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The influence of mill scale on horizontal bandsawing of 1.2312 steel: Wear, forces and vibrations

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A R T I C L E I N F O

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A B S T R A C T

There is a gap in machining literature concerning the cutting of workpieces that carry mill scale on their surface. In this work, we aspire to close this gap for the horizontal bandsawing process. For this, extensive wear tests for 1.2312 steel are conducted. The influence of the presence of mill scale on wear thrust force and vibrations is studied. Additionally, the impact of reducing bandsawing parameters only while cutting through the mill scale layer is studied. The presence of mill scale shows a dramatic increase in wear, thrust force and vibration. That impact can be somewhat reduced solely by deploying said local parameter reduction.

1. Introduction

In scientific literature concerned with metal machining processes using a geometrically defined cutting edge, the bandsawing process is clearly underrepresented. Some fundamental literature is only focused on turning [1], and literature reviews are mainly focused on milling and turning [2] with some also including drilling [3,4].

Metal bandsawing literature is scarce and the most practically useful works [5,6] have been published decades ago, not capturing some of the technological advances made more recently. This has led to the situation that understanding of the bandsawing process basically relies on findings from the aforementioned commonly investigated cutting processes. From a chipping process perspective, this is a broadly valid approach. Bandsawing may be approximated using orthogonal cutting investigations. However, feed per tooth f_z may reach comparatively low values, especially for difficult to cut materials [7]. Due to the size effect laid out amongst others in [8], it is necessary to take into account that a lower limit for f_z exists. (Consequently, this also holds true for f_g as introduced below in Eq. (2)) This has an influence on potential optimizations, including this one.

One aspect in which bandsawing differs from other chipping processes is the surface condition of the workpieces being cut. Milling, drilling, and turning are mostly concerned with machining pre-processed workpieces, especially in those instances most thoroughly investigated in literature. Bandsawing, however, commonly stands on the beginning of the machining process chain: One frequent task is producing cutoffs from pieces still carrying mill scale from the steel production process as illustrated in Fig. 1. There, workpieces to be cut with a bandsaw arrive directly from a hot process like casting, forging or hot rolling. Such processes, when carried out in atmospheric conditions, enable the creation of mill scale on the workpiece surfaces [9].

For steel workpieces, mill scale is made up of the hot oxidation products Wüstite, Magnetite and Hematite [10]. The microscopic structure of mill scale is shown in Fig. 2. We have measured its hardness for the example of 1.2312 steel [11] to be far beyond the bulk metal hardness. With its brittle-hard structure, cutting through mill scale differs considerably from cutting the base metal beneath it. A substantial tool-life reduction effect is to be expected when mill scale is present but cutting parameters and tools are selected based on properties of the base metal. Therefore, investigations specifically focused on cutting mill scale are clearly necessary.

However, the influence of mill scale on machining processes in general and bandsawing in particular has not been scientifically investigated yet with only [12] mentioning it for face milling in one passage. Current research concerning mill scale is mainly focused on its repurposing and recycling [13,14].

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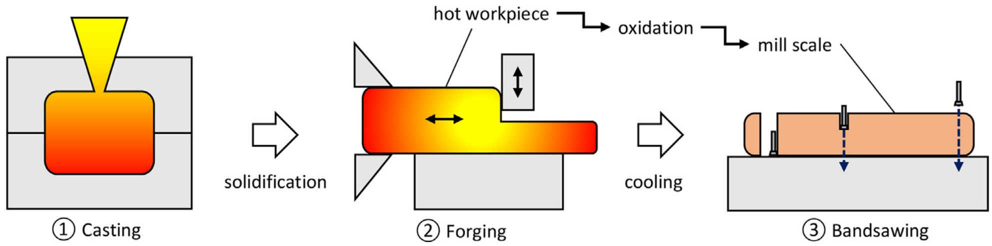

Fig. 1. Hot process steps in steelmaking enable forming of mill-scale.

