Study on wheel cover safety for grinding machines: Effect of compressive strength of abrasive projectile on cover damage

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Abstract. When a high-speed rotating grinding wheel bursts during grinding operation, abrasive fragments are scattered with a high speed. Therefore, a wheel cover is required to maintain the safety of machine tool operators. The wheel cover thickness is determined by the standard ISO 16089. Although various studies have been conducted on the collision phenomenon, few studies using a projectile made of brittle material, such as a grinding wheel, have been conducted. In this study, collision experiments using two types of abrasive products (WA46E12V and WA46O8V) were used for projectiles to determine the effect of the compressive strength of the projectile on safety of the wheel cover.

Introduction

The grinding process is one of the precision machining methods in which material is removed from a workpiece. Material should be removed by the abrasive on the grinding wheel rotating at high speed. Because this process is not sufficiently safe, grinding machines are required to be equipped with appropriate safety mechanisms. A grinding-wheel cover is one of the safety mechanisms that prevents the machine tool operator from scattered abrasive fragments, and the cover thickness is determined by the standard ISO 16089 [1]. The grinding-wheel cover is designed on the supposition that abrasive fragments collide at a speed range of several tens to hundreds [m/s], which is the grinding-wheel peripheral speed. Although various studies have been conducted on the collision phenomenon, studies using a projectile made of brittle material, such as a grinding wheel, have only a few.

The authors developed the experimental equipment capable of performing a collision experiment using an abrasive projectile and conducted a study on wheel cover safety [2]. In the previous studies, the effects of thickness and mechanical properties of the cover material on impact resistance were clarified [3, 4, 5]. However, the abrasive product used for the projectile in the previous studies was unified with WA46O8V. Therefore, the effect of the compressive strength of the projectile on the collision safety of the grinding-wheel cover has not been made clear. In this study, we conducted collision experiments using two types of abrasive projectile (WA46E12V and WA46O8V) against two types of wheel cover material (rolled steel SS400 and SPCC, which are defined in JIS standards) and investigated the effect of the compressive strength of abrasive projectiles.

Material tests

Compression tests on the abrasive products (WA46E12V and WA46O8V) used for the projectile were conducted to obtain their mechanical properties. The compression test specimen was fired in the same condition as the abrasive projectile used for the collision experiments.

The dimensions of the test specimens were 28 [mm] in diameter and 28 [mm] in height. The compression tests were conducted three times by the split Hopkinson pressure bar (SHPB) method [6]. Table 1 shows the average values of the mechanical properties obtained from the compression tests.

The results of the compression tests show that WA46E12V has much lower compressive strength and fracture strain than WA46O8V.

Tensile tests were conducted on wheel cover materials used for collision experiments to obtain the mechanical properties. The tested cover materials were rolled steels SS400 and SPCC. SS400 is a material that is commonly used for a grinding-wheel cover in Japan. Because the composition and properties are similar, SPCC was selected as a substitute for the SS400 with thickness of less than 1.6 [mm] which could not be obtained.

Table 1. Mechanical property of abrasive products

Material	Strength σ_m [MPa]	Strain ε
WA46E12V	23	0.004
WA46O8V	171	0.04

Table 2. Mechanical property of cover materials

Material	Strength R_m [MPa]	Strain ε
SS400	479	0.39
SPCC	393	0.43

The dimensions of the test pieces were 16 [mm] in length for the parallel part and 8 [mm] wide. The thickness of the specimen was 1.6 [mm] for SS400 and 1.4 [mm] for SPCC. An Instron type testing system (Instron 5500R) was used for the tests. The tests were conducted three times under strain rate $\dot{\varepsilon} = 5.0 \times 10^{-2}\,[\mathrm{s}^{-1}]$. Table 2 shows the average values of the mechanical properties obtained from the tensile tests.

Collision experiments

Figure 1 shows a schematic of the equipment developed for the collision experiments. The abrasive projectile is launched using compressed air pressure; it then collides with the wheel cover, which is fixed on the target stand. The projectile speed is measured by the speed meter located at the tip of the launching tube. The cover material is sandwiched between steel frames.

For the thicknesses *t* of the cover materials, SS400's were 1.6, 2.3, and 3.2 [mm], and SPCC's were 1.0, 1.2, and 1.4 [mm], which are defined in JIS standards. The size of the cover was 750 [mm] × 750 [mm], and the size of the exposed part excluding the fixed part was 450 [mm] × 450 [mm]. The dimensions of the exposed part were based on the safety evaluation criteria given in ISO 16089.

Figure 2 shows the abrasive projectile used for the collision experiment. The size of the projectile was φ 90 [mm] × 220 [mm]. The mass of the abrasive projectile varied according to the abrasive product type, 2.8 [kg] for WA46E12V and 3.4 [kg] for WA46O8V. By attaching two Teflon rings to the outer side of the projectile, the friction generated during contact with the launching tube is reduced.

