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Characteristics of sawing force location in the unsteady stage

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Abstract. Although the unsteady sawing stage, an integral part of the complete sawing process, contains the characteristics of the sawing process, few studies have been carried out due to the complexity of processing. In the present work, the varying characteristics of sawing force location were studied based on the cut-in and cut-out unsteady stages. Through using kinematic method, the force location can be calculated based on the measured horizontal and vertical force components converted to the tangential and normal force components. Corresponding experiments were undertaken on a precision sawing machine at a large range. Based on the experimental results and analysis, it is found that the force location increases with the increase of the instantaneous length of contact zone, but it decreases with the increase of depth of cut. The workpiece feed speed and sawblade speed have an influence on the force location. When the instantaneous length of contact zone is close to that of the maximum contact zone, the force location basically acts at 0.6 apart from the bottom of the contact zone, which is due to the shifting behaviour of sawing swarf.

1. Introduction

With the rapid growth use of stone, construction and ceramic materials, sawing with a diamond segmented blade has been most extensively used process of these materials [1-2]. As the wear of diamond sawblade has an obvious influence on the sawing efficiency and cost, there is increasing demand on optimizing the process parameters to reduce wear of tools and production cost. In order to meet the demand, the sawing process is mainly considered in related studies In order to better understand the behavior of diamond sawblade in the sawing process.

Cutting force is one of most important quantities in governing the sawing process besides sawing power and specific energy. The force location not only can indicate to the force distribution along the sawing contact zone, but also reflects the interaction between the workpiece and the sawblade in the contact zone. Hence, many assumptions have been made in order to reveal the force location or force distribution in fixed abrasive machining. The force was firstly assumed to be a uniform distribution and its location acts at 1/2 apart from the bottom of the contact zone in a shallow depth of cut [3]. For the big error in deep depth of cut, it was further assumed to a triangular distribution and its location acts at 2/3 apart from the bottom of the contact zone [4]. Based on such assumption, better results can be obtained, and it was further used in temperature calculation and prediction [4-5]. Therefore, it is of most important to reveal the force location in the machining process in order to better understand the machining mechanism besides controlling and predicting the machining process. In sawing, most scholars were focused on the steady sawing process, but it is hard to reveal the characteristics of sawing force location due to the statistical sawing contact zone. As the unsteady sawing stages have a dynamic sawing contact zone, which provides the possibility for revealing the characteristics of force location.

The present paper demonstrates a method to calculate the force location in the unsteady sawing stage consisting of the cut-in and cut-out sawing stages. According to the measured sawing force components, the characteristics of force location were further studied and analyzed, which can give a better understanding of the interaction between the workpiece and the sawblade in the contact zone.

2. Method of force location

A typical sawing process is shown in Figure 1, it can be seen that the sawblade starts to engage the workpiece at position *A* at time of t_1. With the movement of the sawblade, the contact arc length increases with the increase of the instantaneous depth of cut. As the sawblade contacts the workpiece at position *B* at the time of t_2, the contact arc length reaches its maximum value l_c ($l_c = (a_p d_s)^{1/2}$, here a_p is depth of cut and d_s is the sawblade diameter). Along with the sawing process, the contact arc length keeps constant before the sawblade reaches position *C* at time of t_3. Then, the contact arc length decreases with the movement of the sawblade. When the sawblade reaches position *D* at time of t_4, the contact arc length is decreased to zero. During the sawing process, the contact arc length is changing from position *A* to position *B* (or from time t_1 to t_2), which process stage is named as the cut-in stage. Accordingly, it is named as the cut-out stage from position *C* to position *D* (or from time t_3 to t_4). It can be found that the sawing force increases with the increasing contact arc length from zero to l_c in the cut-in stage; whereas the sawing force decreases with the decreasing contact arc length from l_c to zero in the cut-out stage. As to the steady sawing stage, the sawing force reaches its steady-state value.