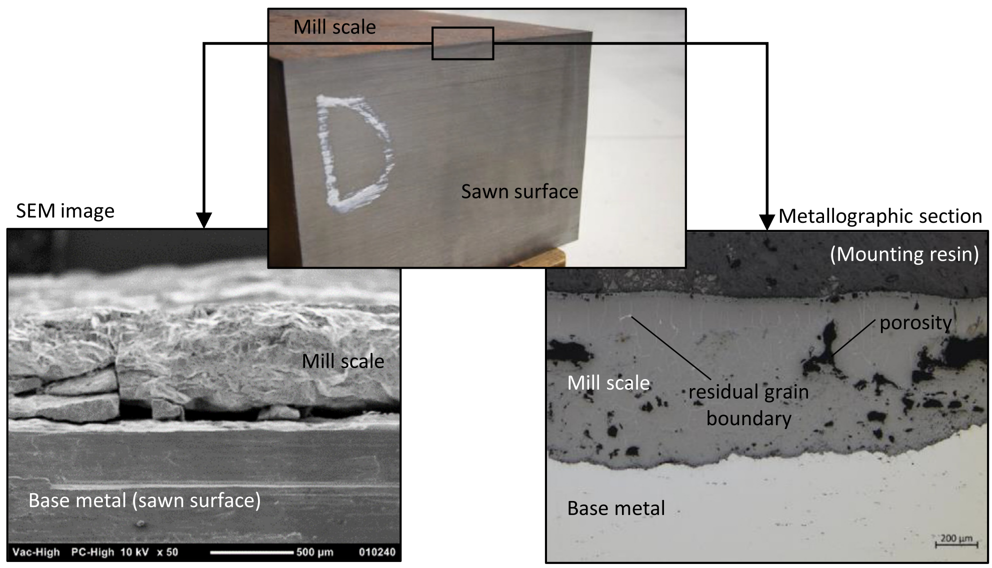

Fig. 2. Mill scale close-up.

Therefore, we conducted our own experimental studies on the impact of mill scale on the bandsawing process. Our previous publication [11] was focused on potential parameter improvements for horizontal bandsawing of 1.2312 steel carrying mill scale. There, we measured the influence of mill scale on feed force work and vibrations. We conducted bandsawing experiments varying cutting speed v_c and f_z, comparing results between specimens with and without mill scale. Across different parameter sets, we compared the measurements were raised due to mill scale. The parameter set with the smallest increase was deemed to be preferable for adapting bandsawing parameters when mill scale is present. Starting from reference parameters, a reduction of f_z while keeping v_c constant yielded the best result. As mentioned above, however, f_z may not be lowered indefinitely and thus, extensive bandsawing tests are necessary to ascertain that wear is indeed reduced.

Expanding upon these findings, we here present a thorough analysis of bandsaw blade wear behavior when sawing workpieces carrying mill scale. We investigate the effect of the aforementioned parameter adaption. Extensive bandsawing experiments show the suitability of this parameter adaption, and more broadly, the drastic difference in wear between workpieces carrying mill scale and those with a machined surface.

2. Experiments

2.1. Experimental procedure and cutting parameters

For bandsaw blade wear experiments, three testing specimens (blocks) were cut from one bigger ingot of 1.2312 steel. This ensures material properties to be the same for all testing scenarios. The original ingot carried a mill scale layer on its top surface and so did the first two blocks A and B. For block C, the mill scale layer was removed (sawn off) to acquire reference data for bandsawing without mill scale. These preliminary cutting operations were carried out using a DANOBAT HDS8A bandsaw with a WIKUS Skalar Premium M42 Blade (1.0-1.4 TPI). Removal of mill scale, and to a lesser degree, variations of the height the forged mill scale surface led to varying cross sections. To afford for this, the progression of measurements over blade life was not carried out using the common notation of a quantity over number of sections cut like in [15]. Instead, as suggested by Reng [5], we used the cumulative sum of the cross sections cut, the total cut surface A_T, calculated as in Eq. (1). To achieve accurate values for the cross-sectional geometries blocks A and B (necessary due to the uneven mill scale surface), a handheld laser scanner (see Table 3) was used to digitize the workpiece surface. A schematic of the blocks used in the bandsawing wear experiments is shown in Fig. 3.

$$A_{T,k} = \sum_{i=1}^{k} A_i = \sum_{i=1}^{k} h_i * b_i \tag{1}$$

Together with workpiece geometry, the sawing parameters used for our experiments are listed in Table 1.

To classify chipping thickness, feed per tooth group f_g as calculated using Eq. (2) is also listed there. As illustrated in Fig. 4, it is the feed distance covered by the bandsaw blade with the passing of 1 tooth group. This tooth group is repeated throughout the bandsaw blade, with the load of cutting the whole kerf width distributed over the differently set teeth as shown in [16]. This shall enable the comparison to blade types with other set patterns.

