

Crack Growth Behavior in Cemented Carbide by Repeated Thermal Shock

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Abstract

In this study, fatigue crack growth (FCG) behavior of cemented carbide under the repeated thermal shock (RTS) was experimentally evaluated by using the thermal-shock experiment method developed by the authors. Tests were carried out using cemented carbide having two different WC crystal grain sizes. In addition, FCG behavior under rotating bending fatigue (RBF) test was investigated using the same cemented carbides. Then the FCG results obtained by the RTS test and the results of the RBF test obtained at stress ratio, R = -1, were compared with each other. Here, the stress ratio R is defined as, R = $\sigma_{\min}/\sigma_{\max}$; σ_{\min} and σ_{\max} are the minimum and the maximum stresses, respectively. From this comparison, it was found that the relation between the rate of fatigue crack growth (FCG) and the maximum stress intensity factor in the RTS tests was equivalent to the one obtained under the RBF tests at stress ratio of -1. From a practical point of view, this result is important as it indicates that it is not necessary to purposely perform RTS experiments. In this research, the effect of WC grain size on the short surface FCG behavior of the cemented carbide was also studied and discussed.

Keywords

Fatigue, Cemented Carbide, Repeated Thermal Shock, Fatigue Crack Growth

1. Introduction

It is well known that microcracks develop and grow in the tool due to the periodic thermal stress [1] that occurs during the intermittent cutting process. As a result, damage occurs in the tool, finally causing tool breakage. This phenomenon is called as the repeated thermal shock. WC/Co cemented carbides are widely used for cutting tools, dies, mechanical parts, etc. [2], since they have superior abrasion resistance and hardness as compared with tool steels and other hard metals. Here, WC and Co are a hard phase and a binder phase of the cemented carbide, respectively. Therefore, for developing a new tool with an excellent resistance to the thermal shock, it is of importance to study and clarify the repeated thermal shock behavior of the cemented carbide. However such studies on the cemented carbides have been very few and limited as compared with other materials, such as ceramics [3] [4] [5] [6]. Ishihara *et al.* [7] proposed the new thermal-shock experiment method that can accurately evaluate the thermal stress generated at thermal shock. Using this new method, they clarified the FCG behaviors of silicon nitride [3] under the RTS tests.

In this study, fatigue crack growth (FCG) behavior of cemented carbide was investigated by repeating thermal shock (RTS). The effect of WC particle size on FCG behavior of cemented carbide in RTS test was also investigated. Further, a rotating bending fatigue (RBF) test was conducted at room temperature to study the FCG behavior of the cemented carbide. Then, the difference between the FCG behavior in the RBF test and the FCG behavior in the RTS test was investigated.

2. Specimens and Experimental Method

2.1. Specimen

The material used in the present study was commercially obtained WC-Co cemented carbide. Their chemical compositions are WC: 72%, TiC: 8%, TaC: 8%, NbC: 2%, and Co: 10%. Material was prepared in the following manufacturing steps; molding of the particulate by pressurization, and followed by pre-sintering, forming, and last sintering. Figure 1 shows the microstructure of the cemented carbides used in the present study. As indicated by the arrows in the figure, the white part is a WC grain, and the gray part is a Co phase. To investigate an influence of WC grain size on the FCG behavior of the cemented carbide, two different cemented carbides with average WC grain sizes of 2.5 µm and 8.5 µm were used for the tests. The cemented carbide was machined into the final specimen shapes. The rectangular-parallelepiped specimen and the round bar specimen were used in the present tests. As can be seen from Figure 2, the sizes of the rectangular specimen were $8 \times 4 \times 25$ (mm). Thermal and mechanical properties of the cemented carbide are Young's modulus: 527 GPa, Poisson's ratio: 0.22 and Linear expansion coefficient: 5.34×10^{-6} /K. These values were obtained from literature.

2.2. Experimental Method

a) Measurement of temperature distribution in the specimen at an instance of thermal shock test [7]

All specimen planes except the bottom were covered with refractory putty to



Figure 1. Microstructure of the cemented carbide.



