Article

Hydrostatic Bandsaw Blade Guides for Natural Stone-Cutting Applications

Ammar Ahsan *![ORCID]**, Kyle Kenney, Jonas Kröger and Stefan Böhm**

Fachgebiet Trennende und Fügende Fertigungsverfahren (TFF), Universitaet Kassel, Kurt-Wolters-Str. 3, 34125 Kassel, Germany; dudlsack@gmail.com (K.K.); j.kroeger@uni-kassel.de (J.K.); s.boehm@uni-kassel.de (S.B.)

* Correspondence: a.ahsan@uni-kassel.de; Tel.: +49-561-804-7702

Abstract: In a bandsaw machine, the blade guides provide additional stiffness and help to align the blade near the cutting region. Typically, these are either in the form of blocks made of carbide or ceramics or as sealed bearings. Abrasive particles, generated while cutting hard and brittle materials like natural stones, settle between the contact surfaces of the guides and the blade causing wear and premature failure. The hydrostatic guide system, as presented in this work, is a contactless blade guiding method that uses the force of several pressurized water jets to align the blade to the direction of the cut. For this investigation, cutting tests were performed on a marble block using a galvanic diamond coated bandsaw blade with the upper roller guides replaced by hydrostatic guides. The results show that the hydrostatic guides help to reduce the passive force to a constant near zero in contrast with the traditional guides. This also resulted in reduced surface roughness of the stone plates that were cut, indicating a reduction in lateral vibration of the band. Additionally, it has also been shown that using hydrostatic guides the bandsaw blade can be tilted to counter the bandsaw drift, opening opportunities for further research in active alignment control. This original research work has shown that the hydrostatic guide systems are capable of replacing, and in fact, perform better than state-of-the-art bearing or block guides, particularly for stone-cutting applications.

Keywords: hydrostatic; blade guides; bandsaw; diamond blade; natural stone; sawing

1. Introduction

Natural stone plates, due to their texture, resistance to stains, scratches, and heat, are used traditionally as luxury countertops, floor and/or wall tiles. In the industry, these are cut out of quarried stone blocks using either gang or wire saws. The cutting tools contain segments or beads of sintered diamond in a metallic binder. In several previous publications of the TFF institute, it has been shown that a bandsaw, specifically with geometrically defined cutting edges, provides a technically and economically viable method for cutting natural stone blocks [1–4].

The bandsaw blade is tensioned using either mechanical or hydraulic systems to provide the required stiffness to the blade for cutting. The main purpose of the bandsaw guides (on two sides of the workpiece) is to keep the alignment of the blade in check and to provide additional stiffness to the blade near the cutting region [5]. Furthermore, guides help to reduce lateral vibration of the bandsaw, especially while cutting at higher feed rates [6]. In most cases, the bandsaws either use a carbide or ceramic block or sealed bearings as blade guides (see Figure 1). The disadvantage of block guides is the considerable sliding (Coulomb) friction between the blade and the guides. The guide material must therefore have a low coefficient of friction with the blade material, and high wear resistance and heat resistance. In the case of the roller or bearing guides, the sliding friction is replaced

by much smaller contact rolling friction. However, high-precision installation of the roller guides is required, and one-sided loading of the bearings turning at high speeds is a cause of lifespan reduction. Furthermore, as the blade deflects and bends against the rollers, very high stresses are generated that further reduce the durability of the blades [7].
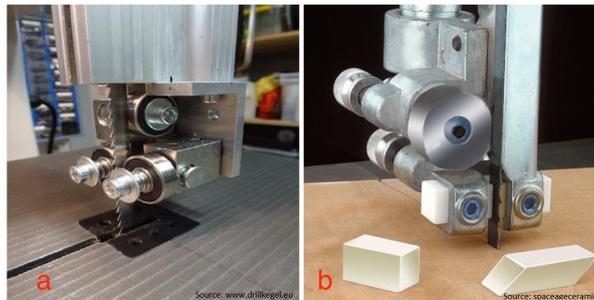
Bandsaw Guide Examples

Figure 1. Typical bandsaw guides. (**a**) Bearing guides; (**b**) ceramic block guides.

