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Analysis of Cracking Pattern in The Brittle Film Coated on a Ductile Disk Under Axisymmetric Tension

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ABSTRACT: In order to characterize the "Island-delamination type" and "Repeating division type" cracking patterns which are often observed in the brittle film on a ductile substrate under equi-biaxial tension, analyses were carried out to introduce the relation among the size of island-crack or the interval of division, the tensile stress at the formation of island-crack or division-crack, film and substrate thickness, surface energy of film, interfacial energy between film and substrate and material's constants. The bulge tests of ceramic film on steel disks show the island delamination cracking, and the size of island-crack increases and the pressure at the formation of island-crack decreases with increase in film thickness. The film thickness dependency of island size and tensile stress at the formation of island-crack calculated from the analysis agree relatively well with the experimental results. The bulge tests of cermet film on the disk show the repeating division cracking, and the characteristics of the division process is explained by the analysis.

Introduction

Various kinds of surface coating methods such as ceramic spraying have been applied to give the heat-, wear-, and corrosion-resistances to machine parts and structures (1,2). In some cases, however, the coating film can be cracked and delaminated by stress- or heat- cycles and over-loading, so that the characterization of cracking and delamination behavior is essential to maintain the reliability of coated structures. Present authors(3-5) have already proposed a method to evaluate the delamination strength from the uniaxial tensile test of a smooth specimen with coating film on the basis of Kendall's analysis(6), where the loading direction is parallel to the film and the delamination of film occurs mainly by shear stress along the interface.

In certain actual structures, such as pressure vessel, the coating film is cracked and delaminated under biaxial tensile stress. In addition, the cracking patterns in the films under biaxial tensile stress are much different from those under uniaxial tension depending on the nature of film, substrate and interfacial strength between film and substrate. It will be important, therefore, both from academic and engineering standpoints to characterize the cracking morphology and to correlate the cracking pattern with delamination strength. In the previous paper (7), one of the present authors has classified the cracking patterns of brittle film under biaxial loading into three types : First is "Cobweb type" cracking where a short crack originates at the center of a disk and it propagates in the radial direction by forming many branches followed by concentric-circle cracks colliding with the branched cracks. This type of pattern is often observed when the film is very brittle while the substrate is ductile enough to support the film without delamination, where the pattern formation is controlled mainly by the cracking process of film. The second is "Island-delamination type", where ideally the hexagonal-network cracking appears on the film and the delamination occurs just after the accomplishment of network cracking. This type of pattern is observed when the interfacial strength is not so high. The third is "Repeating division type" which appears when the interfacial strength is very high. With increasing stress, the film is divided repeatedly to smaller areas until the division stops by the occurrence of delamination.

With regard to the "Cobweb type" cracking, one of the present authors(7,8) has introduced the crack nucleation and propagation law and introduced the "Branching Dimension" to quantitatively connect the crack branching pattern with the applied stress during crack propagation. The purpose of present research is to analyze both the "Island-delamination type" and the "Repeating division type" cracking to introduce the relation between island size or division interval and the properties of film, substrate and film-substrate interface, and to compare the analyses with experimental results.

Experimental Method

Specimen and coating method

Figure 1 shows the shape of disk specimen for biaxial tensile test. Only the central area of 70mm diameter was coated using a mask. The disk specimen of a low carbon steel was sandblasted to make the irregularity and to remove oxide film on the specimen surface, and the pressured air was blowed to clean the blasted surface. Two types of coating films were prepared:

(1) Ceramic film: A mixture of alumina (Al_2O_3:60 mass%) and titania (TiO_2:40 mass%) ceramic powder with 10~40μm diameter was plasma-sprayed on the specimen with the following condition; plasma voltage and current were 36V and 900A. Arc and powder gas was Ar (0.47MPa), and secondary gas was He (0.40MPa). Moving speed of spray gun was 670 mm/s and the spray distance was 100 mm from specimen surface. The film thickness was controlled by changing the rotation speed of hopper.

(2) Cermet film: A mixture of WC (88 mass%) and Co (12 mass%) powder was coated on the specimen by high-velocity flame spraying with following condition; Moving speed of spray gun was 333mm/s, spray pitch was 3mm, the spray distance was 250mm, and spray gas was propylene (580kPa)+oxygen (1080kPa). The film thickness was controlled by changing the number of spray cycles.

Biaxial tensile test

The biaxial tensile test was carried out by using a bulge apparatus shown in Fig.2, in which the oil was driven by a hand pump. At a certain pressure, the film surface was observed by a travelling microscope with a magnification of 40, and a photograph was taken. The bulge height was measured by moving a dial gage in the two radial directions at the center of disk, from which the radius of bulge r was calculated to obtain the biaxial tensile stress σ in the disk

