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Crack Branching Phenomenon of Zirconia Plasma Spray Coating†

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Abstract

Gas tunnel plasma spray coating technology has been introduced as one of the recent advances in smart coating technology. Several factors control the quality of the final product of the coating material. Some factors can be summarized as the gas discharge rate, powder size, powder rate, plasma size and temperature, heating time, cooling rate and time, coating time, number of coating layers, relative speed of the sample and plasma spray, etc. These factors have a certain role in addition to the quality in determination of the safe life time of the coating product. Safe life time length and sustainability are actually control the cost and economy of the coating product. Life and history of coating composite will depend on the ability of the composite material to resist failure through fracture, crack propagation, spreading and delamination. The plasma spray coating composite often suffers from cracks and delaminations. Therefore, this research was carried out as a part of our study of zirconia coating to study fracture in early ages of plasma spray coating. Also, this research introduces a method of studying fracture during the life history of the coating composite. This paper discusses a very important problem in fracture mechanics science which is the branching phenomena of the cracks during the process of fracture. This treatment of the branching phenomena of cracks is newly introduced. It depends on the distribution of stresses at the crack tips under remote loading and involves experimental observations in order to have a logical philosophy and understanding for this abnormal natural phenomenon.

KEY WORDS: (Crack Propagation) (Crack Branching) (Zirconia Coating) (Fracture Spreading) (Delamination) (Global-Local Fracture Criterion) (Linear Elastic Fracture Mechanics) (Elastic-Plastic Deformation)

1. Introduction

This study was carried out to achieve sustainable, durable and economic smart plasma spraying coating composites. The fracture and cracking processes are investigated theoretically and experimentally. Theoretical study is introduced fundamentally using recent fracture theories the effective role of residual stresses is considered. Critical fracture factors, critical stresses and governing parameters are calculated using KR-GL criterion. The study is based on the energy approach in directional form using the strain energy method in three dimensional analyses under plane stress condition since the thickness of the material is very thin. SEM analysis is introduced.

Although the plasma spray coating technology [1-7] is an interesting technique for protecting metals and metallic structures against corrosion, erosion, high temperature and environmental conditions it has some important shortcomings which can lead to serious results. The important problems are fracture and de-lamination [8].

In addition to these phenomena, there is a very serious and dangerous phenomenon which is crack branching and spreading during the propagation of the cracks. These problems cannot be ignored since they will have bad serious effects on the efficiency of the coating, capacity of substrate, lifetime of coating and substrate, maintenance, total quality control and economy. Many researchers have studied plasma spraying coating technology [1-7]. Some researchers introduced comments and discussions on the fracture and cracks but without details or fundamental analysis [1-4]. This type of fracture is very complicated and needs special study and treatment. This research introduces recent steps towards overcoming this problem for safe and economic coatings with high quality without fracture using the Directional Global Local criterion [9].

It is usually recognized during the fracture process of mixed mode cracks that some of cracks propagate in two different directions at the same time at the same crack tip. This usually happens during the experimental work and testing for the fracture of mixed mode central cracks under remote tension stresses as shown in **Figs 1-7**. One of these two directions is an ordinary direction and can be expected and predicted by application of the fracture

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criterion [1-9] while the other one is not normal and can not easily be predicted. Sometimes the second one stops the propagation after certain distance of extension while the first one is still extending with normal behavior during the fracture process. This phenomenon is called crack branching phenomenon. It can be happen for cracks in mixed mode. This phenomenon can be recognized in the experimental work only for some cracks with certain orientations to the loading direction and not for all cases of cracks. This paper studies this phenomenon analytically and experimentally and discusses the reasons in the light of recently developed fracture theories under thermal stresses heating and cooling for Zirconia coatings.

2. Cracking and Branching Phenomena

In this paper we studied zirconia coatings as examples of the gas tunnel plasma spraying technique. This material is very sensitive for cracking. It is a brittle material. It is known that zirconia powder consists of non uniform fine crushed aggregate of particles with sharp edges in irregular shapes. These particles may include pre-cracks. After coating, many types of cracks were recognized such as single cracks (Mode I, Mode II, Mode III) and mixed modes in the coating materials as shown **Figs. 1-7**.

