

Finite Element Analysis of Stress Intensity Factor of Pre-Cracked Coated Substrate under Contact Sliding

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Abstract

This establishes the effect of coating geometry with pre-crack on stress intensity factor (SIF) using Finite Element Simulation. The coating is assumed to be brittle and perfectly adhered to the substrate. The coating surface is loaded by a sliding cylinder across the crack, thus including normal and tangential loads. Results suggest that an increase in the pre-crack length in the coating causes the corresponding increase of the SIF, enhancing the possibility of the crack extension. A thicker coating with a long pre-crack length is predicted to continue increasing stress intensity factor (K) along the sliding path.

1. Introduction

The coating has been widely used in many electrical applications such as printed circuit boards, substrates and electronic components. Functional electronic coating is applied to modify surface properties of the substrate such as wetting behavior, corrosion protection and wear resistance. With the emergence of new coating deposition technique, vast choices are available to industrial end users for their specific applications. However, fundamental understanding in linking the mechanics of deformation of failure and mechanisms to reliability and performance of the coating system is much lacking. Contact mechanics has been widely applied in many branches of engineering, particularly in the studies of indentation and surface.

Molecular interaction between the coating and the substrate has also been included into the contact mechanical model [1]. The contact adhesion based on is the balance between elastic and surface energies. In contact mechanics, macromechanical contact mechanism considers the distribution of stress and strain in the whole contact zone and the total elastic deformation. Micromechanical contact mechanics addresses the crack initiation and propagation, material liberation and particle formation based on stress and strain evolution [2]. Contact mechanics are dictated by the force pressing the two surfaces together to induce the stress field. The contact pressure and deformations in a coated surface could be estimated from the Hertzian solution. The Hertzian theory enables one to calculate: (i) the shape of the contact area and its evolution with increasing load, (ii) the magnitude and distribution of normal and tangential stress on the contact interface, and (iii) the components of elastic stress and deformation in both contacted bodies in the vicinity of the contact [3,4]. An important parameter is the coating hardness and its relationship to the substrate hardness, such effect of hard coatings and soft coating has been reported [2,8]. Soft coatings such as silver and gold may also have the function of reducing sliding-originated surface tensile stresses, which

contribute to undesirable subsurface cracking and subsequently to severe wear. A hard coating on a softer substrate can decrease friction by preventing ploughing, both on a micro scale. Mechanics simulation work on coated substrate have been studied by a number of researchers [5,6,7]. An elastic modulus mismatch between the coating layer and the substrate is particularly important with respect to crack initiation. Some previous work has reported that the crack extension in length with increasing thickness, and that crack propagation in coatings with greater elastic mismatch with the substrate is more sensitive to changes of the coating thickness [5,9].

The stress intensity factors define the crack tip driving force in linear elastic fracture mechanics. They characterize the crack-tip stress field and indicate the propensity for crack extension. The effect of applied tangential displacement (stroke) on the mode I, stress intensity factor, K_I for substrate with cracked of the final propagated crack.

The coating results have been reported [5], indicate that the increased coating thickness is beneficial of cracking resistance. In this paper, the effect of different crack lengths and thickness of brittle coatings on the corresponding variations in SIF when subjected to normal and tangential loading. The effect of elastic modulus mismatch between the coating and substrate on the resulting stress field is also considered.

2. Finite element simulation

2.1 Finite Element Modeling

The geometry of the model consists of a flat substrate with perfectly bonded coating containing a single pre-existing crack in the thickness direction. The rectangular substrate that assumes the properties of Ti-6Al-4V and measures 12 x 6 mm² is used. The applied contact forces are generated by sliding rigid cylinder with a radius of 6 mm across the crack. The geometrical arrangement of the test setup is illustrated in Fig. 1. Testing variables used in the simulation are listed in table 1 while the properties of the substrate and the coating are listed in Table 2. The model is discretized using plane strain elements, thus representing a symmetrical plane with respect to the length of the crack on the surface of the coating. A normal line force of 500 N/mm is applied at the center of the cylinder. Variations of induced contact forces over the distance of 120-180 μ m across the crack is to be predicted. The coefficient of friction, COF=0.3 is assume between the contacting cylinder on the coating. The FE simulation performed using Abaqus FE software ver 6.11.