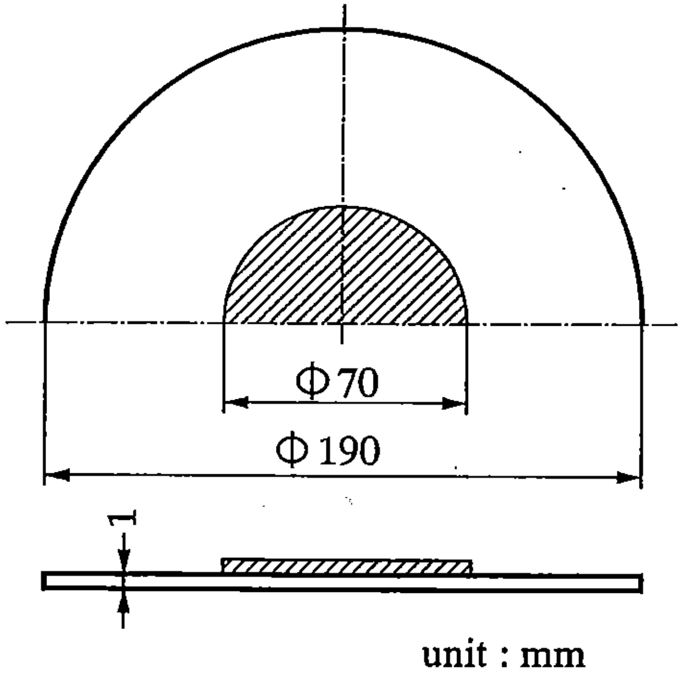

Fig.1 A disk specimen with coating film.

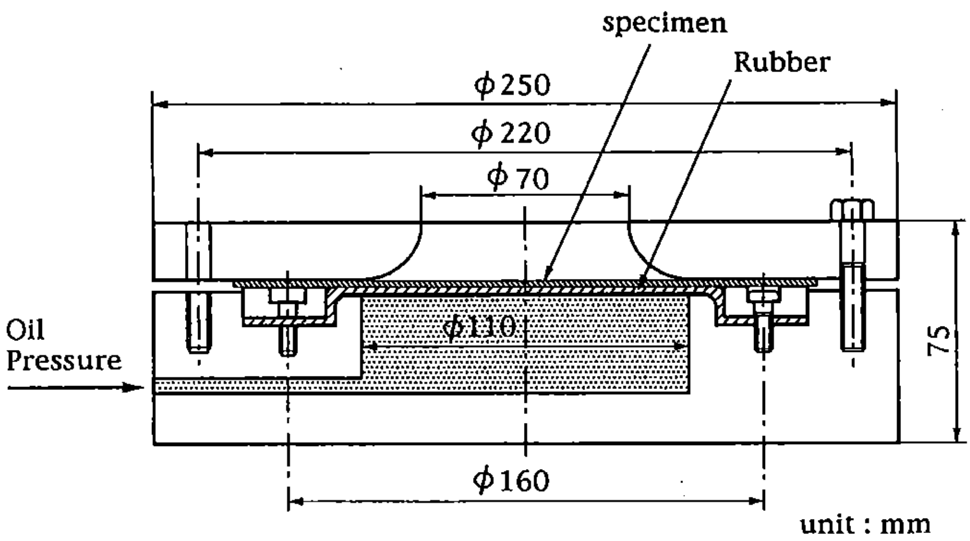

Fig.2 An apparatus for bulge test of disk specimen.

the following equation

$$\sigma = \frac{r\ p}{2\,B_2} \tag{1}$$

where B_2 is the thickness of disk. Because the amount of bulge is not large, B_2 is taken as the thickness before bulge test. The calculated bulge radius is actually constant within the circle area of 60mm diameter, which proves the existence of equi-biaxial stress state in the area.

Figure 3(a) shows the island delamination type cracking pattern for ceramic film after the bulge test. With increasing pressure, after fine cracks appear all over the surface, they branch and connect each other to develop into the network cracking with detectable gap between each island. It is difficult to determine when the delamination has occurred. The pressure when the island cracking is almost completed in the sight of microscope was defined as the pressure p_i at which the delamination started. The size of island $2a_0$ was measured by line-cutting method.

Figure 3(b) shows an example of the repeating division type cracking pattern observed for WC+Co cermet film during a bulge test. At a certain pressure, several long line cracks appear in the film to divide the film to several areas, and the division of the area advances with increasing pressure until the delamination of divided films. The distance between divided cracks were measure by line-cutting method on the photograph.

Analysis

"Island-delamination type" cracking pattern

There is a peculiarity in the "Island-delamination type" cracking compared with other two types of patterns as follows: This type of pattern appears when the delamination strength is not so high. According to the observation, once the island shape cracks are formed in the film, only the delamination of islands occur without additional cracking in the islands, although the actual delamination does not develop so quickly due to the anchor effect by shot-blasting. It has been reported that the progress of delamination of film is neither stable nor unstable in the case of uniaxial tension (3,6). Also under biaxial tension, therefore, the situation seems to be the same, i.e., if the delamination once begins at the edge of island at a certain pressure, it inevitably

