

Effects of coating thickness and interfacial roughness on cracking and delamination strength of WC–Co coating measured by ring compression test

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Abstract. The effects of coating thickness and interfacial roughness on the interfacial fracture toughness of tungsten carbide–cobalt (WC–Co) coatings were evaluated using a ring compression test. WC–Co powder was sprayed on steel (JIS:SS400) rings by a high-velocity air-fuel method in coatings with various thicknesses and values of interfacial roughness. The ring compression test was carried out, and the cracking and delamination behavior of the coatings was observed using charge-coupled-device cameras. The results showed that cracking perpendicular to the loading direction occurred in the coatings during the ring compression test, and the cracking strength obtained from the ring compression test decreased slightly with increasing coating thickness, but was independent of the interfacial roughness. Upon further increase of the compression load, the coatings delaminated from the substrate. The interfacial fracture toughness calculated from the delamination of the coatings during the ring compression test decreased with increasing coating thickness and increased with increasing interfacial roughness.

1. Introduction

In order to improve wear properties of materials for mechanical parts, the tungsten carbide–cobalt (WC–Co) is frequently coated on the surface of the materials by spraying because of its superior wear resistance. However, the improvement effect disappears if the coating delaminates. Therefore, it is very important not only to develop spraying methods that yield coatings with high adhesion strength, but also to quantitatively evaluate the delamination strength of the coatings.

Many methods have been proposed to study the cracking and delamination strength of coatings [1–5]. Kendall developed a tensile testing method to evaluate the delamination strength of brittle coatings on elastic substrates with rectangular (flat) shapes by applying tensile loads to the substrates, and equations were derived to calculate the interfacial fracture toughness [6]. Nakasa et al. extended this method to elastic–plastic substrates, and Zhang et al. further developed this method for specimens subjected to four-point bending [7,8]. In practical applications, WC–Co is frequently sprayed on



columnar or cylindrical substrates to serve as sliding bearings. However, the cracking and delamination strength of the coating sprayed on columnar or cylindrical substrates cannot be evaluated by the tensile testing method, and evaluation method of cracking and delamination strength of coatings sprayed on columnar or cylindrical substrates has not been fully established.

The coating thickness and interfacial roughness are important factors in coating design. In this study, we applied a compression load to WC–Co coating sprayed on ring-shaped substrates to evaluate the effects of the two factors on the cracking and delamination strength of the coating. The validity of this method was also assessed.

2. Experimental procedure

The substrate used in this study was a mild steel (JIS SS400) ring with an outer diameter of 100 mm and a thickness, B_2 , of 4 mm. To investigate the influence of interfacial roughness, the outer surfaces of the substrates were grit-blasted with alumina powder or polished using sandpaper until the surface roughness, R_a , reached 0.062, 0.485, 3.34, and 4.50 μm . After blasting the surface of the substrate, coatings of WC–8.8 mass% Co (grain size of powder: 10–38 μm) with different thicknesses, B_1 , of 0.1, 0.2, 0.5, and 1.0 mm were sprayed on the substrate to investigate the effect of coating thickness. The WC–Co coatings were sprayed using a high-velocity air-fuel (HVOF) method (pressure: 0.41 MPa; distance: 200 mm; fuel supply: 150 L/h; air flow: 12 m^3/min)

A nano-indenter (MZT-4, Akashi Co Ltd.) with a Berkovich indenter was used to measure the indentation hardness, H_I , and the indentation modulus, E_I , of the WC–Co coatings. The indentation test was carried out on the surface of a coating under a maximum load, P_{max} , of 1000 mN, with an indentation speed, v , of 33.3 mN/s. The indentation hardness and the indentation modulus of the WC–Co coatings were obtained according to the procedure in ISO14577-1 [9].

An X-ray diffractometer (MXP-3, MAC Science Co. Ltd.) was used to measure the residual stress in the coating, σ_{rl} . Characteristic X-rays from a Cr target (Cr $K\alpha$; tube voltage: 40 kV; tube current: 40 mA) were selected and the residual stress was measured based on the $\sin^2(\psi - 2\theta)$ method (θ : diffraction angle; ψ : angle between the normal to the diffracting plane and the sample surface; diffraction plane: WC(112); elastic modulus: 700 GPa [10]; Poisson's ratio: 0.20 [10]).