Table 1 : Fe based model for SIF analysis

Coating/substrate	α , Dunders parameter	β , Dunders parameter	Thickness (μm)	Max contact pressure, P_{max} (MPa)	Thickness/contact semi width
$E_c200/\text{Ti-6Al-4V}$	0.245	0.036	100	1363	0.43
			150	1411	0.68
			200	1476	0.93
$E_c100/\text{Ti-6Al-4V}$	-0.096	0.076	100	1243	0.38
			150	1218	0.57
			200	1203	0.74

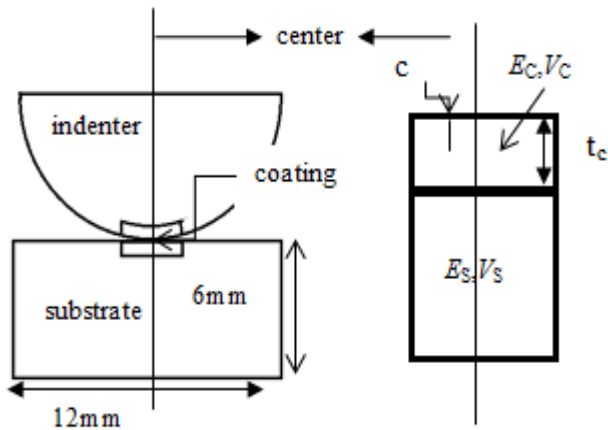


Fig. 1: Half cylinder on plate

Table 2: Properties material for coating substrate

Material	Young modulus, GPa	Poisson's ratio, ν
Ti-6Al-4V	115	0.3
Coating	100	0.2
	200	0.2

2.2. Coating crack modelling

A crack is modeled for linear elastic fracture mechanics (LEFM) analysis of the crack tip. A single surface crack of length, c is inserted into the thickness of the coating at the initial cylinder-coating contact position. This initial crack is modelled as an embedded line or a 'seam' that is originally closed, but can open during an analysis. Overlapping duplicate nodes are placed along a seam when the mesh is generated. These coincident nodes are free to move apart as the seam separates. The traction-free crack faces are assumed not to come into contact with each other. Three different lengths of the pre-existing microcrack, 10, 20 and 30 μm are examined. The fracture toughness, K_{IC} of the coating ranges between 80 to 100 $\text{MPa}\sqrt{\text{mm}}$; these values are typical for thermal spray coatings. A sweep plane strain quadrilateral mesh is used for the contour integral analysis. Along the crack, the element size is set to be 1 μm .

A series of five rings of quadrilateral elements are assigned along the crack seam, centered on the crack tip, as shown in Fig. 2. The radial dimension of the elements along the seam is reduced closer to the crack tip to provide accurate crack tip resolution of displacements, strains and stresses for

the contour integral analysis. The meshes are also refined around the crack path to increase accuracy.

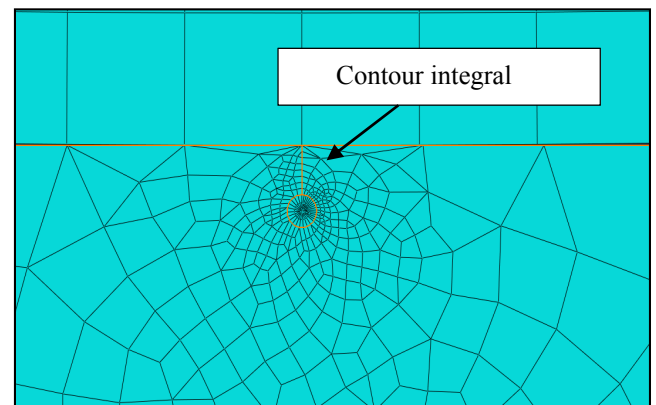


Fig. 2: FE analysis shows contour integral, at the crack.