Granite (Mohs hardness 7–8) and other similar stone types are much harder compared to unhardened steel (4–4.5), and unlike metals, natural stones are highly inhomogeneous [8]. During the cutting of such an inhomogenous material like a natural stone block, "chips", as ideal in metal cutting, are not formed during the cutting process, but rather a slurry of water and stone particles [4]. Highly abrasive particles, generated while cutting stones and transferred via slurry, settle within the contacts between the blade and the guides (regardless of form), causing the steel blade to wear quickly from the sides and fail prematurely [9]. In order to avoid this problem, a contactless (read, air-gap) guide system is required that makes sure that the blade runs straight, while simultaneously avoiding any direct contact with the blade guides and completely eliminating the aforementioned wear and premature failure.

Only a handful of publications exist which have considered contactless blade guide systems for the reduction of vibration of the bandsaw. Unfortunately, the only application where this system has been considered has been in wood sawing [10]. A Curvillinear aerostatic bearing guide design for wood cutting bandsaws was studied by Prokof'ev in [11,12], where an increase in the durability of the blade by a factor of 20 was reported. Electromagnetic guides were considered in a theoretical (modelling) study by Cleave [13]. The missing experimental work for wood bandsaws using electromagnetic active vibration damping guides was performed by Huang in [14]. The author reports that the applied actuation suppressed both the transverse and torsional vibrations of the moving band, significantly reducing the vibration amplitude.

This work is intended as a feasibility study for hydrostatic blade guides i.e. using pressurised water jets as a means to guide the bandsaw blade while cutting natural stones. This contactless mechanism should keep the blade aligned while avoiding the sliding of the blade against the guide surfaces, causing significant reduction in abrasive wear of the bandsaw blade as observed in case of block or roller guides while cutting natural stones.

2. Materials and Methods

2.1. Bandsaw Machine

A modified version of the KASTOplate U3 bandsaw machine consisting of a 700 mm carrier frame increase and a compensating guide arm with a wheel diameter of 700 mm to allow for larger stone-cutting experiments was used for the cutting tests (see Figure 2). The maximum achievable cutting speed on the machine was 150 m/min, feed rate 250 mm/min. The workpiece was a 500 mm × 400 mm × 400 mm [lxwxh] block of white Carrara marble. The bandsaw blade used was a

galvanically coated diamond blade with a width of 67 mm, with a thickness of 1.6 mm and a constant pitch of 30 mm.

Figure 2. Kastoplate U3 bandsaw machine at TFF, Universität Kassel.

2.2. Hydrostatic Blade Guide System

The principle of the hydrostatic blade guide is shown in Figure 3. The force exerted on a wall by a water jet according to Sigloch [15] is given in Equation (1). Where F_{GS} is the reaction of the exerted force on the wall, ρ the density of the fluid (in this case, water), $\dot{V}_D$ the volume flow rate per nozzle, w_D the speed of the jet coming out of the nozzle, and A_D is the cross-section area of the nozzle. In the system shown in Figure 3, for the jet force to balance the passive force in the bandsaw blade while cutting, the reaction force F_{GS} should equal the sum jet force F_{Di}.
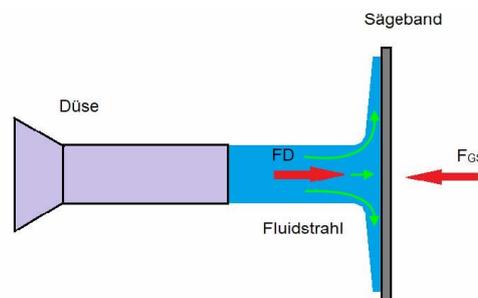

Figure 3. Simplified representation of the water jet on the bandsaw based on [15].

$$F_{GS} = \rho \times \dot{V}_D \times w_D = \rho \times A_D \times w_D^2 \qquad (1)$$