$$f_g = f_z * n_z = \frac{v_f}{v_c} * z_a * n_z \tag{2}$$

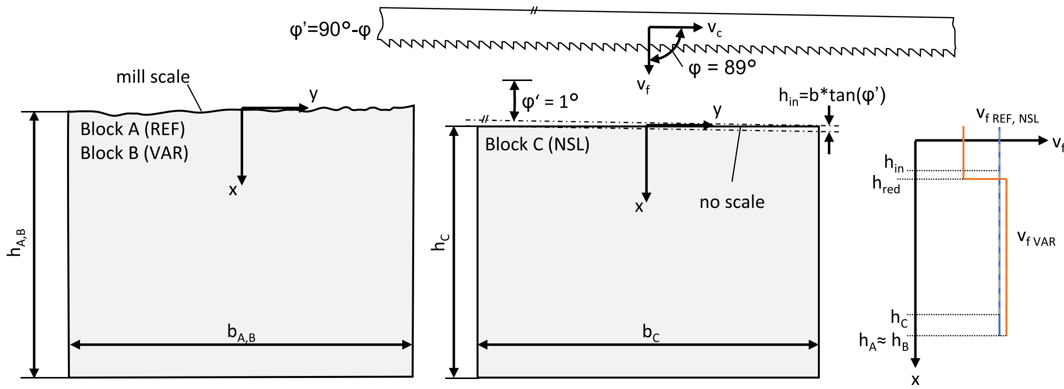

Fig. 3. Specimens, saw blade tilt and feed rate profiles.

Table 1
Cutting parameters and geometry.

Parameters	REF	VAR	NSL
Workpiece	**A**	**B**	**C**
Mean height h [mm]	226.4	226.3	212.5
Mean width b [mm]	311.1	312.0	311.0
Mean in-feed height h_{in} [mm]	7.3	7.4	7.3
Mill scale	top	top	none
Cutting data			
Cutting speed v_c [m/min]	32	32	32
Feed rate v_f [mm/min]	11.9	12.1	11.9
Feed per group f_g [µm]	30	30.5	30
Blade break-in (Cut 1)			
Cutting speed v_c [m/min]	24	24	24
Feed rate v_f [mm/min]	8.9	8.9	8.9
Feed reduction (in-feed)			
Reduced feed per group $f_{g,red}$ [µm]	–	24	–
Reduced feed rate $v_{f,red}$	–	9.5	–
Reduction height h_{red}	–	13	–

$$t_c = \frac{h}{v_f} \tag{3}$$

In the bandsaw blade wear tests conducted, each workpiece was used for one experimental configuration. For all parameters described we carried out bandsawing wear experiments for 60 cuts, each time starting out with a new bandsaw blade. Values for the parameter sets are given in Table 1.

- Block A was cut using the reference parameters from [11], from here on denoted "**REF**".
- For block B, a variable feed rate v_f was used (designation "**VAR**"). In [11] we found reducing the feed per tooth f_z (here equivalent to reducing f_g) at constant cutting speed v_c to be beneficial for bandsawing of mill scale. According to Eq. (2), this translates to reducing v_c in the control unit of the bandsawing machine. Time per cut t_c (Eq. (3)) is the relevant performance metric for bandsawing. Simply reducing v_f would lead to a reduced process throughput which is undesired. Instead, we chose to reduce v_f only while cutting the mill scale layer (during in-feed). To keep t_c truly constant overall using this method, v_f was slightly increased over REF parameters for the remainder of each cut. The bandsaw blade was tilted in the machine used, determining the infeed height h_{in} as illustrated in Fig. 3. Only after passing h_{in}, the whole width of the workpiece is being cut. Consequently, h_{in} would be the minimum value for the feed

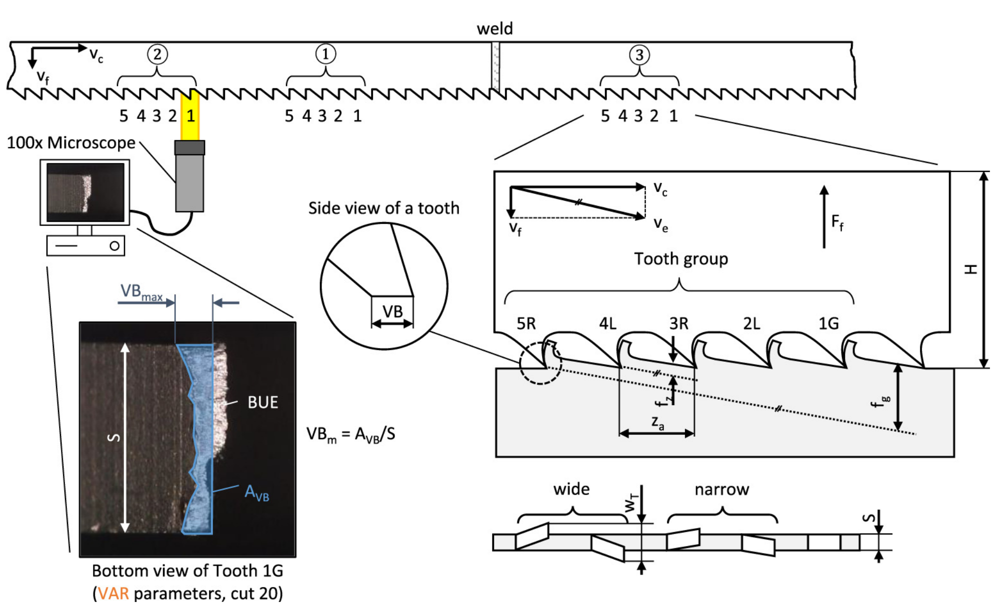

Fig. 4. Wear measurement and blade segment geometry.

