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***Research Paper***

# Delamination Strength of WC-Co Thermal Sprayed Coating Under Combined Stresses by Torsion-Tension Pin-test Method

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In this paper, a newly established delamination strength evaluation method of WC-Co thermal sprayed coatings under combined torsion and tension, called the torsion-tension pin-test, is presented. Firstly, effects of both the pin-diameter and the coating thickness on apparent delamination strength were investigated experimentally. Secondly, stress distributions at around the interface edge between pin and coating were numerically obtained by using the Finite Element Analysis program "MARC". The following conclusions were obtained. (1) It was confirmed that the fractured plane of the torsion pin really coincides with the interfacial plane between coating and the pin. (2) Apparent delamination strength obtained experimentally decreases linearly with increasing pin diameter and increases with increasing coating thickness $t$, but becomes almost stable at $t$ = 400 μm or more. (3) The shear delamination strength decreases with increasing tensile stress. (4) Almost the same stress distributions can be observed at the interface when delaminations occur for rather thick coating, independently of pin diameter. (5) The critical combinations of strength of shear stress fields ($Ks$) with strength of tensile stress fields ($Ka$) which gives the delamination criteria of coating under combined shear and tensile loadings can be obtained for WC-12Co thermal sprayed coating. These combinations were found to be independent of pin diameter and coating thickness.

**Key Words: Thermal Sprayed Coating; FEM Analysis; Shearing Delamination; Stress Singularity; Combined Stresses; Strength of Stress Fields; Delamination Criteria**

## 1. Introduction

Thermal sprayed ceramic coatings have been applied to various important system parts, such as a gas-turbine blade, a combustion chamber wall and a boiler tube, which are used under severe conditions. It is important to establish the delamination strength criteria of such ceramic coating systems for precise designing of such coated parts. Many test methods have been presented to estimate the delamination strength of the thermal sprayed coating [1-4]. As mentioned in the previous report [7], the delamination strength between coating and substrate is closely related to strength of the coating's own and these both strengths have been discussed in a confused manner. As per the current research, many cases are restricted to the tests under simple tension and bending [1-4], and very few researches evaluating the strength under complex stress conditions, which resemble the actual loading conditions, have been presented [5-7]. The strength of a coating's own with a stress singularity zone has already been investigated in the previous report [7].

Here, we have discussed on delamination strength of WC-12Co thermal sprayed coating under combined shear and tensile stress conditions. To achieve the purpose, the new torsion-tension pin test method was developed and the new method was found to be useful as discussed in the previous report [9]. In this report, effects of both the pin-diameter and the coating thickness on the obtained delamination criteria by using the newly developed pin-test method are

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investigated. So, various pin-test specimens of three kinds of pin-diameter and three kinds of coating thickness are tested. And the corresponding stress distribution analysis at around the interface edge between pin and coating are performed on various such specimens under the critical loading conditions.

## 2. Specimen and Experiment

Dimensions of the pin test specimen are shown in Fig. 1. and its materials and other parameters are given in Table 1. Clearance *c* between a pin and hole's wall of the specimen is controlled to be about 10 µm. Jet-coat method has been used for WC-12Co coating. Effects of the coating thickness and the pin diameter on delamination strength are investigated.

Testing apparatus is shown in Fig. 2. Pin of the specimen is subjected to both torsion and tensile loadings by using dead weight. Dead weights are added gradually and very carefully until the failure.