A ring compression test was carried out using a universal tension-and-compression testing machine (AG-50kNI, Shimadzu). Figure 1 shows the schematic diagram of the experimental setup for the ring compression test. The specimen was placed on the testing machine and the compression load, P , was gradually increased. The displacement, δ , was determined from the cross-head displacement. Cameras

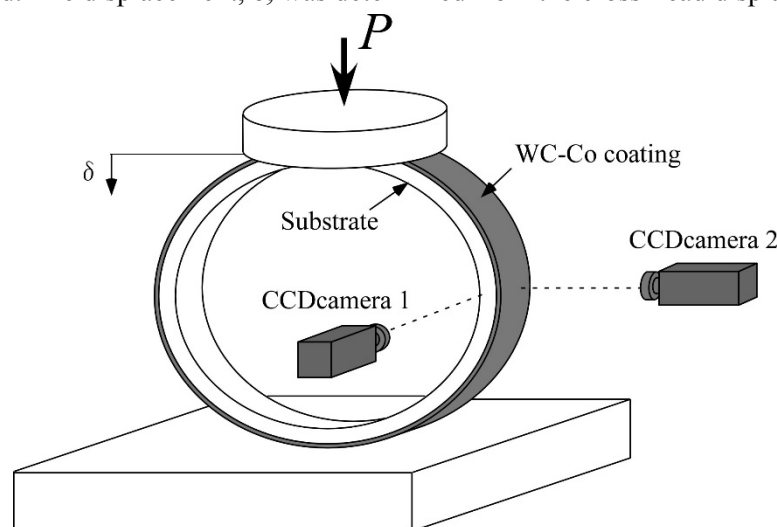


Figure 1. Schematic illustration of ring compression test.

1 and 2 captured the side and surface images of the specimen, respectively. From the images taken by camera 1, the radius of curvature of the specimen, ρ , was calculated.

The interfacial fracture toughness, G_C , was evaluated by expanding the equations derived by Kendall, Nakasa et al., and Zhang et al. [6-8]. G_C can be described by the following equation [11]:

$$G_C = \frac{E_{e1}}{6} \left(\frac{1}{\rho_{AB,d}} - \frac{1}{\rho_0} \right)^2 \left\{ (\eta_{0,d} + B_1)^3 - \eta_{0,d}^3 \right\} - \frac{E_{e2}}{3} \left(\frac{1}{\rho_{C,d}} - \frac{1}{\rho_0} \right)^2 \left\{ (1-\beta) \epsilon_{ys2}^3 \rho_{C,d}^3 + \beta \left(\frac{B_2}{2} \right)^3 \right\} \\ + \frac{E_{e2}}{6} \left(\frac{1}{\rho_{AB,d}} - \frac{1}{\rho_0} \right)^2 \left\{ 2(1-\beta) \epsilon_{ys2}^3 \rho_{AB,d}^3 + \beta (B_2 - \eta_{0,d})^3 + \beta \eta_{0,d}^3 \right\} + \frac{P_d r_x}{2b} \left(\frac{1}{\rho_{C,d}} - \frac{1}{\rho_{AB,d}} \right), \quad (1)$$

where E_{e1} and E_{e2} are the elastic constants of the coating and substrate, respectively; $\rho_{AB,d}$, $\rho_{C,d}$, and ρ_0 are the radius of curvature just before delamination, at delamination, and before loading (initial radius of curvature), respectively; $\eta_{0,d}$ is the distance between the interface and neutral axis at delamination; β is the ratio of the plastic constant to the elastic constant of the substrate (elastic-plastic property of the substrate is approximated to linear hardening material); ϵ_{ys2} is the yield strength of the substrate; P_d is load at delamination; and r_x is the radius of the neutral axis of the substrate.

