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Assessment of the Exit Defects in Carbon Fibre-Reinforced Plastic Plates Caused by Drilling

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ABSTRACT

This paper investigates the formation of the exit defects in carbon fibre-reinforced plates and characterizes their features in terms of drilling conditions. It was found that spalling and fuzzing are the major mechanisms of exit defects. The spalling, consisting of a main region and a secondary region, is caused by chisel and cutting edge actions, in which the former plays a key role. The fuzzing, however, exists in the cutting region where the included angle between the fibre direction of the surface layer and that of the cutting speed is acute. A severer spalling damage corresponds to a high spindle speed, a large feed rate and a great thrust force. Some empirical relationships, including a dimensionless formula, were developed for assessing the characteristic dimension of the spalling damage based on the known drilling conditions.

1. INTRODUCTION

Exit defect is one of the major damages in the drilling of carbon fibre-reinforced plastics (CFRP). The degree of the defect represents the quality of a drilling [1-7], characterised by the so-called spalling at a hole exit, with its size or magnitude determined by the drilling conditions. For example, when drilling a CFRP plate with a twist drill of high-speed steel, it has been found that the spalling damage increases with the feed rate but decreases with the spindle speed. However, the effect of the feed rate is often greater than that of the spindle speed [3, 4]. Some studies [1, 4] reported that the degree of spalling may be minimised by arranging an aluminium or a bakelite plate under the CFRP panel subjected to drilling. In addition, to reduce the exit spalling, it is necessary to control the thrust force, especially at the stage when the chisel edge is penetrating the exit surface of a CFRP plate [1, 3].

However, the investigations above have not explored sufficiently the formation mechanisms of exit defects. As a result, the drilling technology available is unable to avoid the damage and hence allowances of the spalling length (*e.g.*, less than three times the hole diameter) and width (*e.g.*, less than 1.8mm) have been high in the current manufacturing practice [8]. This paper aims to achieve a further understanding of the exit defects in drilling CFRP plates.

2. EXPERIMENTAL DETAILS

The drilling experiment for the exit defect was conducted on a horizontal high-speed drilling machine [9]. Six drill (spindle) speeds and five feed speeds, as listed in Table 1, were taken to examine their effects on the drilling quality. The drills used were 4-facet point solid carbide ones of diameters ϕ4.8mm, ϕ5.5mm, ϕ6mm, respectively. The workpieces were of two kinds of CFRP plates, unidirectional carbon fibre reinforced plastics and multi-directional carbon fibre reinforced plastics, as detailed in Table 2.

To observe and analyse the formation process of an exit defect in drilling, a camera was installed, as shown in Figure 1. The parameter l, which is the average of the spalling lengths at the two sides of the hole exit, l_1 and l_2, i.e.,

$$l = \frac{l_1 + l_2}{2} \tag{1}$$

is defined to assess the magnitude of spalling, as shown in Figure 2.

Table1 Experimental parameters

Spindle speed (rpm)	3000, 6000, 9000, 12000, 18000, 24000
Feed speed (mm/min)	24, 44, 66, 91.2, 120.8
Drill material and geometry	Material: YG6X carbide Geometry: 4-facet point Diameter: ϕ4.8mm, ϕ5.5mm, ϕ6mm

Table 2 Workpiece materials

Multi-directional CFRP	
Carbon fibre	T300 of 7μm in diameter
Matrix	Epoxy resin
Fibre direction	[+45°/0°/-45°/+45°/0°/90°/-45°/0°/90°/0°]s
Fibre volume content	60%
Workpiece thickness	2.5 mm
Unidirectional CFRP	
Carbon fibre	T300, diameter 7μm
Matrix	Epoxy resin
Fibre direction	0°
Fibre volume content	60%
Workpiece thickness	2 mm

