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To cite this article: Z H Peng and C F Fang 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **504** 012112

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Study on force distribution and its location in granite sawing

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Abstract. The present work proposed a model of the location of resultant force based on tangential force distribution. Afterwards, the actual location of resultant force was calculated based on the analysis of the force components in the sawing contact zone. Based on the experimental results, it is found that the distribution coefficient and the location of the resultant force are both great influenced by depth of cut and workpiece feed speed except sawblade speed. The value of the distribution coefficient ranges from 1.375 to 0.416, and the location of the resultant force ranges from 0.727 to 0.568, which both decrease with the increase of depth of cut and workpiece feed speed. Furthermore, a good corresponding relationship between the location of resultant force and the distribution coefficient was obtained, which not only validates the force location model but also further reveals the characteristics of force distribution and its location in the contact zone.

1. Introduction

Sawing with circular diamond sawblade is an important technology in cutting natural stone, construction, ceramic materials, etc., which is due to its advantages of high cutting efficiency and low cost [1]. Since numerous diamond grains participating in cutting a small chip of materials in sawing, the sawing process is very complex. With the increasing wear of diamond grains and the segment matrix, the sawing force and power increase gradually. Accordingly, the machining efficiency and quality also decrease gradually. Therefore, it is of most importance to clarify the distribution force or power in sawing in order to reveal the sawing mechanisms.

In the past few decades, diamond sawing technology has been developed at a high speed, new sawing technologies, such as multi-circular blade sawing, large-circular blade sawing, robotic sawing, etc., have been put forward [2]. Scholars at home and abroad have also been carrying out many studies on the sawing mechanism. In order to better control the sawing process, sawing forces and power were mainly focused in sawing besides wear of diamond tools. The forces were firstly assumed to be uniform distribution in the sawing zone, and it was concluded that the location of the resultant force acts at the middle of the contact zone [3-4]. Unfortunately, big error occurs in force or power prediction when sawing at deep depth of cut. Then, further assumption was made that the force acting along the contact zone probably trends to be triangular distribution due to the undeformed chip thickness increasing from zero at the bottom to h_{max} at the top in the contact zone. Based on this hypothesis, the location of resultant force was found to be located at 2/3 apart from the bottom of the contact zone [5]. Based on this, the force was assumed to be a triangular distribution, and it was found that a better prediction result can be obtained, which is most used in temperature calculation and prediction [6]. However, sawing with diamond sawblades is a dynamic process, which is directly

related to the machining parameters besides material properties and tool morphology. In effect, the location of resultant force basically varies due to the big depth of cut and the effect of sawing swarf [7]. Therefore, it is of most importance to reveal the characteristics of varied location of resultant force in sawing in the aspects of helping to model and predict forces, power, etc.,

This work intends to reveal the characteristics of the location of resultant force during the sawing process. The model of the location of resultant force was established based on the tangential force component analysis. Corresponding sawing experiments were conducted. Based on the experimental results, the influences of sawing parameters on the distribution coefficient and the location of resultant force were further analysed and discussed.

2. Model of the location of resultant force

Circular Sawing is typically characterized by numerous grains participating in cutting chips of small volume of materials. The chip removed by a single grain is generally regarded to an undeformed shape, which is traditionally described as the undeformed chip thickness to reveal the cutting degree of grains. Based on the report that cutting force have an exponential relationship with its depth of cut [8], a power model based on tangential force was proposed by Huang et al. [9], which is given as

$$P = k v_s^{1-x} v_w^{x} a_p^{(1+x)/2}$$

(1)

where a_p is the depth of cut adopted in sawing. v_w is the workpiece feed speed. v_s is the peripheral speed of the sawblade. k and x are the coefficients need to be determined by the sawing conditions.

Since sawing power is the amount of the energy consumed per unit time in sawing, the tangential force component F_t can be calculated as

$$F_t = \frac{P}{v_s}$$

(2)

In sawing, the length of the sawing contact arc l_c is approximately equal to the chord length of the contact zone, and it can be described as

$$l_c = \left(a_p d_e\right)^{1/2}$$

(3)

where d_e is the diameter of the sawblade.

