EFFECT OF INTERLAYER ON THE ELASTIC-PLASTIC DEFORMATION OF COATING SYSTEMS

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ABSTRACT

The finite element method (FEM) was used to study the elastic-plastic contact in the coating systems with interlayer. The results reveal that with the increase of interlayer thickness, the maximum shear stress of coating/interlayer and interlayer/substrate interfaces decreases. Moreover, the sharply changed shear stress between the interfaces of coating/interlayer and interlayer/substrate decreases too. There is no further decrease when interlayer thickness increase to 0.04 mm and above. With the increasing of interlayer elastic modulus, the shear stress of coating/interlayer interface decreases while the shear stress of interlayer/substrate interface increases. Meanwhile, the higher elastic modulus leads to the intensive tensile stress concentration on the interface of coating/interlayer. Hence, the interlayer with appropriate elastic modulus not only reduces the shear stress of coating/interlayer and interlayer/substrate interfaces but also decreases the tensile stress of coating/interlayer interface. The mechanical properties of coating systems were investigated with different interlayer yield strength. The effective hardness and elastic modulus increase with the increase of interlayer yield strength, which is good to protect the substrate from the deformation. In addition, higher indentation load can lead to the decrease of effective hardness and elastic modulus.

Keywords: Interlayer, Shear stress, Tensile stress, Yield strength.

1. INTRODUCTION

In order to reduce wear and friction, a wide variety of coatings have been used in mechanical engineering to protect the contacting surfaces, such as Al_2O_3, DLC, and graded alumina-glass [1-4]. However, the selection of material and composition of coatings are often problems because many factors, such as coating thickness, friction coefficient, modulus of elasticity, thermal and environmental conditions [5-10].

Conventional coatings cannot meet the advanced industrial needs, because it is a challenge to obtain a good bond strength between the coating and substrate [11-13]. One technique that may be helpful, and which is increasingly being used, is to deposit an interlayer on the substrate before the coating is deposited. In some applications, thicker coating is more benefit than thin coating. However, traditional coatings cannot be prepared thicker due to the weak interfacial bonding and abrupt stress distribution between the interface of coating and substrate. Some researchers have investigated the influence of interlayer on the coating systems. Compared with the conventional coatings, coating systems with interlayer can decrease the mismatch in material property between coating and substrate, such as elastic modulus, thermal expansion coefficient etc. [14, 15]. G.A. Fontalvo *et al* [16] have investigated the influence of the Cr interlayer thickness on the tribological response of bi-layer model coatings of CrN on high-speed steel.The results showed that the thickness of interlayer has a great effect on the wear behavior of the coatings by relieving the stress in both the coating and the substrate. The softer interlayer can enhances the wear behaviour of the hard coating due to an improved load support and decreases its critical thickness to lower values. However, if the interlayer is too thick there might be high strains due to plastic deformation of the interlayer which might cause wear increases or failure of the top coating. The smooth

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stress distribution can decrease the sharply changed shear stress in the interface to suppress the cracks and interfacial failure. Besides, the thicknesses of interlayer depends on the mechanical load and the coating and substrate properties. According to these strengths of interlayer, a systematic study on the effect of interlayer parameters on the stress and strain fields of the coating systems is needed.

For the coating systems, the mechanical properties are critical in ensuring their successful application. Hardness and the elastic modulus have been regarded as important material property affecting friction and wear. Some studies [17, 18] have demonstrated that interlayer coating can improve the adhesion and the tribological performance of the coating systems compared to conventional coatings. Moreover, M. Callisti *et al*. [19] have found that the interlayer can led to lower H/Er ratio, which can increase the adhesion of the functional top layer. It also showed interlayer with lower H/Er ratio lead more delamination at increasing the critical load. The friction coefficient, particularly its trend in relation to the applied load, exhibited saturation when the strain field extended through the interlayer. Therefore, reliable measurement of their properties becomes more important for the coating systems. Indentation experiments has been widely used to analyze the mechanical properties of materials. However, it is hard to obtain the stress distribution and elastic-plastic behavior between the interface of coating and substrate. Finite element method (FEM) [20-23] is an effective approach to investigate the mechanical properties of the coating systems in many tribological conditions.