In order to estimate the maximum force exerted by the band on the water jet (F_{GS}) (i.e., the passive force while cutting), cutting tests were performed on a single-tooth linear cutting test rig at the sawing lab of TFF. The linear test rig, along with a single segment of the Diagrit bandsaw blade, is shown in Figure 4. The tests were performed on $500 \times 100 \times 20$ [mm] sized Carrara marble plates with a single segment of the Diagrit bandsaw blade. The linear cutting speed (v_c) was set at 150 m/min and feed per tooth (f_z) of 10 μm. The total quantity of stone which was cut amounted to a surface area of 250 cm^2 in the form of 10 separate grooves, with each having a cut surface area of 25 cm^2. The average of the peak values of the passive force obtained while cutting the last groove was taken as the value to be used for calculation of the nozzle diameter. This was found to be 27 N, which meant that with

the total number of teeth in contact with the marble block on the bandsaw machine to be 10, the total passive force would amount to 270 N.
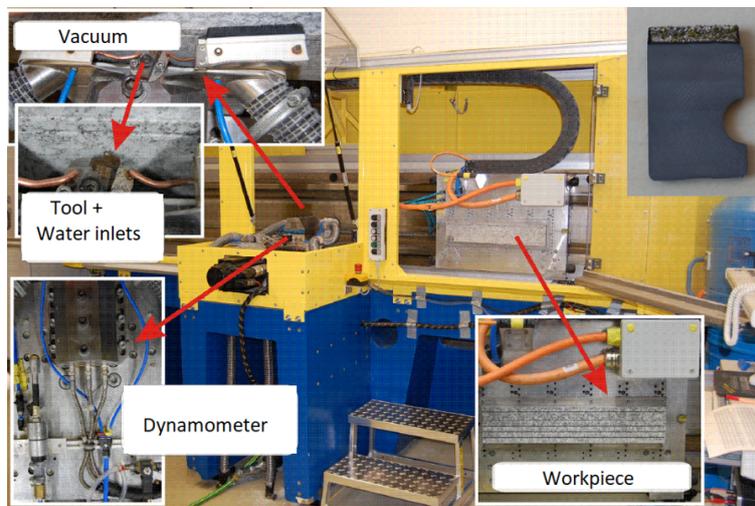

Figure 4. Linear test rig at TFF [3] and wire-eroded single segment of the galvanic diamond bandsaw blade.

The hydrostatic band guides were designed in the form of nozzle plates having nine holes or nozzles. The plates were made of stainless steel X5CNi18-10. The design of the guide system is shown in Figure 5. The water pump attached to the machine, from the French manufacturer Wilo, was a centrifugal pump with a maximum volume flow rate of 14 m^3/h and a maximum achievable pressure of 8 bars. The final design parameter, or the diameter of the individual nozzles, was calculated based on the maximum force, volume flow rate of the pump, and the number of nozzles, as shown in Equations (2)–(5).
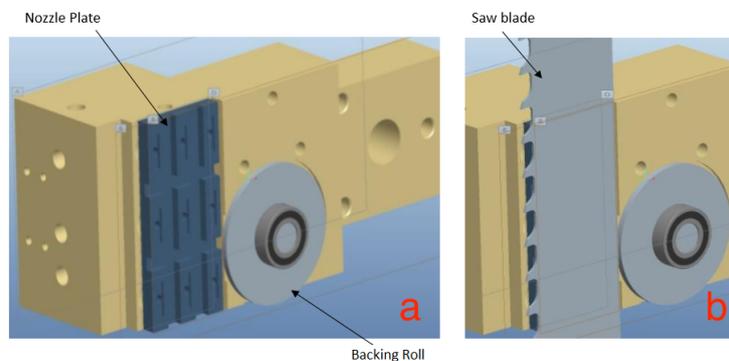

Figure 5. CAD design of the hydrostatic blade guide system showing the nozzle plate, backing roll, and the holding block. (**a**) Without the bandsaw blade; (**b**) with the bandsaw blade.

From the continuity equation of fluid dynamics, the mass flow rate ($\dot{m}$) is given as [15]:

$$\dot{m} = A \times w \times \rho, \text{ whereby }, A \times w = \dot{V} \text{ and } \dot{V}_D = \frac{\dot{V}_{max}}{n}. \tag{2}$$

The values of the parameters used in Equation (2) are given in Table 1.

Table 1. Parameter values for Equation (2).