Based on Eqs. (1)~ (3)，the tangential force component $F_t(l_c)$ can be written as

$$F_t\left(l_c\right) = \frac{k}{d_e^{(1+x)/2}} \left(\frac{v_w}{v_s}\right)^x l_c^{1+x}$$

(4)

Then, the tangential force distribution $q_t(l)$ along the contact zone l can be obtained as

$$q_t\left(l\right) = \frac{dF_t\left(l\right)}{dl} = \frac{(1+x)k}{d_e^{(1+x)/2}} \left(\frac{v_w}{v_s}\right)^x l^x$$

(5)

Assume that the location of the resultant force is located at K apart from the bottom of the contact zone. Then, the value of K can be calculated based on the moment of force, which can be given as

$$F_t\left(l_c\right) K l_c = \int_0^{l_c} q_t\left(l\right) l\,dl$$

(6)

According to Eq. (6), the location of the resultant force K can be obtained as

$$K = \frac{x+1}{x+2}$$

(7)

It can be found based on Eq. (7) that the value of K is related to the distribution coefficient x, which is further determined by the sawing conditions.

3. Experimental details

Circular sawing experiments were undertaken on a high precision HPSM-1 sawing machine in the down mode. The sawblade used in experiments was made by diamond impregnated segments brazed onto the periphery of a circular steel core. The diameter of the sawblade was 600 mm with forty-two diamond segments. The dimension of segments is 40 mm in circumferential length, 4.0 mm in width and 10.0 mm in height. Diamond grains used in fabricating segments are with an abrasive size of 425~600 µm and 35% concentration. Natural gray granite was used as the sawing workpiece material, which consists of approximately 25% quartz, 15% alkaline feldspar, 55% plagioclase and 5% for others. During the sawing process, sawing forces, including the horizontal force component F_h and the vertical force component F_v, were measured with a Kistler 9257BA piezoelectric platform dynamometer. The sawing power was measured by a GX-3 ammeter connected to the spindle motor. 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 by a Matlab program. The experimental set-up for measuring sawing forces and power is illustrated in Fig. 1.
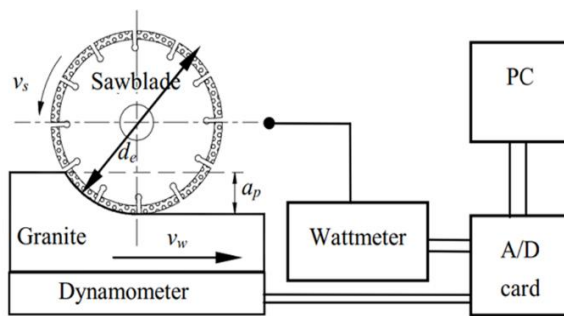
Figure 1. Illustration of experimental set-up.
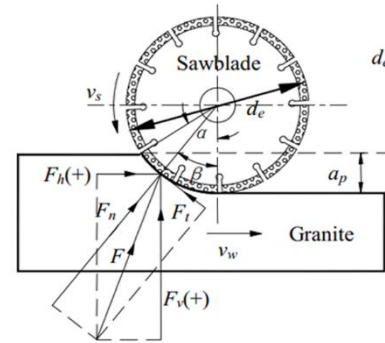
Figure 2. Relationship of force components.

Table 1. Sawing conditions.

Sawblade speed v_s (ms^{-1})	Workpiece speed v_f (mmin^{-1})	Depth of cut a_p (mm)
30, 40, 50	1, 2, 3	5, 10, 15, 20

Based on the sawing power measured in sawing, the tangential force component F_t can be obtained according to the relationship of $P=F_t v_s$. Together with the measured horizontal force component F_h and the vertical force component F_v, the normal force component F_n can be calculated based on the relationship of the resultant force $F_t^2+ F_n^2 = F_h^2+ F_v^2$. With the four force components, the forces acting along the sawblade surface at the contact of length l_c in the down cutting mode can be illustrated in Fig. 2. Accordingly, the location of the resultant force K can be calculated based on the measured forces and power under the specific sawing conditions, which can be given as [7]

$$K = 2\tan^{-1}\left(\frac{F_t - F_h}{F_n + F_v}\right)\Big/ \cos^{-1}\left(1 - \frac{2a_p}{d_e}\right) \tag{8}$$

Series of sawing experiments were conducted to obtain the location of the resultant force K. To keep a constant working state of segment surfaces, the sawblade was dressed by cutting refractory bricks firstly. In the sawing experiments, sawblade speed v_s, workpiece speed v_w and depth of cut a_p were taken into account in a large range, as shown in Table 1.