stretch h_{red} of reduced v_f. To afford for present surface ripple, and the thickness of the mill scale layer itself, this was increased to $h_{red} = 13mm$.

- Block C was cut using the same parameters as REF, to determine the difference in wear and behavior between a scale layer and no scale layer present ("**NSL**" parameters.)

New blade break-in for all three parameter sets was carried out by cutting cut 1 for each bandsaw blade at reduced v_c and v_f (see Table 1). Additional relevant experimental parameters are given in Table 2.

2.2. Measurement set-up

Recording of measurement data was carried out throughout all 60 cuts of each parameter set. Wear measurements were taken intermittently between predefined cuts. Measurement devices are listed in Table 3.

Table 2
Experimental properties.

Properties of bandsawing experiments	
Workpieces	1.2312
Material	1.2312 steel
Bandsawing machine	BEHRINGER HBM 540A
Blade tension [MPa]	300
Bandsaw blade	WIKUS Skalar X3000
Tooth material	HSS, uncoated
Length L × Height H × Thickness S [mm]	7500 × 54 × 1.6
Variable tooth pitch [TPI]	1.4–1.8
Avg. tooth spacing z_a [mm]	16.1
Max. tooth set width w_T [mm]	2.9
Teeth per tooth group n_z	5
Emulsion coolant	BLASER Vasco 6000
Coolant concentration	10 %

Wear measurement is illustrated in Fig. 4, along with cutting kinematics. Tooth flank wear VB was measured to quantify bandsaw blade wear. It is commonly measured parallel to v_c in various possible ways. Images from a microscope positioned in the sawing machine in-between cuts were evaluated to acquire measurements. This was done for all 5 teeth of each of 3 pre-defined tooth groups throughout the life of each blade. (Tooth groups are patterns of alternating tooth types that alternate throughout the length of the blade.) We directly measured the maximum flank wear VB_{max} and the flank wear area A_{VB} and calculated the mean flank wear VB_m across the width of each tooth. VB_{max} was commonly found on either the left or the right tooth corner. For all parameters tested, built-up-edges occurred frequently in cutting. These were, if severe, manually removed before measurement and the remaining were separated from wear in the evaluation procedure.

Sensor positions in the context of the bandsawing configuration are shown in Fig. 5. The sensor for thrust force F_f measured the displacement of a spring vertically supporting the right blade guide. Using a calibration procedure with a dynamometer as discussed in [17], this allows for the measurement of the vertical force acting on the right blade guide. We assume F_f to be the sum of vertical forces in the left and right blade guide. With the approximation of F_f being the resultant of a constant distributed load across the cutting width b, it may be viewed as a singular force acting in the center of the cut. This center position changes for different cutting widths b. From this consideration, we calculated the magnitude of F_f using the measured right blade guide force in a moment equilibrium. The spring pretension of the right blade guide resulted in a lower limit of measurable F_f. In our configuration, this was $800N$ (marked in Fig. 7). F_f was only evaluated for values beyond this pretension.

Three-axis acceleration at the left blade guide was measured to quantify vibrations. Each axis of the accelerometer was calibrated using the earth's gravitational field. A moving RMS average for

Table 3
Measurement devices.

Measurement	Device Type	Make
Saw frame position (x)	Wire sensor	MICRO EPSILON WDS-750-P60-SR-U
Displacement for F_f	Analog inductive sensor	TURCK BI5-M18E-LIU-H1141
Calibration of F_f	Multicomponent piezo dynamometer	KISTLER 9129AA
Acceleration ($a_{x,y,z\ sens}$)	3-axis MEMS accelerometer	ANALOG DEVICES ADXL335
Wear (VB)	Microscope (100x)	KEYENCE VW9000
Set width (w_T)	3D microscope (focus variation)	ALICONA InfiniteFocus G5
Data acquisition	USB DAQ device	NI USB-6343
Workpiece geometry	Handheld laser scanner	SHINING 3D EinScan HX