Parameters	
$\dot{V}_D$	0.778 m^3/h
$\dot{m}_D$	778 kg/h
F_D	30 N
w_D	140 m/s
A_D	1.54 mm^2

These present the diameter of the nozzle to be 1.4 mm. The nozzle design based on this calculation is shown in Figure 6 and the hydrostatic guides mounted on the bandsaw machine are shown in Figure 7. A fluid pocket has been designed to maintain a lubrication film between the band at the guides. This pocket not only helps keep the guides clean, but also to reduce or compensate any kind of friction build-up through possible contact. The negative effects of the discontinuous transition from nozzle to pocket were negligible when compared to the positive effects of the fluid pocket inclusion. It is important to point out that only the upper side of the bearing guides were replaced with hydrostatic guides. Replacement of the lower side of the guides required the machine bed to be heavily modified to allow space for the larger hydrostatic guides to be installed, and thus was not done.
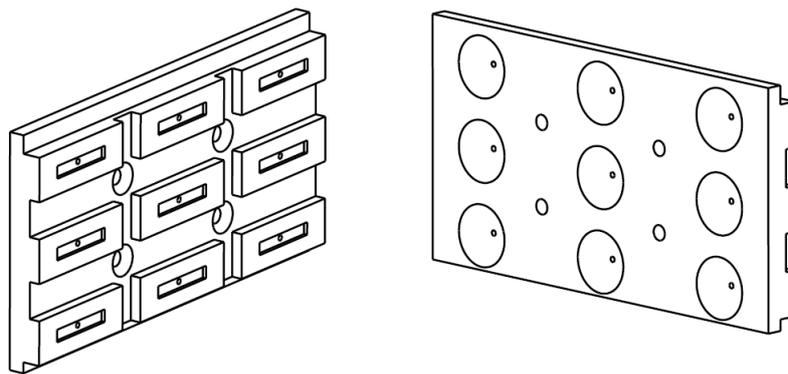
Figure 6. Design of the nozzle plate of the hydrostatic guides.

Figure 7. Bandsaw with upper hydrostatic guides and lower bearing guides.

2.3. Stone-Cutting Tests

For a comparative study, cutting tests on a marble block were performed in three blade guide configurations: firstly, with both upper and lower blade guides being sealed bearings; secondly, with the upper bearing guide replaced with the hydrostatic system; and thirdly, with upper hydrostatic guides and no lower guides. A distance of 0.2 mm was kept between the nozzle plates and the tensioned blade. Under each of these settings, five repetitions of tests were performed, and the results show the average of these five tests. The cutting speed (v_c) and feed rate were fixed at 150 m/min and the feed rate (v_f) at 20 mm/min for all test runs. This translates to a tooth feed (f_z) of 4 µm, about half of that tested on the linear test rig. For the measurement of force, a three-component dynamometer of type Kistler 9257b was mounted on the bandsaw table in stainless steel housing on which the stone block was clamped. In addition, the surface roughness of the plates of marble cut were measured using a FRT white light interferometer.

In the second part of the tests, hydrostatic guides were used to tilt the band to either the left or right while cutting. This was achieved by turning off the valves for two rows of nozzles on each side. The purpose of these tests was to straighten the cutting direction of the bandsaw in case it drifted to one side due to the presence of harder secondary phases in the stone or misalignment of the saw itself. The same technique could also be used to cut curved contours on a natural stone block.

3. Results

3.1. Hydrostatic Guides for Straight Cuts

The generated passive force (F_P) on the bandsaw blade while cutting is a result of the tool's flank face coming in contact with the machined surface. In our case, the thin plates being cut gradually separated themselves from the stone block. Hence, the only sideways force exerted on the blade was from the block side of the stone. Ideally, the passive force should be relatively constant throughout the short cutting cycles employed during these tests. If the band drifts to either side of the straight line, it presses against the bandsaw guides, resulting in an increase of the passive force. Figure 8 shows the average passive force from five repetitions for each of the conditions.
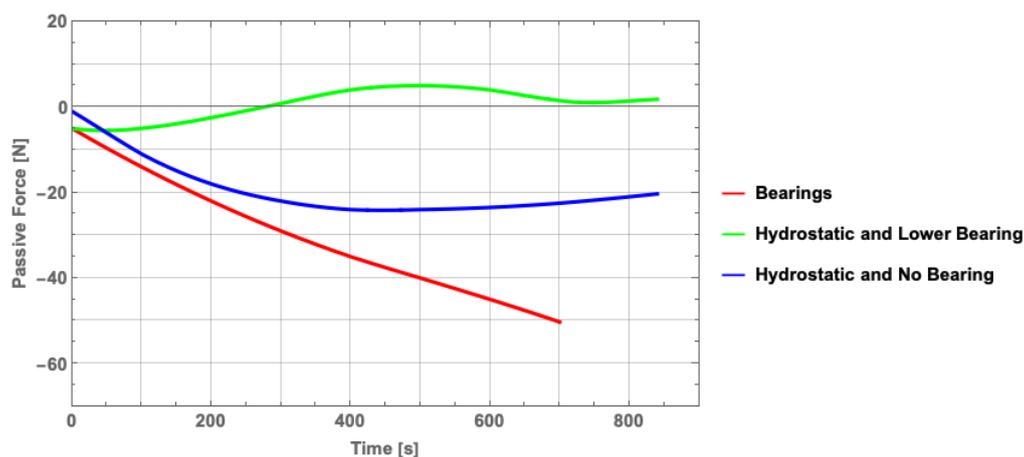

