International Journal of Fracture Fatigue and Wear, Volume 4

Proceedings of the 5th International Conference on
Fracture Fatigue and Wear, pp. 104-108, 2016

T CONVENIENT DEBONDING STRENGTH EVALUATION FOR SPRAY COATING BASED ON INTENSITY OF SINGULAR STRESS

Z. Wang[1], N.A. Noda[2], Y. Sano[2], Y. Takase[2] and K. Iida[2]

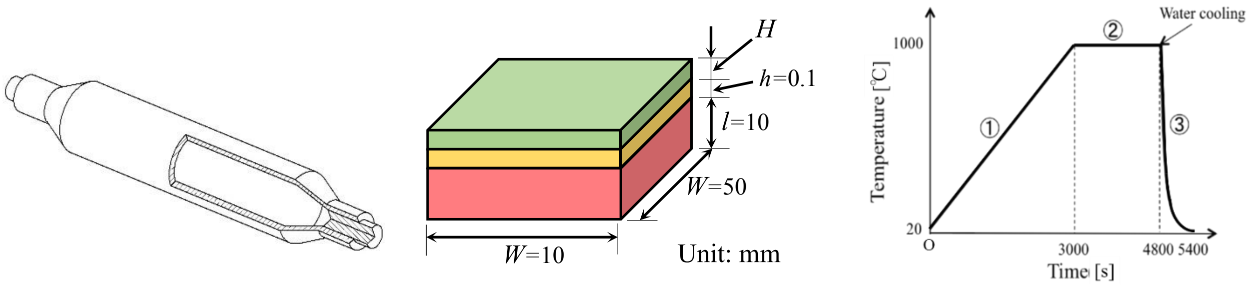
[1]Department of Mechanical Engineering, Kyushu Institute of Technology, 1-1 Sensui-cho, Tobata-ku, Kitakyushu-shi, Fukuoka, 804-8550
[2]Department of Mechanical Engineering, Kyushu Institute of Technology, 1-1 Sensui-cho, Tobata-ku, Kitakyushu-shi, Fukuoka, 804-8550

Abstract: Hearth rolls are used in continuous annealing furnace to produce thin steel sheet. The roll surface is usually coated by using thermal spraying, which has high adhesive strength and wears resistance. However, in the ceramics coating, thermal stress caused during heating and cooling process in the furnace may lead to debonding due to the low toughness of ceramics. In order to improve the heat resistance of the thermally sprayed coating, it is essential to evaluate the debonding strength. Generally, heat resistance of thermal spray coating is evaluated by thermal shock test prescribed by JIS H8304 and it has been discussed in terms of singular stress at the end of the interface for JIS specimen under thermal shock. However there is no research considering the real axial-symmetric geometry condition of the multilayer structure. Thus this paper will focus on the intensity of the singular stress at the end of interface for a 2D axial-symmetric model. Then, the most suitable conditions are discussed with varying the coating thickness and compared with our previous study.

Keywords: ceramics, interface, strength, thermal spraying, thermal shock, Intensity of singular stress

1. INTRODUCTION

In continuous annealing furnace for producing steel sheet, it's common to apply spraying coating on the hearth rolls (Fig. 1 (a)) to improve its adhesive strength and wear resistance. Especially for the ceramic spraying coating rolls, due to its excellent chemical stability and high hardness at high temperatures, it is expected to have expansion of application coverage. However, the peeling of the ceramic coating layer due to prolonged use under heating and cooling process in the furnace should be considered. Therefore, the ceramic coating is not usually sprayed alone, while multi-layer coating with adhesive layer is usually employed.



(a) Roll used in annealing furnace (b) JIS 8304 specimen for thermal shock test 50×50×(H+h+l) (c) Thermal cycle of thermal shock testing

Fig.1 Specimen for thermal shock test and the test conditions

In order to improve the thermal shock resistance of the ceramic coating, it is necessary to accurately evaluate the peel strength of the sprayed coating. The thermal shock resistance of ceramic coating is usually evaluated by the thermal shock test (Fig. 1 (b),(c)) specified by JIS8304 (2007) [1]. Mutoh et al have reported the thermal shock damage characteristics based on experimental results and finite element analysis [2]. However in order to more accurately assess the interfacial strength of dissimilar materials adhesive structures, it is necessary to consider the singularity of thermal stress near the corner of the interface. So far, few studies have been conducted to the research of intensity of singular stress on this multi-layer structure under thermal shock. In this study, the yttrium (Y_2O_3) stabilized zirconia (ZrO_2) sprayed coating shown in Table 1 is used. We mainly focus on the intensity of singular stress near the edge of coating layer during the thermal shock test. In our previous study, an analysis method for the intensity of singular stress in an adhesive bonding plate under bending and tension has been proposed [3, 4]. Thus in this paper, this method is applied to analysis the coating problem under thermal shock.