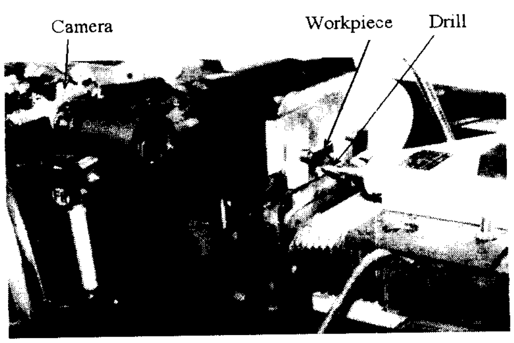


Fig. 1 The experimental set-up of drilling

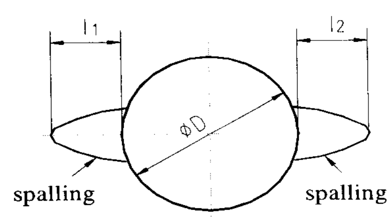


Fig. 2 The spalling

3. OBSERVATION AND DISCUSSION

It was found that the exit defect generally consists of two types of damages, spalling and fuzzing. The following results were obtained by examining the drilling process and the drilled workpieces:

(1) A spalling damage develops along the fibre direction and its dimension is normally bigger than that of the accompanying damage by fuzzing.

(2) The spalling is developed in two phases, the chisel edge action phase and the cutting edge action phase. The first phase begins when the thrust force of the chisel edge onto the exit surface reaches a critical value and ends when the chisel edge just penetrates the plate. By examining the photographs of the exit surfaces and the finished workpieces, it was found that the chisel edge has a strong effect on the formation of the spalling. A small bulge emerges first in the vicinity of the drilling axis and then develops along the fibre direction of the exit surface (Fig. 3 (a)). When the bulge grows to a certain degree, the surface layer splits open, the chisel edge penetrates and the second phase, cutting edge action phase, starts. The spalling damage initiated in the first phase develops further due to the continuous pushing (Fig. 3 (b)) and twisting (Figure 3 (c)) of the cutting edge.

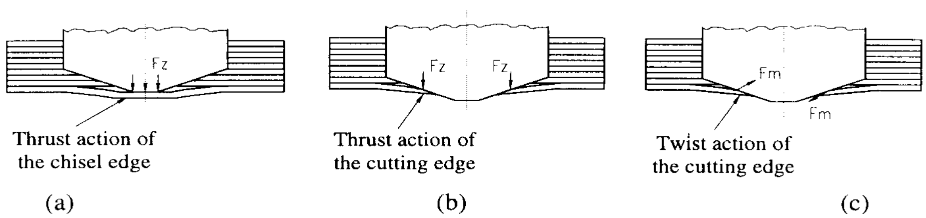
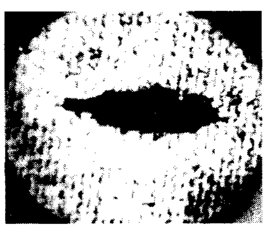
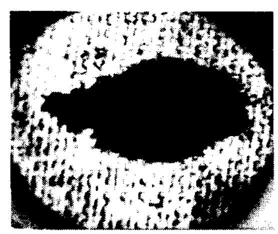


Fig. 3 Schematic of the formation process of the spalling defect

The chisel edge cuts the workpiece material with a big negative rake angle and generates over 50% of the thrust force. Thus the chisel edge plays a key role. The experiment shows that at the moment of the chisel edge penetration, the spalling already grows to a dimension of greater part of its final size. Figure 4(a) shows a spalling at the chisel edge penetration and Figure 4(b) shows the spalling after drilling. We can easily confirm the above observations.



(a) spalling at the chisel edge penetration



(b) spalling after drilling operation

Fig. 4 Spalling at the exit surface generated by a $\phi 6$ carbide drill with the drilling speed of 3000rpm and the feed speed of 91.2mm/min. The workpiece was a multi-directional CFRP plate with the fibre orientation of 0° in its surface layer

Figure 5 qualitatively describes the growth of the spalling damage in the two phases. It shows that the growing rate in the first phase is greater than that in the second phase. If the drilling parameters, such as the feed rate, are appropriately chosen, the drilling force, particularly the thrust force, will become very small at the end of the first phase and the spalling dimension in the phase spalling dimension in the phase will be less than the hole diameter (see the dotted curve in Fig. 5). Then in the second phase, the cutting edges will remove the spalling formed in the first phase and the hole exit after drilling will become spalling-free.

It is found that an exit defect can be characterised by a main region and a secondary region, as illustrated in Figure 6. The main region, which has the maximum spalling, appears radically in the fibre direction as shown. The secondary region is small and is generated in the cutting phase, in which the included angle between the fibre direction and that of the cutting speed is acute. In addition, there often exist small amount of fibres that are not cut off neatly at the edge of the hole in both the main and secondary spalling regions. This defect is called fuzzing, formed by the following causes:

(1) The fibre is not easy to be cut off in the region where the included angle between the fibre direction and that of the cutting speed is acute.