3. Result and Discussion

3.1. Effect elastic modulus mismatch on SIF

Fig. 3(a) and (b) show the effect of elastic modulus mismatch on the SIF for the relatively stiff coating ($\alpha=0.245$) and relatively small elastic mismatch between the coating and the substrate (-0.096) at pre-cracked length of 10 μm . Result show that large modulus mismatch leads to a greater possibility of a crack extension. It is because, the stress field in the surface coating will be distributed such that the stress will be absorbed by the more compliant phase. Fig. 3(b) indicates that the peak of the SIF curve for low mismatch ($\alpha=-0.0096$) is lower. Crack extension is expected when SIF, $K_I > 80$ to 100 $\text{MPa}\sqrt{\text{mm}}$. However, with increasing tangential displacement to 100 μm , the SIF reached to minimum value, so the initial pre-crack does not to propagate.

3.2. Effect of thickness and crack length on SIF.

The effects of coating thickness and pre-crack length on the calculated SIF are shown in Fig. 4. Result show that the calculated SIF is higher for a thinner coating. The higher SIF curve for the case with longer crack length are also observed, as would be predicted by LEFM. A thin coating thickness is 100 μm , the SIF increases with a tangential displacement up to a peak value before decreasing back at large displacement. However, for thicker coating thickness and longer crack, a constant SIF value at larger tangential displacement is

predicted. The peak magnitude of the SIF for coating thickness varies from 106 to 130 $\text{MPa}\cdot\text{mm}^{1/2}$ corresponding to the pre-existing crack length of 10 to 30 μm , respectively.

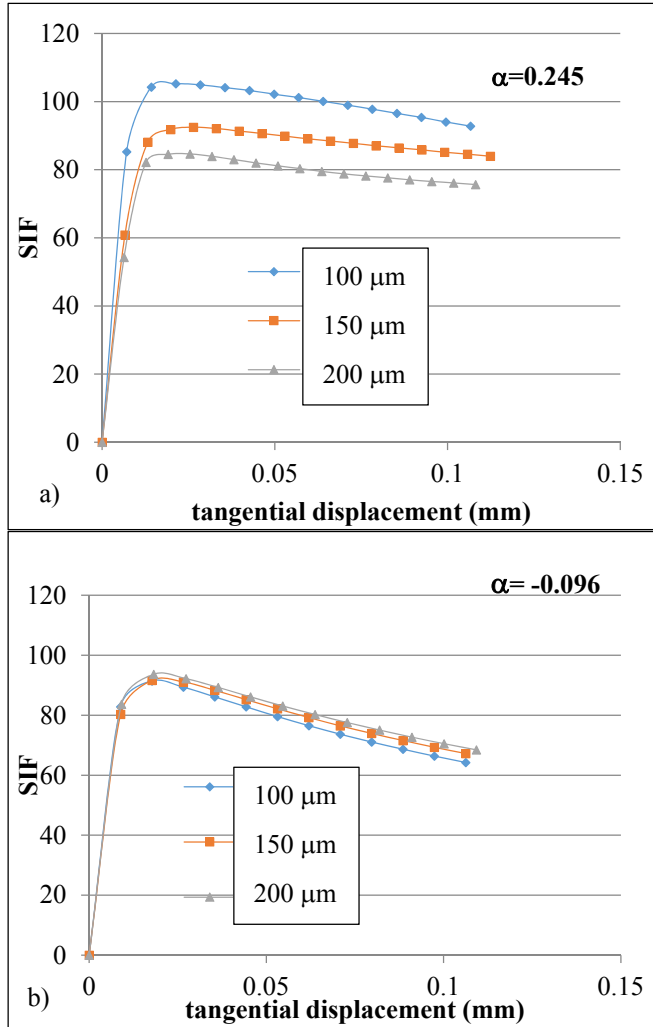


Fig. 3 : Variation of SIF with tangential displacement for different Dundurs' parameter values and different coating thickness value (a) $\alpha=0.245$ (b) $\alpha=-0.096$. ($P=500\text{N/mm}$, $\mu=0.3$, $K_{IC}= 80 \text{ MPa mm}^{1/2}$, Crack length, $c= 10 \mu\text{m}$)

Moreover, it can be observed in detail based on the parameter, tangential displacement, δ at $0.013\mu\text{m}$ and ($t=200\mu\text{m}$) in each pre-microcrack length. At ($c = 10\mu\text{m}$), the SIF reached $80 \text{ MPa}\cdot\text{mm}^{1/2}$, while at ($c = 30\mu\text{m}$), the SIF is $60 \text{ MPa}\cdot\text{mm}^{1/2}$. This indicates that each tangential displacement of indenter will give stress to the coating surface to open pre-microcrack. The shorter of pre-microcrack length, at least sliding displacement. High stress field acting on the crack tip needed to open the crack. In contrast, the longer the pre-microcrack length, at the early sliding displacement, SIF value increased slightly due to the lower stress field value for opening. Consequently, increasing sliding displacement will increase the SIF and stress region value, thereby increasing the potential for pre-microcrack to propagate.

