Measurement of Kinetic Energy of Flying Fragments in Bending Test of WC-10 mass%Co Cemented Carbide

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Received September 2, 1996

SYNOPSIS

The kinetic energy (E_k) of flying fragments in three-point bending test of WC-10mass%Co cemented carbide was experimentally evaluated by our devised convenient method for a test piece with size of $4 \times 3 \times 36 \text{ mm}^3$ and a span of 30mm, and the ratio of E_k to the elastic strain energy (E_{es}) which was stored in the test piece just before the fracture was calculated. It was found that E_k increased from 0.016J to 0.046J and the ratio of E_k/E_{es} increased from 0.09 to 0.15 with increasing flexural strength (σ_m). It was suggested that the error due to E_k in the relative value of fracture toughness (K_{IC}) estimated by using the equation of $\sigma_m = \psi K_{IC} S_{mf}^{1/2}$ (ψ is a factor including the shape of fracture source, the roughness of fracture surface and the correction parameter, etc., and S_{mf} is the total macroscopic area of fracture surfaces of fragments of one test piece), in the derivation of which E_k is neglected, was +6.5%, if the effect of the other factors on the relative value of K_{IC} are small.

KEY WORDS

kinetic energy, elastic strain energy, fracture toughness, fracture surface area, cemented carbide.

1. Introduction

In our previous study^{1,3)} on the room temperature bending strength (σ_m) and total macroscopic area of fracture surfaces (S_{mf}) of plural fragments of one test piece on WC-Co cemented carbide and Si_3N_4 base ceramics, we have empirically found that S_{mf} increased with increasing σ_m . We analyzed this phenomenon and theoretically derived the following equation (1)^{2,3)}, assuming that the elastic strain energy (E_{es}) stored in the test piece just before the bending fracture mainly converts to the formation energy of fracture surfaces of all fragments which is proportional to S_{mf} and also that both fracture toughness (K_{IC}) equation and Griffith-Orowan equation are applicable to the fracture of hard materials by changing the shape factors contained in these two equations.

$$\sigma_m = \psi K_{IC} S_{mf}^{1/2} \quad (1)$$

where ψ is a factor including the following four parameters; Φ_1 and Φ_2 relating to both the size and

shape of the fracture source and the size of test piece, Φ_3 relating to the volume of test piece and Φ_4 , expressing the roughness of fracture surface, i.e., the ratio of microscopic true fracture surface area (S_{if}) to $S_{mf}^{1/2}$. The experimental results supported the equation (1); a good correlation was observed between σ_m and S_{mf} for each WC-Co cemented carbide and Si_3N_4 ceramics, and the ratio of the slopes of two σ_m - $S_{mf}^{1/2}$ regression lines for both specimens was in good accordance with the ratio of K_{IC} measured by SEPB (Single Edge Precracked Beam) method. And from the latter result, the value of ψ was considered to be a constant at least for these hard materials.

Strictly speaking, however, we have noticed that there remain two problems about equation (1); one is on the value of ψ , and the other is on the accuracy of the derivation of the equation. As for the concrete value of ψ , it can empirically be estimated from the slope of σ_m - $S_{mf}^{1/2}$ or σ_m - $K_{IC} S_{mf}^{1/2}$ correlation line al-

though the value of K_{IC} have to be experimentally measured. However, it can not theoretically be derived at present, because the shape of fracture source (pore, aggregate of hard phase particles, etc.^{5,6)} in cemented carbide and ceramics is not so simple as that of the crack assumed in the derivations of both K_{IC} equation⁷⁾ and Griffith-Orowan equation⁷⁾, and thus the values of parameters Φ_1 and Φ_2 are not known. Furthermore, the measurement of the microscopic roughness of fracture surface or the value of Φ_4 , e.g., with AFM (atomic force microscope) or STM (scanning tunneling microscope) is not so easy, because these AFM and STM are said to be applicable to macroscopically relatively flat surface and also the microscopic fracture surface area of all fragments of one test piece is so large that the time necessary for the measurement will be remarkably long.