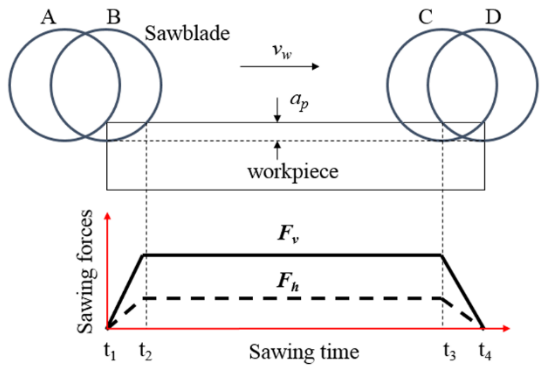


Figure 1. A typical process of a sawing pass.

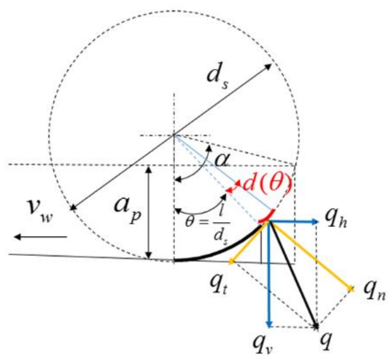


Figure 2. Relationship of the sawing force components.

It is known that the sawing forces are usually studied by measuring the horizontal and vertical force components, and the two forces are further converted to the tangential and normal force components in order to reveal the sawing mechanism. It is assumed that the sawing force is distributed continuously on the sawblade surface along the contact arc length. According to the measured horizontal component $F_h(l)$ and the vertical force component $F_v(l)$ along the contact arc length l, the corresponding horizontal force distribution $q_h(l)$ and the vertical force distribution $q_v(l)$ along the contact arc length l can be given as

$$q_h(l) = \frac{dF_h(l)}{dl} \tag{1}$$

$$q_v(l) = \frac{dF_v(l)}{dl} \tag{2}$$

Based on the relationship of the sawing force components in the sawing contact zone shown in Figure 2, the tangential distribution $q_t(l)$ and the normal force distribution $q_n(l)$ can be obtained as

$$q_t(l) = q_v(l)\sin(\theta) - q_h(l)\cos(\theta) \tag{3}$$

$$q_n(l) = q_v(l)\cos(\theta) + q_h(l)\sin(\theta) \tag{4}$$

where θ is the angle of the instantaneous contact zone ($\theta = l/d_s$), and d_s is the diameter of the sawblade.

Based on the tangential and normal force distributions, the tangential force component $F_t(l)$ and the normal force component $F_n(l)$ are the integral of the corresponding load acting along the contact arc l, which can be calculated as

In the cut-in stage:

$$F_t(l) = \int_{l_c - l}^{l_c} q_t(l)\,dl \tag{5}$$

$$F_n(l) = \int_{l_c - l}^{l_c} q_n(l)\,dl \tag{6}$$

In the cut-out stage:

$$F_t(l) = \int_0^{l} q_t(l)\,dl \tag{7}$$

$$F_n(l) = \int_0^{l} q_n(l)\,dl \tag{8}$$

Based on the sawing forces of $F_t(l)$, $F_n(l)$, $F_h(l)$ and $F_v(l)$, the force location $k(l)$, indicating the position of resultant force in the sawing contact zone, can be given as [6]

$$k(l) = 2\tan^{-1}\left(\frac{F_t(l) - F_h(l)}{F_n(l) + F_v(l)}\right) \Big/ \cos^{-1}\left(1 - \frac{2a_p}{d_s}\right) \tag{9}$$

Thus, the force location can be revealed in the cut-in and cut-out stages during the sawing process, which is helpful to understand the interaction in the sawing contact zone.

3. Experimental procedure

Sawing experiments were carried out on a HPSM-1 machine in the down mode, as shown in Figure 3. A diamond impregnated sawblade was used to cut stone. The diameter of the sawblade is 600 mm with forty-two diamond segments. The dimension of diamond segments is 40 mm in circumferential length, 4.0 mm in width and 10.0 mm in height. The size of diamond used in fabricating segments is about 512 μm, and the concentration of grains in segments is about 35%. The stone used in the present work is natural gray granite, the mineral composition and properties of the granite is shown in Table 1.