Figure 2. Shape and dimensions of the specimen. (a) Repeated thermal shock (RTS) tests, (b) rotating bending fatigue (RBF) tests (R = -1).

provide an adiabatic condition. Then, the specimens were heated in a furnace about 20 minutes, until the specimen temperature reached to the pre-determined temperature. After the specimen temperature reached a steady value, thermal shock was applied to the specimen by contacting only the specimen bottom with a cooling medium for 5 minutes. For the cooling medium, the water kept at the temperature of 293 K was used.

The equipment used for the present RTS tests is schematically shown in **Fig-ure 3**. Thermal shock was applied to the specimen as follows; the specimen was lifted up into the furnace and heated, then was contacted with water. This action



Figure 3. An experimental apparatus.

was repeated using a timer controlled electric motor. At the thermal shock time, the temperature distribution caused in the specimen height direction was measured using alumel-chromel thermocouples with diameter of 0.2 mm. Five thermocouples were attached to the specimen surface at the positions, 0, 1, 2, 4 and 8 mm, from the bottom of the specimen. Thermocouples were spot welded to the specimen surface.

From the preliminary experiment, it was confirmed that the temperature change in the specimen height direction was mainly generated, and those in the longitudinal as well as in the width direction of the specimen were small enough to be neglected. The temperature measurements were carried out five times for each of the heating temperature. The averaged measurement values were used for calculation of the unsteady thermal stresses that was caused during the RTS tests.

b) Evaluation of thermal stress caused in the RTS tests

If temperature change at the time of thermal shock is generated only in the specimen height direction, thermal stress generated in the longitudinal direction of the specimen, σ_x , can be calculated using the following equation [7].

$$\sigma_{x}(t, y) = -\frac{\alpha ET(t, y)}{1 - \nu} + \frac{1}{2c(1 - \nu)} \int_{-c}^{c} \alpha ET(t, y) dy + \frac{3y}{2c^{3}(1 - \nu)} \int_{-c}^{c} \alpha ET(t, y) y dy$$
(1)

where, *a*, *E* and *v* are linear expansion coefficient, Young modulus, and Poisson's ratio of the material, respectively. And, 2c is the specimen height, and *t* is an elapsed time. T(t, y) is the temperature distribution as functions of an elapsed time, *t*, and the coordinate, *y*, in the specimen height direction.

In order to calculate the first, the second and the third terms in the equation, it is necessary to substitute the temperature-distribution, T(t, y), which was experimentally measured, into those terms. The integral in the Equation (1) was executed using the numerical integration method. Physical properties of the material, such as a, E and v in Equation (1) are generally function of temperature. However, in the present study, for simplicity, the mean values of the physical properties of the material within the range of temperature were used, because they do not show a large temperature dependency.

At a time of thermal shock, thermal boundary-conditions at the interface between the specimen bottom and cooling medium are usually unknown. Even in such case, the thermal stresses caused by the thermal shock can be evaluated using Equation (1) by substituting the temperature distribution measured in the specimen height direction.

When the material is isotropic, the thermal stress that was evaluated by Equation (1) was validated by the finite element method analysis (FEMA). In the FEMA, the actual three-dimensional specimen shape and dimensions and the temperature distribution in the specimen height direction were taken into a consideration [8].

c) FCG behavior in the repeated thermal shock (RTS) tests

Crack length of the short surface crack in the RTS tests was measured using the replica method [9]. The RTS tests were interrupted periodically. Then, to collect replicas of the specimen surface, specimen was loaded to 80% of the maximum thermal stress calculated by Equation (1). Then, acetyl cellulose film was pasted on the specimen surface to take the replicas of the specimen surface. Acetone was used as a solvent of the film. These replicas were then examined to measure the crack length with an optical microscope at magnifications of 100 ~ 200. Sometimes these replicas were observed with a scanning electron microscope (SEM) for a detailed observation.

Stress intensity factor, K, for these surface cracks were evaluated using Newman-Raju's equation [10] of a surface crack under bending moment. In these calculations, a crack aspect ratio (b/a) of 0.74 was used, where b is a crack depth and 2a is a length at the surface. The value of 0.74 was used on the basis of the related studies [11]. The maximum stress intensity factor K_{max} was calculated using the maximum thermal stress expressed by Equation (1) and the crack length.