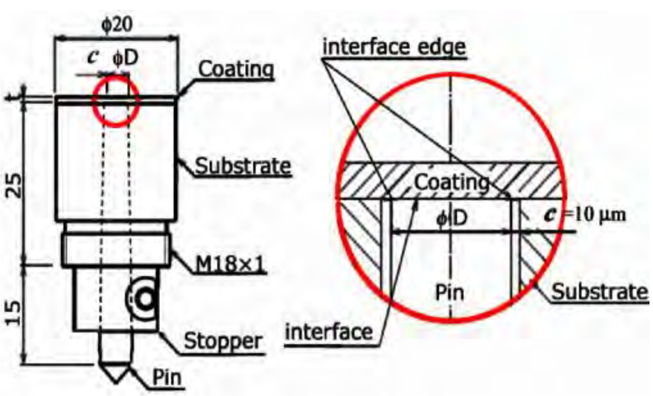


**Fig.1: Pin-test specimen**

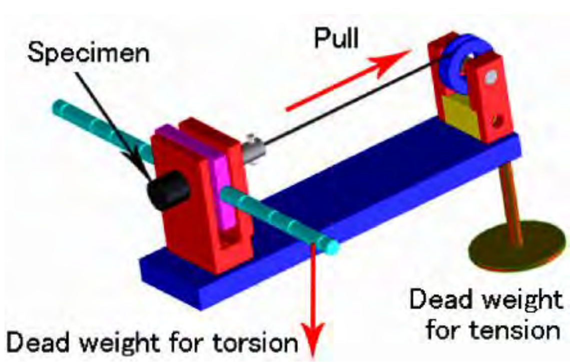


**Fig.2: Test-apparatus**

**Table 1: Materials and parameters of the pin-test specimen**

| | |
|---|---|
| Material of pin & substrate | SCM435 steel |
| Blasting material | Alumina #400 |
| Material of coating | WC-12Co |
| Diameter of pin | φ2, 3, 4 [µm] |
| Thickness of coating | 200, 400, 600 [µm] |

## 3. FEM Analysis

Stress-strain distributions at the interface edge are calculated by using FEM analysis software MARC. Material constants used in the analysis are shown in Table 2. Axisymmetric two-dimensional mesh model of the specimen is shown in Fig. 3. As shown in the figure, the bottom end of the substrate having a pin hole is fixed in the longitudinal, radial and circumferential directions. Mesh elements are the 4-nodes- isoparametric elements and the minimum size of the element is 0.95 nm long. Effects of the porosity of the coating and surface roughness at the interface between the coating and the substrate are neglected. Both of torsion and tension are applied at the right side end of the pin.

## 4. Experimental Results

Figs. 4 to 6 show the results of the experiments on delamination strength of WC-12Co thermal sprayed coating under combined shear and tensile loading by the torsion pin test method. In these Figs. 4 to 6, the ordinate indicates the maximum shear stress $\tau_{max}$ caused by the critical torsion load $T$ at delamination, that is,

$$\tau_{max} = 16T/(\pi d^3) \quad (1)$$

where $d$ means the diameter of the pin and the maximum shear stress means the apparent delamination strength. The abscissas indicate the diameter of the pin, the thickness of coating and tensile average stress, respectively.

In Figs. 4 and 6, we can see that the apparent delamination strength decreases with increasing pin diameter and tensile stress. In Fig. 5, the apparent delamination strength $\tau_{max}$ is found to increase with