On the other hand, the accuracy of the derivation of equation (1) have not been fully understood at present. This is because we had not taken into consideration some factors in the derivation. Therefore, we have been studying the effects of factors such as the volume of test piece⁷⁾ and the area of internal fracture surfaces formed by stopped cracks⁸⁾ on the value of ψ or the relative value of K_{IC} (i.e., ψK_{IC}) estimated by equation (1). Furthermore, there remains at least two other factors which we have not taken into consideration in the derivation of the equation (1); the kinetic energy (E_k)³⁾ of fragments of test piece which flies after the bending fracture, and the vibrational energy⁹⁾ which is emitted during crack development and finally converts to thermal energy.

In this study, we investigated E_k . First, we experimentally estimated E_k for WC-10mass%Co cemented carbide and calculated the ratio of E_k to E_{es} . Next, we theoretically derived an equation expressing the relation between σ_m and S_{mf} in case of taking into consideration E_k , third theoretically derived an equation for the error due to the neglect of E_k in K_{IC} value estimated by equation (1), and fourth evaluated the error on WC-10mass%Co cemented

carbide, assuming that the effect of other factors is small.

2. Specimens and Experimental Procedure

WC-10mass%Co cemented carbide with high carbon content in WC+ γ (Co-WC solid solution) two phase region¹⁰⁾ was used as the specimen. The preparation methods of the alloy and its test pieces were the same as in our previous report¹⁻⁶⁾. The value of K_{IC} measured by SEPB method (JIS R1607) was $10.7 \text{ MPa}\cdot\text{m}^{1/2}$. Five test pieces with size of $4 \times 3 \times 36 \text{ mm}^3$ were three-point bending tested by using a special jig (span is 30mm) so that large flying fragments do not crash against the surface of the jig. And σ_m , S_{mf} and E_k were investigated.

S_{mf} was measured with the method schematically shown in **Fig.1**, which is the same as in our previous study^{4,6)}, but the details had not been described; as schematically shown in Fig.1(a), (1) the fragment was set in a movable X-Y stage equipped with two micrometers so that the longitudinal axis (Z-axis) of the fragment was perpendicular to the stage, and (2) the measuring part of laser displacement meter (Keyence Company, Inc., Type LC-2440; average beam diameter is $28\mu\text{m}$) was arranged above the fragment so that the axis of laser beam was parallel to the Z axis of the fragment. Next, as schematically shown in Fig.1(b), (3) the coordinate (x, y) of the lattice points of triangles were set up at regular intervals of 0.5mm on the fracture surfaces with micrometer, and (4) the coordinate z at each (x, y) were measured by using laser displacement meter. Finally, (5) S_{mf} was obtained by summing the areas of the triangles which were calculated by substituting the three dimensional coordinates (x, y, z) to Heron's equation.

$E_k (=mv_0^2/2; m$ is the mass of fragment and v_0 is the initial velocity of fragment) was calculated by the following convenient method which we originally devised. The initial flying angle (θ) and the coordinate (x_L, y_L) of landing point of the fragment which are needed for the calculation of v_0 were measured with the method schematically shown in

Fig.1(a),(b) Figure (b) shows an enlarged figure of the fragment in figure (a) and lattice points of triangles. These are schematic illustrations of the method for measuring the coordinates of lattice points (o) of triangles which are used for calculation of the total macroscopic area of fracture surfaces (S_m) of fragments by using Heron's equation.