The FCG rate, da/dN was determined from the relation of 2a vs. *N*, where 2a is a crack length and *N* is the number of stress cycles.

d) FCG behavior in the RBF tests

FCG rate for the cemented carbide was investigated in laboratory air at room temperature of 298 *K* using the rotating bending fatigue (RBF) testing machine. The test was carried out with a sinusoidal waveform at a frequency of 30 Hz and a stress ratio R = -1. The round-bar specimen shown in Figure 2 was used for the RBF tests. Length of the short surface crack was measured using the replica method [9]. Fatigue tests were interrupted periodically to collect replicas of the specimen surface. Acetyl Cellulose film was used for the replica film. Acetone was used as a solvent of the film. Then, collected replicas of the specimen surface were observed using an optical microscope to measure crack lengths. Maximum stress intensity factors, K_{max} for the surface cracks were evaluated using the

Newman-Raju [10] expression for a bending load. In these calculations a crack aspect ratio, b/a, of 0.74 was used, where b is a crack depth and 2a is its length along the surface. The above aspect ratio was determined from the shape of surface crack that was observed in the fracture surface of the specimen.

3. Experimental Results

3.1. FCG Behavior in the RTS Tests (Effect of WC Grain Size)

Figure 4 shows the relationship between the rate of crack growth and the maximum stress intensity factor K_{max} , which was obtained by the RTS test of the cemented carbide. In this figure, the data for the two different cemented carbides whose average WC grain sizes are 2.5 and 8.5 µm are plotted on the log-log paper. As seen from this figure, in the high K_{max} region, a difference due to WC grain size is not clearly seen. However, in the low K_{max} region, an effect of WC grain size can be observed. Specifically, the threshold value of the FCG for the cemented carbide with average WC grain size of 8.5 µm is larger than that of 2.5 µm.

3.2. FCG Behavior in the RBF Tests

Figure 5 shows the relationship between the rate of FCG, da/dN, and maximum stress intensity factor, K_{max} , which was obtained under the RBF tests. Two different cemented carbides with WC grain sizes, 2.5 and 8.5 µm were used in the tests. As can be seen from the figure, the effect of WC grain size on the rate of FCG is hardly seen in the high K_{max} region. While in the low K_{max} region, the effect of WC grain size can be clearly seen. The value of threshold of FCG, K_{maxth} , for the cemented carbide with average WC grain size of 8.5 µm is larger than



Figure 4. da/dN vs. K_{max} relations for the two cemented carbides with different WC grain sizes, which were obtained under the repeated thermal shock test. Effect of WC grain size on the relation was found in the low K_{max} region.



Figure 5. Effect of WC grain size on the relation, da/dN- K_{max} , which was obtained in the RBF tests (R = -1). The effect of WC grain size appears in the low K_{max} region. That is, the threshold level for the WC grain size 8.5 µm is greater than the threshold level for the WC grain size 2.5 µm.

that for the one with average WC grain size of 2.5µm. Regarding the effect of WC grain size on the relation, da/dN vs. K_{max} , which was obtained under the RBF tests, similar results as in the present study were also observed in other study [12].

3.3. Comparison of the FCG Behavior in the RTS Tests with That under the RBF Tests (R = -1)

Figure 6 compare the FCG behavior in the RBF tests (R = -1) with that in the RTS tests of the materials. Figure 6(a) and Figure 6(b) are the results for the WC grain sizes of 2.5 µm and 8.5 µm, respectively. As seen from these figures, there is no difference between the relation, da/dN- K_{max} , which was obtained under the RBF test (R = -1) and the relation which was obtained under the RTS test. This result was observed in common regardless of WC particle size.

4. Discussions

4.1. Comparison between FCG Behavior under the RTS Tests and the one under the RBF Tests (R = -1)

No difference exists between FCG behavior in the RTS test and the one in the RBF test at R = -1, as shown in **Figure 7**. In other words, the FCG behavior of the RTS test can be replaced by the relationship of RBF test at R = -1. Such observation results were also observed in RTS test of silicon nitride ceramics [3]. From a practical point of view, this result is important as it indicates that it is not necessary to purposely perform RTS experiments. From an academic point of view, this result also shows that the thermal stress occurring in the specimen at



Figure 6. Comparison of FCG behavior in the RTS tests with those in the RBF tests (R = -1). No difference exists between the relation, da/dN- K_{max} , which was obtained under the RBF and the relation which was obtained under the RTS test. (a) WC grain size of 2.5 µm, (b) WC grain size of 8.5 µm.





thermal shock can be accurately evaluated using Equation (1). The reason why the FCG behavior in the RTS test is almost the same as the FCG behavior in the RBF test at R = -1 is considered as follows.