4. Results and discussion

4.1. Distribution coefficient x

Through using the regress method, the distribution coefficient x under different sawing conditions can be obtained based on the measured sawing power, the results are shown in Fig. 3. It can be observed that the distribution coefficient x decreases sharply with the increasing depth of cut a_p when fixing the sawblade speed v_s and the workpiece feed speed v_w. The x value basically ranges from 1.375 to 0.416. When fixing the same sawblade speed v_s and depth of cut a_p, the distribution coefficient x gradually decreases with the increasing workpiece feed speed. But, the distribution coefficient x is basically not influenced by the sawblade speed v_s, which value ranges from 0.617 to 0.497.
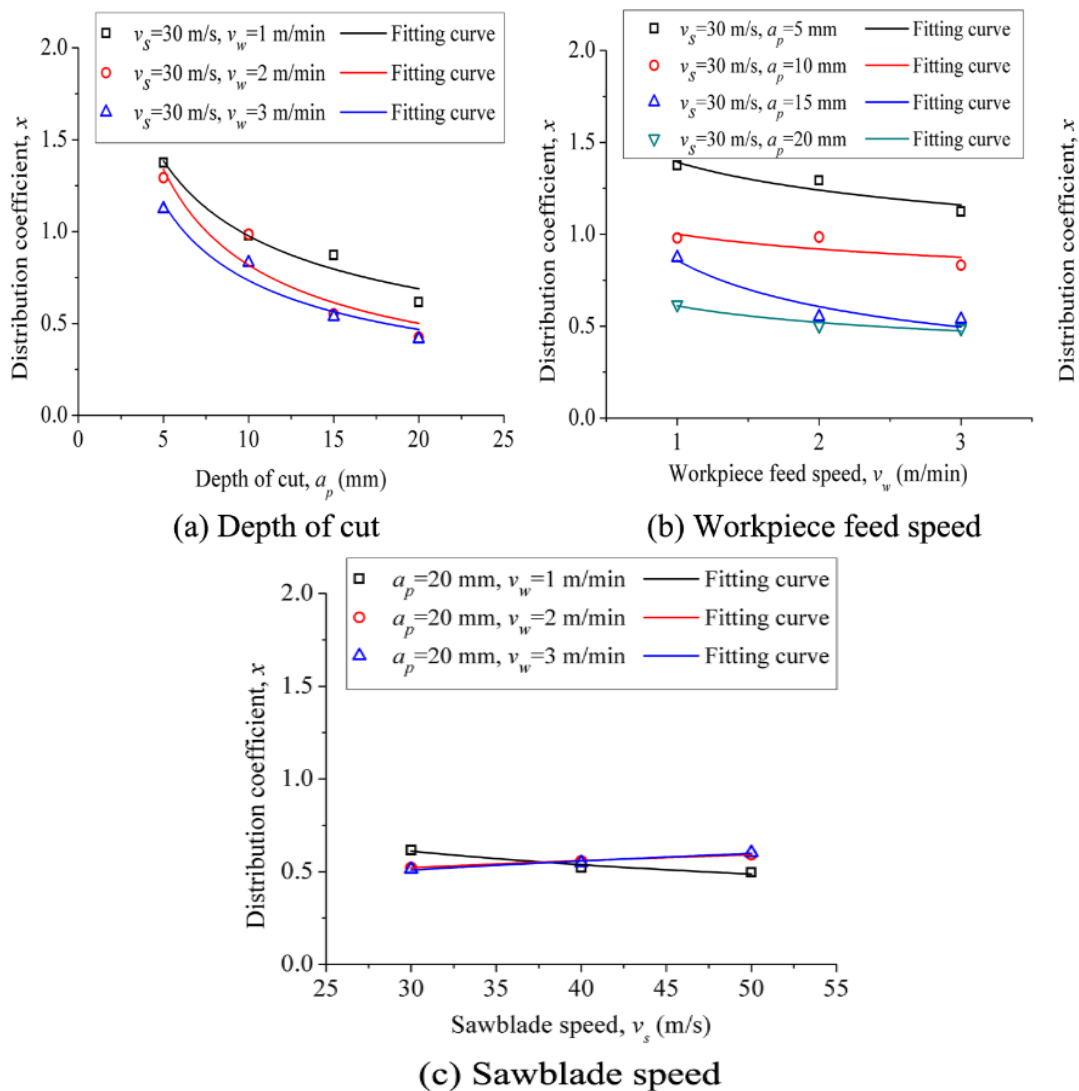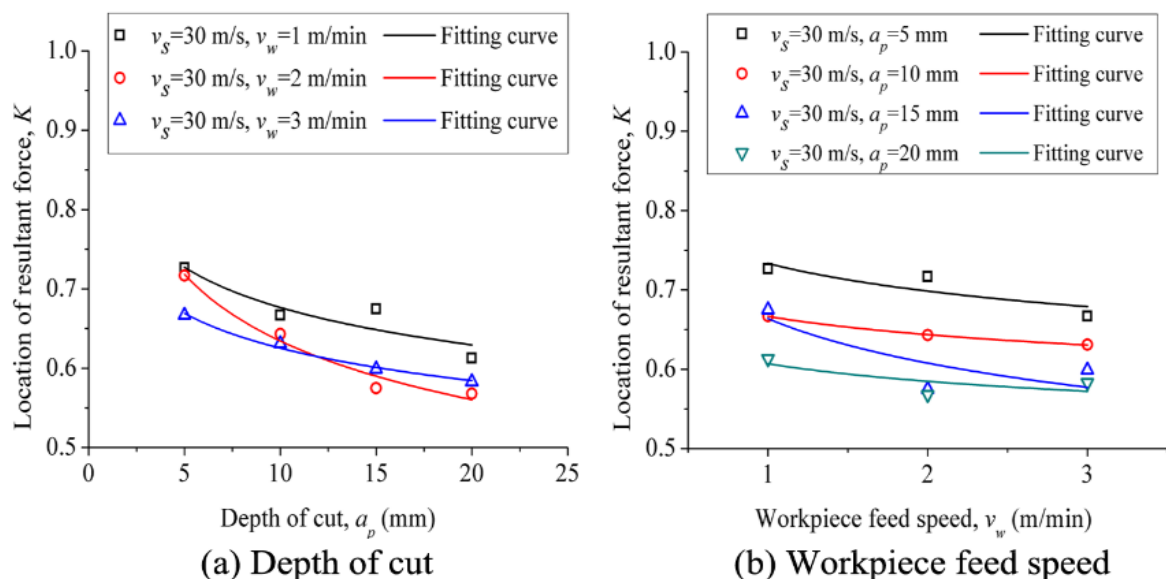

