Evaluation of abrasive grain distribution of the grinding belt based on information entropy

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Abstract. An information entropy theory was proposed to evaluate the abrasive grain distribution over a wide range for abrasive-grain fixed-type tool face. To demonstrate the effectiveness of the proposed method, models with varying abrasive grain number and abrasive grain distribution were prepared, and the abrasive grain distributions were evaluated. The result shows that, as the number of abrasive grains increases, there is a problem with simply increasing the entropy; therefore, the ratio entropy needs to be considered. This makes it possible to relatively evaluate the distribution state of the abrasive grains even when the number of abrasive grains and its distribution are different. Based on this result, the relationship between the abrasive grain distributions on the belt, the grinding ability, and life span of the actual belt were clarified using information entropy. When examining two belts with different life spans, the ratio entropy of the abrasive grain distribution of the surface part involved in the grinding process was found to significantly fluctuate, because of the longer life span of the belt.

Introduction

In this paper, a method of evaluating the abrasive grain distribution of a fixed abrasive type tool face is proposed. As the abrasive grain process differs from a cutting process in terms of the number of micro abrasive grains distributed on the tool surface, it is important to analyze the method of evaluating the distribution state of the abrasive grains. Numerous studies have evaluated the abrasive grain distribution on the work surface of grinding wheels [1, 2, 3]. However, most studies conducted the evaluation in a narrow range with high imaging magnification. Therefore, if the evaluation is conducted in a wide range, the measurement locations need to be changed several times.

In this research, to evaluate the abrasive grain distribution over a wide range, the static transfer method is applied to the tool surface. The transferred abrasive grain distributions were rationally evaluated using entropy theory [4]. The entropy represents the degree of disorderly states according to the definition. Moreover, it is known that disorderly states have high entropy, conversely, when the states exhibit less disorder, the entropy is low. If this concept can be applied to the abrasive grain distribution, the disorder of the abrasive grain distribution and the degree of scattering of the abrasive grains can be reasonably evaluated. Note that this research focuses on a grinding belt. As the grinding process a progress, the abrasive grain distribution of the belt is evaluated in terms of the entropy, and the relationship between entropy and the processing amount (or the life of the belt) is clarified.

Application of information entropy

The combination entropy.

For an abrasive grain located on the grinding belt, two information sources X and Y exist along the belt width direction (x direction) and circumferential direction (y direction), respectively. Let $P(X)$ be the probability that one information source X (x_1, x_2, ..., x_m) is generated, then the information volume $I(X)$ can be obtained as follows.

$$I(X) = -\log_2 P(x) \tag{1}$$

In addition, the entropy will be $H(X)$, expressed as follows.

$$H(X) = -\sum_{i=1}^{m} P(x_i) \log_2 P(x_i) \qquad [\text{bit}] \qquad \text{where } \sum_{i=1}^{m} P(x_i) = 1 \tag{2}$$

Likewise, $I(Y)$ and $H(Y)$ can be expressed.

When information sources X and Y occur simultaneously, the combined entropy of Equations is expressed as follows.

$$H(X,Y) = -\sum_{i=1}^{m} \sum_{j=1}^{n} P(x_i,\ y_j) \log_2 P(x_i,\ y_j) \qquad [\text{bit}] \tag{3}$$

In general, $H(X, Y)$ represents disorder and complexity, and the greater the value, the greater is the disorder.

Calculation example of $H(X, Y)$ with simple distribution model.

Fig. 1 shows the states in which 16 abrasive grains are randomly distributed in the region of points a to d; the region is divided into 16 square boxes, same as the number of abrasive grains. The x and y axes represent the width and circumferential directions of the belt, respectively. First, the number of abrasive grains in each cell is counted, and is divided by the total number of abrasive grains to create a probability distribution.

This information, $H(X, Y)$ is calculated using Equation (3) as follows.