3. Results and discussion

3.1. Indentation modulus and indentation hardness

To investigate the effect of the coating thickness, B_I , on the indentation hardness and the indentation modulus of the WC-Co coatings, indentation tests were carried out on the coatings with thicknesses ranging from 0.1 to 1.0 μm . The results are shown in Figure 2 (open circles: average value of 10 measurements; error bars: maximum and minimum values). The indentation hardness and the indentation modulus of the WC-Co coatings were both independent of the coating thickness.

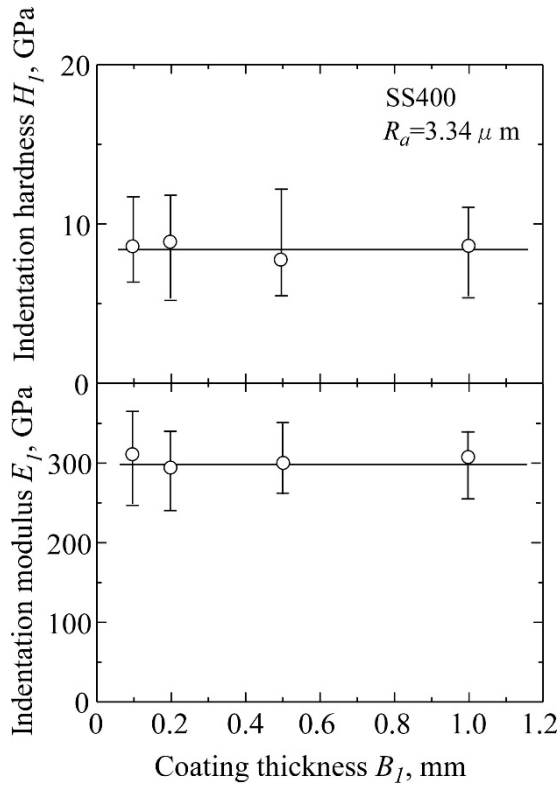


Figure 2. Effect of coating thickness on indentation modulus and indentation hardness.

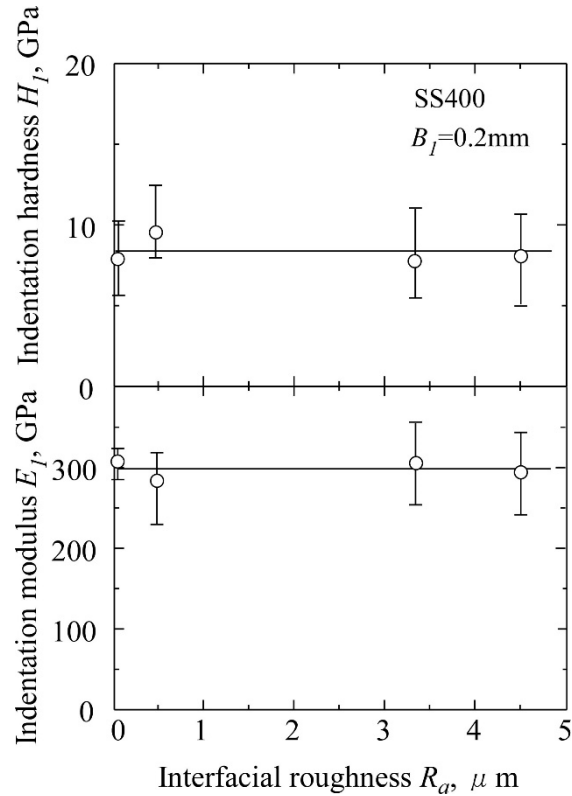


Figure 3. Effect of interfacial roughness on indentation modulus and indentation hardness.

Figure 3 shows the effect of the interfacial roughness, R_a , on the indentation hardness and indentation modulus of the WC–Co coatings. Both parameters had almost constant values irrespective of increases in the interfacial roughness. This means that the indentation hardness and the indentation modulus of the surface of the WC–Co coatings were both independent of not only the coating thickness but also interfacial roughness.