Also, there were de-bonding cracks at the biomaterial interface between coating material and substrate and between coating layers themselves [9].

These cracks are mainly occurring under thermal stresses which produce input thermal energy for both the coating and substrate.

It is recognized that the de-bonding may occur without coating cracks or failure [9].

On the other hand coating cracks may occur without de-bonding.

It is known for all researchers working in the field of fracture mechanics that the mixed mode cracks under remote tension stress usually propagate in a direction different from the original crack direction, which tends to be normal to the direction of the load. They consider this propagation direction as a fact and intrinsic fracture phenomenon [1-9]. All the fracture studies regarding the prediction of fracture direction and fracture trajectory consider that the mixed mode cracks extend in only one direction at each crack tip.

The analytical studies depending on the fracture theories can predict the fracture direction. These theories can predict the fracture direction and fracture path giving results which coincide with some experimental work and logical theoretical assumption but differ from some other cases. But the theoretical studies can not predict the mixed mode cracks under tension which may propagate, not only in one direction at the same tip but also in another one completely different from the traditional well known direction.

3. Mechanism

The displacements in the coating layer/layers are different from the displacements in the substrate in quantity and may be in the direction as described in the following section.

Due to heating and cooling conditions and the existence of a bond between substrate and coating, the displacements will produce shear stresses on the bi-material interface which will destroy the bond between them globally making full failure or making local failure associated with cracks in the coating. This mechanism is clear in some cases of coating but the normal case does not always include many cracks. This means that the bond between the coating and substrate is still good without de-bonding due to shear stresses. This means that the cracks which are in opening mode or mixed mode cracks may be formed before the formation of bond strength between coating and substrate due to thermal stresses. Then the bond occurring after cracking formation and the thermal stresses produced as shear stresses can just extend the cracks without making de-bonding globally but may make local de-bonding.

This can be happen between substrate and one layer of coating. This approach will be applied for the multi layer coating and the same procedures will be between each two layers of the coating. This means that the effect of stresses on the cracking in the top layer will be more than the second layer while the second layer will be more than the third layer and so on [8, 9]. Therefore, the effect of the number of the layers is clear in the fracture of the coating.

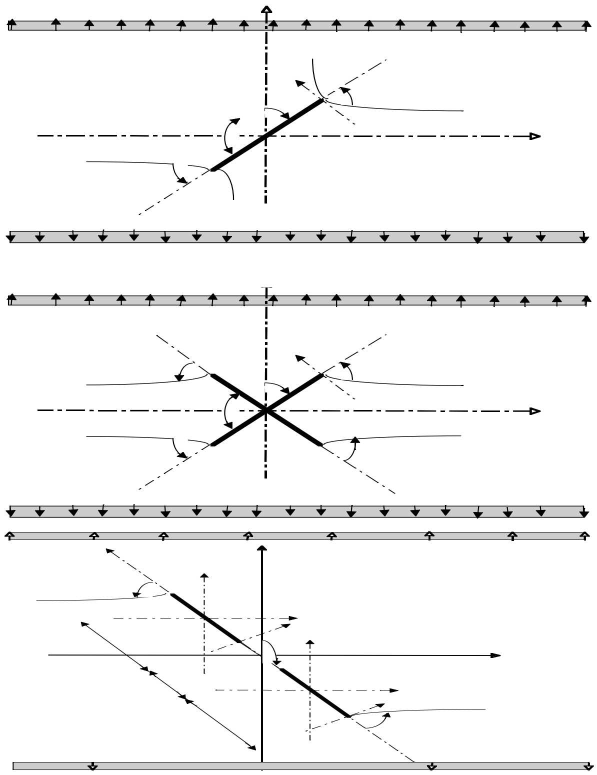

Fig. 1 Some types of crack propagation and crack branching.