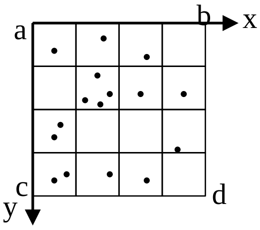
$$H(X,Y) = 5 \times 0 + 8 \times \left(-\frac{1}{16}\log_2\frac{1}{16}\right) + 2 \times \left(-\frac{2}{16}\log_2\frac{2}{16}\right) + 1 \times \left(-\frac{4}{16}\log_2\frac{4}{16}\right) = 3.25$$

If all the abrasive grains are uniformly distributed in the cell, the value of $H(X, Y)$ is 4.00. Thus, when the number of abrasive grains is fixed, $H(X, Y)$ is lower as the distribution is more biased, and $H(X, Y)$ increases as the grain size becomes uniform.

Fig. 2 shows the case wherein the number of abrasive grains differs from the distribution of the abrasive grains. In this case, $H(X, Y)$ is influenced by the number of abrasive grains, i.e. it increases with the increase in the number of abrasive grains. Therefore, if the number of abrasive grains is different, the distribution cannot be simply compared with $H(X, Y)$. Hence, the following equation is defined as the ratio entropy (HR) to take into account the abrasive grain number and its distribution.

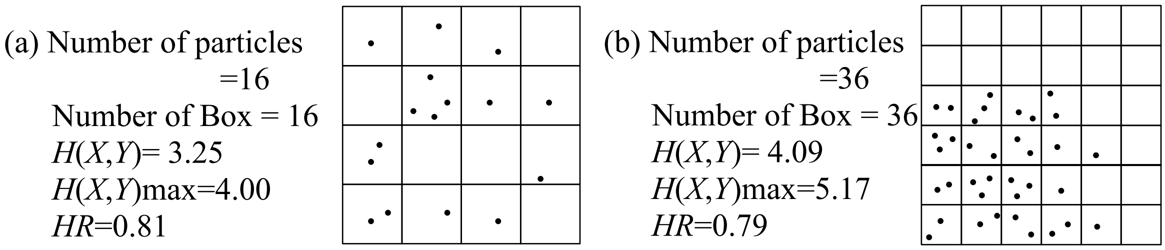
$$HR = H(X,Y)/H(X,Y)_{\max} \tag{4}$$

In Equation (4), the denominator is the entropy for states wherein the number of abrasive grains allocated to each box is the same as the number of boxes. The entropy under this condition is $H(X, Y)_{\max}$. The ratio entropy has a maximum value of 1.0 when the denominator and numerator are equal. The ratio entropy for the distribution model, shown in Fig. 2, was once again determined using this equation. As a result, the ratio entropy of (a) becomes greater than that of (b), which seems to be a reasonable result.



	x_1	x_2	x_3	x_4
y_1	1/16	1/16	1/16	0
y_2	0	4/16	1/16	1/16
y_3	2/16	0	0	1/16
y_4	2/16	1/16	1/16	0

Fig. 1 Schematic and a probability distribution of abrasive distributions



(a) Number of particles =16
Number of Box = 16
$H(X,Y)$= 3.25
$H(X,Y)$max=4.00
HR=0.81

(b) Number of particles =36
Number of Box = 36
$H(X,Y)$= 4.09
$H(X,Y)$max=5.17
HR=0.79

Fig. 2 Examples wherein the number of grains and distribution are both different

Examination with an actual grinding belt

The grinding belt used in this study has a width of 50 [mm] and a perimeter of 915 [mm]. Four areas on this belt were arbitrarily chosen, and the changes in the *HR* with the progress of grinding were tracked. The dimensions of one area were 40 [mm] × 40 [mm].

In this study, the abrasive grain distribution was measured using the transfer method; however, the number of abrasive grains transferred to the film depends on the pushing force. As the pushing force from the top is increased with respects to the film placed on the belt surface of a single layer, it reaches a point where the number of abrasive particles transferred does not increase further. This condition is regarded as the belt base surface. The pressing force is first increased, and the abrasive grain distribution at the belt base surface is examined. Based on this result, the *HR* of the abrasive grain distribution is tracked until the end of the belt life.