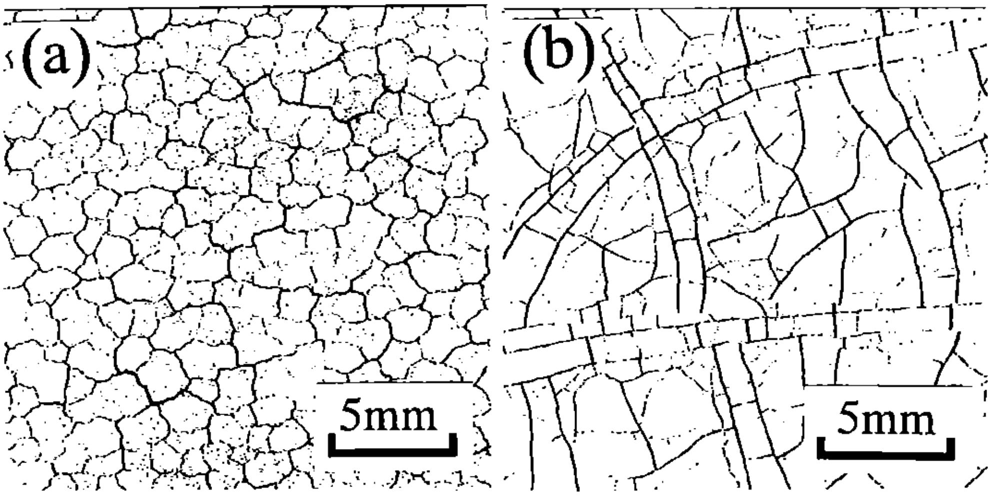

Fig.3 (a) Island-delamination type cracking observed for ceramic film (film thickness B_1= 0.4mm) and (b) repeating division type cracking observed for cermet film (B_1= 0.2mm).

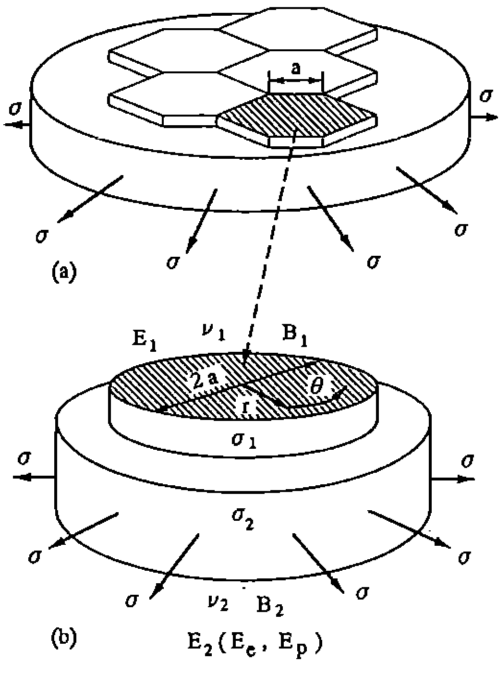

Fig.4 Modeling of an actual island-film shape to (a) a hexagonal and (b) a cylindrical film shapes.

develops along whole of the interface of island without stopping. Thus, if an energy consideration is effective to explain the formation of island, both the cracking and delamination processes should be taken into account at the same time.

For the simplicity of analysis, the island cracking and delamination are assumed to occur ideally as a hexagonal plate of film with a side of *a* under equi-biaxial tensile stress σ as shown in Fig.4(a), and the hexagonal plate is again replaced by a disk with diameter of 2a as shown in Fig.4(b). In this model, σ_{r1} and $\sigma_{\theta 1}$ denote the stresses in the film in the radial and tangential directions, and σ_{r2} and $\sigma_{\theta 2}$ those in the substrate. Similarly, the stains in the film and the substrate in the radial and tangential directions are denoted as ε_{r1}, $\varepsilon_{\theta 1}$ and ε_{r2}, $\varepsilon_{\theta 2}$. Because the thickness of film and substrate are small enough compared with the diameter of disk specimen (the stresses in the z direction are small), the following relations hold for the disk with thin film under equi-biaxial tension.

$$\sigma_{r1} = \sigma_{\theta 1} \equiv \sigma_1, \quad \sigma_{z1} \fallingdotseq 0$$

$$\sigma_{r2} = \sigma_{\theta 2} \equiv \sigma_2, \quad \sigma_{z2} \fallingdotseq 0$$

$$\varepsilon_{r1} = \varepsilon_{\theta 1} \equiv \varepsilon_1, \quad \varepsilon_{r2} = \varepsilon \quad \equiv \varepsilon_2 \qquad (2)$$

In the present combinations of ductile steel substrate and brittle ceramic film, the delamination of film occurs after the plastic deformation of substrate. For convenience of analysis, the deformation behavior of substrate is expressed by that of a liner hardening body with an elastic constant E_e and a plastic constant E_p(the gradient of plastic region of σ - ε curve). The plastic deformation process under a multi-axial stress can be expressed by using equivalent stress, and the yield stress under equi-biaxial tension σ_{ys} is the same as that under uniaxial tension independently of which criterion of Tresca or Mises is applied. So that the stress-strain relation obtained under uniaxial tension can be used for the analysis of substrate under equi-biaxial tension. Thus, the strain of film under elastic deformation, ε_1, and that of substrate under plastic deformation, ε_2, are expressed as follows:

$$\varepsilon_1 = (\sigma_1 - \iota_1 \sigma_1)/E_1 = (1 - \iota_1)\sigma_1/E_1$$

$$\varepsilon_2 = (1 - \iota_2)\sigma_2/E_e \qquad \sigma_2 \leqq \sigma_{ys}$$

$$\varepsilon_2 = (1 - \iota_2)\{\sigma_{ys}/E_e + (\sigma_2 - \sigma_{ys})/E_p\} \qquad \sigma_2 \geqq \sigma_{ys} \qquad (3)$$

Here E_1 and ι_1 are the elastic constant and Poisson's ratio of film, and ι_2 is the Poisson's ratio of substrate which is assumed to be equal both in elastic and plastic deformation.