In the RTS test, heating and cooling of specimen are alternately repeated. By contacting only the bottom surface of the heated specimen with the cooling medium, the temperature distribution occurs mainly in the specimen height direction. By this temperature distribution, a tensile thermal stress is generated at the specimen surface that contacted with cooling medium. While, when the specimen is heated again in the furnace, though the heating rate is slower than the cooling rate, a compressive thermal stress is generated at the same specimen surface as above. Therefore, in the RTS tests, tensile and compressive thermal stress is loaded alternately on the specimen's surface that contacts with cooling medium. This situation is schematically shown in **Figure 7**. Therefore, in the RTS tests, tensile and compressive forces are alternately applied to the specimen, as in the RBF test at stress ratio of -1. This is considered to be the reason why the FCG behavior of the RTS test is equal to the FCG behavior of the RBF test at R = -1.

4.2. Effect of WC Grain Size on the FCG Behavior of Cemented Carbide

Figure 8 shows the SEM photograph showing an appearance near the fatigue crack tip in the cemented carbide. As indicated by the arrows in the figure, the bridge portion connecting the upper and the lower crack faces is formed behind the crack tip. These bridges are formed by the WC particles. It is expected that FCG driving force is lowered by the crack bridging [13] [14] [15] [16] [17]. Therefore, in the cemented carbide, when a bridge portion is formed by the WC grains, the rate of FCG decreases.

The value of the threshold, K_{maxth} , of FCG of the cemented carbide with WC grain size of 8.5 µm is bigger than that of the one with WC grain size of 2.5 µm, as seen from **Figure 4** and **Figure 5**. As schematically illustrated in **Figure 9**, in the former (8.5 µm), the bridging parts are more easily formed and more hardly eliminated, than in the latter (2.5 µm). Since the existence of the bridging part



Figure 8. Bridging portion by the WC grain existing near the main crack-tip.



Figure 9. Bridging is loosened and eliminated by applying the shearing stress range along the WC/Co interface. As the WC grain size increases, bridging tends to be formed and it is difficult to be removed.

reduces the crack growth rate, it is considered that the threshold value of FCG in the material with WC grain size of 8.5 μ m will become higher than that in the material with WC grain size of 2.5 μ m.

5. Conclusions

The following conclusions were reached from the RTS tests and RBF tests on the cemented carbides.

1) It was found that the relation, da/dN, and the maximum stress intensity factor, K_{max} in the RTS tests was equivalent to the one obtained under the RBF tests at stress ratio of -1. From a practical point of view, this result is important as it indicates that it is not necessary to purposely perform RTS experiments.

2) In the RTS test, heating and cooling of the specimen are alternately repeated. By cooling rapidly the heated specimen, a tensile thermal stress is generated at the specimen surface that contacted with cooling medium. While, when the specimen is heated again in the furnace, though the heating rate is slower than the cooling rate, a compressive thermal stress is generated at the same specimen surface as above. Therefore, in the RTS tests, tensile and compressive thermal stress is loaded alternately on the specimen's surface. This situation is the same as in the case of RBF tests at stress ratio of R = -1.

3) In both the RBF and RTS tests, an effect of WC grain size on the relation da/dN vs. K_{max} was confirmed. The value of the threshold of FCG, K_{maxth} , for the cemented carbide with average WC grain size of 8.5 µm was found to be bigger than that of 2.5 µm. Because, in the former (8.5 µm), the bridging parts are easier to be formed and harder to be eliminated than those in the latter (2.5 µm).

4) It is necessary further to study the FCG characteristics in the RTS test of cemented carbide with a WC grain size of 1 μ m or less and other tool materials such as high speed steel, since they will be increasingly used in the manufacturing company.

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