The pushing force from the top was increased from 100 to 500 [N], and the increase in the transferred abrasive grains was examined with grinding belt of Alumina zirconia #24. Fig. 3 shows the relationship between the load acting from above and the number of transferred abrasive grains. At 300 [N] or more, the number of abrasive grains is largely constant. This is considered the belt base surface. Loads of 100, 200 and 300 [N] were set to obtain the transfer images in this study. Fig. 4 shows the transfer images of one measurement area of the actual belt.

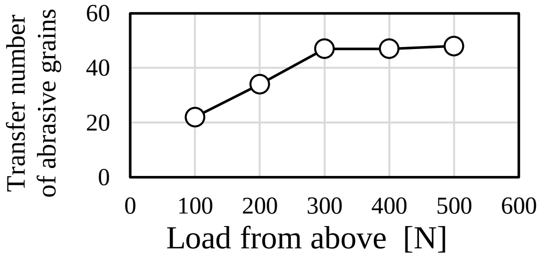


Fig. 3 Change in the number of transferred abrasive grains with respect to the load

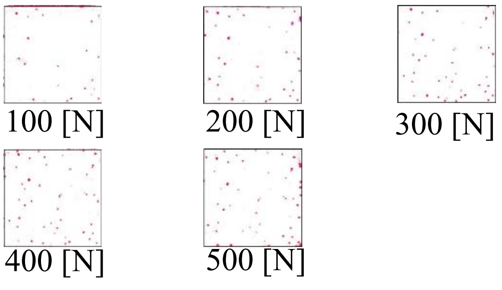


Fig. 4 Transfer images with respect to the load

Grinding experiment and measurement

Table 1 lists the experimental conditions. Fig. 5 shows the experimental apparatus. In the experiment, as the fixed states of the abrasive grains on the new belt surface are unstable, preliminary grinding is carried out for 5 [min], and this is considered the initial condition. Subsequently, the grinding process and the transfer of the abrasive grain distribution were repeated every 10 [min]. This process continued until the grinding amount reduced. A pressure measurement film was used for transferring the belt. In the pressure measurement film, the pressed part exhibits red color. The *HR* was then obtained as the average value data corresponding to the four areas of the belt.

Table 1 Experimental conditions

Grinding belt	RIKEN CORUNDUM Z767 : Alumina zirconia#24 A767 : Black silicon carbide#24 50 [mm] × 915[mm]
Work	S45C (Steel containing 0.45% carbon) 40 [mm] × 40 [mm]
Belt grinder	Processing speed: 470 [m/min] Contact wheel: 100 [mm] × 54 [mm]
Processing load	10 [N] (Weight of work)
Transfer film	FUJIFILM Prescale LLLW

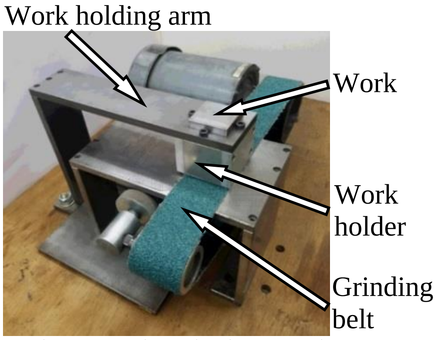
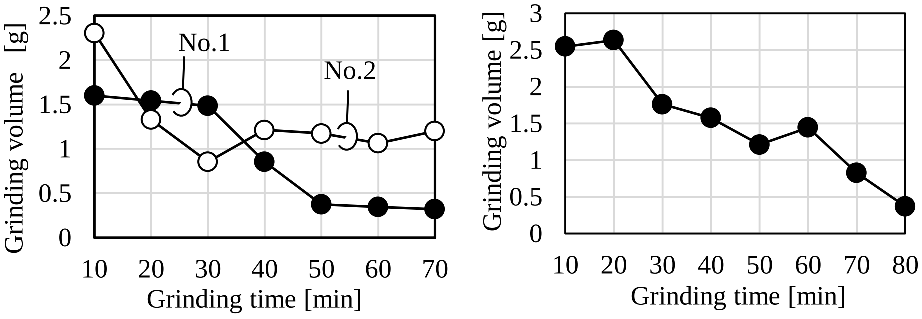