Fig.2; (1) two sheets of thin paper, which were partially cut at regular intervals of 3mm so that its fracture strength was decreased, were vertically arranged at a lateral distance (L) of 60mm from the central point between span center and jig bar on each side. After the bend fracture, two large fragments flew diagonally to the left and right directions in the figure, respectively, broke through the papers and made one hole in the paper on each side. The small fragments with size of 1-6mm (the number was 2-7, these total volume is about 24mm³ which is only about 6% of the volume of the test piece) were con-

sidered to drop at low speed near the jig, because the small fragments were found to exist inside or near the jig without making any bruise on the surface of the jig, and thus the kinetic energy of these small fragments was neglected, (2) the value of θ_i was calculated by using the height (H) and L of the hole in the thin papers. Then, the coordinate (x_L, y_L) of the landing point of each large fragment was measured, and v_o , i.e., the velocity of the fragment just after the fragment passed through the paper was calculated by using the following equation, where g is the acceleration of gravity and (x, y) is the coor-

Fig.2. Schematic illustration of the method for measuring the variables necessary for calculating the apparent kinetic energy (E_k^a) of flying fragments. The value of y_L is -1050mm in this experiment.

dinate of each fragment.

$$v_o^2 = g x_L^2 \{2 \cos^2 \theta_i (x_L \tan \theta_i - y_L)\}^{-1} \quad (2)$$

which can be obtained from the following two equations (3) and (4), where t is the time after the fracture or the beginning of flying of fragments.

$$x = t v_o \cos \theta_i \quad (3)$$

$$y = t v_o \sin \theta_i - g t^2 / 2 \quad (4)$$

where the air resistance to the flying of fragment is ignored because its effect is very small¹¹⁾. At the time of landing, (x, y) is (x_L, y_L) and thus equation (2) becomes the following.

$$v_o^2 = g x_L^2 \{2 \cos^2 \theta_i (x_L \tan \theta_i - y_L)\}^{-1} \quad (2')$$

Then, E_k was calculated as follows.

$$E_k = E_k^a + E_p \quad (5)$$

$$E_k^a = m v_o^2 / 2$$

$$= m g x_L^2 \{4 \cos^2 \theta_i (x_L \tan \theta_i - y_L)\}^{-1} \quad (6)$$

where E_k^a is the apparent kinetic energy, i.e., the value calculated without taking into consideration E_p which is the energy lost when the fragment broke through the thin paper.

E_p was measured with the following method as schematically shown in **Fig.3**; the same thin paper as that in Fig.2 was arranged horizontally to the ground and the typical large fragment was free dropped to the paper from the position of various height. E_p is nearly equal to the potential energy of mgh , where h is the smallest height at which the fragments could break through the paper.

Then, $E_k - \sigma_m$ relation and $(E_k/E_{cs}) - \sigma_m$ relation

Fig.3. Schematic illustration for measuring method of the energy (E_p) which is lost when the flying fragment breaks through the paper used in Fig.2.

were investigated, where E_{cs} is the elastic strain energy of the flying fragments just before the fracture of the test piece and equals to $V \sigma_m^2 / 18 E^{12)}$, where V is the volume of the portion of the test piece on which bending stress operates and E is the Young's modulus. Finally, the error caused by E_k in the relative value of K_{IC} calculated by equation (1) was evaluated with the equation (11) which will be shown in the next section, by assuming that the effects of vibrational energy (E_v) and other unknown factors on equation (1) are small.

3. Experimental Results and Discussion

The σ_m of five test pieces ranged from 2.3GPa to 3.0GPa and the average was about 2.6GPa. Thus, $E_{cs} (=V \sigma_m^2 / 18 E^{12)}$, $E=570\text{GPa}$ and $V=360\text{mm}^3$ ranged from 0.18J to 0.30J and the average was 0.25J. **Table 1** shows the measured values of variables such as σ_m , m , H , θ_i , x_L and y_L shown in Fig.2 and the values of v_o of fragment and E_k^a of one test piece calculated from these variables. With increasing σ_m , the value of E_k^a increased from 0.010J to 0.040J and also the average value of v_o of two fragments of one test piece increased from 1.9m/s to 3.8m/s. The value of E_p was about 0.006J. **Fig.4** shows $E_k (=E_k^a + E_p)$ and E_k/E_{cs} as a function of σ_m . With increasing σ_m , E_k increased

Table 1 The measured values of variables in Fig.2 and the value of E_k^a calculated from these variables for five test pieces (No.1-5). The value of y_L is -1050mm.