(2) The exterior of the surface layer at the hole exit is a free surface so that the fibres are not subjected to shear deformation.

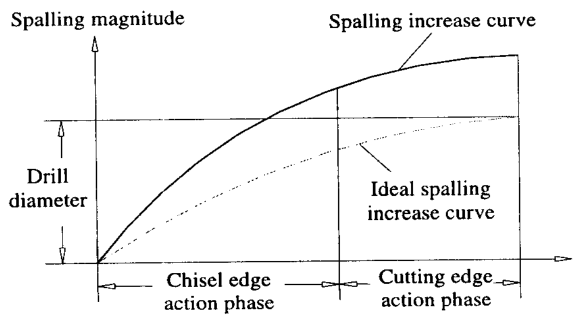


Fig. 5 The development of the spalling defect in the two phases.

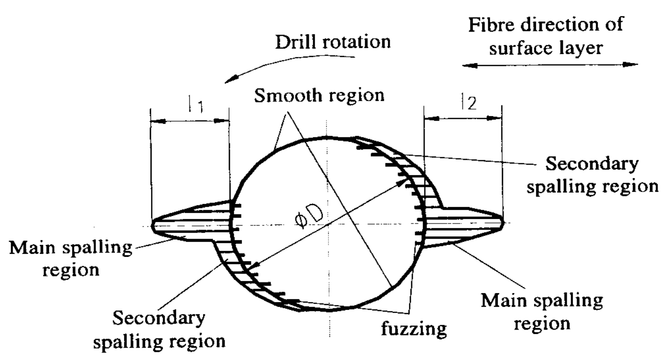


Fig. 6 The characteristics of an exit defect.

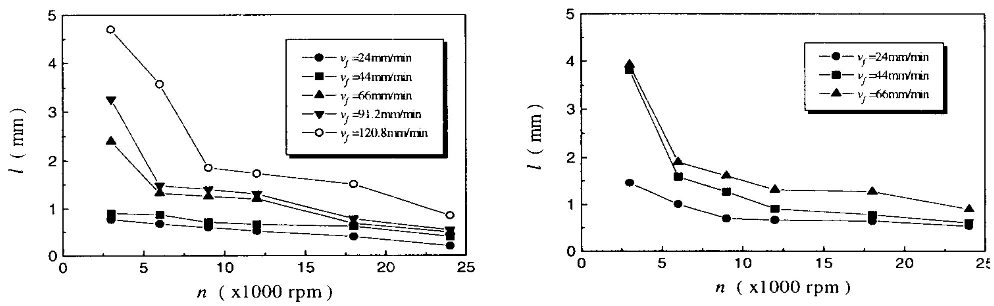
Spalling and fuzzing usually co-exist and both their magnitudes have the same variation tendency, *i.e.*, the bigger the spalling the severer the fuzzing and *vice versa*. However, when the spalling decreases to a certain extent, the fuzzing disappears.

4. EFFECT OF DRILLING CONDITIONS

4.1. Drilling Speed and Feed Speed

Figure 7 shows the size variation of the spalling defect with the drilling speed, n, and feed speed, v_f, for the CFRP plates with unidirectional and multi-directional fibre-reinforcements, respectively. It can be seen that the defect size decreases with n but increases with v_f, no matter what kind of CFRP is. This is similar to the drilling force variation [9].

For the multi-directional CFRP, at a high feed speed of v_f = 66~120.8mm/min, the spalling size decreases quickly, especially at the lower drilling speed. This effect becomes negligible when the feed speed v_f becomes lower, *e.g.*, between 24 and 44mm/min. The same behaviour exists in drilling the unidirectional CFRP. It is thus clear that there are two methods to reduce spalling, *i.e.*, using small feed speed or operating at a high drilling speed. However, a lower feed speed leads to a lower machining efficiency. Thus an operation with a high drilling speed is preferable. By comparing Fig. 7(a) with 7(b), it can also be seen that the spalling in the unidirectional CFRP is generally bigger than that in the multi-directional CFRP under identical cutting conditions. It is understandable because in the former composite the constraints among fibres are much weaker.