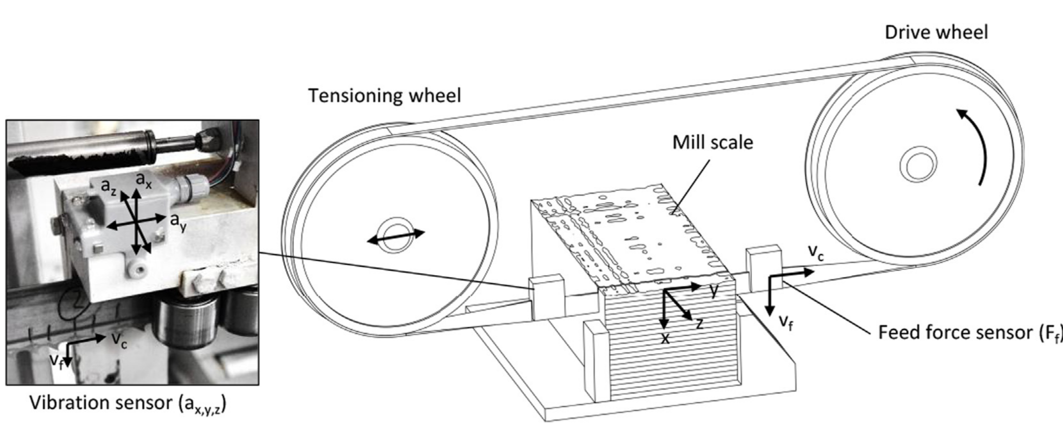

Fig. 5. Bandsawing configuration and sensor positions.

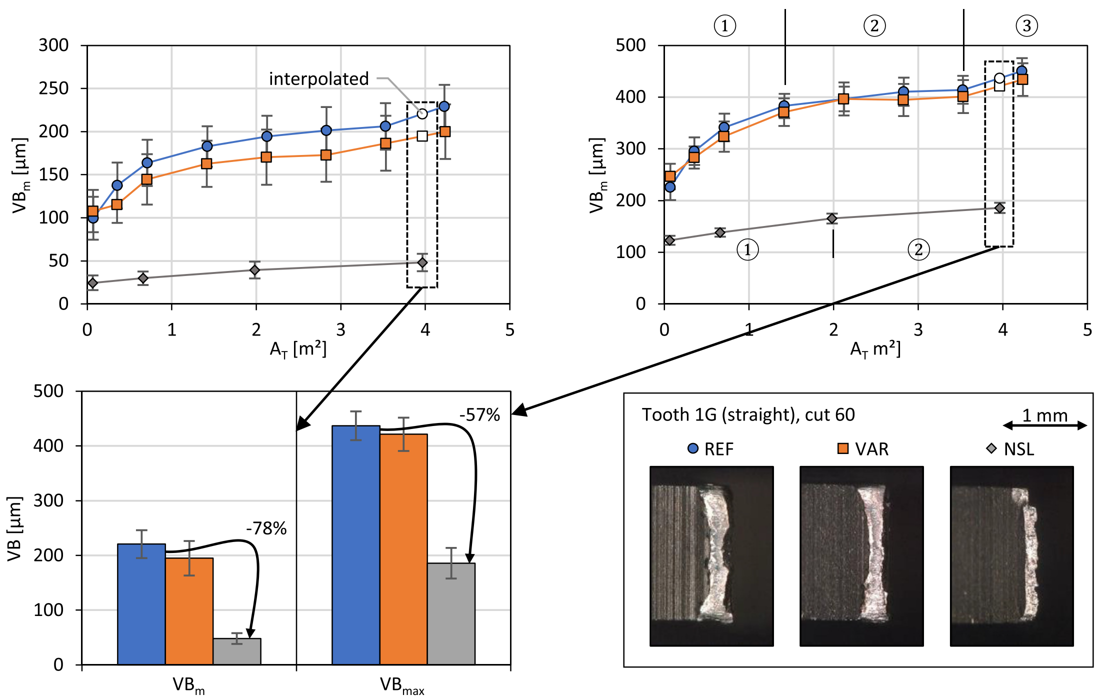

Fig. 6. Wear results. ①, ②, ③...wear stages.