3.2. Residual stress

The residual stress in the coating, σ_{rI} , shown in Figure 4(a). Compressive residual stress is introduced in the coating, and the stress becomes more compressive with increasing coating thickness. This tendency qualitatively agrees with the results reported by Stokes *et al.* [12]. In the coating, the cooling and quenching stresses (residual stresses) arose because of the thermal mismatch during cooling after spraying was finished, as well as the impact and quenching of individual lamella [12,13]. Stokes *et al.* analytically explained the effect of coating thickness on the residual stresses [12]. On the other hand, the residual stress of the specimens with different interfacial roughness was around -600 MPa, independent of the interfacial roughness, as shown in Figure 4(b).

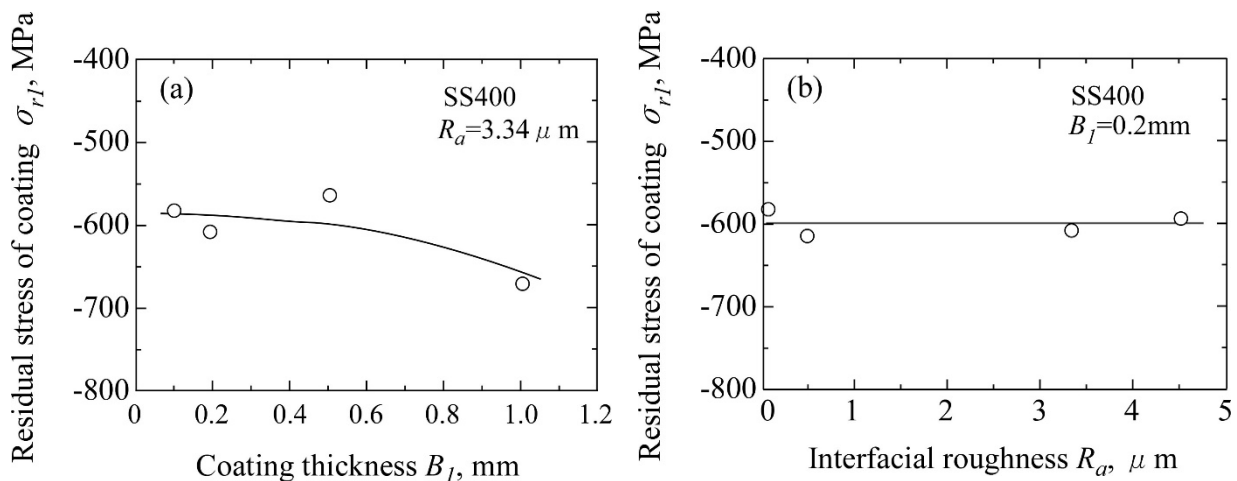


Figure 4. Effects of (a) coating thickness and (b) interfacial roughness on residual stress.

3.3. Ring compression test

3.3.1. Cracking and delamination of coating. Figure 5 shows a typical example of the coating surface during the ring compression test. When the load reaches a critical value after the beginning of the plastic deformation of the substrate, cracking of the coating occurs perpendicular to the loading direction (Figure 5b). The number of cracks increases with increasing load (Figure 5c–e), and the coating delaminates from the substrate when the load reaches the critical value, P_d (Figure 5f).

The surfaces of the coatings with different thicknesses at the beginning of delamination are shown in Figure 6. When the coating is thin (Figure 6a), many cracks are introduced in the coating and small area of the coating delaminates. The number of cracks decreases with increasing coating thickness. When the coating becomes thick (Figure 6c and d), only one or two cracks are observed. The coating does not peel off but is lift up from the substrate. The surfaces of the specimens with different interfacial roughness just before delamination are shown in Figure 7. Almost the same cracking behavior is observed for every specimen.