2. THERMAL SHOCK TEST FOR EVALUATING THE PEELING STRENGTH OF SPRAYED COATING

The specimen is cubic shaped with length×width×thickness: 50mm×50mm×10mm. The substrate SUS304 and the top coating yttrium (ZrO_2) with 8wt% ~ 20wt% of Y_2O_3 (The following % will be omitted) are bonded with CoNiCrAlY(See Fig. 1(b)). Fig.1(c) shows the history of one cycle thermal shock test. Repeat the process and the evaluation of delamination was performed by visual inspection, the number of cycles will be recorded until cracks, peeling or blistering of specimen occurs. The thermal shock resistance is evaluated by the numbers of cycles. Fig. 2 shows the relationship between the debonding strength and the percentage of Y_2O_3.

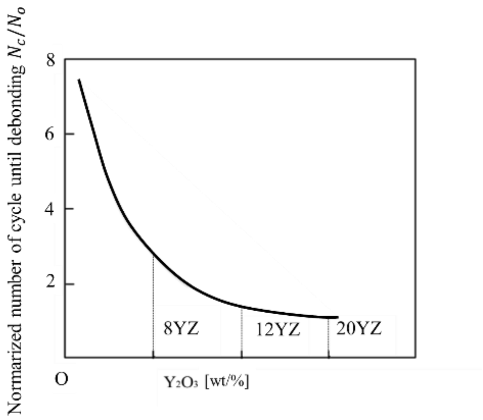
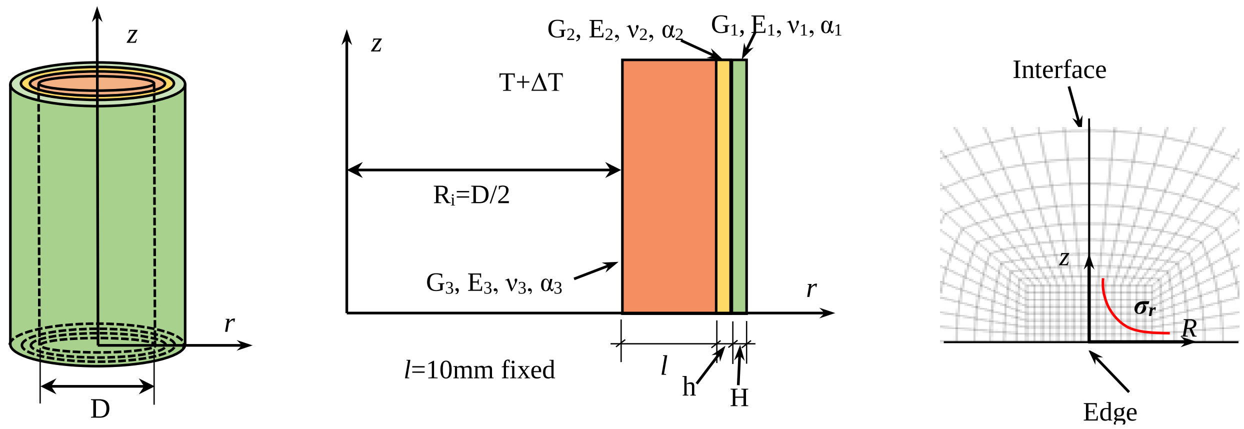


Fig. 2 Results of thermal shock test



(a) Overview (b) Analysis model (c) FEM mesh

Fig. 3 Analytical model and FEM mesh

3. ANALYSIS METHOD FOR THE SINGULARITY OF THERMAL STRESS

In this study, FEM is use to analysis the destruction conditions of the sprayed coating by focusing on the failure initiated from the end of bonded interface. The JIS specimen is a plane strain problem, while the roller is cylindrical and it should be an axial-symmetric problem in practical engineering. Therefore in this research the 2-D axial-symmetric model shown in Figure 3 is use as the analysis model, the subscript 1 ,2 and 3 represent the top coating, bond coating and substrate respectively, with the corresponding material properties shown Table 1.