Because the strains are the same everywhere in the film and substrate in plastic deformation before the cracking and delamination, i.e. $\varepsilon_1 = \varepsilon_2$, the following equation holds:

$$(1-\iota_1)\sigma_1/E_1 = (1-\iota_2)\{\sigma_{ys}/E_e + (\sigma_2 - \sigma_{ys})/E_p\} \tag{4}$$

The balance of force between the applied load and the reaction forces in the film and the substrate is given by

$$B_2\sigma = B_2\sigma_2 + B_1\sigma_1 \tag{5}$$

so that the stresses in the film and substrate, σ_1 and σ_2, are obtained from eqs.4 and 5:

$$\sigma_1 = \frac{(1-\iota_2)}{(1-\iota_1)} \cdot \frac{E_1}{E_p}\{\sigma - (1 - \frac{E_p}{E_e})\sigma_{ys}\} / \{1 + \frac{(1-\iota_2)E_1B_1}{(1-\iota_1)E_pB_2}\}$$

$$\sigma_2 = \{\sigma + \frac{(1-\iota_2)}{(1-\iota_1)} \cdot \frac{E_1B_1}{E_pB_2}(1 - \frac{E_p}{E_e})\sigma_{ys}\} / \{1 + \frac{(1-\iota_2)E_1B_1}{(1-\iota 1)E_pB_2}\} \tag{6}$$

Next, the energy consideration after Griffith theory is applied to introduce the stable size of island crack $2a_0$ as a function of material constants and thickness of film and substrate. Because the decrease in stress does not occur in the substrate at the cracking and delamination of film, the application of energy consideration on the basis of elastic theory is possible.

The increase in surface energy by the formation of a disk-shape crack in the film, W_1, is:

$$W_1 = 2\gamma_c \pi a B_1 \tag{7}$$

where γ_c is the surface energy of film per unit area which corresponds to the fracture toughness of film. The increase in interfacial energy W_{12} when the delamination occurs along whole of the interface between film and substrate is expressed as:

$$W_{12} = 2\gamma_{12}\pi a^2 \tag{8}$$

where γ_{12} is the interfacial energy per unit area. By considering that the strain energy per unit volume stored in an elastic body under biaxial tension is $U=(1-\iota)\sigma^2/E$, the strain energy of film released by the delamination, U_1, is calculated as follows:

$$U_1 = (1-\iota_1)\sigma_1^2 \pi a^2 B_1/E_1 \tag{9}$$

When the delamination occurs under a constant applied stress, σ, the increase in strain energy in the substrate, U_2, is given by the next equation similar to the eq.9:

$$U_2=(1-\iota_2)(\sigma^2-\sigma_2^2)\pi a^2 B_2/E_p \tag{10}$$

The work done by external load for the cracking and delamination, T, is calculated as follows considering the strains in the substrate before and after the delamination:

$$T=(2\pi a\sigma B_2)(\varepsilon_r-\varepsilon_{r2})a=(1-\iota_2)2\pi a^2\sigma(\sigma-\sigma_2)B_2/E_p \tag{11}$$

Because the change of free energy by the island shape cracking and delamination, ΔF, is

$$\Delta F=W_1+W_{12}-U_1+U_2-T \tag{12}$$

the stable diameter of island crack $2a_0$ is obtained from the 2a which satisfies the next condition:

$$\frac{\partial(\Delta F)}{\partial a}=0 \tag{13}$$

Thus, the $2a_0$ is expressed as:

$$2a_0=\frac{2\gamma_c B_1}{(1-\iota_1)B_1\sigma_1^2/E_1+(1-\iota_2)B_2(\sigma-\sigma_2)^2/E_p-2\gamma_{12}} \tag{14}$$

According to the eq.14, $2a_0$ is smaller when γ_c or γ_{12} is smaller. In addition, the denominator of eq.14 should be positive in order that the equation retains physical meaning. If γ_c is much smaller than γ_{12}, the delamination stress (σ, σ_1 or σ_2) is small and $2a_0$ can take a negative value, and "Island-delamination type" cracking can no longer be achieved. In such a case, the "Cobweb type" or the "Repeating division type" cracking will appear.