(a) multi-directional CFRP (b) unidirectional CFRP

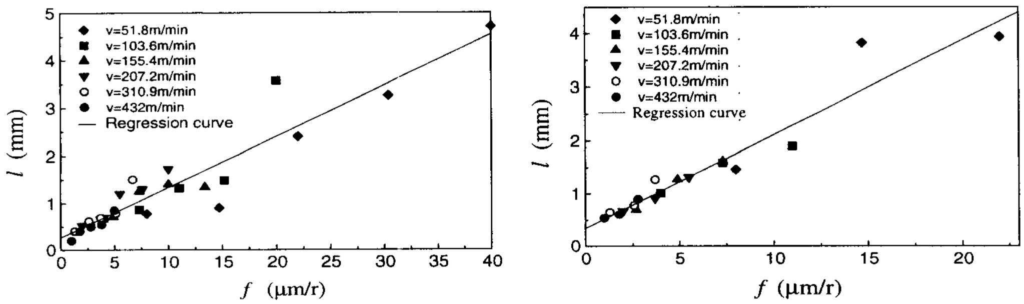
Fig. 7 The size variation of the spalling defect with drilling speed and feed speed. The drill diameter is ϕ5.5mm.

4.2. Cutting Speed and Feed Rate

Figure 8 shows the spalling variation with cutting speed v and feed rate f when drilling multi-directional CFRP and unidirectional CFRP respectively, where v is the linear speed at the outer edges of the cutting lip. It can be seen that the size of the spalling defect increases with the feed rate. It is also interesting to note that all the experimental data with various cutting speeds (51.8~432m/min) collapse to a line and it is particularly true when f is low. This seems to conclude that the feed rate is a dominant variable for spalling defects. A similar phenomenon was observed in the variation of the drilling force [9]. This will become clearer if our discussion in the previous section is recalled, *i.e.*, spalling is caused by the chisel and cutting edge actions and drilling forces (thrust force and torque) reflect the overall response of the workpiece material in the two phases. By ignoring the influence of cutting speed, the linear relationship between the feed rate and the spalling can be expressed as two empirical equations when a linear regression is carried out, that is,

$$l = 0.26 + 0.11 \cdot f \qquad \text{for multi-directional CFRP}$$
$$l = 0.34 + 0.18 \cdot f \qquad \text{for unidirectional CFRP}$$

where l is the spalling size in millimeter defined by Eq. (1) and f is the feed rate in μm/rpm.

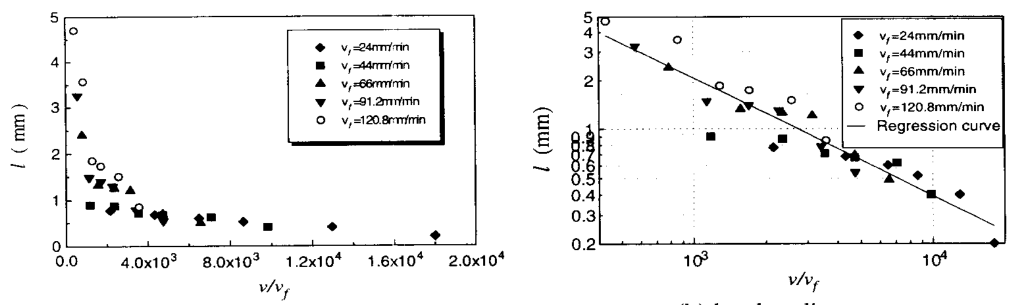


(a) multi-directional CFRP (b) unidirectional CFRP

Fig. 8 The effects of the cutting speed and feed rate on the size of the spalling defect. The drill diameter was ϕ5.5mm.

4.3. Ratio of Cutting Speed to Feed Speed

Figures 9 and 10 present the spalling variation with the ratio of cutting speed to feed speed, v/v_f, when drilling multi-directional CFRP and unidirectional CFRP respectively, where Figures 9(a) and 10(a) are with linear plotting axes and Figures 9(b) and 10(b) are with log-log axes. From Figures 9(a) and 10(a), it can be seen that under different feed speed, the experimental data all distribute in the vicinity of a curve. With the increase of v/v_f, the spalling generally decreases regardless of the type of CFRP, *i.e.*, unidirectional or multidirectional. When v/v_f is smaller than 4000, the spalling size l decreases more quickly. Further increasing the ratio does not make a noticeable change of l. A similar phenomenon also exists in the variation of the drilling force. A critical value of v/v_f is therefore approximately 4000, which is helpful for selecting drilling parameters in production. When v/v_f is in the regime beyond the critical value, the spalling size generated will be small.