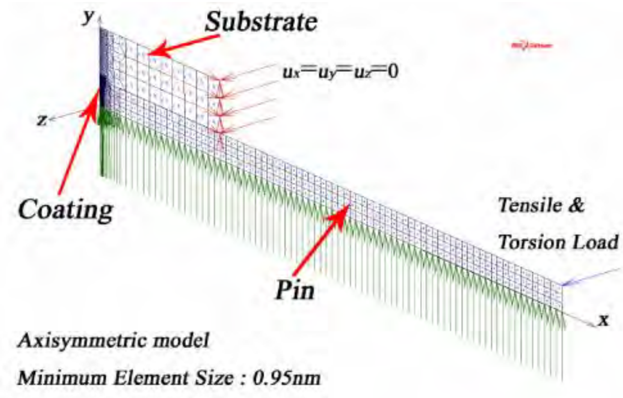


**Fig.3: Mesh-model of the pin-test specimen and boundary conditions**

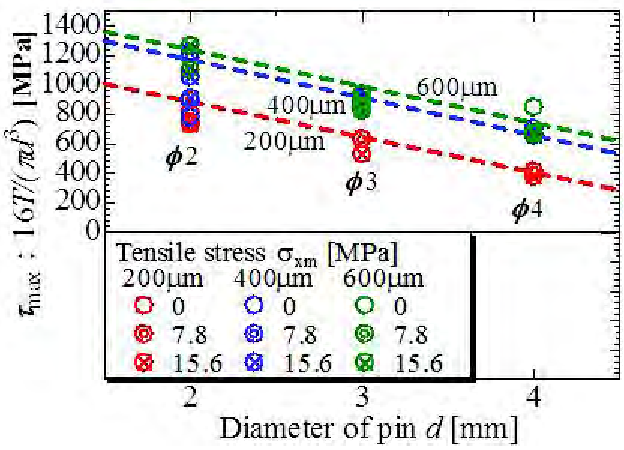


**Fig.4: Maximum shear stresses for various pin diameters at failure**

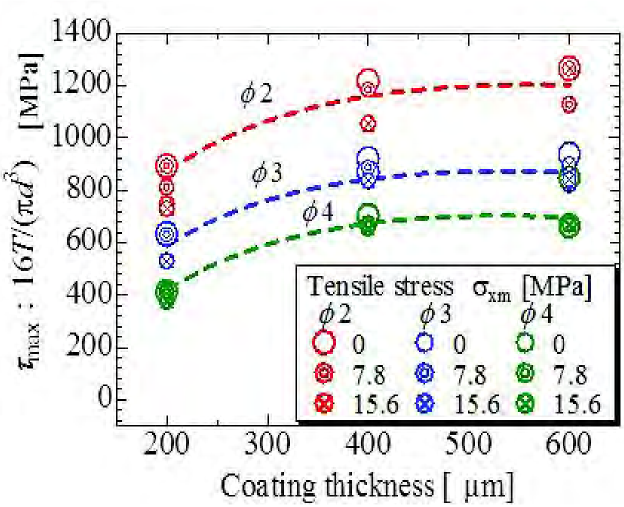


**Fig. 5: Maximum shear stresses for various coating thickness at failure**

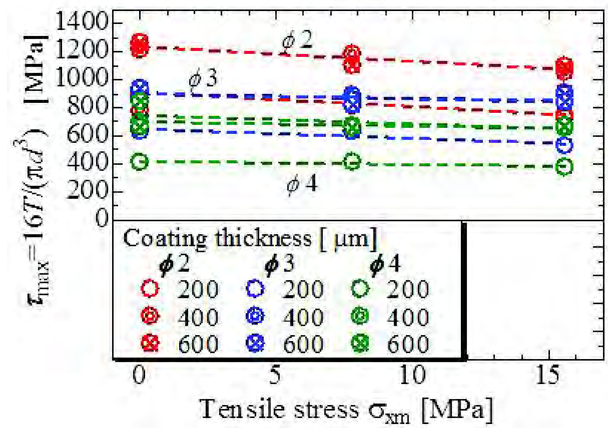


**Fig.6: Maximum shear stresses for various tensile stresses at failure**

increasing coating thickness, but become stable at 400 µm or more in thickness. Fig. 7 shows some fractured surface views of the pin with three kinds of thickness in coating, where bright area is metal surface. Such bright interfacial delamination area increases with increasing coating thickness. So, we can see that delamination tends to occur inside of the coating when the coating thickness is thin. Thin coating is found to be weak than that of thicker one. This is because the compressive residual stress becomes higher with an increase in coating thickness.