The deformation pattern of the cover material after the collision experiment can be classified into three patterns, plastic deformation (○), crack generation without penetration (△), and penetration (×). The pattern (△) is defined as the "border area." In addition, the impact energy of the projectile in the border area is defined as the "border energy." In this study, the border energy is the evaluation criterion of experimental results.

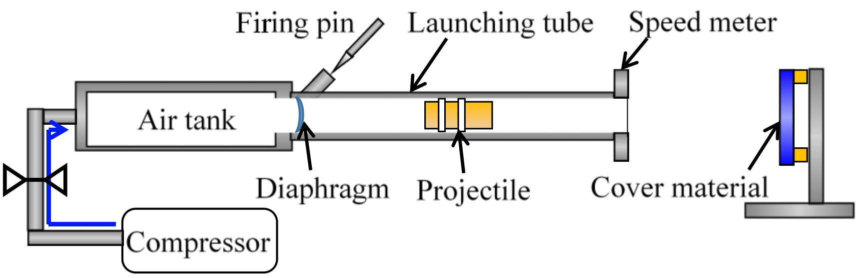


Fig. 1. Schematic of developed collision experimental equipment

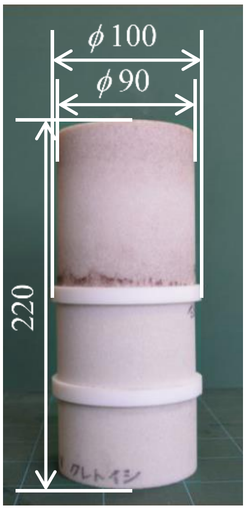


Fig. 2. Abrasive projectile

Table 3 presents the results of the collision experiments using SS400 cover material. The WA46E12V projectile with a compressive strength of 23 [MPa] could not penetrate, even with the collision energy needed for penetration by the WA46O8V projectile. After the experiment, the WA46O8V projectile kept its original shape, although there was slight chipping at the edge part. However, the collision part of the WA46E12V projectile suffered severe damage. Therefore, the WA46E12V projectile has insufficient compressive strength for penetrating an SS400 cover material having a thickness of 1.6 [mm].

Table 4 presents the results of collision experiments using the SPCC cover material. The WA46E12V projectile with a compressive strength of 23 [MPa] was able to penetrate the SPCC cover, which is thinner and has a lower tensile strength than SS400. Fig. 3 shows the appearance of the abrasive projectile after the experiment. The edge parts of the projectiles were damaged and rounded. However, the WA46E12V projectile maintained the shape as a projectile. Therefore, it is considered that the WA46E12V projectile has sufficient compressive strength for penetrating the SPCC cover material having thickness of 1.4 [mm].

Figure 4 shows the fracture/deformation shape of the SPCC cover at the "border area." The diameter of the fracture part by the collision of a WA46O8V projectile with a compressive strength of 171 [MPa] was approximately 90 [mm]. However, the diameter of the fracture part by the collision of the WA46E12V projectile with a compressive strength of 23 [MPa] was approximately 75 to 80 [mm]. In addition, the collision part of the SPCC cover was rounded roughly the same as tip part of the projectile after the collision experiment.

Table 3. Experimental result using SS400

Projectile	Thickness t [mm]	Energy E [J]	Result
WA46E12V	1.6	2800	○
		3962	
		4716	
		7072	
		7768	
WA46O8V	1.6	3582	△
	2.3	7338	
	3.2	14201	

Table 4. Experimental result using SPCC

Projectile	Thickness t [mm]	Energy E [J]	Result
WA46E12V	1.0	2534	○
		4522	△
		6649	×
	1.2	3754	○
		4196	
		5530	
		6289	△
		6575	
		7097	×
		7884	
	1.4	8155	○
		8889	△
WA46O8V	1.0	1605	△
	1.2	2184	

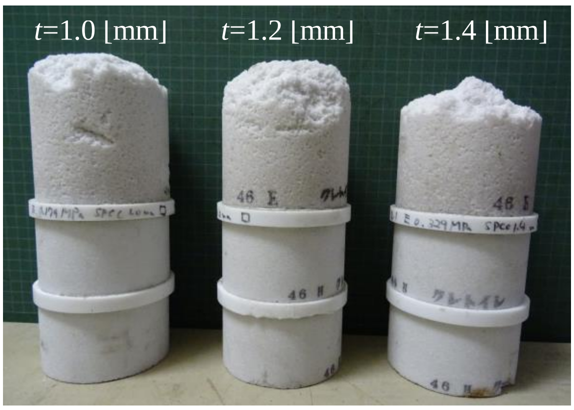
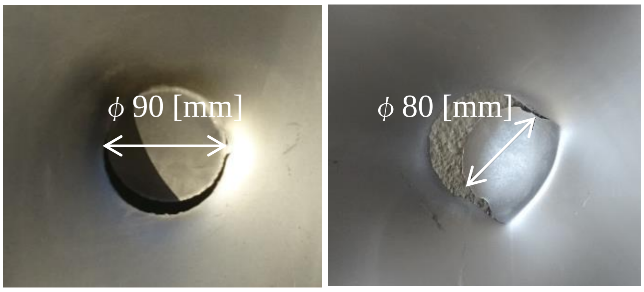