(a) linear diagram (b) log-log diagram

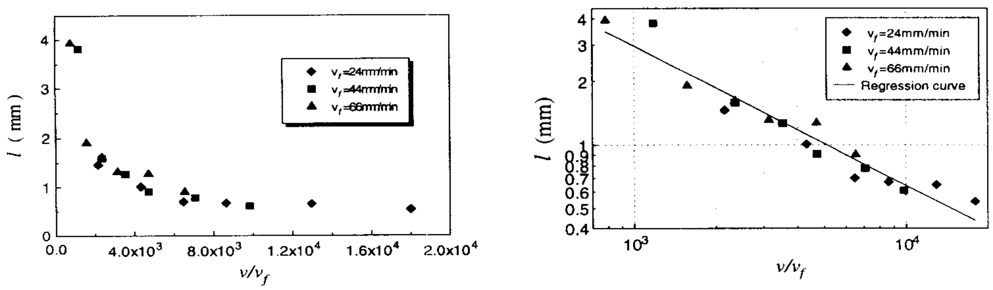
Fig. 9 The effect of v/v_f on the size of spalling defects when drilling multi-directional CFRP plates using a drill of ϕ5.5mm.

Using the log-log diagrams, Figures 9(b) and 10(b), the empirical relationship between v/v_f and l can also be expressed as

$$l = 302 \cdot \left(v / v_f\right)^{-0.72} \qquad \text{for multi-directional CFRP}$$

$$l = 288.4 \cdot \left(v / v_f\right)^{-0.66} \qquad \text{for unidirectional CFRP}$$

where l is in millimeter.



(a) linear diagram (b) log-log diagram

Fig. 10 The effect of v/v_f on the size of spalling defects when drilling unidirectional CFRP plates using a drill of ϕ5.5mm.

4.4. Drill Diameter

Figure 11 shows the spalling variation with the drill diameter. The solid carbide, which has three different diameter (ϕ6, ϕ5.5, ϕ4.8), is used in the experiment. It can be seen that with the increase of the drill diameter, the spalling increases, and this is independent of the feed and drilling speeds.

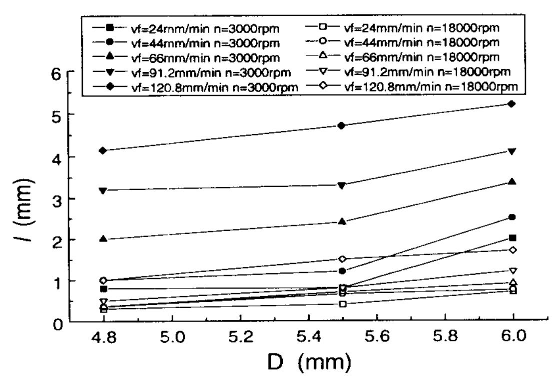


Fig. 11 The effect of drill diameter on the size of spalling defects when drilling unidirectional CFRP plates.

4.5. Drilling Force

Figure 12 shows the effect of the thrust force when drilling multi-directional CFRP. With the increase of the thrust force, the spalling size increases in quadratic manner as

$$l = 0.76 - 0.04F_z + 0.001F_z^2$$

where l is in millimetre and F_z is the thrust force in N.

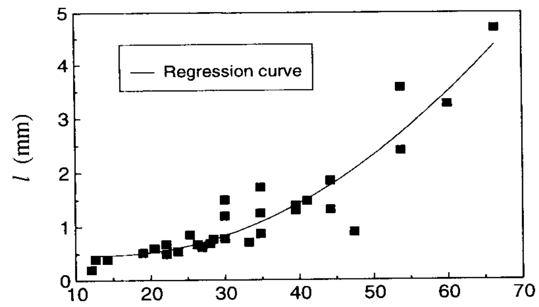


Fig. 12 Relationship between the spalling size and the thrust force.
(ϕ5.5mm solid carbide drill, multi-directional CFRP)

5. AN EMPIRICAL FORMULA

As investigated above, the variables that affect the spalling size l are drill diameter D, drilling speed n, feed speed v_f, cutting speed v, feed rate f, drilling force F_z and elastic modulus of CFRP plates E. But the number of the independent variables, as listed in Table 3, is only 5, *i.e.*, drill diameter D, drilling speed n, feed speed v_f, drilling force F_z and elastic modulus of CFRP plates E, because f is determined by v_f and v is defined by n and D. For simplicity, the longitudinal modulus E_l of the unidirectional CFRP will be used to represent the elastic modulus E. Clearly, there are three primary units in the independent variables, *i.e.*, mass M, length L and time T, thus according to the π-theorem for dimensional analysis, three independent non-dimensional variables must be formed.