In these experimental results, it is generally found that the delamination shear stress shows very high amount in comparison with delamination tensile stress measured by the conventional tensile pin test method and decreases with a slight increase of tensile stress. This is because the shearing delaminations really occur at the interface as shown in Fig. 8(a), where many bright circular lines are the surfaces of the metal substrate, but delaminations occur at inside of the

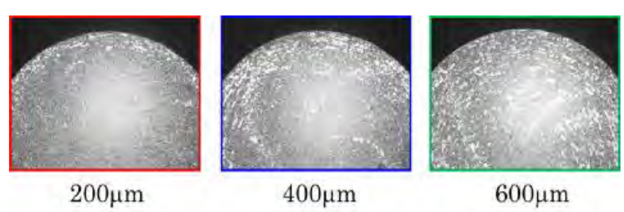


**Fig. 7: Views of the fractured surface of the pin by torsion for various coating thickness**

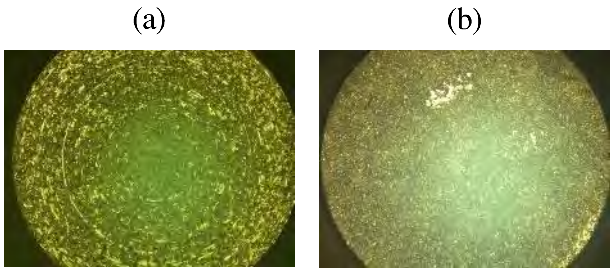


**Fig. 8: (a) View of the fractured surface of the pin by torsion; (b) View of the fractured surface of the pin by tension**

coating under tension as shown in Fig. 8(b) and also rather higher stress concentration occurs at the interface edge in the case of tensile loading.

From these experimental results, we can get approximation lines as shown in these figures, which show the apparent delamination strength depending on both the pin diameter and the coating thickness. On the basis of these approximated lines, the critical loading, tensile and shear stress distributions at around the interface edge under the critical loading are calculated by FEM analysis in the next chapter.

## 5. Calculated Results and Discussions

### *5.1 Stress Distribution at the Stress Singularity Field Around the Interface Edge*

Fig. 9 shows the typical stress distributions at around the interface edge. Stress distributions at the singularity point like the interface edge of the specimen are generally approximated to the expression (2), where $\sigma$ means stress components or equivalent stress, $r$ indicates the length measured from the interfacial edge, $\lambda$ means the singularity parameter and $K$ means the strength of stress singularity.

$$\sigma = Kr^{-\lambda} \tag{2}$$

Strength of stress fields $K$ can be determined as the intercept of the approximated red line at $r = 1$ for the stress distributions at the area of $1 \times 10^{-5} < r < 1 \times 10^{-3}$ mm, as shown in Fig. 9. The singularity parameter $\lambda$ can be obtained as the gradient of the approximated red line.

It is a quite reasonable supposition usually that a principal stress is dominant in adhesive failure of such brittle coating as WC-Co cermet. But, the principal stress which works on the failure surface in the perpendicular direction should be discussed. In the pin tests, all failures (or delaminations) really occur at the interface, so both of shear and tensile stress components should be taken into consideration for investigating the delamination criteria of coating.

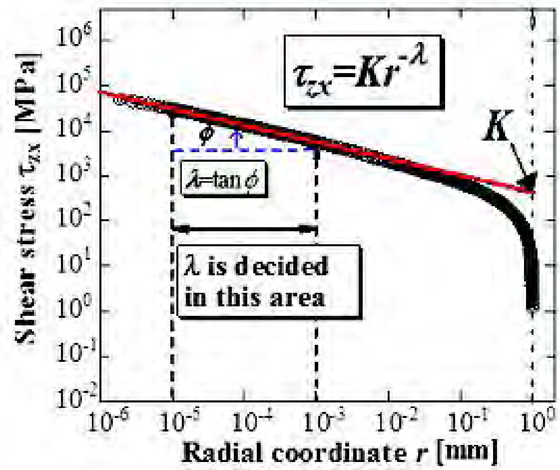


**Fig. 9: Typical shear stress distributions at around the interface edge and determination of stress intensity factor $K$ and singularity parameter $\lambda$**

### *5.2 Stress Singularity Analysis Under Constant Apparent Loading*

Fig. 10 shows the shear stress distributions for various pin diameters and coating thickness under constant $\tau_{max}$ = 800MPa and Fig. 11 shows the tensile stress distributions under constant $\sigma_{max}$ = 7.8MPa without torsion. From these results, it is found that although the apparent stress is the same, stress distributions at the interface edge are different from each other depending on pin diameter and coating thickness. But, we can see that the gradients of these stress distributions are almost the same with each other, so the stress distributions are expressed by their strength of stress field $Ks$ for torsion and $Ka$ for tension.