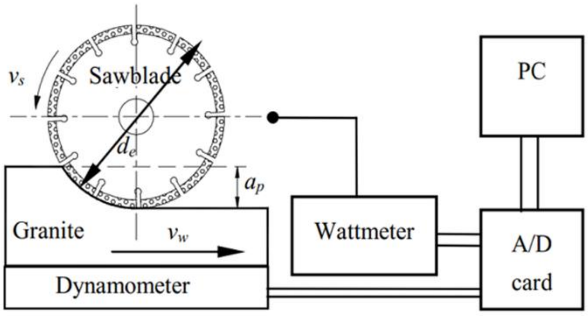


Figure 3. Illustration of experimental set-up.

Table 1. Mineral composition and properties of grey natural granite.

Major minerals				Shore hardness (HS)	Compressive strength (Mpa)	granite density (gcm^{-3})	Particle size
Quartz (%)	Feldspar (%)	Plagioclase (%)	Others (%)				
25	15	55	5	92.5	185	2.7	Medium

Table 2. Sawing conditions in the work.

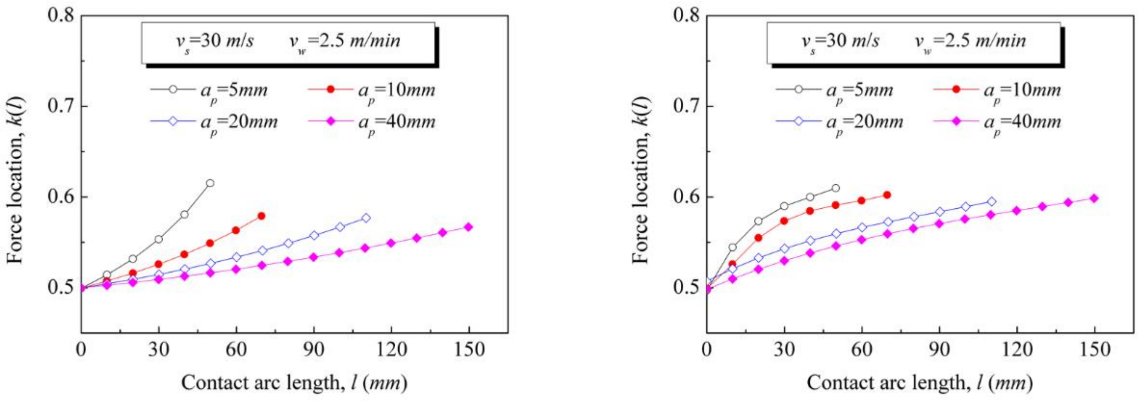
Sawblade speed v_s (ms^{-1})	Workpiece speed v_f($mmin^{-1}$)	Depth of cut a_p (mm)
30, 40, 50, 60	2.0, 2.5, 2.8, 5.0	5, 10, 20, 40

In the experiments, the horizontal and vertical force components were measured by a dynamometer (Kistler 9257BA). The consumed power was measured by an ammeter (GX-3). The sawing forces and power signals were acquired at a sampling frequency of 1 kHz by a personal computer after passing through an A/D board. And the final output of the sawing forces and power were filtered at a cut-off frequency of 20Hz. The processing parameters used in experiments are shown in Table 2.

4. Results and discussion

4.1. Depth of cut

Figure 4 shows the variations of force location under different depth of cut in the cut-in and cut-out sawing stages. It can be seen that the value of force location increases with the increase of the instantaneous contact arc length in both cut-in and cut-out stages, but it increases more rapidly in the cut-in sawing stage than that in the cut-out sawing stage. With the depth of cut increases, the value of force location decreases in both cut-in and cut-out stages.



(a) Cut-in stage (b) Cut-out stage

Figure 4. The variations of force location under different depth of cut.

It can be further found that the value of force location ranges from about 0.499 to 0.615 in the cut-in sawing stage, but it ranges from about 0.497 to 0.609 in the cut-out sawing stage. With the same depth of cut, the value of force location is a little smaller in the cut-in sawing stage than that in the cut-out sawing stage, which is due to different interaction status between the sawblade and the workpiece. In the cut-in sawing stage, the sawblade firstly contacts the workpiece at the top the contact zone, the contact arc increases with the increasing instantaneous depth of cut. The sawing swarf can be more easily ejected from the sawing zone due to the interaction occurs at the top of the contact zone and the incomplete contact zone. Whereas in the cut-out stage, the sawing swarf only can be ejected from the bottom of the sawing zone due to the relatively complete contact zone. Based on the variation of force location shown in Figure 4, it can be demonstrated that the force location shifts from the middle to the top of the sawing zone, and basically near 2/3 apart from the bottom of sawing zone. This phenomenon indicates that the force tends to be a uniform distribution at a very shallow depth of cut, but it tends to be a nearly triangular distribution at a deep depth of cut.