3.3.2. Cracking strength of the coating. The cracking strength, σ_{1C} , was calculated from the following equation:

$$\sigma_{1C} = E_1 \left(\frac{1}{\rho_i} - \frac{1}{\rho_0} \right) \left(B_1 - \frac{B_2}{2} \right), \quad (2)$$

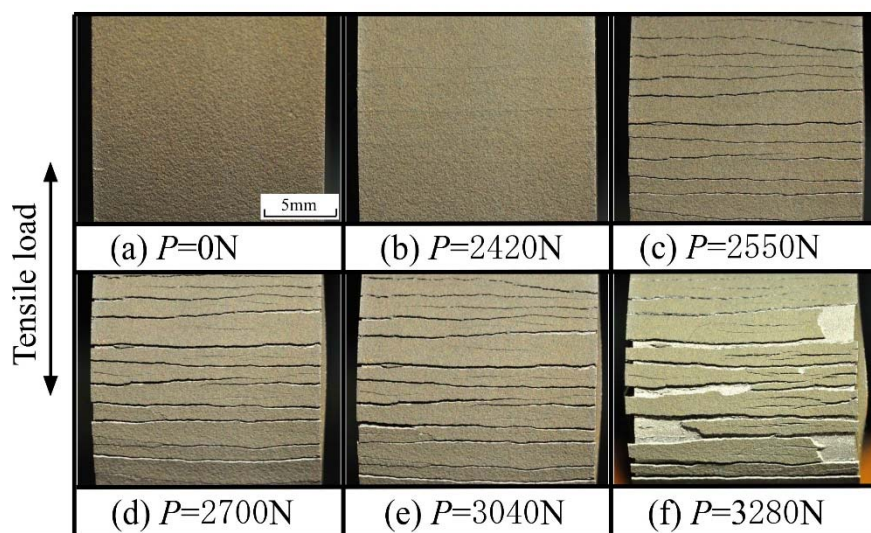


Figure 5. Surface of WC—Co coating during ring compression test (substrate: SS400; $B_I = 0.2$ mm, $R_a = 3.4$ μm).

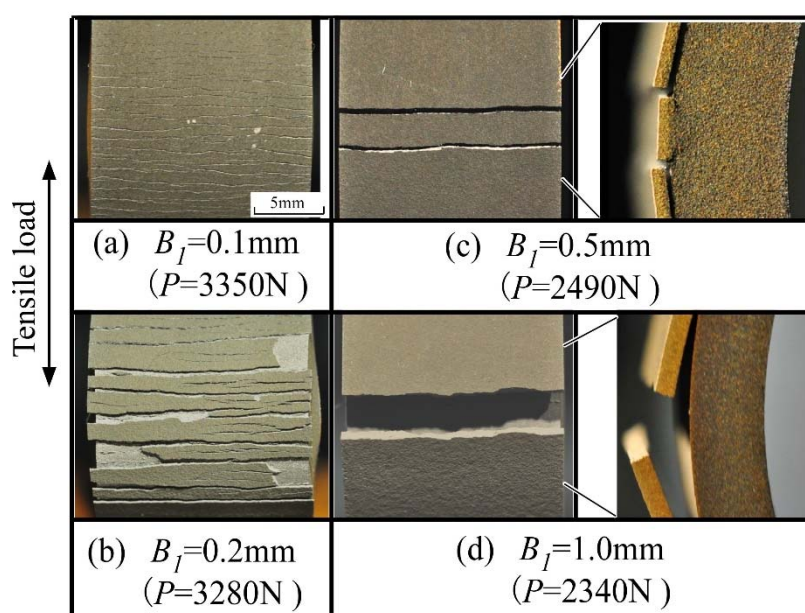


Figure 6. Surface of WC—Co coating at delamination (substrate: SS400; $R_a = 3.4$ μm).

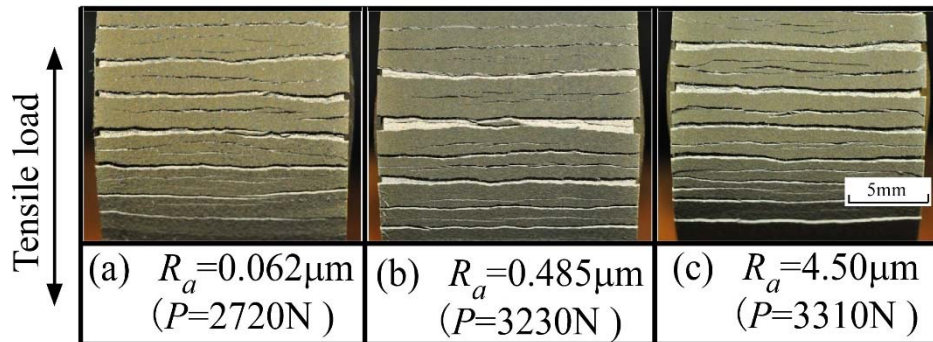


Figure 7. Surface of WC–Co coating at delamination (substrate: SS400; $B_I = 0.2$ mm).