Fig. 12 shows variations in the strength of shear stress field $Ks$ calculated for various pin diameters and coating thickness under the apparent constant loading of $\tau_{max}$ = 800MPa without tension. Fig. 13 shows variations in the strength of tensile stress field $Ka$ calculated for various pin diameters and coating thickness under loading conditions of $\tau_{max}$ = 800MPa

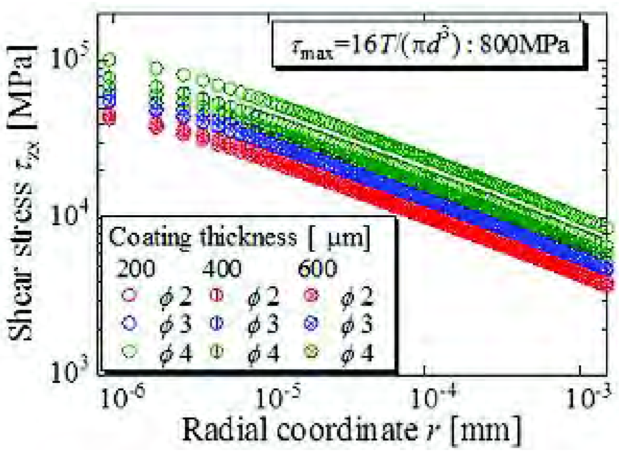


**Fig. 10: Shear stress distributions at the interface edge for various pin-diameter and coating thickness under $\tau_{max}$ = 800MPa**

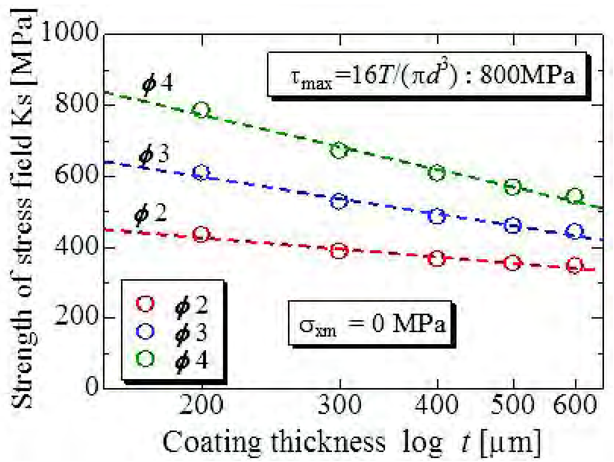


**Fig. 12: Strength of shear stress fields *Ks* for various pin-diameter and coating thickness under $\tau_{max}$ = 800MPa**

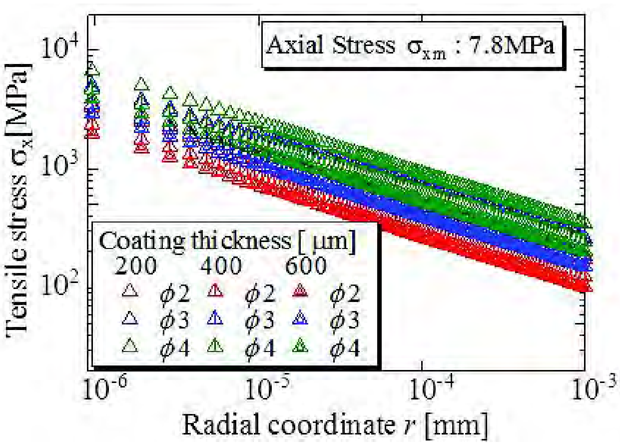


**Fig. 11: Tensile stress distributions at the interface edge for various pin-diameter and the coating thickness under $\tau_{max}$ = 0 and $\sigma_{max}$ = 7.8MPa**