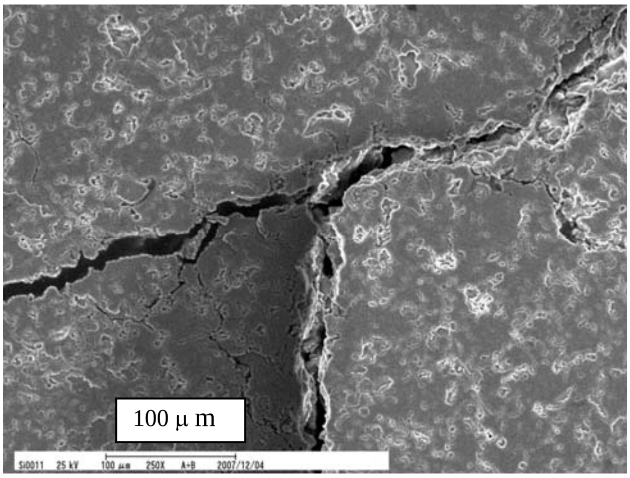

Fig. 2 Global body crack branching of zirconia coating under heating stresses.

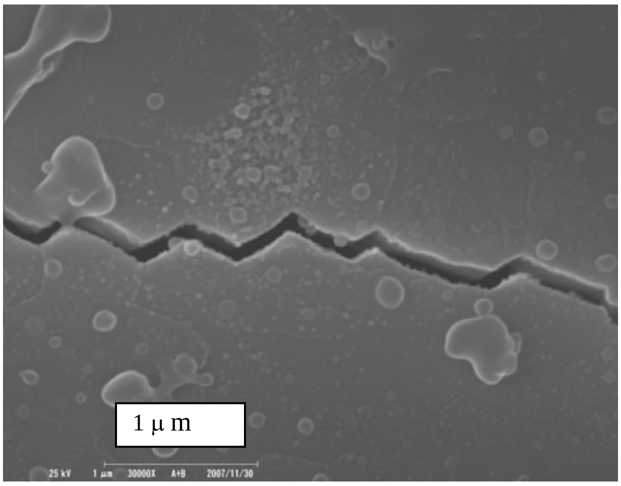

Fig. 3 Mixed mode crack propagation and branching of Zr coating due to heating.

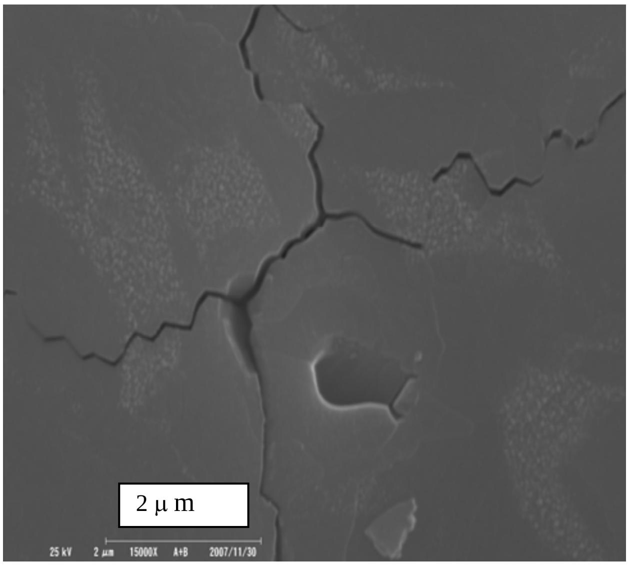

Fig. 4 Global and local crack propagation under both heating and cooling stresses.

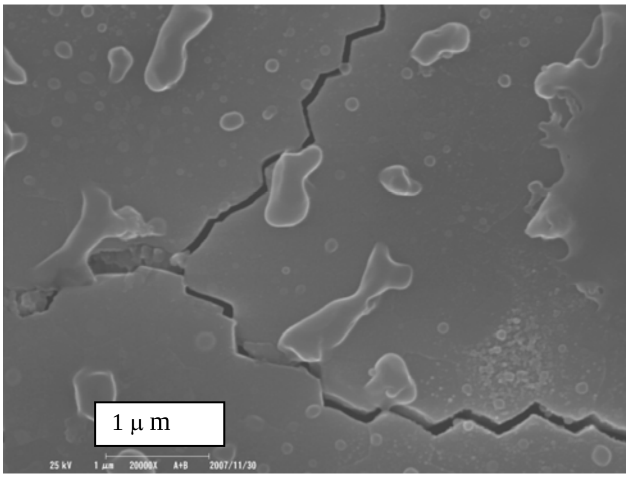

Fig. 5 Global and local crack propagation and crack branching under both heating and cooling stresses.