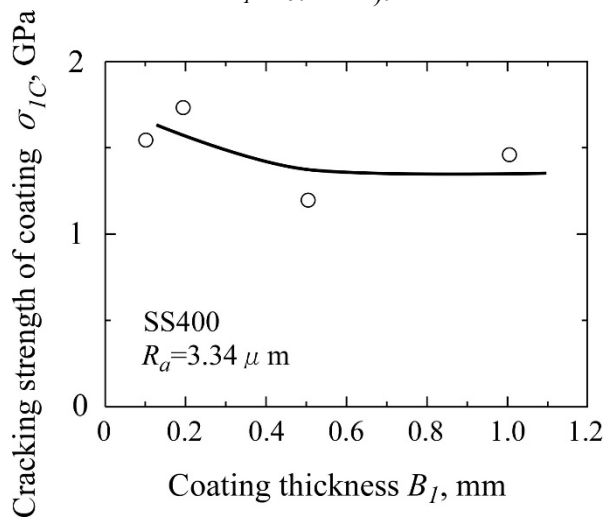


Figure 8. Relationship between coating thickness and cracking strength of coating.

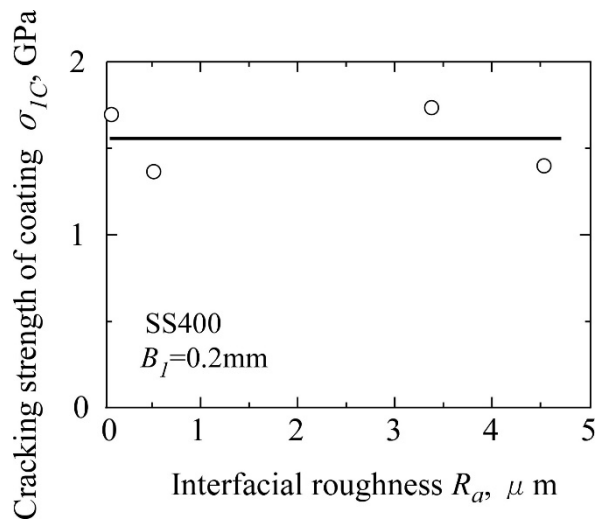


Figure 9. Relationship between interfacial roughness and cracking strength of coating.

where ρ_i is the radius of curvature at crack initiation. The crack initiation was detected using the images taken by camera 2 shown in Figure 1.

The relationship between the coating thickness and the cracking strength of the coating is shown in Figure 8. A small decrease in cracking strength is observed with increasing coating thickness.

Figure 9 shows the relationship between the interfacial roughness and cracking strength of the coating. The cracking strength ranges between 1.3 and 1.8 GPa, and the obvious effect of the interfacial roughness is not observed. According to the results reported by Stokes et al., the amount of the residual stress changes with increasing coating thickness [12]. On the other hand, the influence of interfacial roughness on the residual stress is considered to be negligibly small as the residual stress is almost constant under the same coating thickness. Therefore, it is implied that main factor affecting the cracking strength of our specimens is the residual stress, which causes damage to the coatings and changes the stress distribution in the specimens.

3.3.3. Interfacial fracture toughness. The interfacial fracture toughness of the specimen with various coating thicknesses calculated using Equation (1) is shown in Figure 10. E_{e1} and E_{e2} were measured using the nano-indenter, and β was obtained from the load-displacement curve. The interfacial fracture toughness decreases with increasing coating thickness. Similar to the cracking strength, it can be said that the interfacial fracture toughness of the specimens is affected by the residual stress.