4.2. Workpiece feed speed
The variations of force location under different workpiece feed speed in the cut-in and cut-out stages are shown in Figure 5. It can be also observed that the value of force location increases with the increase of the instantaneous contact arc length in both cut-in and cut-out stages, but it increases more rapidly in the cut-out sawing stage than that in the cut-in sawing stage. With workpiece feed speed increases, the value of force location basically decreases in both cut-in and cut-out stages.

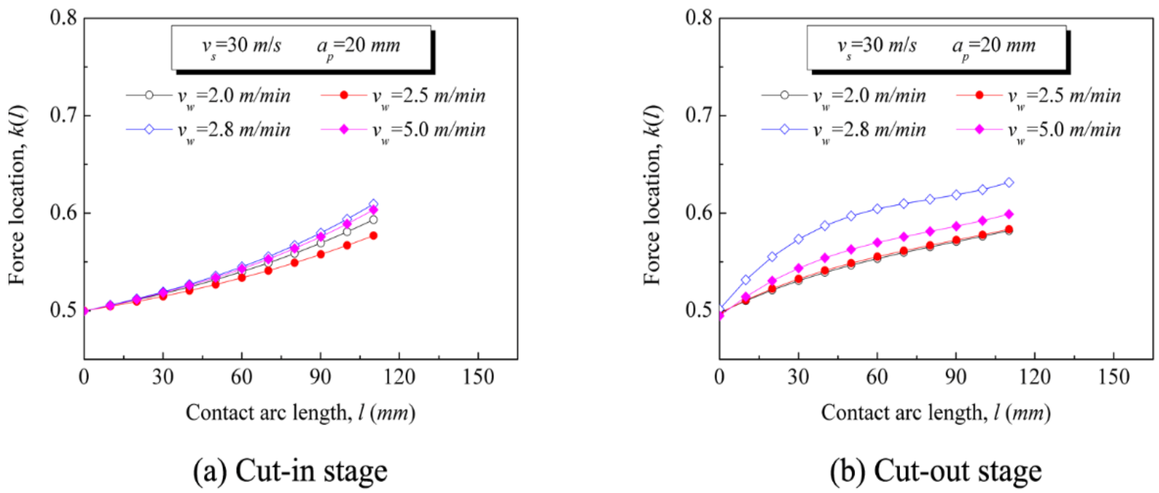


Figure 5. The variations of force location under different workpiece feed speed.

Based on Figure 5, it can be further found that workpiece feed speed have a little influence on the force location in the cut-in sawing stage, but it has an obvious influence on the force location in the cut-out stage, this is due to the different interaction and swarf ejecting behavior as discussed in the section of depth of cut. With workpiece feed speed increases, the value of force location basically decreases, which value ranges from 0.499 to 0.593 for the cut-in sawing stage, and from about 0.497 to 0.632 for the cut-out sawing stage. The decreasing force location is due to the increased material removal rate when workpiece feed speed increases. Thus, higher material removal rate means more sawing swarf generated in the sawing zone, and the swarf is shifting before it ejects from the contact zone. Due to the shifting behavior in the contact zone, the force distribution is accordingly changed, and finally leads to force location more near to the bottom of the sawing contact zone.

4.3. Sawblade speed
Figure 6 shows the variations of force location under different sawblade speed in the cut-in and cut-out sawing stages. It can be seen that the value of force location increases with the increase of the instantaneous contact arc length in both cut-in and cut-out stages, but it increases more rapidly in the cut-out sawing stage than that in the cut-in sawing stage, which is much similar with that shown in Figure 4. With sawblade speed increases, the value of force location increases in both cut-in and cut-out stages.

Based on Figure 6, it can be further found that the value of force location ranges from about 0.499 to 0.577 in the cut-in sawing stage, but it ranges from about 0.497 to 0.632 in the cut-out sawing stages. The difference of force location is mainly due to the different interaction in the contact zone as stated above. However, the value of force location basically increases with the increase of sawblade speed in the cut-out sawing stage, which is due to the great friction effect caused by the sawblade speed. As demonstrated by Xu et al. [6-8], the increase of sawblade speed will increase the friction effect in the actual sawing process, which will subsequently lead to an increase in sawing power consumption.