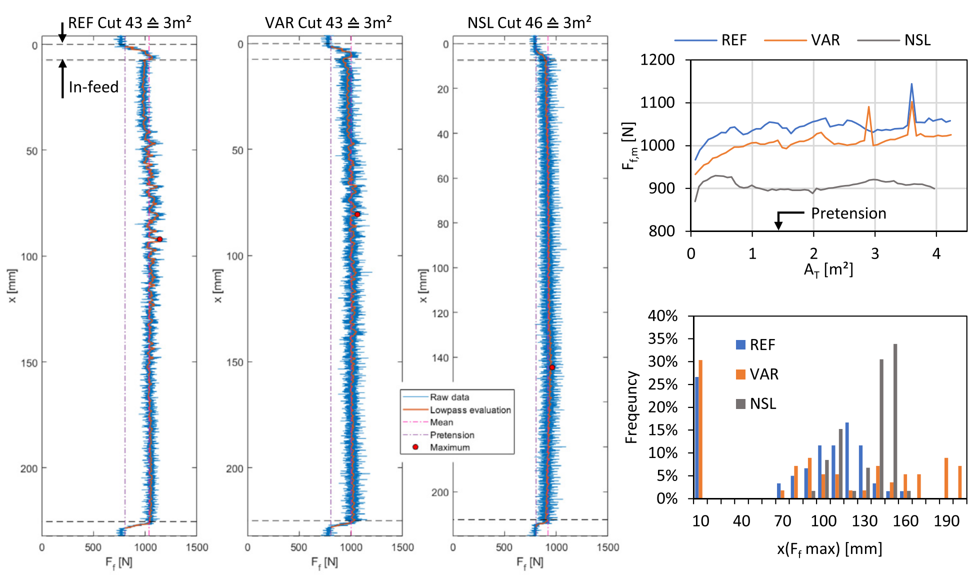

Fig. 7. Thrust force measurements. Left: Typical recordings, each at the A_T. Top right: $F_{f,m}$ over blade life. Bottom right: distribution of the x position where maximum F_f was measured for each cut.

each coordinate with a time window of $\Delta t = 15s$ was calculated as shown in Eq. (4). These are the actual quantities used in the evaluation.

$$a_{x,y,z}(t) = \sqrt{\frac{1}{\Delta t}\int_{t-\Delta t/2}^{t+\Delta t/2}\left(a_{x,y,z\ sens}\left(\bar{t}\right)\right)^2 d\,\bar{t}} \quad (4)$$

3. Results and discussion

The results of the wear measurements as mean values of all measured teeth for each blade are shown in Fig. 6. Wear for bandsawing without mill scale (NSL) was considerably lower than for REF and VAR parameters (with mill scale). Linear interpolation was calculated for REF and VAR to compare their wear measurements to NSL at the same A_T. At $4m^2$, VB_m was 78 % lower for NSL than for REF and VB_{max} was reduced 57 %. This means that for REF, 78 % of VB_m may be attributed to cutting mill scale and only 22 % to cutting the base metal of the remainder of each cut.

Also shown in Fig. 6, the three wear stages as described in [18] could be identified: ① initial degressive wear, ② linear steady-state wear, ③ accelerated progressive wear. It is evident, that for both tests with mill scale REF and VAR, ③ had already started before $A_T = 4m^2$. Stage ③ commonly marks the onset of tool failure. In contrast to this, NSL was still in stage ② at $4m^2$, with no sign of a progressive wear rate. It is clear that stage ③ had not started yet. From this observation and with the measured dramatically increased bandsaw blade wear it may be predicted that mill scale substantially decreases blade life when sawing with non-adapted parameters.

The reduction of wear for VAR in respect to REF is not as significant as the impact of the complete removal of mill scale. Nevertheless, wear at $4m^2$ is reduced by 12 % and 4 % for VB_m and VB_{max} respectively only by the simple measure of momentary reducing v_f while cutting through mill scale. To gain a better insight on the beneficial effects this reduction promises, F_f and RMS acceleration a are evaluated in the following.

Overall, F_f was lowest for NSL and highest for REF with VAR in-between as shown in Fig. 7. The mean thrust force for each cut $F_{f,m}$ also exhibits an increase over blade life similar to VB_m, resulting in the linear correlation to the mean for F_f over each cut in Fig. 8. This correlation appears to be valid throughout all three configurations REF, VAR and NSL. However, a clear distinction can again be made along this trend for NSL appearing for lower values of F_f and VB_m. Aside from the difference in mean F_f, the recorded plots also differ during blade in-feed. As this is the x-range where cutting of mill scale happens, a momentary increase is observable there for REF and VAR but not for NSL. Fig. 7, bottom right shows that the absolute maximum of F_f frequently occurred during in-feed for VAR and REF while it never did for NSL.