As we know, plastic deformation is a major problem in the selection and design of coating systems because the failure usually initiates and propagates from the plastic deformation zone. Relatively little work has been carried out on the analysis of elastic-plastic contact of coating, interlayer and substrate systems. In this work, we focus on the study of the interlayer properties on the effect of the stress distribution and mechanical properties of the coating systems under indentation by using the finite element method (FEM). The results are expected to provide some guidance to design of coating systems with interlayer and improvement of the bond strength of coating systems.

2. FINITE ELEMENT MODELLING

2.1 The Finite Element Contact Model

The ABAQUS software was used to create the finite element model that constituted of a rigid ball, coating, interlayer and the substrate from top to bottom. In order to reduce the data computation time, an axial symmetric problem was chosen in the paper. The boundary conditions used in the calculations are shown in Fig. 1, where the displacement of each nodal point along the symmetry axis was constrained in X-direction and the fixed boundary condition was applied to the substrate. The load was applied on the center of the ball and the ball could move only vertically. The ball was modeled as an analytical rigid element. The coating, interlayer and substrate

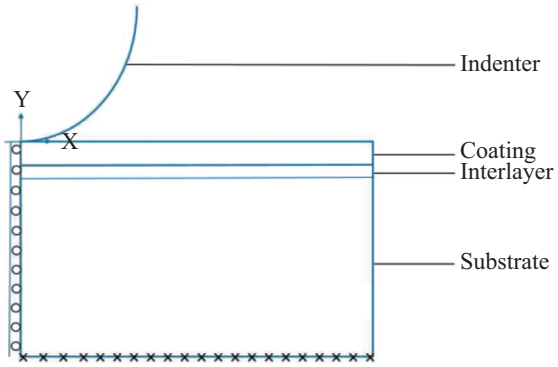


Fig. 1 Finite element model and coordinate system.

were represented by 4-node axisymmetric quadrilateral element (CAX4R). To insure accurate analysis of the strain and stress fields, a very fine mesh was used in the coating and the interlayer, especially under the contact area. Relatively large elements were used in the substrate, which away from the contact zone. The finite element meshes were composed of 1E5 elements for the substrate and 2E4 for the coating. The contact type of between rigid ball and coating was frictionless contact type. The contact type of coating/interlayer and interlayer/substrate were tie contact type. The coating, interlayer and substrate were modelled as isotropic, elastic-perfectly plastic. For isotropic materials, elastic deformation ceases and yielding commences when the von Mises yield criterion is satisfied.

2.2 Material Properties

To accurate analysis of stress distribution, there are several basic assumptions for the simulations. It is assumed that all the materials are isotropic, linear elastic-perfectly plastic materials and coating, interlayer and substrate are perfectly bonded to each other, which means there is no delamination or slippage between interfaces.

The main emphasis of this work is the influence of interlayer on the stress distribution and plastic behavior of the coating systems, which is an effective approach to obtain a good bond strength between the coating and substrate. It should be pointed out that the parameter values considered in this study do not correspond to specific materials, but these values cover a wide range of coatings. Similarly, the thickness of the interlayer correspond to a wide range of very thin to relatively thick coatings. In this work, all the coating/interlayer/substrate systems had the same substrate material, whose Elastic modulus, Poisson's ratio and Yield strength were E_S = 200 GPa, 0.3 and 0.4 GPa respectively. The thickness of all the coatings were assumed to be 0.05 mm and which had the same Elastic modulus (E_C = 800 GPa) and Poisson's ratio (0.3). The interlayer thickness has been investigated from 0.01 mm to 0.05 mm in the present FE model. The elastic modulus of interlayer from 200 GPa to 800 GPa which covers a wide range of industrially applied coatings. The Poisson's ratio of the interlayer was 0.3 as same as coating and substrate [24].

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Table 1 Material properties used in FE calculation.