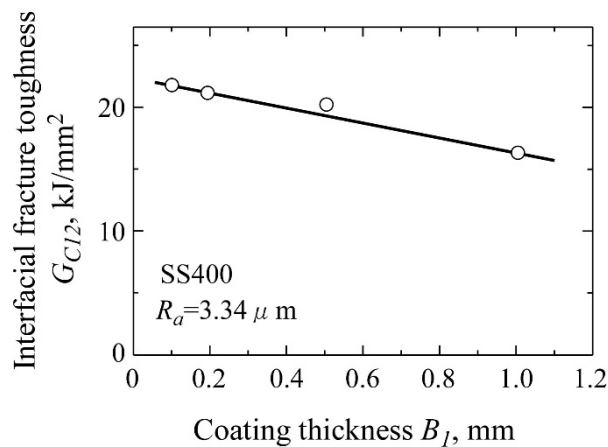


Figure 10. Relationship between coating thickness and interfacial fracture toughness.

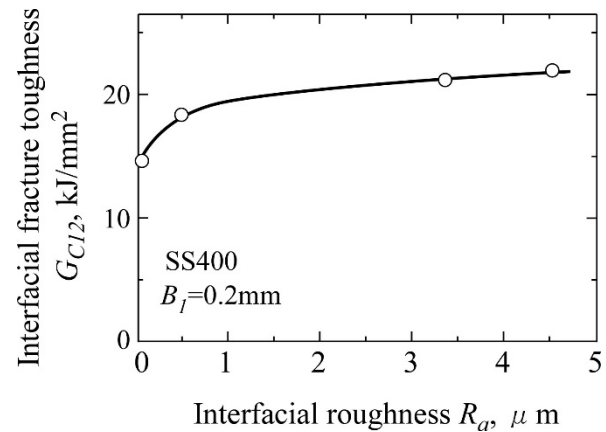


Figure 11. Relationship between interfacial roughness and interfacial fracture toughness.

According to the stress analysis at the interface, both tensile and shear stresses are introduced (mixed mode) [14]. In Figure 6, the delaminated coating with a thickness (d) of 1.0 mm recovered almost elastically. The recovery force (mode 1 component) increase with increasing coating thickness based on the theory of elasticity, and hence the mode ratio (mode 1/mode 2) increases with increasing coating thickness. Therefore, it is considered that the change of the mode ratio is another factor affecting the interfacial fracture toughness of the specimens.

The interfacial fracture toughness increases with increasing interfacial roughness, and the effect is shown in Figure 11. These results qualitatively agree with those reported by Fukumoto et al. [15], who noted that the increase resulted from both the anchor effect and the physical adhesion effect. Moreover, the value of the interfacial fracture toughness obtained in this study (15–22 kJ/m²) is close to that measured by a four-point bending test [8].

From this study, we conclude that the ring compression test is a valid means to evaluate the effects of coating thickness and interfacial roughness on the cracking and interfacial fracture toughness of WC–Co spray-coated using the HVOF method.

4. Conclusions

To evaluate the effect of coating thickness and interfacial roughness on the cracking strength and interfacial fracture toughness of WC–Co coatings, a ring compression test was carried out on the WC–8.8 mass% Co coating formed on mild steel substrate using the high-velocity air-fuel (HVOF) spraying method. The results are summarized as follows:

- (1) The indentation hardness and indentation modulus measured by the nano-indenter were independent of both the coating thickness and interfacial roughness
- (2) The residual stress in the coating, measured by X-ray diffraction, was compressive, and the amount of stress increased with increasing coating thickness.
- (3) During the ring compression test, cracking perpendicular to loading direction and delamination of the coatings occurred. The number of cracks decreased with increasing coating thickness.
- (4) The cracking strength decreased slightly with increasing coating thickness, but was constant irrespective of interfacial roughness.

(5) The interfacial fracture toughness decreased with increasing coating thickness and increased with increasing interfacial roughness. The measured interfacial fracture toughness ranged between 15 and 22 kJ/m².

(6) The ring compression test is applicable to the evaluation of the effects of coating thickness and interfacial roughness on the cracking and interfacial fracture toughness of WC–Co coatings sprayed using the HVOF method.

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