"Repeating division type" cracking pattern

This type of cracking is observed when the delamination of film is difficult to occur. Fig.5 schematically shows the repeating division of film under biaxial tension. At a certain stress, a straight crack with length $a=a_1$ is initiated, and with increasing stress the second division by $N=6=3\times 2$ cracks with length of $a_2=a_1/2$ occurs, and the division process continues until the delamination of film. Because the number of cracks, N, at division stage n is expressed by $N=3\times 2^{2n-3}$ and the crack length an at division stage n by $a_n=a_1/2^{n-1}$, the next relation is obtained.

$$\log N=\log(3/2)-2\log(a_n/a_1) \tag{15}$$

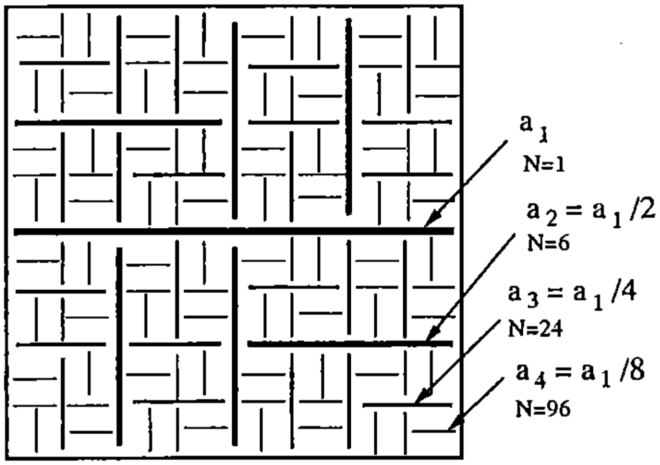

Fig.5 Model of repeating division of film by cracks under biaxial tension.

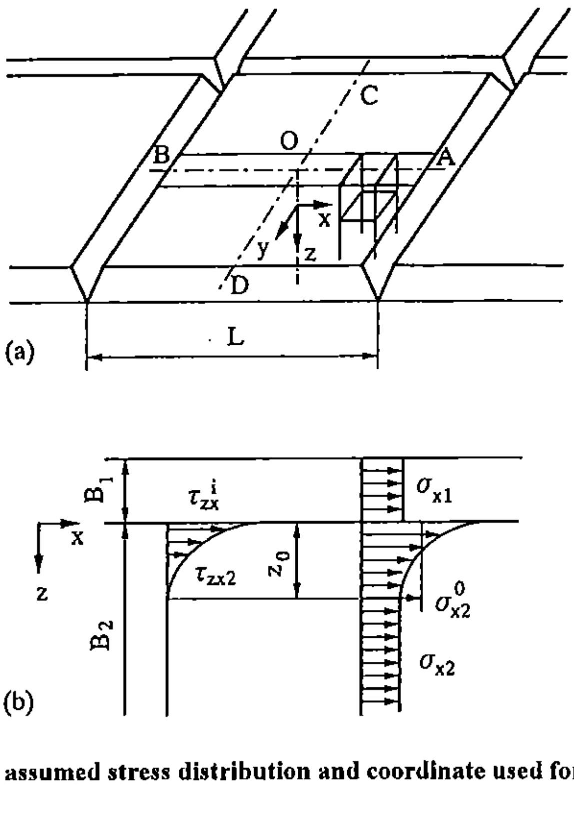

Fig.6 Stresses, assumed stress distribution and coordinate used for analysis.

When the division is repeated, the stress distribution in the disk is no longer homogeneous near divided cracks. In order to predict the division process of film under biaxial loading due to the increase in tensile stress or pressure, the similar analysis introduced by J.Jeong and D.Kwon(9) for that under uniaxial tension is utilized in the present research, and the equations are rewritten for the convenience of explanation with small modification for biaxial problem.

Figure 6(a) and (b) show the rectangular coordinate system in an infinitesimally small cube in the band region along the center line of film across which the division of film occurs. It will be sufficient to analyze the stress and strain distribution in the band region because the tensile stress σ_{x1} is smaller near the edge (point C and D) and the crack nucleation occurs at the center of the region(point O). In the figure, σ and τ mean normal stress and shear stress, and the subscripts 1 and 2 indicate the film and substrate, respectively. By considering the equilibrium of force in the band in the x direction and considering that $\tau_{xy1}=0$, the next equation is obtained:

$$B_1 \frac{d\sigma_{x1}}{dx} = -\tau_{zx}^{i}(x) \tag{16}$$

where $\tau_{zx}^{i}(x)$ is shear stress at interface and τ_{zx2} will disappear at a certain distance $z=z_0$ from interface (Fig.6(b)). Also for the y direction, the similar equation is obtained for the band region along C-D line by exchanging the subscript x for y. The balance of force both in the film and the substrate in the x direction is expressed as:

$$\sigma z_0 dy + \sigma (B_2 - z_0)dy = \sigma_{x1}B_1 dy + \sigma_{x2}^{0} z_0 dy + \sigma_{x2}(B_2 - z_0)dy \tag{17}$$