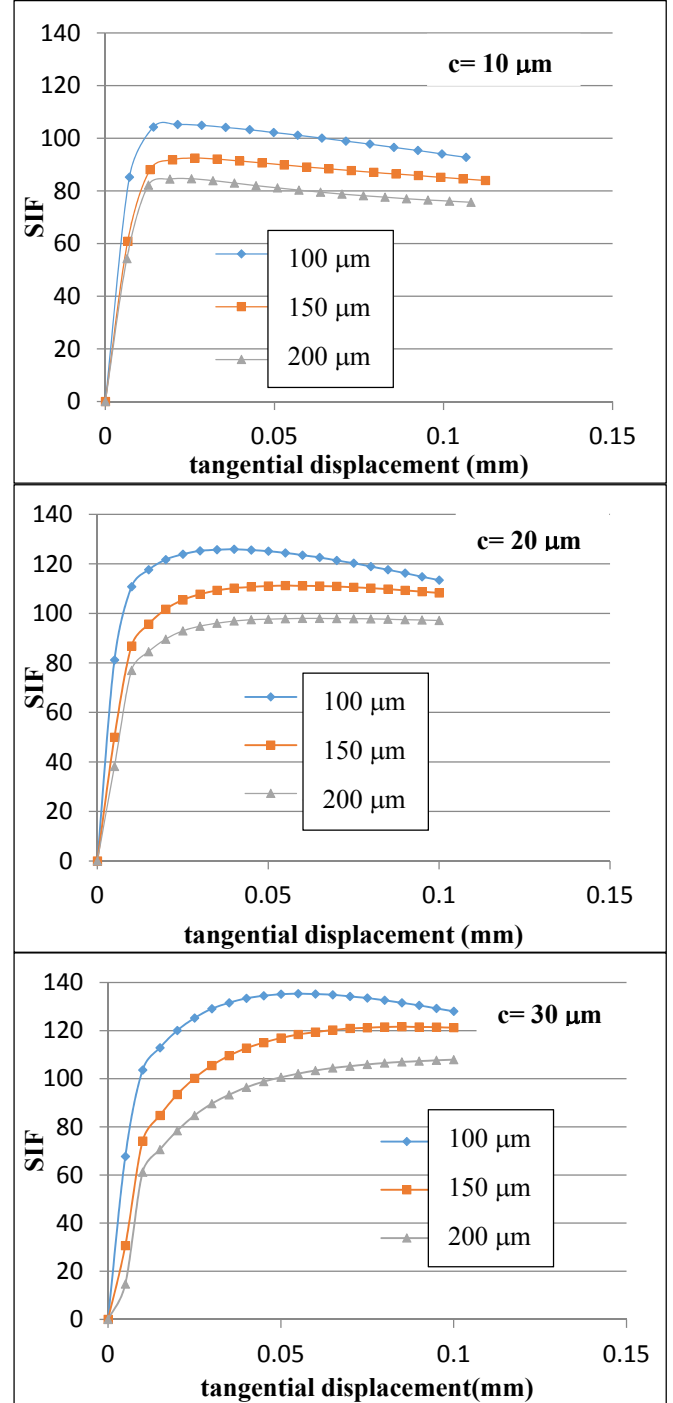


Fig. 4 : Predicted K_I -different crack length, c (a) $c= 10 \mu\text{m}$ (b) $c= 20 \mu\text{m}$ (c) $c= 30 \mu\text{m}$ ($P=500\text{N/mm}$, $\mu=0.3$, $K_{IC}= 80 \text{ MPa mm}^{1/2}$, $\alpha= 0.245$)