There are two important parameters α and β known as Dundurs' parameters which are expressed by the following equations[5,6], here v is Possion's ratio and $G = E/2(1+\nu)$ is shear modulus.

$$\alpha = \frac{G_1(\kappa_2+1)-G_2(\kappa_1+1)}{G_1(\kappa_2+1)+G_2(\kappa_1+1)},\ \beta = \frac{G_1(\kappa_2-1)-G_2(\kappa_1-1)}{G_1(\kappa_2+1)+G_2(\kappa_1+1)},\quad \kappa_j = \begin{cases} \dfrac{3-\nu_j}{1+\nu_j}(plane\ stress) \\ 3-4\nu_j(plane\ strain) \end{cases} \quad (j=1,2) \tag{1}$$

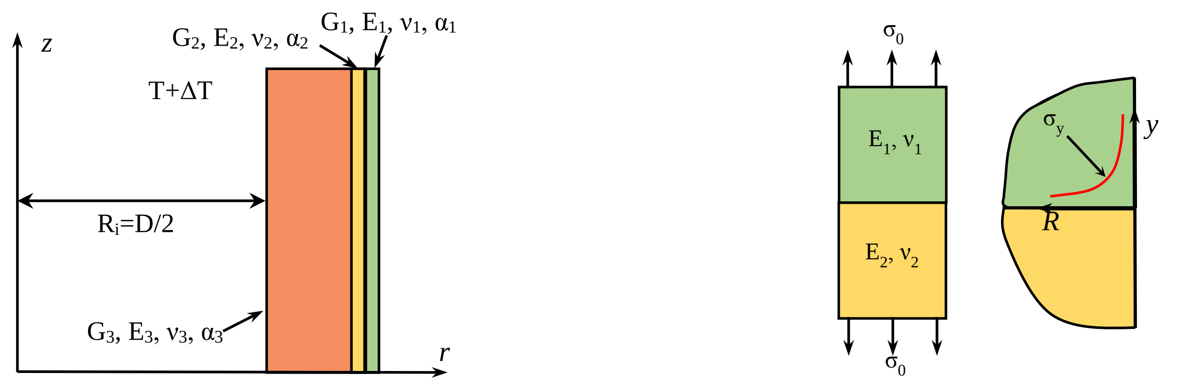
Furthermore, the singular index λ, appeared as the exponent of r in Fig.3(b), can be obtained by solving the following equation. Here r is the distance from the end of interface in a dissimilar materials bonded plate.

$$\left[sin^2\left(\frac{\pi}{2}\lambda\right)-\lambda^2\right]\beta^2+2\lambda^2\left[sin^2\left(\frac{\pi}{2}\lambda\right)-\lambda^2\right]\alpha\beta+\lambda^2\left(\lambda^2-1\right)\alpha^2+\frac{sin^2(\pi\lambda)}{4}=0 \tag{2}$$

Table 1 Material Properties depending on temperature

Material		Young's modulus E [GPa]	Poisson's ratio v	Thermal expansion $\alpha_e[10^{-6}/K]$
Top Coating	20YZ (ZrO_2-20wt%Y_2O_3)			7.5-9.7
	12YZ (ZrO_2-12wt%Y_2O_3)	20	0.25	8.3-9.93
	8YZ (ZrO_2-8wt%Y_2O_3)			8.7-10.05
Bonded Coating(CoNiCrAlY)		103-180	0.33	2.8-16.8
Substrate(SUS304)		85-200	0.3	16.8-19.2

Table 1 shows the material properties of three layers: young's modulus E and coefficient of expansion α_e. It's found that all properties of these three materials vary with the temperature except the Poisson's ratio of top coating. Therefore, the singular stress field is also changed by the variety of material properties. And in this study, we will mainly focus on the singularity between top coating and bond coating as shown in Fig.3.