Here σ is the nominal tensile stress in the disk which is nearly equal to the nominal stress in the substrate($\sigma \fallingdotseq \sigma_{x2}$), and σ_{x2}^{0} is the mean tensile stress in the substrate near interface ($0<z<z_0$). The differentiation of eq.17 with x reduces to:

$$B_1 \frac{d\sigma_{x1}}{dx} = -z_0 \frac{d\sigma_{x2}^{0}}{dx} \tag{18}$$

Next, the equilibrium of force in the infinitesimally small cubic part of substrate near interface is expressed by following equation.

$$\frac{d\sigma_{x2}^{0}}{dx} + \frac{d\tau_{zx2}}{dz} = 0 \tag{19}$$

Substitution of eqs.16 and 19 into 18 gives the next relation.

$$\frac{d\tau_{zx2}}{dz} = -\frac{\tau_{zx}^{i}(x)}{z_0} \qquad (20)$$

Because $\tau_{zx2} = \tau_{zx}^{i}(x)$ when $z=0$ and $\tau_{zx}^{i}(x)=0$ when $z=z_0$, the next equation is obtained:

$$\tau_{zx2} = \tau_{zx}^{i}(x)\left(1-\frac{z}{z_0}\right) \qquad 0 \leqq z \leqq z_0 \qquad (21)$$

If the division of film occurs under plastic deformation of substrate near interface and it is expressed by linear hardening behavior($\gamma = \tau_{ys}/G_2 + (\tau - \tau_{ys})/G_{2p}$), the next equation holds:

$$\tau_{zx2} = G_{2p}\left(\frac{\partial u_2}{\partial z} - \frac{\partial w_2}{\partial x}\right) + \frac{G_2 - G_{2p}}{G_2}\tau_{ys} = \tau_{zx}^{i}(x)\left(1-\frac{z}{z_0}\right) \qquad (22)$$

where G_2 and G_{2p} are elastic and plastic shear moduli, τ_{ys} is shear yield strength of substrate, and $\partial w_2/\partial x \fallingdotseq 0$. By integrating u_2 from $z=0$ to z_0, and putting the u_2 at $z=0$ as u_2^+ and u_2 at $z=z_0$ as u_2^-, the eq.22 becomes

$$u_2^- - u_2^+ = \frac{\tau_{zx}^{i}(x)}{2G_{2p}} z_0 - \frac{G_2 - G_{2p}}{G_2 G_{2p}}\tau_{ys} z_0 \qquad (23)$$

By substituting eq.16 into 23, and differentiating the equation with x, the next equation is obtained.

$$\frac{d^2\sigma_{x1}}{dx^2} = \frac{2G_{2p}}{z_0 B_1}\left(\frac{du_2^+}{dx} - \frac{du_2^-}{dx}\right) \qquad (24)$$

Here du_2^+/dx means the strain of substrate at interface under constraint by film and is equal to the strain of film, ε_{x1}, while du_2^-/dx is the strain of substrate, ε_{x2}, with no constraint by film. The stress-strain relation in the film under biaxial loading is given as follows because $\sigma_{z1} \fallingdotseq 0$,

$$\varepsilon_{x1} = \frac{1}{E_1}(\sigma_{x1} - \nu_1 \sigma_{y1}) \qquad (25)$$

so that from eqs.24 and 25, the next expression is obtained.

$$\frac{d^2\sigma_{x1}(x)}{dx^2} - \alpha^2\sigma_{x1}(x) + \alpha^2(\nu_1\sigma_{y1} + E_1\varepsilon_{x2}) = 0$$

$$\alpha^2 \equiv \frac{2G_{2p}}{z_0 B_1 E_1} \qquad (26)$$

Because the change of σ_{y1} is not large, it is treated as a constant value independent of x. By solving the above differential equation under the condition that $\sigma_{x1}(L/2) = \sigma_{x1}(-L/2) = 0$, and

$\sigma_{x1}(0)=\sigma_{y1}$, the next result is obtained.

$$\sigma_{x1}(x)=\frac{E_1\,\varepsilon_{x2}\cosh(\alpha L/2)}{(1-\nu_1)\cosh(\alpha L/2)+\nu_1}\left\{1-\frac{\cosh(\alpha x)}{\cosh(\alpha L/2)}\right\} \tag{27}$$

The shear stress at interface is obtained by substituting eq.27 into eq.16 as follows.

$$\tau_{zx}^{i}(x)=\frac{E_1\,B_1\,\alpha\,\varepsilon_{x2}\sinh(\alpha x)}{(1-\nu_1)\cosh(\alpha L/2)+\nu_1} \tag{28}$$

Because the tensile stress in the film is maximum at the center of film (x=0), the division occurs when the next equation is satisfied:

$$\frac{E_1\,\varepsilon_{x2}[\cosh(\alpha L/2)-1]}{(1-\nu_1)\cosh(\alpha L/2)+\nu_1}=\sigma_c \tag{29}$$

where σ_c is a critical tensile strength of film. Because ε_{x2} is given by eq.3 and $\sigma_2(\doteqdot\sigma)$ is calculated by eq.1 form measured radius of curvature and pressure, the relation between σ_2 and division interval L will be calculated from eq. 29 if σ_c is given.