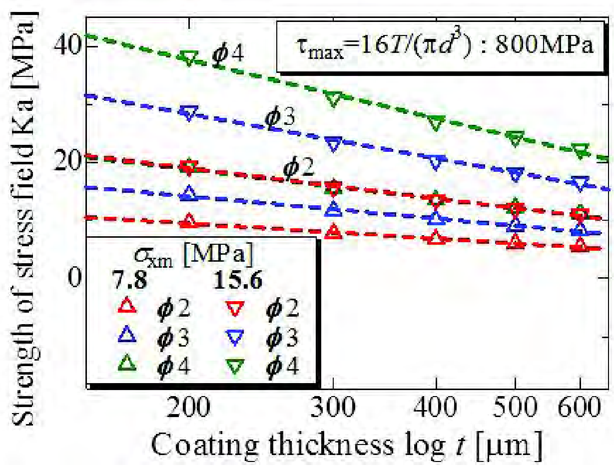


**Fig. 13: Strength of tensile stress fields *Ka* for various pin-diameter and coating thickness under $\tau_{max}$ = 800MPa and $\sigma_{max}$ = 7.8, 15.6MPa**

with $\sigma_{max}$ = 7.8, 15.6MPa. In these figures, abscissa means logarithm of the coating thickness *t*. We can see that both *Ks* and *Ka* decrease linearly with increasing log (*t*) and increase with increasing pin diameter. Effects of coating thickness on *Ks* and *Ka* increase with increasing pin diameter.

### *5.3 Stress Distributions at the Singularity Fields When Delaminations Occur*

Fig. 14 shows the critical shear stress distributions when delaminations occur under torsion. It is found that almost the same stress distributions can be observed around the interface edge for various pin diameters with coating thickness of 400μm or more. These stress distributions mean the critical stress conditions for delamination. So, the critical value of the strength of shear stress field *Ks* can be determined as the delamination condition under torsion without tension.

The critical values of *Ks* as the delamination conditions for combined torsion loading with slight tensile stress can be determined in the same way, as shown in Fig. 15. The critical values of *Ks* are found to decrease quickly with increasing tensile stress.

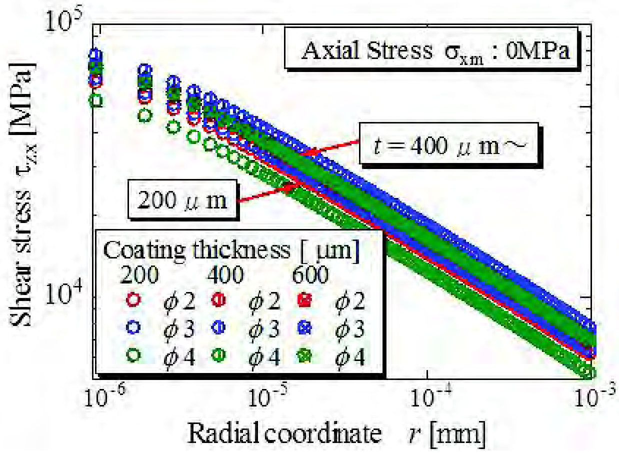


**Fig. 14: Shearing critical stress distributions at the interface edge for various pin-diameter and coating thickness at delamination**