Figure 3. Characteristics of distribution coefficient x under different sawing conditions.

Based on the results shown in Fig. 3, it can be found that the degree of the influence of depth of cut, workpiece feed speed and sawblade speed on the distribution coefficient gradually decrease. The obvious influence of depth of cut and workpiece feed speed on the distribution coefficient indicates that the material removal rate Q_w ($Q_w = a_p v_w$) significantly affects the sawing process. A higher material removal rate means a bigger undeformed chip thickness, and the force on a single grain trend to be a triangular distribution. Moreover, a higher material removal rate also means more sawing swarf needs to be ejected from the contact zone, secondary crushing and friction will occur when these chips move along the contact zone, and this will results in a more uniform distribution of forces along the contact zone. Hence, the distribution coefficient is basically determined by the undeformed chip thickness and the swarf friction in the sawing zone. As the chip thickness and swarf friction varies in sawing, they both affect the distribution coefficient comprehensively.

4.2. Location K

Based on the experimental results, the location of resultant force was calculated based on Eq. (8). Fig. 4 shows the characteristics of the location of resultant force under different sawing conditions. It can be seen that the value of K decreases with the increasing depth of cut and workpiece feed speed, but it changes little with the increase of sawblade speed. The value of K ranges from about 0.727 to 0.568.

Based on the results shown in Fig. 4, it can be further found that the location of resultant force is obviously influenced by depth of cut and workpiece feed speed. Although the value of K decreases with the increase of depth of cut and workpiece feed speed, it basically does not vary with the increase of sawblade speed. This phenomenon is similar with the relationship between the distribution coefficient and sawing parameters. The small value of K means the location of resultant force acts near the bottom of the contact zone, and the force trend to be close to a uniform distribution. Based on the smallest value of $K=0.568$, the force along the contact zone is not distributed uniformly. Based on the influence of swarf friction, it can be revealed that the influence of swarf friction becomes more obviously when depth of cut and workpiece feed speed increase, and this leads to more swarf chips moving along the contact zone until they all have been ejected from the contact zone. The shifting behavior of swarf chips changes the force distribution, and leads to the location of resultant force moving near to the bottom of the contact zone. With the increase of sawblade speed, the value of K changes little. This is due to the influence of sawblade speed on the chip thickness and shifting behavior. A higher sawblade speed means smaller chips. The smaller chips can shift more smoothly along the contact zone and finally ejects from the bottom, and especially the increased sawblade speed makes swarf chips easier to shift.