Figure 8. Average passive force progression from five repetitions with: (**red**) sealed bearings as both upper and lower guides; (**blue**) hydrostatic upper guide and bearing lower guide; (**green**) hydrostatic upper guide and no lower guide.

The surface roughness was measured using an optical profilometer of the FRT GmbH, Germany on the samples of the plates cut under each setting. Only the plates cut in the first repetition (out of five) under each setting were used for topography analysis. The 3D surface profiles obtained with the software Mark-3 for samples cut under the three band guide combinations are shown in Figure 8a–c,

respectively. The mean roughness depth, R_z according to the norm DIN 4786, was found to be 71.28 µm for the combination of both upper and lower guides being sealed bearings. When the upper guides were replaced with the hydrostatic guides, R_z was found to be 53.88 µm, while R_z was found to be 95.65 µm when only the upper hydrostatic guides were in place. The 3D surface profiles obtained with the software Mark-3 for samples cut under the three band guide combinations are shown in Figure 9a–c, respectively. Figure 10 shows the values of the roughness parameter R_z for the three samples.
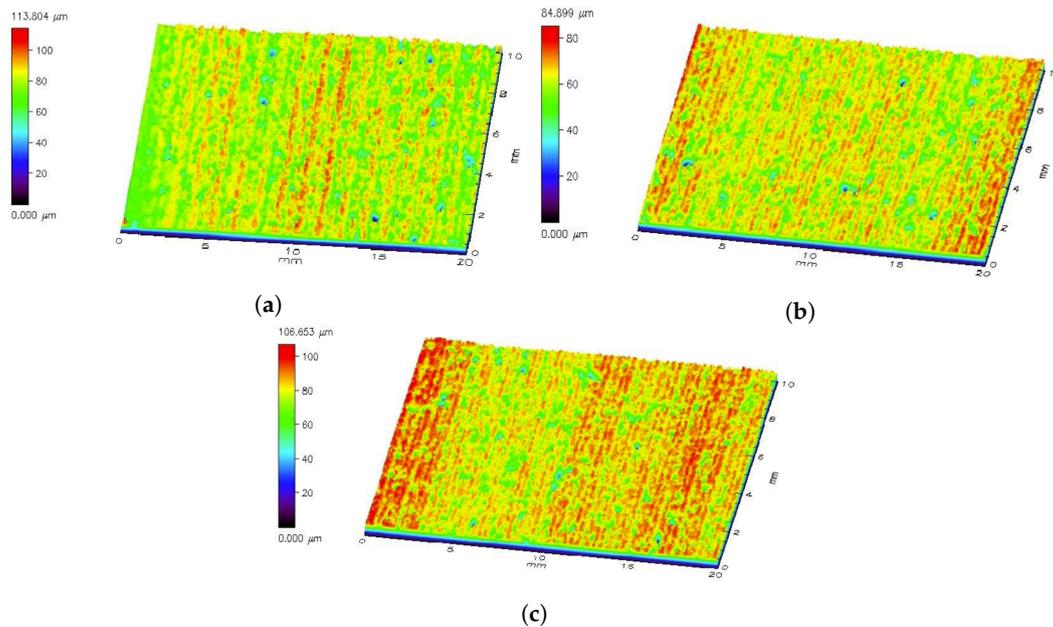