	σ_m (GPa)	m (g)	H (mm)	θ_i (degree)	x_L (mm)	v_o (m/s)	E_k^a (J)
No. 1	3.0	2.81	50	40	3000	4.5	0.040
		2.58	30	27	1700	3.0	
No. 2	3.0	2.93	20	18	2200	3.8	0.038
		2.75	50	40	2000	3.5	
No. 3	2.5	2.70	50	40	1200	2.3	0.017
		2.61	60	45	1500	2.8	
No. 4	2.4	2.94	40	34	1300	2.4	0.016
		2.65	20	18	1200	2.3	
No. 5	2.3	2.97	15	14	920	1.9	0.010
		3.04	20	18	900	1.8

Fig.4. Kinetic energy of flying fragments (E_k) and the ratio of E_k to the elastic strain energy (E_{es}), i.e., E_k/E_{es} , as a function of flexural strength (σ_m) on WC-10mass%Co cemented carbide.

from 0.016J to 0.046J and the ratio of E_k/E_{es} increased from 0.09 to 0.15. The average values of E_k and E_k/E_{es} were 0.030J and 0.13, respectively.

As mentioned in the section of "1. Introduction", equation (1) was theoretically derived assuming that E_{es} mainly converts to the formation energy of fracture surfaces; E_k in this study was not taken into consideration. Therefore, we derived theoretically the relation among σ_m , K_{IC} and S_{mf} in case of taking into consideration E_k , and to evaluate the error due to E_k in K_{IC} value estimated by equation (1).

By squaring both sides of equation (1), the following equation is obtained.

$$\sigma_m^2 = \psi^2 K_{IC}^2 S_{mf} \quad (1')$$

The following is obtained by multiplying the above equation by $\Phi_3 E^{-1}$,

$$\Phi_3 E^{-1} \sigma_m^2 = \Phi_3 E^{-1} \psi^2 K_{IC}^2 S_{mf} \quad (7)$$

where $\Phi_3 E^{-1} \sigma_m^2$ in equation (7) means E_{es} just before the bending fracture and thus $\Phi_3 E^{-1} \psi^2 K_{IC}^2 S_{mf}$ in the right side is equal to the formation energy of fracture surfaces, i.e., $\Phi_4(\gamma+P)S_{mf}$ in case of not taking into consideration E_k . When E_k is taken into consideration, the energy of $\Phi_3 E^{-1} \sigma_m^2 - E_k$ has to be equalized to the formation energy of fracture surfaces instead of $\Phi_3 E^{-1} \sigma_m^2$. Thus, we obtain the following equation.

$$\Phi_3 E^{-1} \sigma_m^2 - E_k = \Phi_3 E^{-1} \psi^2 K_{IC}^2 S_{mf} \quad (8)$$

Here, K_{IC}^k means the fracture toughness calculated with σ_m - S_{mf} equation derived by taking into consideration E_k . Equation (8) can be rearranged to the

following.

$$\sigma_m^2 = \{1 - (E_k / \Phi_3 E^{-1} \sigma_m^2)\}^{-1} \psi^2 K_{IC}^2 S_{mf} \quad (9)$$

Because $\Phi_3 E^{-1} \sigma_m^2$ is E_{es} as above mentioned, the following is obtained.

$$\sigma_m = \{1 - (E_k / E_{es})\}^{-1/2} \psi K_{IC}^k S_{mf}^{1/2} \quad (10)$$

From equations (1) and (10), the error due to the neglect of E_k in K_{IC} value or the percentage of the deviation of K_{IC} from K_{IC}^k , i.e., $(K_{IC} - K_{IC}^k)/K_{IC}^k$, can be derived by dividing equation (1) with equation (10) and then rearranging.