(a) Depth of cut   (b) Workpiece feed speed

(c) Sawblade speed
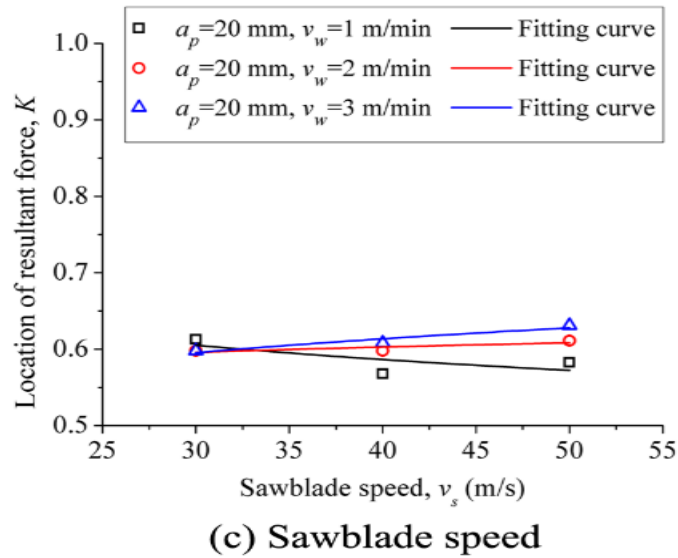
Figure 4. Characteristics of location of resultant force *K* under different sawing conditions.

4.3. Relationship analysis

Based on the results of the location of resultant force and the distribution coefficient, the relationship between them were further analyzed. Fig. 5 shows the location of resultant force versus the distribution coefficient. It can be found that the location of resultant force increases with the increase of the distribution coefficient. The bigger distribution coefficient indicates the location of resultant force acts far away from the bottom of the contact zone, and this leads to the force acts along the contact zone trend to be close to a triangular distribution.
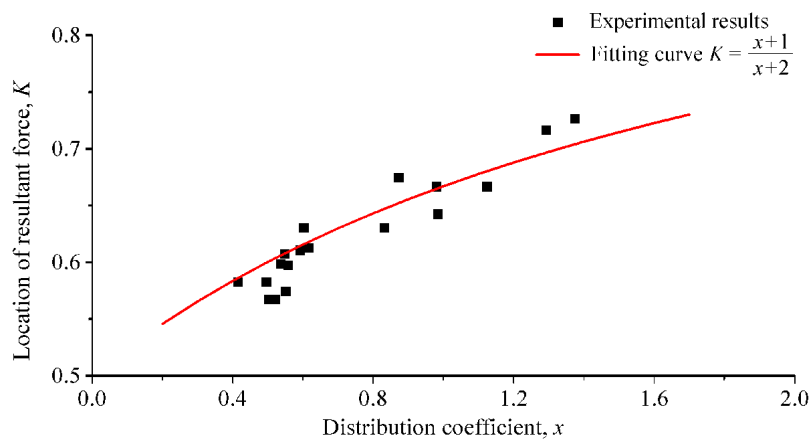
Figure 5. Location of resultant force *K* versus the distribution coefficient *x*.

According to Eq. (7), a fitting curve of *K* based on the results of the distribution coefficient was also plotted in Fig. 5. It can be observed that there is a good correspondence between the location of resultant force and the distribution coefficient. The results not only reveal that the force acts at the sawing contact zone trends to be an exponential distribution determined by the distribution coefficient, but also indicate that the distribution coefficient can be used to evaluate the location of resultant force.

Based on the above analysis, it can be concluded that the sawing force trends to be an exponential distribution along the contact zone, which is determined by the chip thickness cutting by abrasive

grains and the shifting behavior of swarf chips moving in the contact zone. With the increase of depth of cut and workpiece feed speed, more swarf chips moves along the contact zone, and finally leads to the location of resultant force shifts from the top to the bottom of the contact zone. With the increase of sawblade speed, swarf chips become much smaller. They can move through the contact zone more easily, this leads to little influence on the location of resultant force.

5. Conclusions
The present work proposed a model in order to reveal the actual location of resultant force and the distribution coefficient. Based on the results and discussion, conclusions are summarized as follows:
- Sawing force trends to be an exponential distribution along the sawing contact zone due to the obvious influence of swarf shifting in sawing.
- The values of the coefficient and the location of resultant force both decrease with the increase of depth of cut and workpiece feed speed. The coefficient basically ranges from 1.375 to 0.416, and the location of resultant force ranges from 0.727 to 0.568.
- A good relationship between the location of resultant force and the distribution coefficient was obtained, which can used to reveal the characteristics of force distribution and its location.

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