Fig. 5 Belt grinder used for the experiment

Results and discussions

First experiments were carried out with two belts of the same type and grain size (Alumina zirconia#24), but they were different initial *HR* (initial distribution states). And the relationship between the *HR* and the processing amount (or the life of the belt) was clarified. Next experiments were carried out using grinding belts with the different types of abrasive grains （Black silicon carbide#24） .

Fig. 6(a) shows the result of the two belts of alumina zirconia #24, and Fig. 6(b) shows the result of black silicon carbide #24. In Fig. 6(a), the results show that the grinding capacity of belt No. 2 is greater than that of belt No. 1 in the first 10 [min]. In both the cases, the grinding volume decreases overall as the grinding process progresses. Belt No. 1 has lower grinding capacity after 30 [min]. Thereafter, i.e. after 50 [min], the grinding volume decreases considerably compared to the initial state, and this condition is considered as nearly lifetime. On the other hand, belt No. 2 maintains a high grinding capacity even at 60 [min], as opposed to belt No. 1. Similarly, the result pertaining to the belt of the black silicon carbide, shown in Fig. 6(b), is considered as nearly lifetime after 80 [min].



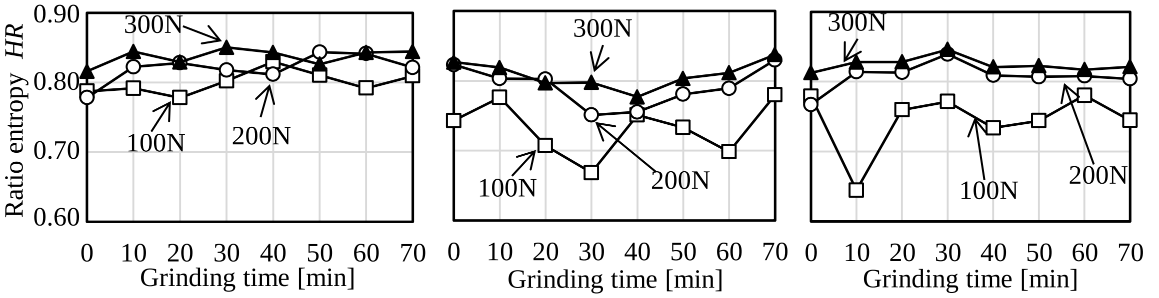
(a) Alumina zirconia #24 (b) Black silicon carbide #24

Fig. 6 Transition of the grinding volume of the two belts

The difference between the belts was compared in terms of the ratio entropy *HR*. Fig. 7(a) and Fig. 7 (b) show the results of alumina zirconia #24. Overall, the *HR* of Belt No. 2(Fig. 7(b)) was found to be lower than that of belt No. 1(Fig. 7(a)). In particular, the *HR* at a load of 100 N fluctuates at 0.75 or lower. This indicates that a slightly biased distribution is more advantageous for the grinding process as opposed to a uniformly dispersed distribution.