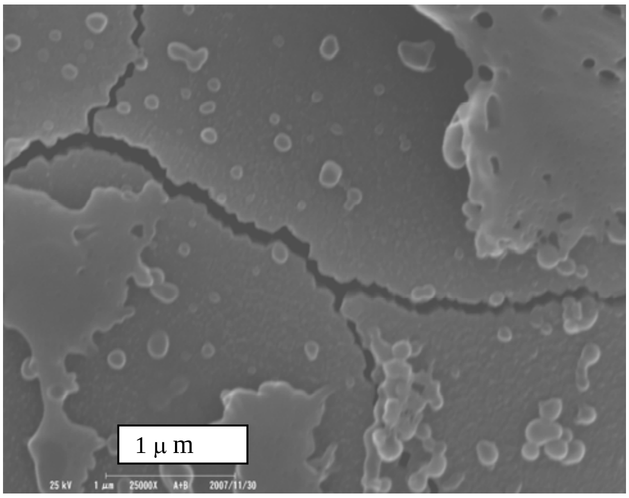

Fig. 6 Global and local crack propagation under heating and cooling for mixed mode with different crack widths.

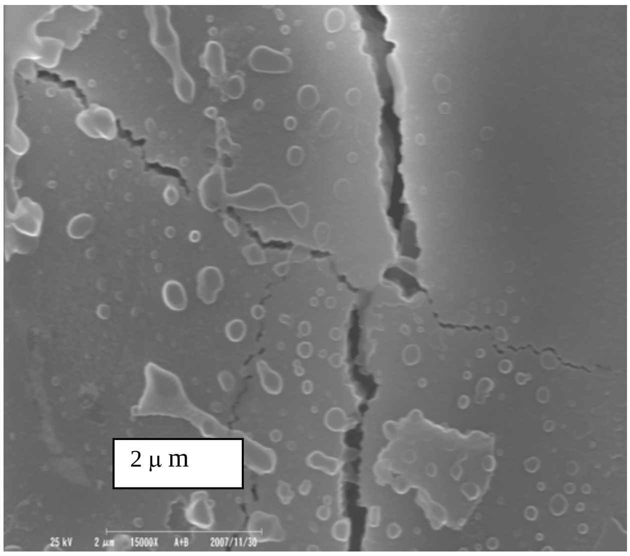

Fig. 7 Intersected cracks of zr coating under both heating and cooling stresses.

4. Analysis

According to the observations of the experimental results, it is recognized that the crack may have double fracture directions and produce double fracture paths at the same crack tip. But this phenomenon may happen only for some cases of cracks and not happen for other cases.

The crack may be found in one of the following categories:

1. Cracks with inclination (β); to the loading direction; of (β = 0.0) may extend in only one direction which has a path parallel to the loading direction representing a Single Branching Phenomenon (SBP).
2. Cracks with inclination of (0.0 < β < 45.0) may extend in two directions at the same time, one direction is normal to the loading direction while the other one is parallel to it. This behavior represents the Double Branching Phenomenon (DBP).
3. Cracks with inclination of (45.0 =< β < = 90.0) may extend in only one direction with a path normal to the loading. This phenomenon represents another type of Single Branching (SBP).

The last category (No.3) is the most traditional and well-known phenomenon.

All fracture theories concentrate attention on the investigation of this type neglecting or forgetting the other two categories (No. 1 & No. 2).

In order to study and understand the philosophy of the crack branching phenomenon at the crack tip one should return to the original form of the stress and strain equations at the crack tip.