	Material Parameters			
	Thickness (mm)	Elastic modulus E (GPa)	Poisson's ratio v	Yield strength Y (GPa)
Substrate	3	200	0.3	0.4
Interlayer	t	E_I	0.3	Y_I
Coating	0.05	800	0.3	6

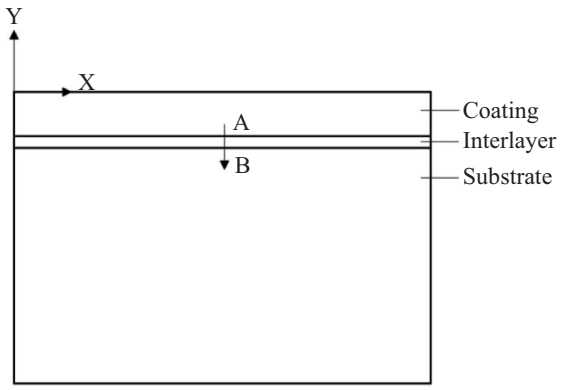


Fig. 2 Schematic illustration of coordinate system (zero point is A and end point is B).

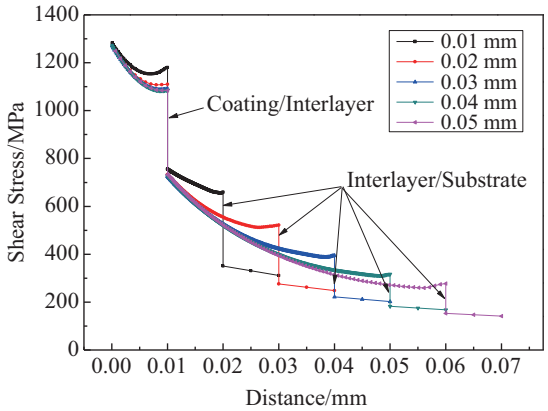


Fig. 3 Relationship of shear stress and interlayer thickness.

The material properties used in the analyzed models are given in Table 1.

3. RESUTLTS AND DISCUSSION

3.1 Effect of Interlayer Thickness

In practice, the layer interfaces can only sustain a certain level of stress corresponding to the interfacial strength. Therefore, a detailed knowledge of the magnitude and the distribution of the shear stress is required for a better understanding of the failure mechanisms which may occur in coating systems. To analysis the effect of the thickness on the stress distribution of systems, there is no plastic deformation in coating, interlayer and substrate. When different thicknesses were taken into account, the elastic modulus of interlayer was constant E_I = 400 GPa. In order to make the shear stress described more clearly, the zero point (A) is 0.01 mm at a distance above the bottom of the coating and the end point (B) is 0.01 mm at a distance below the top of the substrate, which is illustrated in Fig. 2.

Figure 3 shows the maximum shear stress τ along y-direction with different interlayer thickness t under the same indentation load. As shown in Fig. 3, with the increase of interlayer thickness, the shear stress between the interface of interlayer/substrate decreases, and the coating/interlayer interface shows the similar trends. It can be seen that increasing interlayer thickness can significantly decrease the stress of the coating/interlayer/substrate systems. Therefore, it should try to avoid the interlayer is too thin when design the coating structure. For the interlayer/substrate interface, the decreasing of the maximum shear stress can protect the substrate from the plastic deformation.

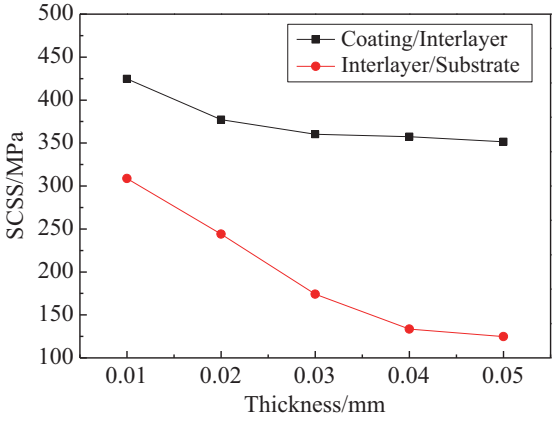


Fig. 4 The influence of interlayer thickness on sharply changed shear stress.