Generally, the ranking for vibration measurements $a_{x,y,z}$ is the same as for F_f with NSL producing the lowest values and REF the highest. A similar trend as for F_f may be observed for $a_{z,m}$, the mean value of a_z calculated for entirety of each cut, in Fig. 8, right. This means that $a_{z,m}$ also increases over blade life. The proportion of maximum values occurring through in-feed with mill scale is even

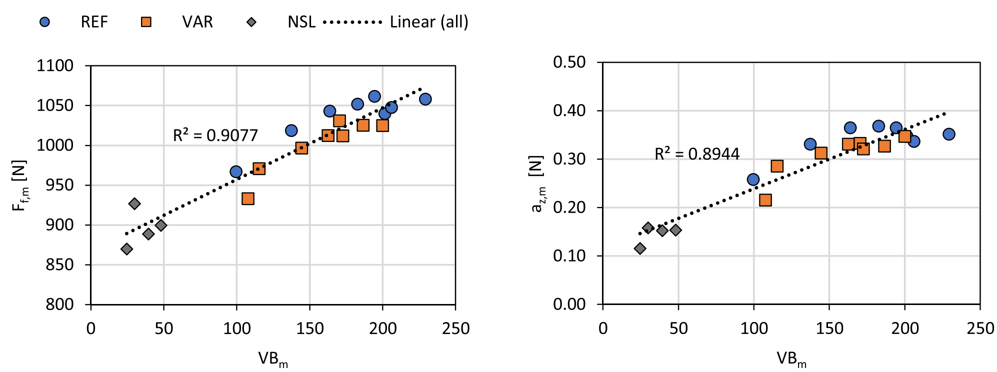

Fig. 8. $F_{f,m}$ (right) and $a_{z,m}$ (left) both showed a linear correlation to VB_m(wear), excluding cut 1: break-in). REF, VAR and NSL fulfill the same correlation.