(a) Thermal singular stress field for ceramic coating as a unknown problem for the analytical

(b) The bonded strip model as the reference problem

Fig. 4 Comparation of known problem and unknown problem

Thermal stress σ_r is caused by entire body temperature difference ΔT in the bonded structure shown in Fig. 4(a). In our previous research, it is found that there is non-singular terms $\tilde{\sigma}_r$ in the stress component as shown in Eq. 3, thus it is necessary to eliminate the non-singular term[12]. There is also another non-singular term σ_0 caused by thermal stress [8]. Therefore, by eliminating the non-singular terms σ_0, and $\tilde{\sigma}_r$ the remaining singular term $(\sigma_y - \sigma_0 - \tilde{\sigma}_r)$ has a singularity of $r^{1-\lambda}$ expressed as Eq. 3

$$\begin{cases} \sigma_z^{Axial} - \sigma_0 = \lim_{r\to 0} \dfrac{K_\sigma^{Axial}}{r^{1-\lambda}} + \tilde{\sigma}_z \\ \sigma_r^{Axial} - \sigma_0 - \tilde{\sigma}_r = \lim_{R\to 0} \dfrac{K_\sigma^{Axial}}{R^{1-\lambda}} \end{cases} \quad (3)$$

This intensity of singular stress field caused by thermal stress is equivalent to the one that subjected to the tension of σ_0 determined by Eq. 4[8].

$$\sigma_0 = -\Delta\alpha \Delta E \Delta T \quad (4)$$

where, $\Delta\alpha = \begin{cases} \alpha_1 - \alpha_2 \ (\text{plane stress}) \\ (1+\nu_1)\alpha_1 - (1+\nu_2)\alpha_2 \ (\text{plane strain}) \end{cases}$, $\Delta E = 8 \Big/ \left[\dfrac{(\kappa_1 - 3)}{G_1} - \dfrac{(\kappa_2 - 3)}{G_2} \right]$

$$\kappa_j = \begin{cases} \dfrac{3-\nu_j}{1+\nu_j} (\text{plane stress}) \\ 3 - 4\nu_j \ (\text{plane strain}) \end{cases}, \quad G_i = \frac{E_i}{2(1+\nu_i)} \begin{pmatrix} i = 1: \text{Top coat,} \\ i = 2: \text{Bond coat} \end{pmatrix}$$

The problem of finite bonded plate subjected to tension shown in Fig. 4(b) has been accurately calculated by using body force method [10, 11]. Since the singular stress fields are similar if the material angles of two bonded structures are same, then the stress intensity of unknown problem shown in Fig. 4(a) can be determined by apply this known solution (Fig.5(b)) to Eq. 5[3-4,9].

$$\frac{K_\sigma}{K_\sigma^*} = \frac{F_\sigma \sigma_0 W^{1-\lambda}}{F_\sigma \sigma_0^* W^{1-\lambda}} = \frac{\sigma_{r,FEM} - \sigma_0 - \tilde{\sigma}_r}{\sigma_y^{FEM*}} \quad (5)$$

Here the superscript * means known reference problem.

4. RESULTS

Here, three materials of the top coating with different content of yttrium (20YZ, 12YZ, 8YZ) are analysed to determine the maximum intensity of singular stress field under thermal shock test. Here we fix the top coat thickness as 0.1mm. And it is found that the material 8YZ with the lowest content of Y_2O_3 exhibits the best thermal shock resistance under any thickness, which means thermal shock resistance has a negative correlation to the amount of added yttrium. And it can also be found that thinner top coating has higher thermal shock resistance.

Table 2 K_σ for 8YZ at 1000℃ for top coat and bond coat

(Red figure shows minimum value when H=const.) [MPa·$m^{0.1127}$]

H(mm)		0.15(Axial-symmetric)	0.15(Plane strain)[13]
h(mm)	0.025	299.40	419.34
	0.06	295.54	413.93
	0.075	295.50	413.88
	0.10	295.81	414.31
	0.15	297.23	416.30

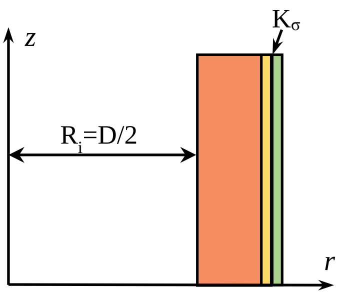


Table 2 shows the value of K_σ in case of changing the bond coat thickness h from 0.025mm to 0.15mm. From Table 2, it can be found that the singular stress intensity reaches its minimum value when the film thickness ratio of surface layer and the intermediate layer H/h≅2. In engineering application the ratio H/h≅2 is mostly used in the coating thickness design, and therefore the effectiveness of the present study on intensity of singular stress can be verified.