4.1 Stresses at tips of mode (I) crack

The stresses at crack tip of mode I are represented **Eqs. 1**. in the condition of plane strain. These equations can be changed to plane stress condition by replacing $\sigma_z = 0$, and $(\nu/(1+\nu))$ instead of (ν).

$$\sigma_{xI} = \left[K_I/(2\pi r)^{1/2}\right]\left(\cos(\theta/2)\left[1-\sin(\theta/2)\sin(3\theta/2)\right]\right) + \sigma\cos(2\beta)$$
$$\sigma_{xI} = \left[K_I/(2\pi r)^{1/2}\right]\left(\cos(\theta/2)\left[1-\sin(\theta/2)\sin(3\theta/2)\right]\right) + \sigma\cos(2\beta)$$
$$\tau_{xyI} = \left[K_I/(2\pi r)^{1/2}\right]\left(\sin(\theta/2)\left[\cos(\theta/2)\cos(3\theta/2)\right]\right)$$
$$\sigma_z = \nu(\sigma_x + \sigma_y), \tau_{xz} = \tau_{yz} = 0 \qquad (1)$$

where K_I is the stress intensity factor for mode I crack , σ_{xI}, σ_{yI}, τ_{xyI} are the normal and shear stresses at the crack tip for mode I crack. Where (σ) is the applied remote stress, (β) is the crack inclination angle to the loading direction and the item of (σ cos 2β) represents the free stress at the crack tip. The researchers used to neglect this item in the calculations and the analysis considering it without any effect on the crack propagation especially in case of mixed mode cracks

4.2 Stresses at tips of mode (II) crack

The stresses at crack tip of mode II are represented **Eqs. 2** in the condition of plane strain. These equations can be changed to plane stress condition by replacing $\sigma_z = 0$, and $(\nu/(1+\nu))$ instead of (ν)

$$\sigma_{x\Pi} = \left[K_I/(2\pi r)^{1/2}\right]\left(\cos(\theta/2)\left[1-\sin(\theta/2)\sin(3\theta/2)\right]\right)$$
$$\sigma_{y\Pi} = \left[K_I/(2\pi r)^{1/2}\right]\left(\cos(\theta/2)\left[1-\sin(\theta/2)\sin(3\theta/2)\right]\right)$$
$$\tau_{xy\Pi} = \left[K_I/(2\pi r)^{1/2}\right]\left(\cos(\theta/2)\left[1-\sin(\theta/2)\sin(3\theta/2)\right]\right)$$
$$\sigma_z = \nu(\sigma_x + \sigma_y), \tau_x = \tau_{yz} = 0 \qquad (2)$$

where K_{II} is the stress intensity factor for mode II crack , σ_{xII}, σ_{yII}, τ_{xyII} are the normal and shear stresses at the crack tip for mode I crack. To change the above equations for mode I and mode II to plane stress, replacing $\sigma_z = 0$, and $(\nu/(1+\nu))$ instead of (ν).

Mixed mode cracks which contain mode I and mode II will be calculated using the directional fracture approach [8, 9] regarding that the stress intensity factor will be in the form of $K_{I\text{-}II} = \phi(K_I, K_{II})$.

4.3 Global thermal stresses

4.3.1 Derivation of Thermal stresses without cracks

The thermal stresses for the coating and substrate without consideration of coating cracks are derived from **Eqs. 3-8** as the following:

Energy supply = Kinetic energy + Thermal energy

Energy supply = 0.5 m V^2 + m α Δ t

$V = V_{powder} + V_{Plasma}$

Energy Supply = energy absorbed + energy losses

Energy absorbed = energy dissipated + residual energy

Where:

$\Delta L = \alpha t L_o$, $\Delta L_c = \alpha(t_c - t_o) L_{co}$,

$\Delta L_S = \alpha(t_S - t_o) L_{So}$

$\varepsilon = \Delta L / L_o$,

$\varepsilon_c = \Delta L_c / L_{co} = \alpha_c(t_c - t_o)$,

$\varepsilon_S = \Delta L_S / L_{So} = \alpha(t_S - t_o)$.