$$(K_{IC} - K_{IC}^k)/K_{IC}^k = \{1 - (E_k / E_{es})\}^{-1/2} - 1 \quad (11)$$

The value of $(K_{IC} - K_{IC}^k)/K_{IC}^k$, i.e., $\{1 - (E_k / E_{es})\}^{-1/2} - 1$, was plotted as a function of σ_m in Fig.5. The value of $(K_{IC} - K_{IC}^k)/K_{IC}^k$ varied from +0.05 to +0.08 with increasing σ_m and the average was +0.065. This result indicates that the average error of K_{IC} or the average percentage of the deviation of K_{IC} from K_{IC}^k is +6.5%. This value is relatively small. Therefore, it can be said that equation (1) has adequate accuracy, if the effect of other factors on the relative value of K_{IC} is small.

However, as described in the section of "1. Introduction", there are the other factors which should be considered, such as vibrational energy E_v and the value of ψ or microscopic true fracture surface area. These are not so easy to evaluate, because the research on the former seems not to have been reported and the measurement of the latter is hard as mentioned in the section of "1. Introduction". If the value of E_v is not small, equation (10) should be changed as follows by using nearly the same way as

Fig.5. The error of fracture toughness (K_{IC}) due to the neglect of E_k , i.e., $(K_{IC} - K_{IC}^k)/K_{IC}^k$ which is equal to $\{1 - (E_k / E_{es})\}^{-1/2} - 1$, as a function of σ_m .

in the derivation of equation (10).

$$\sigma_m = \{1 - (E_k + E_v)/E_{es}\}^{-1/2} \psi K_{IC}^{kv} S_{mf}^{1/2} \quad (12)$$

where K_{IC}^{kv} means the fracture toughness calculated with equation (12) derived by taking into consideration both E_k and E_v . Even if E_v/E_{es} or $(E_k + E_v)/E_{es}$ is large, the value of $\{1 - (E_k + E_v)/E_{es}\}^{-1/2}$ or $\{1 - (E_k + E_v)/E_{es}\}^{-1/2} \psi$ is presumed to be nearly constant, irrespective of σ_m . This presumption is based on the observation that a linear correlation experimentally holds between σ_m and $S_{mf}^{1/2}$ or $K_{IC} S_{mf}^{1/2}$, as suggested in equation (1). We will investigate them in detail, hereafter.

4. Conclusion

The kinetic energy (E_k) of flying fragments in three-point bending test of WC-10mass%Co cemented carbide was experimentally evaluated by our devised method for a test piece with size of $4 \times 3 \times 36 \text{ mm}^3$ and a span of 30mm. And the error due to the neglect of E_k in the relative value of fracture toughness (K_{IC}) calculated by using our proposed equation of $\sigma_m = \psi K_{IC} S_{mf}^{1/2}$ (σ_m is the flexural strength and ψ is a factor), in the derivation of which E_k is not taken into consideration. The results obtained were as follows;

- (1) The value of E_k increased from 0.016J to 0.046J and the ratio of E_k/E_{es} increased from 0.09 to 0.15 with increasing σ_m , where E_{es} is the elastic strain energy stored in the test piece just before the bending fracture.
- (2) An equation expressing the relation between σ_m and S_{mf} in case of taking into consideration E_k was theoretically derived to be $\sigma_m = \{1 - (E_k/E_{es})\}^{-1/2} \cdot \psi K_{IC}^{kv} S_{mf}^{1/2}$ and the error due to the neglect of E_k in K_{IC} value, i.e., $(K_{IC} - K_{IC}^k)/K_{IC}^k$ was $\{1 - (E_k/E_{es})\}^{-1/2} - 1$, where K_{IC}^k is the fracture toughness derived in case of taking into consideration E_k .

- (3) Based on the above two results (1) and (2), the average error, i.e., the average $(K_{IC} - K_{IC}^k)/K_{IC}^k$ value was experimentally estimated to be +6.5%, if the effect of the other factor on the relative value of K_{IC} is small.

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