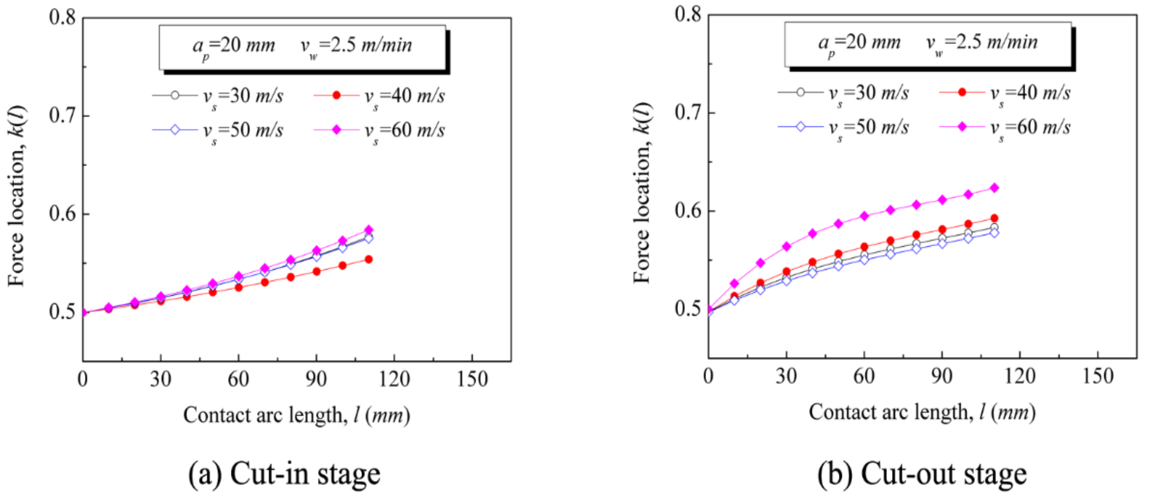


Figure 6. The variations of force location under different sawblade speed

According to the influence of depth of cut, workpiece feed speed and sawblade speed on the force location, it can be reported that the force location will move from the middle to the top of the contact zone when the sawblade speed increase, but it move from the top to the middle of the contact zone when depth of cut and workpiece feed speed increase, in other words, the material removal rate increases. Compared with the three processing parameters, it can be further found that depth of cut governs the force location greatly, later is sawblade speed, and the last is workpiece feed speed. Compare with the two unsteady sawing stages, it can be found that the difference in force location is mainly due to the different interaction between the sawblade and the workpiece. In the cut-in sawing stage, the sawing swarf is more easily and early to ejected from the bottom of the contact zone due to the instantaneous incomplete sawing zone; but it is hard to eject from the sawing zone in the cut-out sawing stage due to its complete shifting behavior along the contact zone. Therefore, reasonable swarf shifting behavior can be taken into account by optimally designing sawblade structure besides optimal processing parameters adopted in sawing.

5. Conclusions

The present work demonstrates a method to calculate the force location based on the measured horizontal and vertical force components in the unsteady sawing stages. Based on the corresponding sawing experimental results, the influence of depth of cut, workpiece feed speed and sawblade speed on the force location were further analyzed and discussed, and the main conclusions are summarized as follows:

- The location of force acts at middle of the contact zone when depth of cut is very small, it will move from the middle to the top of the contact zone when depth of cut becomes larger. With the increase of depth of cut, the force location is about 0.6 apart from the bottom of the sawing zone.

- The value of force location decrease with the increase of workpiece feed speed, but it increases with the increase of sawblade speed. Compared with depth of cut, the influence of workpiece feed speed and sawblade speed on the force location is a little smaller.
- The difference of force location in the cut-in and cut-out sawing stage is due to the different ejecting behavior of sawing swarf, which swarf can be more easily and earlier ejected from the contact zone in the cut-in sawing stage.
- Under the complete sawing contact zone, the value of force location basically ranges from 0.566 to 0.632, which indicates the obvious influence of the sawing swarf in the contact zone.

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