Fig. 3. Appearance of WA46E12V projectile after the collision experiment (the border area)



(a) WA46O8V(2184 [J]) (σ_m = 171 [MPa]) (b) WA46E12V(6575 [J]) (σ_m = 23 [MPa])

Fig. 4. The fracture / deformation shape of the SPCC cover (t = 1.2 [mm]) at the "border area"

Effect of the cover thickness on impact resistance

The previous study using a WA46O8V projectile against an SS400 cover showed the experimental equation of the border energy. When the damage of an abrasive projectile is small, the effect of the cover thickness of SS400 can be described by Eq. (1).

$$E_{\mathrm{p}} = 1387t^2 . \quad (1)$$

where E_{p} is border energy, and t is the thickness of the cover material.

Figure 5 shows the relationship between the collision energy of the abrasive projectiles and the cover thickness of the SPCC cover material. The border energy by the WA46E12V projectile with a compressive strength of 23 [MPa] is also proportional to the square of the cover thickness. Therefore, the border energy of WA46E12V can be described by Eq. (2).

$$E_{\mathrm{p}} = 4522t^2 . \quad (2)$$

The proportionality constant of Eq. (2) was calculated back from the experimental value of the border energy at the cover thickness of 1.0 [mm]. However, the border energy by the WA46O8V projectile against the SPCC cover is expressed by Eq. (3).

$$E_{\mathrm{p}} = 1605t^2 . \quad (3)$$

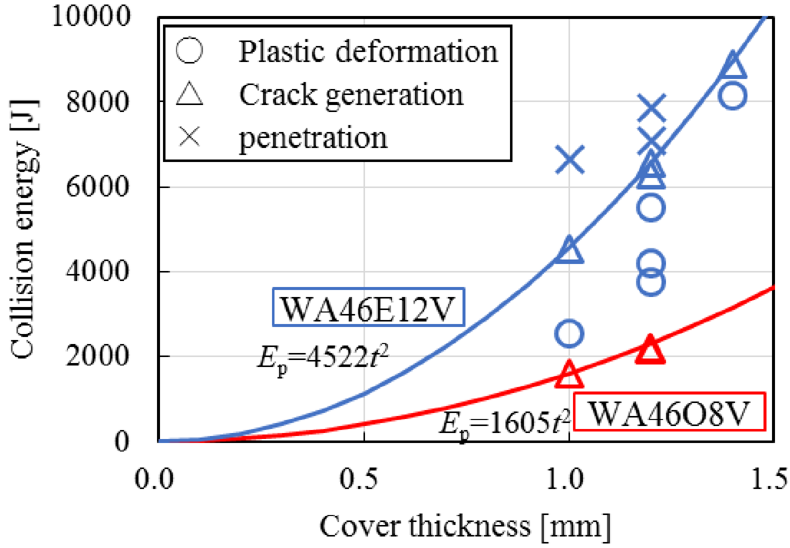


Fig. 5. Effect of cover thickness on the border energy

From Eq. (2) and Eq. (3), the border energy by the WA46E12V projectile is approximately 2.8 times higher than that of the WA46O8V projectile. This result shows that the compressive strength of the projectile affects the border energy. Therefore, one can assume that when the abrasive fragment is a rigid body, in the collision safety evaluation of the wheel cover, it is safer but not appropriate.

Penetrability of the abrasive projectile

The WA46E12V projectile with a compressive strength of 23 [MPa] could not penetrate the SS400 cover material with a thickness of 1.6 [mm]. Therefore, an attempt was made to predict the penetrability from the strength of the cover material and abrasive projectile.

Figure 6 shows a collision model in which the projectile is not damaged. The penetration of a cylindrical projectile is similar to a punching process. Therefore, the strength required for a projectile to penetrate the cover can be calculated by Eq. (4).

$$\frac{\pi d^2 \sigma_{\mathrm{m}}}{4} \geq k_{\mathrm{m}} \pi d t . \quad (4)$$

where d is the diameter of the projectile, σ_{m} is the compressive strength of the projectile, and k_{m} is the shearing strength of the cover. When the inequality is not satisfied, because of the insufficient strength of the projectile, the projectile cannot penetrate the cover. From the von Mises yield criterion, k_m can be calculated by Eq. (5) [7].

$$k_m = \frac{R_m}{\sqrt{3}} . \tag{5}$$

where R_m is the tensile strength of the cover material.