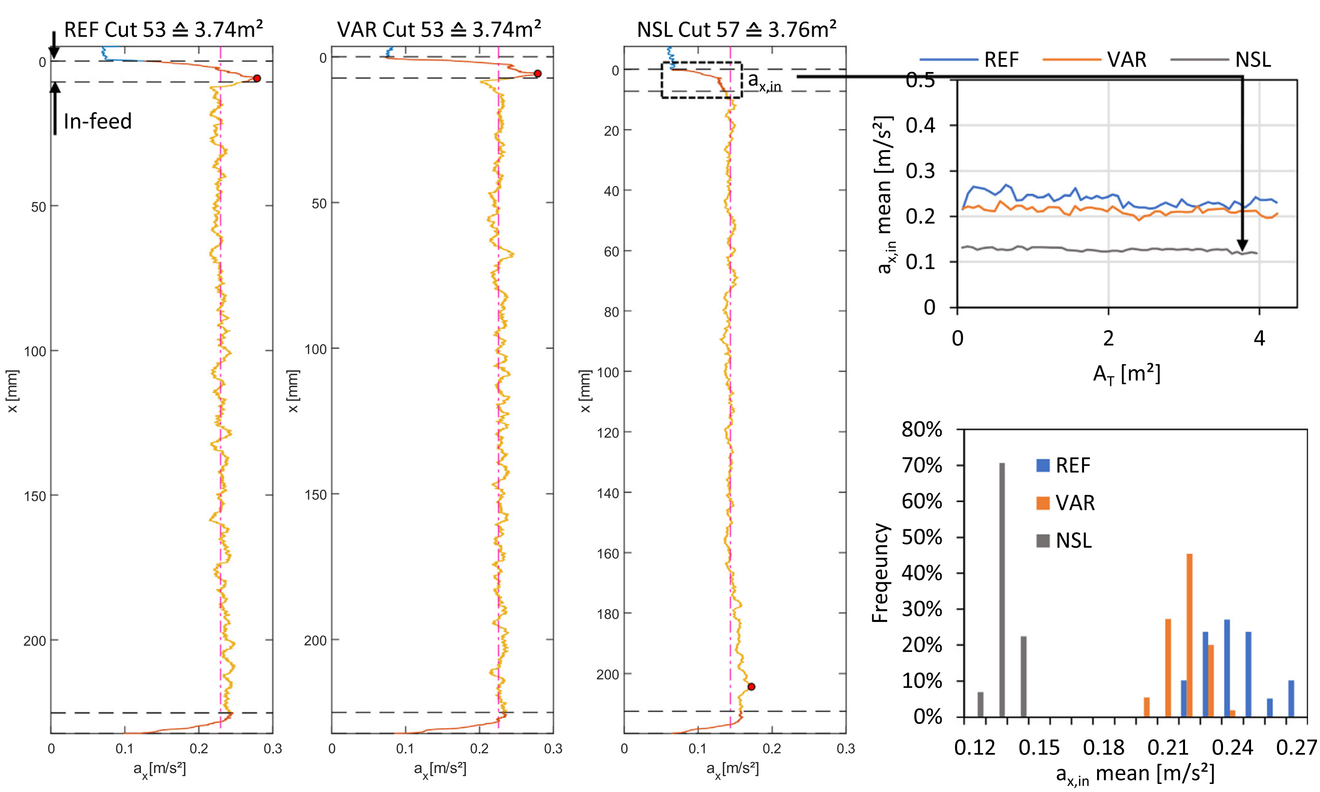

Fig. 9. Typical recordings and measurements for. a_x

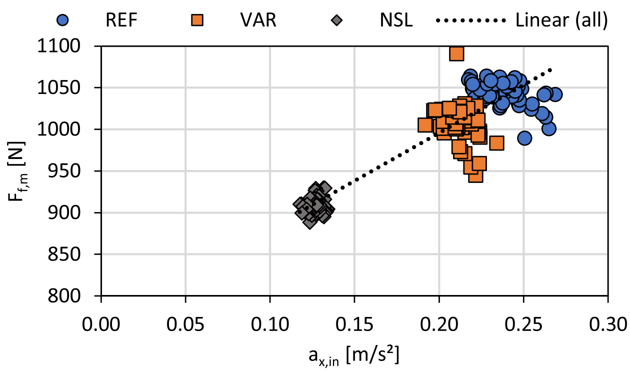

Fig. 10. Measurements of F_f and $a_{x,in}$ constitute clusters (data excluding cut 1: break-in).

higher for a, ranging from 42 % for a_x of VAR up to 100 % for a_z of REF and VAR. For NSL, there was only one single measurement where a_z achieved its maximum during in-feed. A local maximum during in-feed was also frequently observable for NSL, however. With this, the observation of elevated vibration during in-feed made in [11] could be reproduced here.

As a relevant and stable measurement for in-feed vibrations, the mean value for a_x during in-feed was chosen ($a_{x,in}$, Fig. 9 top right). It did not show a measurable wear influence and may therefore be attributed mainly to the three different parameter sets. As shown in Fig. 9 bottom right, $a_{x,in}$ exhibits three separate distribution maxima. The maximum for NSL was the lowest, again followed by VAR and then by REF. This lower distribution peak for VAR shows the direct impact of reduced v_f on cutting through mill scale.

Combining $a_{x,in}$ and $F_{f,m}$, a general treatment of the mill-scale impact can be undertaken. This is shown in Fig. 10. There, the measurement points for all cuts excluding break-in form distinct clusters for REF, VAR and NSL. In normalized units relative to the mean of NSL, the center of VAR points is 22 % closer to NSL than the center of REF. This shows that VAR cutting was more "NSL-like" meaning the influence of the presence of mill scale was clearly lower than for REF. With this, the approach of reducing f_g (by reducing v_f) while cutting through mill scale could be verified for our experimental configuration.

4. Conclusions and outlook

We found that mill scale has a substantial impact on the bandsawing process:

- For our experiments, the presence of mill scale dramatically increased wear, feed force and vibration. We measured tooth wear that was more than double for workpieces with mill scale than it was for ones without. Consequently, bandsawing of parts carrying mill scale will likely lead to noticeably shorter bandsaw blade life.
- We also demonstrated that lowering feed (quantified by f_g) while cutting through mill scale of a workpiece and then reverting to a higher value for the bulk material improved sawing conditions. While wear, feed force and vibrations were lowest for the workpiece without mill scale, this approach also successfully lowered these factors, albeit to a less significant extent. Its advantage, if executed correctly, is unchanged productivity.

Therefore, if feasible, mill scale should ideally be removed in an additional process step before bandsawing, as we did during our specimen preparation. In case this is not economically viable, the impact of present mill scale may be reduced by the method of temporary feed reduction.

However, additional investigations are necessary to further enhance understanding of the process and to make use of our findings in real (and thus more variable) machining operations. Amongst others, the following should be studied:

- Determining the optimum reduction percentage of feed while cutting through mill scale of varying constitution.
- Finding the ideal value for h_{red}. This is the pre-programmed distance in feed direction the saw frame travels while feed is reduced when cutting mill scale. This would be greater than the mill scale thickness, depending influences like material properties, cutting width, blade tilt angle, mill scale thickness and surface condition.
- As a more flexible alternative to the approach of predefined feed reduction, a feed control algorithm could also be developed for this task. There, feed would be actively controlled using the measurements from our acceleration sensor as input. We aim to further investigate this approach in the future.
- Literature on machining of mill scale is generally lacking, as discussed in section 1. Thus, similar investigations as the one on hand should be carried out for other chipping processes. Of interest would be, amongst others, face milling and bar peeling. They are also used for removal or cutting through mill scale in some applications.

CRediT authorship contribution statement

Johannes Diebold: Conceptualization, Data curation, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Friedrich Bleicher:** Funding acquisition, Supervision, Writing – review & editing.

Data availability

The data that has been used is confidential.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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