Meanwhile, the sharply changed shear stress (SCSS) between the interfaces of the coating systems are shown in the Fig. 4. It can be seen that the sharply changed shear stress decrease between the interface of coating and interlayer with the increasing of interlayer thickness. Meanwhile, the sharply changed shear stress between the interface of interlayer and substrate also show a similar trend. Besides, the SCSS of coating/interlayer reaches a platform value when interlayer thickness is to 0.03 mm and above. And the SCSS of interlayer/substrate do not further decreases when interlayer thickness is greater than 0.04 mm. Considering a thicker interlayer will result in high economic cost and material waste. Therefore, the interlayer thickness of 0.04 mm is an optimal value for bond strength and low cost.

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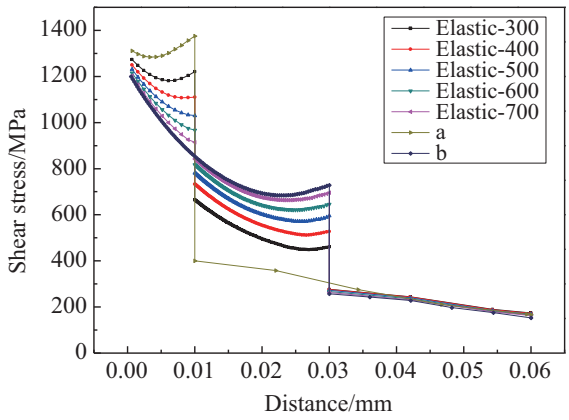


Fig. 5 Relationship of shear stress and interlayer elastic modulus.

Table 2 Different interlayer elastic modulus used in FE calculation.

Elastic modulus /GPa	Thickness of interlayer /mm	Thickness of coating /mm	Sharply changed shear stress/MPa	
			0.01 mm	0.03 mm
	-	0.05(a)	1026.18335	-
300	0.02	0.05	556.16435	184.24393
400	0.02	0.05	377.12556	251.94235
500	0.02	0.05	248.81162	323.60181
600	0.02	0.05	149.89482	379.03775
700	0.02	0.05	72.370615	433.67944
	-	0.07(b)	-	471.60982

3.2 Effect of Interlayer Elastic Modulus

The effect of interlayer elastic modulus on the distribution of shear and tensile stresses were investigated. Figure 5 shows the shear stress along y-direction with different elastic modulus. Table 2 shows the elastic modulus in detail and the thickness of the interlayer is 0.02 mm. For comparison, the interlayer is replaced by substrate and coating were also investigated, which named as a and b separately. To analysis the effect of the elastic modulus on the stress distribution of systems, there is no plastic deformation in coating, interlayer and substrate. In order to make the shear stress described more clearly, the zero point is 0.01 mm at a distance above the bottom of the coating and the end point is 0.03 mm at a distance below the top of the substrate.

Instead of having smooth shear stress distribution inside the coating systems, discontinuous stress distribution at the interfaces of coating/interlayer and interlayer/substrate exists due to the material property differences. As shown in Fig. 5, an increase of 0.02 mm interlayer promotes a great decrease of the shear stress between the coating and substrate interface. This finding means the shear stress can be more obviously decreased by the introduction of an interlayer than increasing the coating thickness. With the increasing of interlayer elastic modulus, the sharply changed shear stress of coating/interlayer interface decreases while the interlayer/substrate interface increases, which is shown in Fig. 6. The

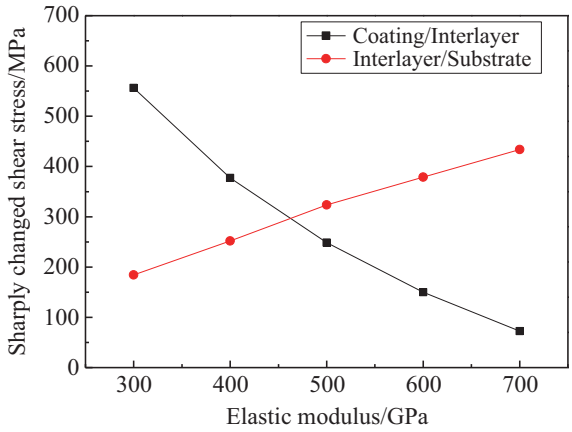


Fig. 6 Relationship of sharply changed shear stress and interlayer elastic modulus.