$\varepsilon_c = \varepsilon_S$,

$$\varepsilon_c / \varepsilon_S = (\Delta L_c / L_{co}) / (\Delta L_S / L_{So}) = \alpha_c(t_c - t_o) / [\alpha_S(t_S - t_o)] \qquad (3)$$

a- Tension or compression in both of coating and substrate producing no full debonding and no crack propagation but may produce primary cracks.

$$\varepsilon_c / \varepsilon_S = (\Delta L_c / L_{co}) / (\Delta L_S / L_{So}) = \alpha_c(t_c - t_o) / [\alpha_S(t_S - t_o)] = 1 \qquad (4)$$

b - Tension in coating and compression in substrate producing cracks only or full debonding or cracks and local debonding.

$$\varepsilon_c / \varepsilon_S = (\Delta L_c / L_{co}) / (\Delta L_S / L_{So}) = \alpha_c(t_c - t_o) / [\alpha_S(t_S - t_o)] > 1 \qquad (5)$$

c – Compression in coating and tension in substrate producing cracks only or full debonding or cracks and local debonding

$$\varepsilon_c / \varepsilon_s = (\Delta L_c / L_{co}) / (\Delta L_S / L_{So}) = \alpha_c (t_c - t_o) / [\alpha_S (t_S - t_o)] < 1 \quad (6)$$

d- Global Stress intensity (tension or compression)

The global stresses are represented in **Eqs. 7**.

$$\sigma = E\,\varepsilon,\ \sigma_c = E_c\ \varepsilon_c = E_c\,\alpha_c (t_c - t_o) = \sigma_x = \sigma_y = \sigma_z,$$
$$\sigma_S = E_S\ \varepsilon_S = E_S\,\alpha_S (t_S - t_o) = \sigma_x = \sigma_y = \sigma_z \quad (7)$$

e- Local stresses

The local stresses will be in the following form of **Eq. 8**.

$$(\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \tau_{xy}, \tau_{xz}, \tau_{yz}) = \phi(K_I, K_{II}, K_{III}) \quad (8)$$

4.3.2. Derivation of Thermal stresses with cracks

The thermal stresses for the coating and substrate without consideration of coating cracks are derived from **Eqs. 9-12** as the following:

$$\Delta l = \alpha\, t\, l + \Sigma\, w_i \text{ (crack widths)},\ i = 1 \text{ to } n$$

Then:

$$\alpha\, t\, l = \Delta l - \Sigma\, w_i$$
$$\varepsilon = \Delta l / l = (\alpha\, t\, l + \Sigma\, w_i) / l$$
$$\varepsilon = (\alpha\, t\, l + \Sigma\, w_i) / l$$
$$\varepsilon = \alpha\, t + (\Sigma\, w_i / l)$$
$$\sigma = [\alpha\, t + (\Sigma\, w_i / l)]\, E$$
$$\sigma x = [\alpha\, x\, t + (\Sigma\, w\, x_i / l\, x)]\, E\, x$$
$$\sigma y = [\alpha\, y\, t + (\Sigma\, w\, y_i / l\, y)]\, E\, y \quad (9)$$

Inclined cracks with angle β (mixed mode) will have the following equations; **Eqs. 10**:

$$\sigma x = [\alpha\, x\, t + (\Sigma\, w_I \sin\beta / l\, x)]\, E\, x$$
$$\sigma y = [\alpha\, y\, t + (\Sigma\, w_i \cos\beta / l\, y)]\, E\, y \quad (10)$$

4.3.2a Isotropic materials for single mode

Equation 11 represents the stresses for isotropic materials.

$$\sigma = [\alpha\, t + (\Sigma\, w_i / l)]\, E \quad (11)$$

4.3.2b Mixed modes

Equation 12 represents the stresses for isotropic mixed mode crack.

$$\sigma x = [\alpha\, t + (\Sigma\, w\, x_i / l\, x)]\, E$$
$$\sigma y = [\alpha\, t + (\Sigma\, w\, y_i / l\, y)]\, E \quad (12)$$

4.4 Applied theory

Three dimensional analyses are introduced by using the Global-Local Directional fracture Criterion (KR-GL Criterion) under tri-axial (X-Y-Z) thermal stresses for both heating and cooling conditions.

