caused by the wedging and sharp discontinuities at the weld are the probable cause of uneven tool wear during the band sawing process. Localized tool wear is expected to be the consequence of local force peaks along the length of the blade. It can be expected that more precisely built or ground blades would reduce force variations and thus result in more even wear throughout the blade which would extend tool life. Especially peak force reduction is expected to considerably extend tool life.

Additional experiments on a hollow 40×40 profile at specific process conditions revealed presence of chatter phenomena. Chatter was detected in the cutting force signal and it was shown that spectrogram contains some characteristic information about the phenomena. Since chatter can cause damage to tool, machine parameters should be adjusted to avoid chatter.

Future work will be directed toward early detection and online monitoring of tool wear and its correlation to the local peak forces along the blade length. Multisensory chatter detection methods will be explored with focus on robust online chatter detection during the band sawing process. The perspective of successful chatter detection is to design and implement an adaptive mechanism for online chatter suppression on a band sawing machine.

Another area open for research is minimization of peak forces during band sawing by an active or passive machine element with the aim to maximize tool life and thus improve economy of cutting.

ACKNOWLEDGMENTS

Operation partly financed by the European Union, European Social Fund. Operation implemented in the framework of the Operational Program for Human Resources Development for the period 2007-2013, Priority axis 1: Promoting entrepreneurship and adaptability, Main type of activity 1.1.: Experts and researchers for competitive enterprises.

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