smaller sharply changed shear stress of interlayer/substrate can prevent interlayer spall from substrate, which can avoid the substrate damaged by wear and corrosion. However, to prevent coating spall from interlayer, the sharply changed shear stress between coating and interlayer should also be considered. In coating systems, the cracks may be redirected, deflected or stopped when it approach interfaces. But, it may also cause premature layer delamination, especially under high loading. Be-

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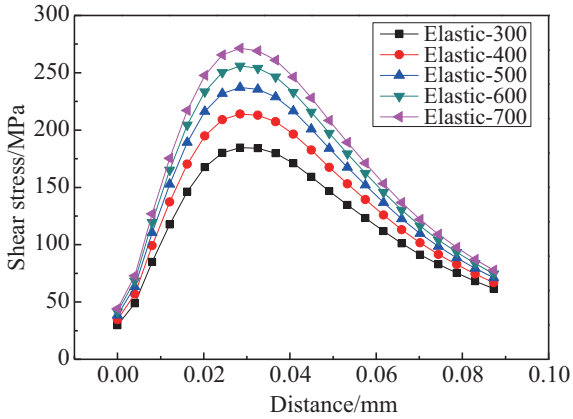


Fig. 7 The tensile stress distribution at coating/interlayer interface.

Table 3 Different interlayer yield strength used in FE calculation.

	Material Parameters			
	Thickness (mm)	Elastic modulus E (GPa)	Poisson's ratio v	Yield strength Y (GPa)
Substrate	3	200	0.3	0.4
Interlayer	0.02	500	0.3	0.6-4.8
Coating	0.05	800	0.3	6

cause the plastic deformation usually occurs at the interfaces instead of inside coating or substrate. Hence the interlayer with elastic modulus of 400-500 GPa not only reduces the shear stress of coating/interlayer interface but also decreases the shear stress of interlayer/substrate interface obviously. These decreases can improve the bond strength of the combined materials.

The tensile stresses at the interface between interlayer and coating at the same loading conditions were calculated. The distribution of tensile stress is shown in Fig. 7. It can be seen that with the increase of interlayer elastic modulus, the maximum tensile stresses increase too. It is obvious that high elastic modulus will increase the tensile stress at the interface between the coating and interlayer, which is prone to delaminate coating from the interlayer. Besides, the maximum tensile stress occurs at the interface between the coating and interlayer near the edge of contact.

3.3 Effect of Interlayer Yield Strength

The effect of interlayer yield strength on the mechanical properties of coating systems were investigated by the indentation test. The Oliver-Pharr (O&P) method [25, 26] is used to determine the effective hardness and effective modulus from indentation load-displacement data obtained during one cycle of loading and unloading. The material properties [27] used in the simulation are shown in Table 3.

According to the Oliver-Pharr (O&P) method, the contact depth h_c can be calculated using the following formula based on the unloading curve:

$$h_c = h - \varepsilon \frac{P(h)}{S} \tag{1}$$

Where h is the maximum pressure depth, $P(h)$ is the corresponding load, ε is the correction constant (here ε = 0.75) and S is the slope of the unloading curve (S = dP/dt).

Hardness (H) as a function of plastic depth can be determined by the following relationship:

$$H = \frac{P}{A_c} \tag{2}$$

Where the P is the maximum load, A_c is the contact area. The formula of contact area is as follows:

$$A_c = 24.65h_c^2 + \alpha_1 h_c + \alpha_2 h_c^{1/2} + \cdots + \alpha_8 h_c^{1/128} \tag{3}$$