This theory depends on the energy release and energy absorbed approaches in the form of strain energy. Strain energy has two components which are dilatational strain energy and distortional strain energy [8, 9]. Globally the energy supply (absorbed energy) and energy release (energy dissipation) will be calculated [9]. Locally the strain energy will be calculated based on the local stress concentration due to the thermal stresses [9].

5. Results and Discussions

It was found from the experimental work that some cracks can propagate in two paths at the same crack tip one of them tends to be normal to the load direction (σ) and the other tends to be parallel to the load direction (σ). These observations have different behaviors from the theoretical analysis made by all researchers to predict the fracture direction and crack path.

Most of the old fracture theories have some certain success to predict only one fracture path which is the normal to the load direction [1-7] while other theories had a full success in predicting the fracture direction and its final fracture trajectory for tension mixed mode cracks. This propagation can be called Single Branching Phenomenon SBP and is relating to the stress singularity field at the crack tip using the components of strain energy density approach in directional form. But according to experimental observations the propagation can be called as Double Branching Phenomenon for the same cases of cracks. If we look at the stresses at the crack tip, we can observe that the free stresses due to the item of free stresses ($\sigma \cos 2\beta$) which equal to for mixed mode is usually neglected by all researchers.

On the other hand, If we compared the quantity of ($\sigma \cos 2\beta$) to the cases of crack propagation we will find the following:

1- Cracks having crack angle $\beta = 0.0$ the free stress value = ($\sigma \cos 2\beta$) = σ which will act as a tension free stress in X direction at the crack tip causing a propagation for the crack in Y direction i.e. propagation in the same direction of the remote loading. The crack in this case will have only one fracture direction.

2- Cracks having crack angle of $0.0^o < \beta < 45.0^o$, then the free stress component will be in **Eq. 13**.

$$\sigma > \sigma \cos 2\beta > 0.0 \quad (13)$$

In this region the cracks may extend under two effects:

a. Effect of free stresses ($m\sigma$), $1 > m > 0$, causing propagation in Y direction which is the same direction of the remote loading.

b. Effect of the singular stress distribution at crack tip due to remote tension stress causing propagation path tending to be normal to the loading direction.

3. Cracks having crack angle of $45.0^o < \beta < 90.0^o$, then the free stress component will equal **Eq.14**:

$$\sigma \cos 2\beta < 0.0$$
$$\sigma \cos 2\beta = n\,\sigma,\ n < 0.0 \quad (14)$$

In this region the cracks may extend only in one path which will be normal to the loading direction. They will propagate due to the effect of singular stress distribution while the free stresses will be compression stresses at the crack tip without propagation effect.

The followings are recognized from the results of this research:

5.1 Powder size and conditions effects

It can be recognized that plasma each factor has an important role in the fracture process of the coating. As an example of the effects of these factors there are defects due to:

1. Non melted or partially melted powders.
2. Segregation of powders, cracks and de-bonding due to non melting or partially melted powders.
3. Cracks with de-bonding means that these cracks may be formed after the forming of partially or full bonding process.
4. Cracks with bond without failure means the cracks may be formed before the forming of full bonding process or during the formation of partially bonding process.
5. Cracks in some layers that hidden under another layer means that the cracks formed and propagated layer by layer are due to loss of pre-absorbed energy for bonding which means energy dissipation or energy release for fracture.
6. The energy dissipation of the coating means energy absorbed for the substrate or another coating layer and substrate. The energy absorption for the substrate will be for bond and dissipation by cooling process.
7. The powder speed and direction will affect the coating energy.
8. The powder rate will affect the kinetic energy.
9. Temperature degree of the plasma will affect the thermal energy.
10. Gas rate will affect the speed and temperature degree and therefore affect the thermal and kinetic energies.

These factors will affect the crack formation and propagation which will lead to early formation of cracks in the coating due to non full melting. Then non full bond between the powder particles of melted powders or just partial bond between partially melted powder grains. It is recognized that the honeycomb microstructure can be recognized only in the zones of melted powders which confirm this approach.