Results and Discussion

"Island delamination type" cracking

By the bulge tests of disks with ceramic film, the size of island cracking, $2a_0$, and the pressure at island cracking formation, p_i, were measured at each film thickness, B_1. With increase in B_1, $2a_0$ increased while p_i decreased. In order to examine the validity of eq.14 by comparing with the experimental results, it is necessary to evaluate many material constants which are contained in eqs.6 and 14. First, according to the previous experiment(3), the elastic constant of film is $E_1=9.1\times10^3$MPa, which has been obtained from the cantilever bending tests of films by measuring the deflection of free edge. The elastic constant of substrate $E_e=2.05\times10^5$MPa is used as normally reported for steel. The plastic constant E_p and yield strength σ_{ys} of the substrate have been obtained in the previous experiment(3) as $E_p=2.9\times10^3$MPa and $\sigma_{ys}=2.4\times10^2$MPa. The interfacial energy $2\gamma_{12}$ between ceramic film and steel substrate has been already obtained also in the previous research(3) from the uniaxial tensile test of smooth plate specimen with film, where the load has been applied parallel to the film. The surface energy of ceramic film, which is connected to the fracture toughness K_{Ic} as $2\gamma_c = K_{Ic}^2/E_1$, was measured by three point bending tests of notched film specimens with notch root radius of 0.25mm and thickness of 0.25mm or 0.6mm. Thus, $2\gamma_c = 42J/m^2$ is determined by assuming that the effective notch root radius ρ_0 under which the fracture toughness is constant is not less than 0.25mm for such a brittle material.

Figure 7 shows the calculated and experimental relations between film thickness and size of island. The calculated values are much smaller than the experimental data. The main reason for such a large difference will be that the denominator of eq.14 contains square terms of stresses, and the small error in the measured stress at island delamination σ_i and the yield strength σ_{ys} largely affect the calculated values of $2a_0$. By a trial, if the 5% smaller values of σ_i than the observed values are substituted in the eq.14, the calculated $2a_0$ become almost twice of the experimental values or the denominator of eq.14 take negative values, while if the 10% larger values are used, the calculated values become about 1/10 of the experimental values. Thus, a characteristic of eq.14 expands a small error of measured σ_i or σ_{ys} to a large error of calculated $2a_0$.

Figure 8 shows the calculated and experimental relations between film thickness and the stress at island delamination σ_i. The calculation of σ_i was carried out by the substitution of measured $2a_0$ and other material constants into eq.14. In this case, the calculated σ_i agree relatively well with the experimental values, where again the characteristic of eq.14 is reflected on the calculation, i.e. even relatively large error of $2a_0$ and other material constants do not so much affect the calculation of σ_i. From the contrast of coincidence between calculation and experiment in both figures, it is concluded that the large discrepancy in Fig.7 does not necessarily degrade the validity of eq.14.

"Repeating division type" cracking

Photographs of repeating division cracks were taken at each pressure to follow the division process, and the crack length, a_i, were measured. Because the division is random and the crack length a_i have distribution, the measured crack length are classified to some groups, e.g.

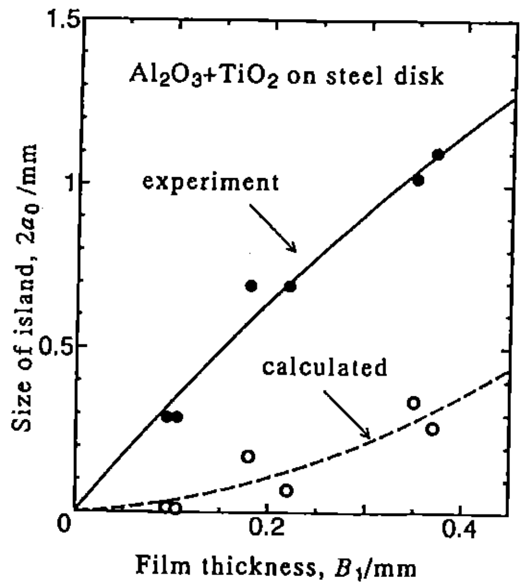

Fig.7 Comparison of the calculated relation between film thickness and size of island with the experimental relation for ceramic film.

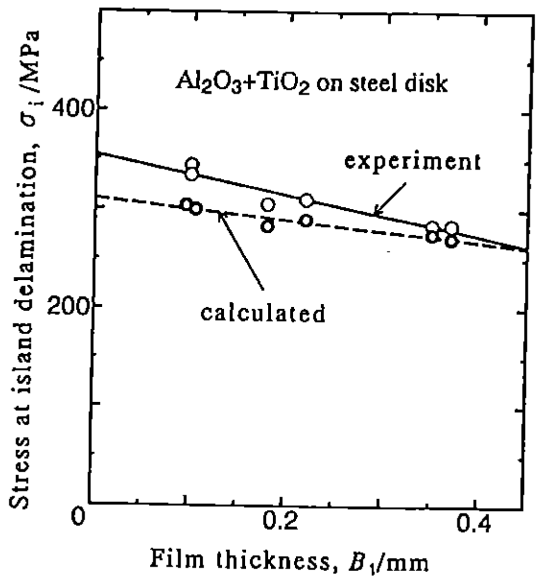

Fig.8 Comparison of the calculated relation between film thickness and pressure at island formation with the experimental relation for ceramic film.