However, in actual collisions, damage occurs at the edge of the abrasive projectile at the time of a collision. Fig. 7 shows a collision model considering the damage of the abrasive projectile. To simplify the phenomena, it was assumed that the damage direction of the projectile was 45° from the tip edge. In this figure, d_f is the tip diameter of the projectile after damage and the shear diameter of the cover. For the equilibrium of forces of the projectile edge part at the time of a collision, the area S_e of the edge part after the damage necessary for shearing the cover material to the diameter d_f can be calculated by Eq. (6).

$$S_e = \frac{\sqrt{2}\left(d^2 - d_f^2\right)}{4} = \frac{k_m}{\sigma_m} \pi d_f t . \tag{6}$$

For the projectile to penetrate the cover, the strength of the projectile tip surface and the shearing force of the cover material must satisfy Eq. (7).

$$\frac{\pi d_f^2 \sigma_m}{4} \geq k_m \pi d_f t . \tag{7}$$

Table 5 presents the diameter d_f of the tip surface of the projectile after damage obtained by Eq. (6) and the penetrability obtained by Eq. (7). From this table, the diameter of d_f from Eq. (6) roughly agreed with the experimental result (approximately 75 to 80 [mm]) using the SPCC cover. In addition, this equation also shows that the WA46O8V projectile can penetrate the SS400 material cover with a thickness of 3.2 [mm] without significant damage, which is the same result as in the previous study [3]. Furthermore, Eq. (7) shows that the WA46E12V projectile can penetrate the SPCC cover with a thickness of 1.4 [mm] and cannot penetrate the SS400 cover with a thickness of 1.6 [mm], which is the same as the experimental result. Therefore, the penetrability of the abrasive projectile against the wheel cover can be predicted from Eq. (6) and Eq. (7).

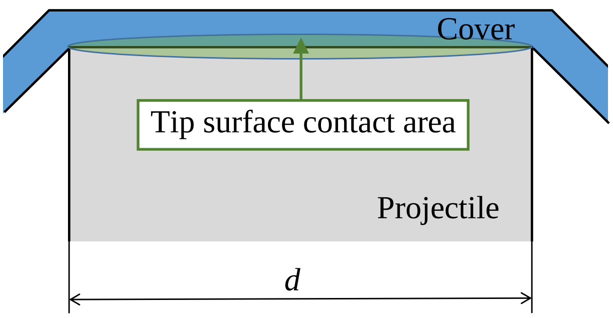


Fig. 6. Collision model without considering the projectile compressive strength

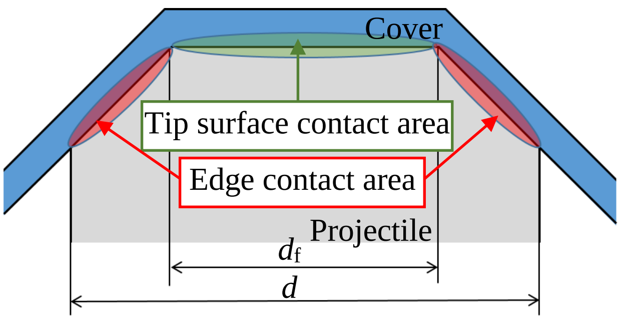


Fig. 7. Collision model considering the projectile compressive strength

Table 5. Prediction of projectile damage and penetrability

Cover material	Thickness t [mm]	WA46E12V (σ_m = 23 [MPa])		WA46O8V (σ_m = 171 [MPa])	
		Eq. (6) d_f [mm]	Eq. (7)	Eq. (6) d_f [mm]	Eq. (7)
SPCC (R_m = 393 [MPa])	1.0	77.1	Satisfied	88.1	Satisfied
	1.2	74.8	Satisfied	87.8	Satisfied
	1.4	72.6	Satisfied	87.4	Satisfied
SS400 (R_m = 479 [MPa])	1.6	66.8	Unsatisfied	86.4	Satisfied
	2.3	59.0	Unsatisfied	84.9	Satisfied
	3.2	50.8	Unsatisfied	83.0	Satisfied

Conclusions

The following conclusions are drawn based on the results of collision experiments using two types of abrasive projectile with different compressive strengths.

1) The border energy is proportional to the square of the cover thickness regardless of the compressive strength of the projectile.
2) The compressive strength of the projectile affects the quantity of the border energy.
3) An empirical equation for the penetrability of abrasive projectiles—Eq. (6) and Eq. (7)—was derived based on the experimental results.

Acknowledgments

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