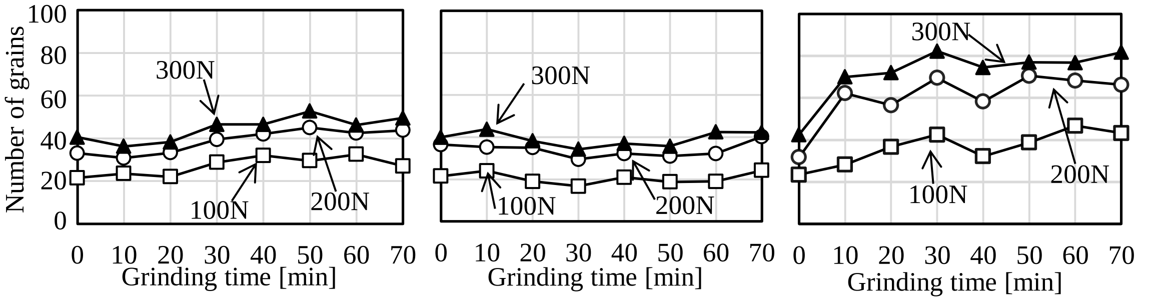
Furthermore, Fig. 8(a) and Fig. 8(b) show the number of transferred abrasive grains. The number of transferred abrasive grains of No. 1 (Fig. 8(a)) seems to slightly increase. In addition, alumina zirconia abrasive grains have high hardness and high toughness. As such, in No. 1, abrasive grains do not drop off or crack; however, abrasion occurs to such an extent that the number of transferred abrasive grains increase. On the other hand, in No. 2 (Fig. 8(b)), as the number of transferred abrasive grains remains the same and as *HR* fluctuates, it is considered that the distribution changes because the abrasive grains fall off.

Fig. 7(c) and Fig.8(c) show the result pertaining to the black silicon carbide abrasive grains with high hardness but low toughness. From Fig. 8(c), the number of abrasive grains increases until a grinding time of 20 [min], and thereafter remains largely constant. In addition, the value of *HR* is lower than about 0.75, which is relatively fluctuating. In the early stages of grinding with the belt of black silicon carbide, cracking, dropping off, and abrasion of the abrasive grains would be thought, and the number of abrasive grains increased. During the constant state, there are changes in the distribution because of the cracking and dropping off of the grains; however, the transfer abrasive grains do not increase. Under all the conditions, shown in Fig. 7, a common observation is that at the final stage of grinding time, the three *HR* values are approaching 0.75 or more, and it can be said that this is approaching the tool life.



(a) Alumina zirconia #24, No.1 (b) Alumina zirconia #24, No.2 (c) Black silicon carbide #24

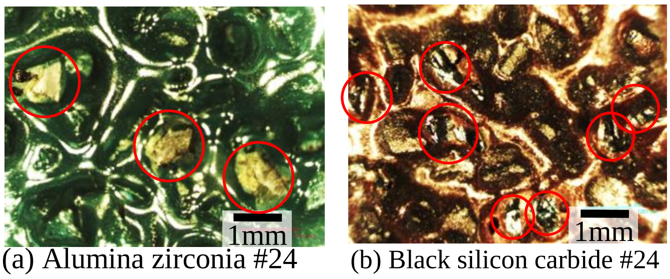
Fig. 7 Relation between *HR* and Grinding time



(a) Alumina zirconia #24, No.1 (b) Alumina zirconia #24, No.2 (c) Black silicon carbide #24

Fig. 8 Change of number of abrasive grains

Fig. 9 shows the state of the abrasive grains on the surface of the tool that has reached the end of its life. Fig. 9(a) shows the belt surface of the alumina zirconia abrasive grain, wherein the abrasive grains are worn out. The average particle diameter of the #24 abrasive grains is 0.8 mm, which is close to the size of the worn-out grains. Fig. 9 (b) shows the black silicon carbide, which has the same average particle size. However, because of cracking and chipping, the abruptly worn-out abrasive grains are not observed, as in Fig. 9(a).



(a) Alumina zirconia #24 (b) Black silicon carbide #24

Fig. 9 Images of abrasive grains on the belt surface after grinding

Conclusions

A new method of evaluating the abrasive grain distribution using information entropy was proposed. The following are the results of this study.

1) A quantitative evaluation was made possible by introducing entropy and the ratio of entropy for models with different abrasive grain numbers and distributions.
2) By comparing the ratio entropy of the belt, the ratio entropy of the abrasive grain distribution of the surface part involved in the grinding process was found to fluctuate repeatedly at an *HR* of 0.75 or lower, because of the long life span of the belt. However, it was revealed that the belt with a shorter life span exhibited a low fluctuation range when it comes to the ratio entropy.

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