Figure 9. The 3D surface topography of marble test samples cut with the bandsaw using (**a**) sealed bearings as both the upper and the lower guides; (**b**) hydrostatic upper guides and lower bearing guides; (**c**) hydrostatic upper guide and no lower guide.
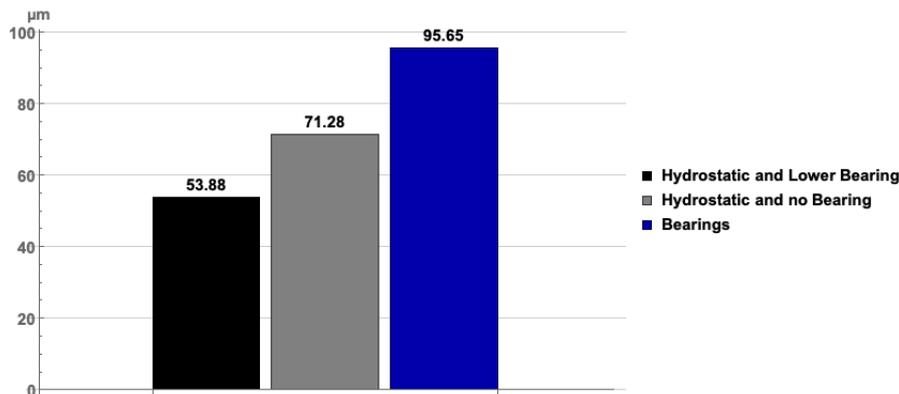

Figure 10. Values of the surface roughness parameter R_z for the three guide configurations.

3.2. Band Deflection with Hydrostatic Guides

The goal of these tests was to find out whether the hydrostatic guides were able to deflect the bandsaw blade in case it drifted to either side while cutting. For this purpose, two additional cutting test routines were performed (five repetitions each) whereby the band was deflected in both directions, that is, towards the block or towards the plate being cut. This was achieved by turning off the valves for two rows of the nozzle on both sides, as shown in Figure 11. The actual deflection or tilt of the band could not be measured due to complications of nature of the cutting process, particularly coolant flooding and film production. However, the passive forces observed during the deflection gave a clear indirect indication of the band being deflected towards either side, as shown in Figure 12.
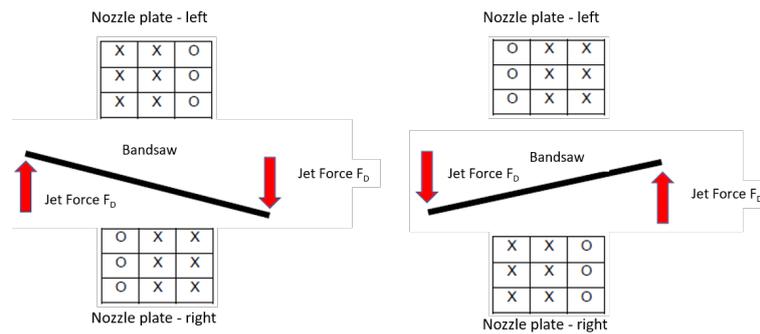
Figure 11. Nozzle plate configuration for band deflection towards the plate being cut (**left**) and towards the remaining stone block (**right**), whereby 0: open nozzle; X: closed nozzle.
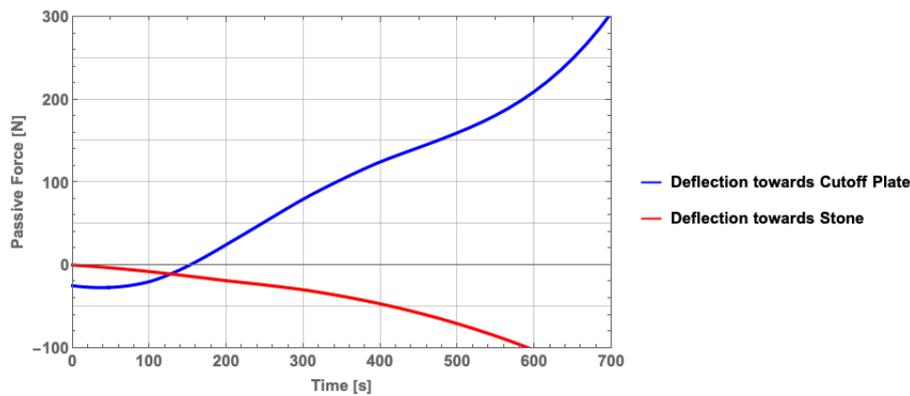

Figure 12. Average passive force for (**blue**) band deflection towards the plate being cut (**red**) band deflection towards the remaining block of stone.