Table 3 List of variables and dimensional formula

Variable	Symbol of variable	Dimensional formula
Spalling size	l	L
Drill diameter	D	L
Drilling speed	n	T^{-1}
Feed speed	v_f	LT^{-1}
Drilling force	Fz	MLT^{-2}
Elastic modulus	E_l	$ML^{-1}T^{-2}$

Using the method of dimensional analysis of Ref. [10], the relationship between the spalling size and other independent variables can be found to be

$$\frac{l}{D} = g\left(\frac{nD}{v_f}, \frac{Fz}{E_l D^2}\right) \tag{2}$$

with the function g unrestricted. In the above equation, $\frac{l}{D}$ is called the spalling factor, indicating the relative size of the spalling defect to the drill diameter, $\frac{nD}{v_f}$ is the ratio of the drilling speed to the feed speed and $\frac{Fz}{E_1 D^2}$ represents the effect of material property of the workpiece and the hole diameter on the drilling force. All these are dimensionless variables.

A multi-variable regression analysis showed that the spalling factor is a simple power function of the power product of other governing dimensionless variables,

$$Y = k \cdot X^{-1.15} \tag{3}$$

where $Y = \frac{l}{D}$, $X = \left(\frac{nD}{v_f}\right)^{\alpha} \cdot \left(\frac{Fz}{E_1 D^2}\right)^{\beta}$ and k, α and β are dimensionless constants that were found to be $k = 1.3$, $\alpha = 0.8$ and $\beta = 0.5$. As shown in Fig. 13 all the experimental measurements collapse very well to a single curve specified by formula (3).

Equation (3) can be used to select drilling parameters. For instance, with a given limit of the spalling size, drill diameter, drilling speed and drilling force, the feed speed required can be determined easily.

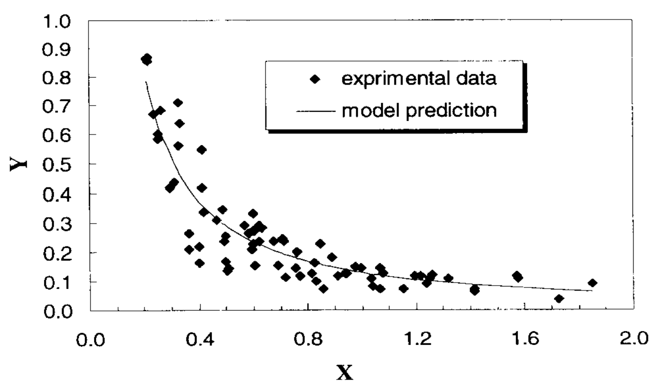


Fig. 13 The relationship between spalling factor and governing dimensionless variables

6. CONCLUSIONS

From the study above, the following conclusions were drawn:

(1) Spalling and fuzzing are the major mechanisms in an exit defect caused by drilling, but spalling is usually a severer damage.
(2) Spalling is caused by the chisel and cutting edge actions, in which the former plays a major role.
(3) Fuzzing usually exists in the cutting region where the included angle between the fibre direction of the surface layer and that of the cutting speed is acute.
(4) The spalling in a unidirectional CFRP plate is bigger than that in a multi-directional CFRP plate under the same cutting conditions.
(5) The size of the spalling defect is an increasing function of drilling speed n, feed rate f, drill diameter D and feed speed v_f, while cutting speed has a negligible effect.
(6) There exists a critical ratio of cutting speed to feed speed, $v/v_f \approx 4000$, beyond which the spalling size can be minimised.
(7) The simple empirical formula developed can be used easily to evaluate the relationship between the spalling size and other drilling conditions. Because the formula is dimensionless, its application is not limited to the cases tested in this study.

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