Where α_1 … α_8 are constants determined by curve fitting procedures [26]. The effective elastic modulus follows from its relationship to contact area and the measured unloading stiffness through the relation:

$$E_r = \frac{S\sqrt{\pi}}{2\sqrt{A_c}} \tag{4}$$

The effective hardness and elastic modulus of coating systems are shown in Fig. 8. The effective hardness values of coating systems is seen to decrease with the increase of maximum loads (Fig. 8(a)). This is because the Mises stress in the coating systems increases with the increase of loads. When the indentation begins, the coating systems go through elastic deformation and then the plastic deformation will occurs after the Mises stress increases to the yield strength. The increase of plastic deformation in the coating systems can promote the generation of crack. Therefore, the effective hardness of the coating systems decreases with the increase of

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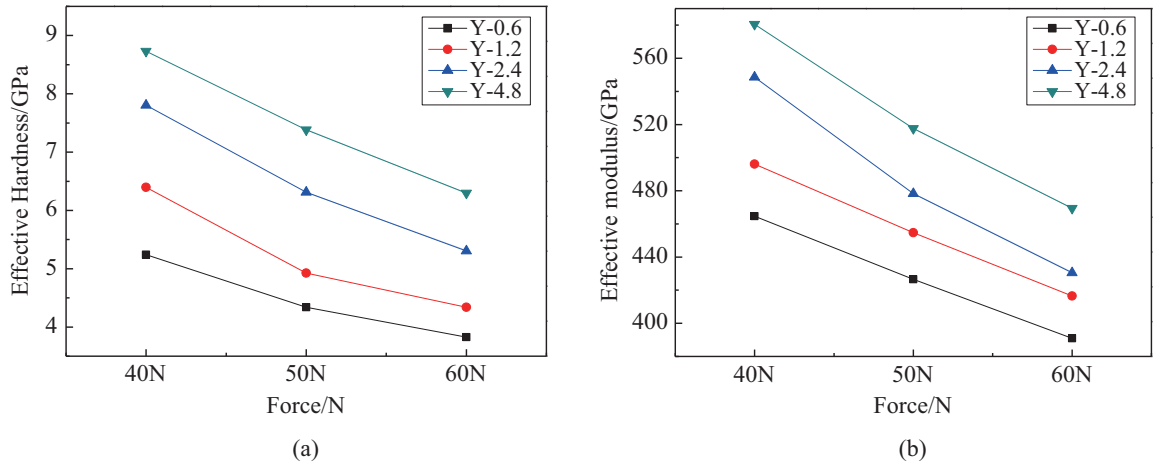


Fig. 8 Effective hardness (a) and elastic modulus (b) of coating systems with different interlayer yield strength.

maximum loads. Besides, under the same load, the effective hardness of coating systems is seen to increase with the increase of the interlayer yield strength. This is because the interlayer as barrier for the propagation of the plastic deformation to the substrate. In other words, the presence of interlayers with higher yield strength leads to the reduction of the plastically deformed region in the substrate, with consequent increasing hardness.

The effective elastic modulus shows the similar trend. As shown in Fig. 8(b), the effective elastic modulus values of the coating systems are sensitive to the interlayer yield strength, showing an increase in the values of the effective elastic modulus with increasing yield strength. Under the same maximum indentation load of 50 N, the modulus values increases from 426.52 GPa to 517.67 GPa for the interlayer yield strength increases from 0.6 GPa to 4.8 GPa, which corresponds to increase of 7, 12 and 21%, respectively. Meanwhile, the effective elastic modulus of coating systems decrease with the increase of maximum indentation load. It is related to the increase of load attenuated the propagation of the plastically deformed region to deeper soft substrate. Because the elastic modulus of substrate govern the effective elastic modulus, where the effect becomes more sensitive as the load increases.

4. CONCLUSIONS

The stress distribution and the mechanical properties of the coating systems with interlayer are analyzed by using the finite element method. The effects of thickness, elastic modulus and yield strength of the interlayer are investigated. The simulations show the following conclusions:

1. The interlayer thickness has a great influence on the distribution of the shear stress between the interfaces of coating/interlayer and interlayer/substrate. With the increase of interlayer thickness, the shear stress between the interfaces are obviously decrease. When the thickness increases to 0.04 mm or above, the SCSS of coating/interlayer achieve a platform value. And the SCSS of interlayer/substrate do not further decreases. Based on the economic cost, the interlayer with 0.04 mm thickness is an optimal value.