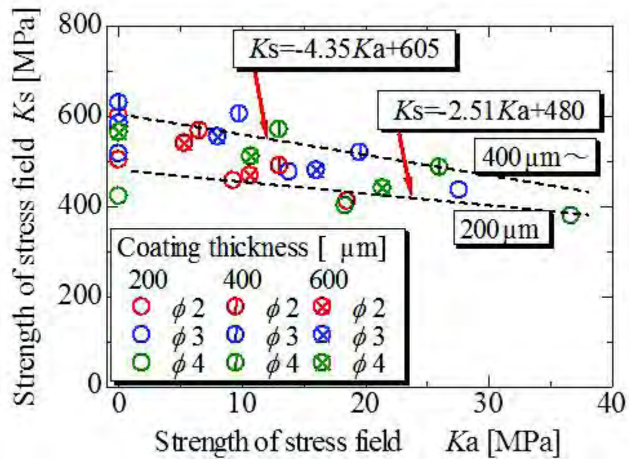


**Fig. 16: Delamination critical combinations of *Ks* and *Ka* for WC-12Co thermal sprayed coating under combined shear and tensile loadings**

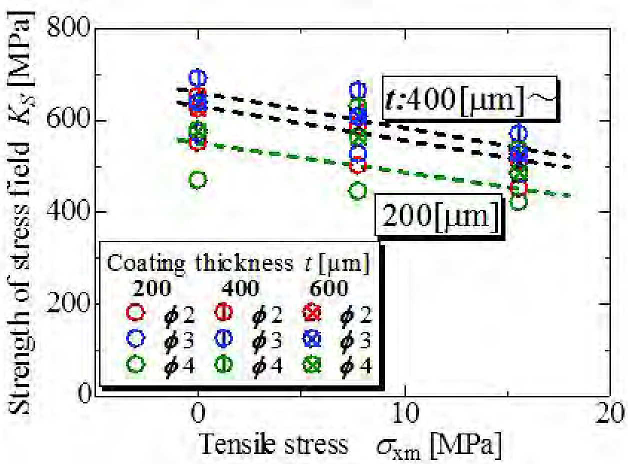


**Fig. 15: The critical *Ks* values as the delamination condition at the interface edge under combined torsion with various tensile stresses**

**Table 2: Mechanical properties of the specimen's materials**

| Materials | Young's modulus | Poisson's ratio |
|---|---|---|
| SCM435 | 208 GPa | 0.268 |
| WC-12Co | 154 GPa | 0.230 |

From these calculated results, it is thought that the delamination criteria of the coating can be expressed by the function of *Ks* and *Ka*.

Fig. 16 shows the combinations of *Ks* with *Ka* which are obtained for various tensile stresses and various pin diameters. This result shows the critical delamination conditions of coating under combined shear and tensile stresses, which are found to be independent of pin clearance as we mentioned in the previous report as well.

These results show the newly developed torsion pin test method is very useful to estimate a delamination strength of coating under combined shear and tensile loadings. In the near future, investigations on the fatigue strength effects of pin diameter and thickness of coating on the test results in the torsion pin-test will be presented and the reliability of the testing system will be discussed.

## 7. Conclusions

In this report, the newly developed delamination strength test method which was named as "torsion pin test method", is presented. Delamination strength of WC-12Co thermal sprayed coating under combined shearing and tensile stresses was investigated experimentally and analytically. The following results were obtained.

(1) It was confirmed that delamination occurred really at the interfacial plane between coating and substrate. So, it was found that shearing delamination strength can be estimated precisely by the torsion pin test without tension.

(2) Apparent delamination strength obtained experimentally decreases linearly with increasing pin diameter and increases with increasing coating thickness *t*, but becomes almost stable at $t = 400\mu m$ or more.

(3) The critical shear stress decreases with increasing tensile stress.

(4) Almost the same stress distributions can be observed at the interface when delaminations occur for rather thick coating, independently of pin diameter.

(5) The critical combinations of shear stress intensity factor (*Ks*) with tensile stress intensity factor (*Ka*) as the delamination criteria of coating under combined shear and tensile loadings can be obtained for WC-12Co thermal sprayed coating. These combinations were found to be independent of pin diameter and coating thickness.

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