In addition, the shape of the graph pattern for Figs. 4 (a), (b) and (c) is different. At $c = 10\mu\text{m}$, the pattern of the graph decreased, whereas at the early indenter sliding, the maximum SIF value was observed but towards the end of the graph, it slid downwards. This is due to the short pre-microcrack length. When the force is applied at the indenter, high stress will be formed at the coating surface. Hence, crack will be opened even the indenter does not slide yet. This phenomenon is known as contact slip. When the indented slides far, the tensile stress opens the crack at maximum, hence the SIF value will decrease. However, for a long crack,

the SIF value increased, as shown in Fig. 4 (c). When the indenter slides on the surface of the coating, friction and force will act on the surface of the coating and produce stress for crack opening. The farther the sliding displacement, longer crack will open a long and wide pre-crack, resulting in the increase of SIF value. Fig. 5 shows the schematic force and friction act on the coating surface and crack.

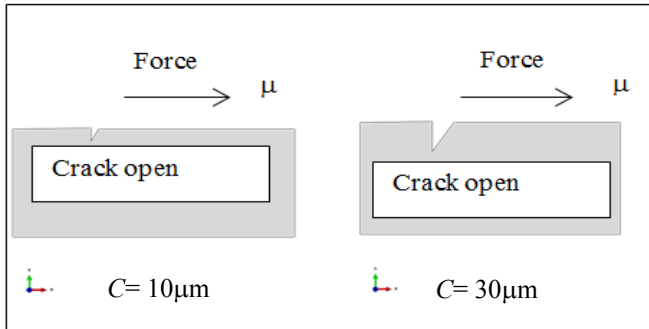


Fig. 5 : Schematic force and friction act on coating surface

The results of this can also be attributed to differences in the distance between the period graph $c = 10$ and $c = 30$, where the distance between each period of the graph is greater follow to the pre-crack length.

The different coating thickness also affects the SIF, as shown in graph 4, if the observed value of SIF at $t_c = 100\mu\text{m}$ is higher than $t_c = 150\mu\text{m}$ and $200\mu\text{m}$. This occurs due to the high stress is the surface coating and then stress will distributed to entire areas of the coating. The thickness of the thin stress will be spread on a small area and cause stress on the coating is high and vice versa to the thick coating. Fig. 6 shows that the stress distribute in the coating area.

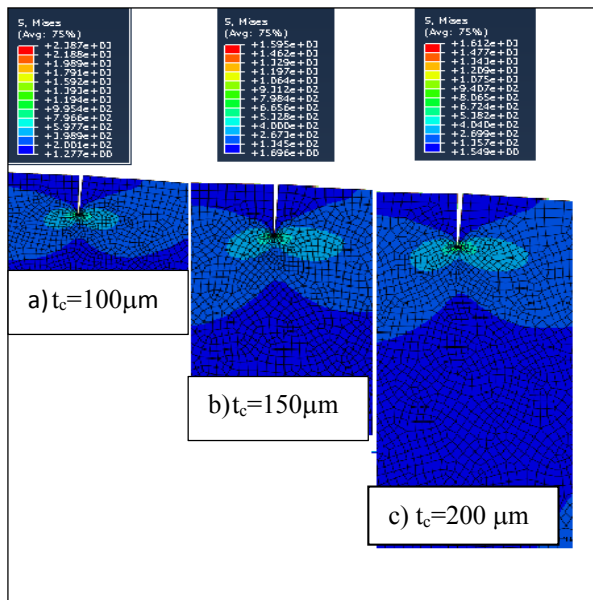


Fig. 6: Stress region with different thickness

4. Conclusion

Finite element simulation of brittle like coating with pre-existing crack low metallic substrate has been performed. Effect of coating thickness, and pre-crack length on stress

intensity factor (SIF) under the contact sliding load has been established. The predictions lead to the following conclusions:

- The stress from contact between coating surface and indenter distributed to the area in the coating, so the stress will be lower in large area and vice versa to a small area. It shows that the thick coating produces small stress and thus reduce the risk crack propagate.
- Increasing crack length will increase SIF value at the end of sliding displacement. In because, crack open during indenter in coating to the coating surface, its call contact slip and enhancing the possibility of the initial pre-crack to propagate during the indenter sliding through the coating surface.
- To reduce stress on the long crack length, thick coating be used to ensure that the stress is distributed the entire coating.

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