2. The elastic modulus of interlayer also influences the stress distribution. The smooth shear stress are obtained in the interface of coating/interlayer and the sharply changed shear stress decrease with the increase of interlayer elastic modulus. However, the interface of interlayer/substrate shows opposite trends.

3. The interlayer with different yield strength could not optimize the Mises stress in the coating systems. However, the plastic deformation decrease with the increase of interlayer yield strength, which can reduction the crack in the coating systems. Therefore, the effective hardness and elastic modulus increase with the increase of interlayer yield strength. Besides, the higher indentation load can lead to the plastic deformation in the coating systems, which cause the decrease of hardness and elastic modulus of coating systems.

The study of interlayer thickness, elastic modulus and yield strength can provide a guidance for the design of coating systems.

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REFERENCES

1. Naghibi, S. A., Raeissi, K. and Fathi, M. H., "Corrosion and Tribocorrosion Behavior of Ti/TiN PVD Coating on 316L Stainless Steel Substrate in

https://doi.org/10.1017/jmech.2018.46 Published online by Cambridge University Press

Ringer's Solution," *Materials Chemistry and Physics*, **148**, pp. 614-623 (2014).

2. Gawronski, A., Patzig, C., Höche, T. and Rüssel, C., "Effect of Y_2O_3 and CeO_2 on the Crystallisation Behaviour and Mechanical Properties of Glass–Ceramics in the System $MgO/Al_2O_3/SiO_2/ZrO_2$," *Journal of Materials Science*, **50**, pp. 1986-1995 (2015).
3. Jeng, Y. R., Islam, S., Wu, K. T., Erdemir, A. and Eryilmaz, O., "Investigation of Nano-Mechanical and- Tribological Properties of Hydrogenated Diamond Like Carbon (DLC) Coatings," *Journal of Mechanics*, **33**, pp. 769-776 (2017).
4. Bian, D., Aradhyula, T. V., Guo, Y. and Zhao, Y., "Improving Tribological Performance of Chemically Bonded Phosphate Ceramic Coatings Reinforced by Graphene Nano-Platelets," *Ceramics International*, **43**, pp. 12466-12471 (2017).
5. Gao, Y. F., Xu, H. T., Oliver, W. C. and Pharr, G. M., "Effective Elastic Modulus of Film-on-Substrate Systems under Normal and Tangential Contact," *Journal of the Mechanics and Physics of Solids*, **56**, pp. 402-416 (2008).
6. Ren, X. D. *et al*., "A Finite Element Analysis of Thermal Relaxation of Residual Stress in Laser Shock Processing Ni-Based Alloy GH4169," *Materials & Design (1980-2015)*, **54**, pp. 708-711 (2014).
7. Wang, L. *et al*., "Modeling of Thermal Properties and Failure of Thermal Barrier Coatings with the Use of Finite Element Methods: a Review," *Journal of the European Ceramic Society*, **36**, pp. 1313-1331 (2016).
8. Huang, X. Q. and Pelegri, A. A., "Finite Element Analysis on Nanoindentation with Friction Contact at the Film/Substrate Interface," *Composites Science and Technology*, **67**, pp. 1311-1319 (2007).
9. Piao, Z. Y., Xu, B. S., Wang, H. D. and Pu, C. H., "Effects of Thickness and Elastic Modulus on Stress Condition of Fatigue-Resistant Coating under Rolling Contact," *Journal of Central South University of Technology*, **17**, pp. 899-905 (2010).
10. Tang, G. and Shen, Y. L., "Numerical Assessment of Compressive Deformation in Metal-Ceramic Multilayer Micro-Pillars," *Journal of Mechanics*, pp. 1-9 (2017).
11. Zhang, X. C., Xu, B. S., Wang, H. D., Wu, Y. X. and Jiang, Y., "Effects of Compositional Gradient and Thickness of Coating on the Residual Stresses within the Graded Coating," *Materials & Design*, **28**, pp. 1192-1197 (2007).