5. CONCLUSION

(1) There is obvious difference between the results of axial-symmetric model and JIS specimen model. The new result is 28% less than the our previous results for plane strain model, which means the inner radius of the roller can't be omitted.

(2) The optimal thickness ratio of top coat bond coat H/h is discussed from the view of intensity of singular stress near the end of interface. The theoretical analysis and engineering application all indicated that the optimal thickness ratio H/h≅2.0.

6. REFERENCES

[1] JIS H 8304：2007．Ceramic Thermal Spraying

[2] Y.Mutoh, I.Sakamoto, O.Waranabe and T.Nishimura, Failure Characteristics of Zirconia-Coated Structural Steel Under Thermal Cycling and Thermal Shock, Quarterly Journal of the Japan Welding Society, Vol. 7 (1989) No. 2, pp. 208-213.

[3] Y.Zhang, N.A.Noda, K.Takaishi and X.Lan, Effect of Adhesive Thickness on the Interface of Singular Stress at the Adhesive Dissimilar Joint, Transactions of the Japan Society of Mechanical Engineers Series A, Vol. 77 (2011) No. 774 pp. 360-372

[4] Y.Zhang, K.Takaishi, N.A.Noda and X.Lan, Effect of Adhesive Thickness on the Intensity of Singular Strength for the Adhesive Joint (Comparison between Bending and Tension), Transactions of the Japan Society of Mechanical Engineers Series A, Vol. 77 (2011) No. 784 pp. 2076-2086.

[5] Bogy, D.B., Two Edge Bonded Elastic Wedges of Different Materials and Wedge Angles under Surface Tractions, Journal of Applied Mechanics, Vol.38 (1971), pp. 377-386.

[6] Bogy, D.B., Edge bonded dissimilar orthogonal elastic wedges under normal and shear loadings, Journal of Applied Mechanics, Vol.35 (1968), pp.146-154.

[7] S.Ioka, S.Kubo, K. Ohji and J.Kishimoto, Thermal Residual Stresses in Bonded Dissimilar Materials and Their Singularity, Transactions of the Japan Society of Mechanical Engineers Series A, Vol. 60 (1994) No. 572 pp. 1049-1055.

[8] D.H.Chen, K.Nonomura and K.Ushijima, Stress Intensity Factor at the Edge Point of a Bonded Strip under Thermal Loading, Transactions of the Japan Society of Mechanical Engineers Series A, Vol. 66 (2000) No. 646 pp. 1204-1209.

[9] T.Teranishi and H. Nishitani, Determination of Highly Accurate Values of Stress Intensity Factor in a Plate of Arbitrary Form by FEM , Transactions of the Japan Society of Mechanical Engineers Series A, Vol. 65 (1999) No. 638 pp. 2032-2037.

[10] Chen, D.H., and Nisitani, H., Intensity of Singular Stress Field near the Interface Edge Point of a Bonded Strip, Transactions of the Japan Society of Mechanical Engineers Series A, Vol. 59 (1993) No. 567 pp. 2682-2686.

[11] Noda, N.A, Shirao, R., Li, J. and Sugimoto, J.S., Intensity of Singular Stress at the End of a Fiber under Pull-out Force, International Journal of Solids and Structures, Vol. 44, No.13(2007), pp. 4472-4491.

[12] Tatsujiro MIYAZAKI, Nao-Aki NODA, Zefeng WANG, Yoshikazu SANO. Analysis of Intensity Of Singular Stress Field for Bonded Cylinder in Comparison with Bonded Plate. Transactions of the JSME, vol.81 (829) (p.1-14), 2015.08

[13] Nao-Aki Noda, Takumi Uchikoba, Masayasu Ueno, Yoshikazu Sano, Kazuki IIda, Zefeng Wang, Guohui Wang, Convenient Debonding Strength Evaluation for Spray Coating Based on Intensity of Singular Stress, ISIJ International, Vol. 55, No.12(2015), pp.2624-2630.