4. Discussion

Both bearing or block guides cause abrasive wear of the band from the sides when the hard stone particles settle on the guide surfaces. Hydrostatic guide system as presented in this work, is a contactless blade guiding method that uses force of several water jets to keep the blade aligned without a direct contact with the blade. In addition to avoiding the blade wear as in case of the aerostatic bearing guides as proposed in [7,11,12] and electromagnetic guides as proposed in [13,14], the hydrostatic guides also allow for an active alignment control of the bandsaw.

In Figure 8 the effect of the hydrostatic guide on the cutting process is seen evidently. With only the upper guides being hydrostatic, the average passive force drops down to a constant near zero. This indicates that the blade is cutting in a straight line and is experiencing equal force from both sides of the material being cut. In contrast, when both upper and lower guides are bearings (red plot in Figure 8), the passive force continuously increases indicating a slight drift of the bandsaw.

Reduction of vibration while cutting with a bandsaw, particularly while cutting natural stones, is of pivotal importance. The cutting and feed force experienced by the individual teeth of a bandsaw while cutting a stone is inherently different than those while cutting wood or metal. Due to harder inclusions, the process forces undergo large peaks (up to 3 times higher than the average force [1]) causing edge chipping and failure of the welded or brazed joints of the saw teeth [16]. Avoiding the direct contact between the blade and guides while cutting causes significant reduction in the vibration as indicated by the plots in Figure 9 comparing the surface roughness of the cut-off plate with and without the hydrostatic guides. Almost a 45% reduction in surface roughness parameter R_z was observed (see Figure 10).

The explanation, in the opinion of the authors, of the considerably higher passive force observed when deflecting the band towards the plate being cut (in Figure 12) is that the rear edge of the band presses against the solid stone block causing much higher forces. In comparison, the forces observed

when the back edge presses against the plate being cut are much lower as the plate, having being partially cut already, is able to deform. This explanation also affirms the relatively greater deflection in the cut when the band was tilted towards the stone block compared to when it was tilted towards the plate. Although this study is a special case of cutting natural stone with a diamond bandsaw having undefined cutting edges, the hydrostatic guides could in fact also be used for other cutting applications where bandsaw drift is a problem. As shown in Figure 11, the simple nozzle configuration used here, is able to deflect the band in either direction in order to compensate for the drift. For this work, only the upper guides of the bandsaw were replaced with the hydrostatic system and further improvement could be obtained by having both upper and lower guides replaced with hydrostatic ones. Furthermore, a system with live measurement of blade drift and its automated compensation via dividual nozzle flow control are the future research opportunities.

5. Conclusions

In this work, an original experimental research was presented on the feasibility of hydrostatic blade guides as replacements for the bearing or block guides for bandsaws when cutting natural stones. For this investigation, cutting tests were performed on a marble block using a galvanic diamond coated bandsaw blade. Passive force progression during the cutting operation was used as the measured quantity to ascertain the effect of hydrostatic guides on the process. The main results were:

- With the upper blade guide replaced with hydrostatic guides, the average passive force reduces to almost zero and remains relatively constant throughout the cutting cycle. In contrast, the bearing guides cause the passive force to increase continuously until the end of the cutting cycle indicating a blade drift (see Figure 8).
- A reduction in surface roughness of the marble plates from R_z of 96 μm with the bearing guides to R_z of 54 μm when the upper bearing guide was replaced with a hydrostatic guide (see Figure 10) was observed. The result indicates a reduction in lateral vibration of the saw band due to hydrostatic guides.
- Hydrostatic guides are also able to compensate for the blade drift by turning nozzles on and off in certain configurations (see Figure 11) and tilt the blade in the opposite direction to the drift resulting in a straight cut.

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