12. Djabella, H. and Arnell, R. D., "Finite Element Comparative Study of Elastic Stresses in Single, Double Layer and Multilayered Coated Systems," *Thin Solid Films*, **235**, pp. 156-162 (1993).
13. Yang, Y., Liao, N., Zhang, M. and Li, F., "Evaluation of the Elastic-Plastic Properties of SiCN Coating System by Finite Element Simulations," *Journal of the European Ceramic Society*, **37**, pp. 3891-3897 (2017).
14. Kim, J. H., Miranda, P., Kim, D. K. and Lawn, B. R., "Effect of an Adhesive Interlayer on the Fracture of a Brittle Coating on a Supporting Substrate," *Journal of Materials Research*, pp. 222-227 (2003).
15. Jiang, C., Jordan, E. H., Harris, A. B., Gell, M. and Roth, J., "Double-Layer Gadolinium Zirconate/ Yttria-Stabilized Zirconia Thermal Barrier Coatings Deposited by the Solution Precursor Plasma Spray Process," *Journal of Thermal Spray Technology*, pp. 895-906 (2015).
16. Fontalvo, G. A., Daniel, R. and Mitterer, C., "Interlayer Thickness Influence on the Tribological Response of Bi-Layer Coatings," *Tribology International*, pp. 108-112 (2009).
17. Guab, L., Keb, P., Zoua, Y., Lib, X. and Wangb, A., "Amorphous Self-Lubricant MoS₂-C Sputtered Coating with High Hardness," *Applied Surface Science*, pp. 66-71 (2015).
18. Bernoulli, D. *et al*., "Improved Contact Damage Resistance of Hydrogenated Diamond-Like Carbon (DLC) with a Ductile Alpha-Ta Interlayer," *Diamond and Related Materials*, pp. 78-83 (2015).
19. Callisti, M. and Polcar, T., "The Role of Ni–Ti–(Cu) Interlayers on the Mechanical Properties and Nano-Scratch Behaviour of Solid Lubricant W–S–C Coatings," *Surface and Coatings Technology*, **254**, pp. 260-269 (2014).
20. Djabella, H. and Arnell, R. D., "Finite Element Analysis of the Contact Stresses in Elastic Coating/ Substrate Under Normal and Tangential Load," *Thin Solid Films*, **223**, pp. 87-97 (1993).
21. Kot, M., Rakowski, W., Lackner, J. M. and Major, Ł., "Analysis of Spherical Indentations of Coating-Substrate Systems: Experiments and Finite Element Modeling," *Materials & Design*, **43**, pp. 99-111 (2013).
22. Vlachos, D. E., Markopoulos, Y. P. and Kostopoulos, V., "3-D Modeling of Nanoindentation Experiment on a Coating-Substrate System," *Computational Mechanics*, **27**, pp. 138-144 (2001).
23. Zhang, X. C., Xu, B. S., Wang, H. D., Wu, Y. X. and Jiang, Y., "Hertzian Contact Response of Single-Layer, Functionally Graded and Sandwich Coatings," *Materials & Design*, **28**, pp. 47-54 (2007).
24. Djabella, H. and Arnell, R., "Finite Element Analysis of Contact Stresses in Elastic Double-Layer Systems under Normal Load," *Thin Solid Films*, **223**, pp. 98-108 (1993).
25. Oliver, W. C. and Pharr, G. M., "An Improved Technique for Determining Hardness and Elastic Modulus Using Load and Displacement Sensing Indentation Experiments," *Journal of Materials Research*, **7**, pp. 1564-1583 (1992).
26. Oliver, W. C. and Pharr, G. M., "Measurement of Hardness and Elastic Modulus by Instrumented Indentation: Advances in Understanding and Re-

https://doi.org/10.1017/jmech.2018.46 Published online by Cambridge University Press

finements to Methodology," *Journal of Materials Research*, **19**, pp. 3-20 (2004).

27. Sun, Y., Bloyce, A. and Bell, T., "Finite Element Analysis of Plastic Deformation of Various TiN Coating/Substrate Systems under Normal Contact with a Rigid Sphere," *Thin Solid Films*, **271**, pp. 122-131 (1995).

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