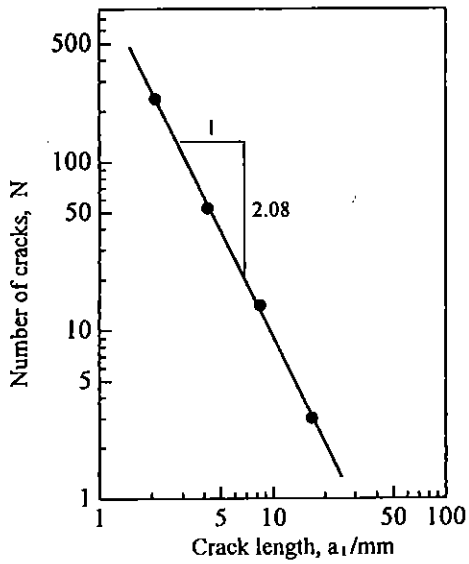

Fig.9 Relation between crack length and number of cracks after repeating division obtained for cermet film (B_i=0.2mm).

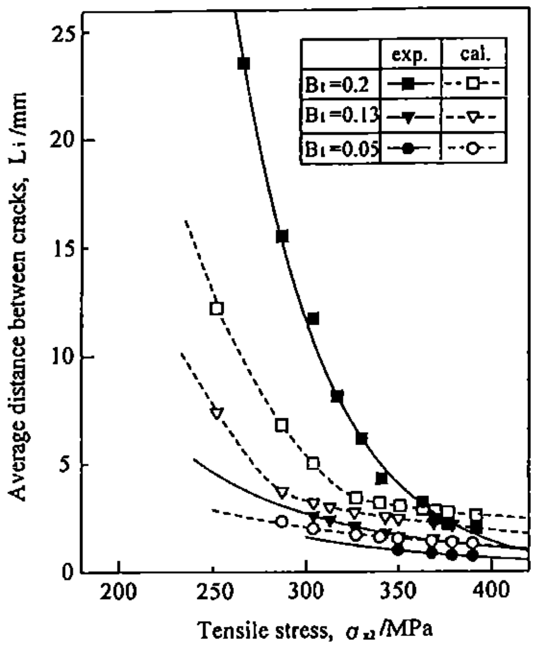

Fig.10 Comparison of the calculated relation between stress of disk and crack interval with the experimental relation for cermet film.

$0.75a_1/n<a_1/n<1.5a_0/n$ (n=2,4,8,16.....), and the number of cracks in the class, N, were calculated. Fig.9 shows the relationship between crack length a_i and number of cracks N by logarithmic plot. The gradient of the line is about 2, which means that the division occurs randomly but regularly according as the eq.15.

Figure 10 shows the relation between stress of substrate σ_{x2}, and the crack interval L_i measured by line-cutting method, which corresponds to crack length at the pressure. With increasing stress, the crack interval decreases due to the progress of division, and the division interval is small when the film thickness is small at constant stress. Because the stress at division exceeds the yield strength of substrate, the division of film seems to occur under the plastic deformation of substrate near interface. In the present research, $\alpha^2=k\times 2G_{2p}/z_0B_1E_1$ is used, where k(=0.3) is a factor which compensates all of the discrepancy between analysis and experiment, such as the effect of simplification of plastic deformation of substrate near interface by linear hardening behavior, the generation of residual strain and change of mechanical properties near interface due to spraying. The dotted line in Fig.10 is the result of calculation using modified α, where the elastic constant of film $E_1=1.63\times 10^5$MPa(4), the plastic shear modulus of substrate $G_{2p}=E_e/2=1.45\times 10^3$MPa and z_0=0.5mm are used, and the strength of film is assumed to be σ_c =250MPa. According to this figure, the tendency of calculation agrees relatively well with experimental results. Thus, the stress analysis carried out in the present research is effective to characterize the "Repeating division type" cracking although further consideration may be necessary.

Conclusion

Analyses were carried out for the "Island delamination type" and "Repeating division type" cracking patterns observed on disks with brittle film under equi-biaxial tensile stress. The theoretical relation between island size or division interval and material constants of film and substrate was compared with the experimental relation obtained by the bulge tests of steel disks with $Al_2O_3+TiO_2$ ceramic film by plasma spraying or WC+Co cermet film by high-velocity flame spraying. The results obtained are as follows:

(1) The ceramic film shows the island delamination cracking under the biaxial tensile stress. The size of island $2a_0$ increases and the pressure at delamination p_i decreases with increase in film thickness B_1. Griffith type energy analysis introduces $2a_0$ as a function of the stress at island formation σ_i, surface energy of film $2\gamma_c$, interfacial energy between film and substrate $2\gamma_{12}$, film and substrate thickness, elastic constant of film, elastic constant, plastic constant and yield strength of substrate, which agree relatively well with experimental values.

(2) The cermet film shows the repeating division type cracking pattern. The division process observed by experiment is expressed qualitatively by stress analysis.

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