5.2 Microstructure of the zirconia coating

Although the zirconia powders are non uniform aggregates with sharp edges[9] and some particles includes pre-cracks[9], the microstructure is a very fine with regular hexagonal Honeycomb structure[9]. The bond between the hexagonal units of the Honeycomb structures controls the capacity of the fracture resistance of the Zirconia coating. It pre-determines the direction of the fracture and propagation. It controls the fracture increment length and the fracture surface shape [8].

5.3 Crack formation and propagation

It was recognized that the coating contains cracks without failure. This means that the coating still has a good bond with the substrate. If all cracks are formed and propagated after the finishing of the spraying process, this will produce shear stresses between coating and substrate due to the displacement of the crack widths. This will produce debonding between substrate and coating which will mean coating pull out and failure. But actually the coating is still good without failure. This means that the crack formation occurs during the spraying process before the full bond between the coating layer and substrate or between the coatings layers itself [9].

5.4 Fracture mechanism

The mechanism of the cracking can be understood in the view of Directional energy approach. As introduced, the bond between coating layers and between coating and substrate are due to absorbed thermal energy while the fracture is due to the released energy and propagated due to the residual energy.

5.5 Coating layers and size effects

It was recognized that the single layer coating can be cracked more than the multilayer coating and the debonding can easily occur between coating layer and substrate while in the multilayered coating this problem is less than for the single layer. This is because the input energy to the single layer coating is very high and cooling rate while the absorbed energy by substrate and residual energy by the cooling process are not enough to reduce the residual energy of the coating. Then the displacements of the coating layer will be higher to produce cracks and de-lamination. In the case of multilayer coatings, the second layer will reduce the input energy for the top layer and the third layer will reduce the input energy for the second layer and so on until the bottom layer.

Therefore, the energy will be absorbed by all layers producing bonds between each two layers and the top layer may close the cracks of the underneath layer and so on to repair the cracks and reduce the fracture effects. In addition, the cooling time will reduce the residual stresses and reduce the residual energy.

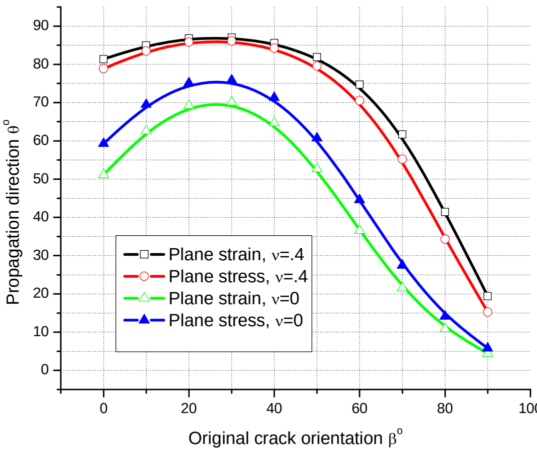

Fig. 8 Propagation direction for bidirectional tension –tension under heating with bi-axial ratio $\lambda = 0.5$.

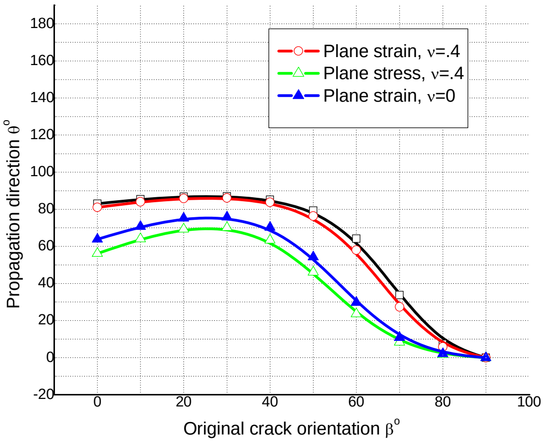

Fig. 9 Propagation direction for bidirectional tension –tension due to heating with bidirectional l ratio λ=0.5.

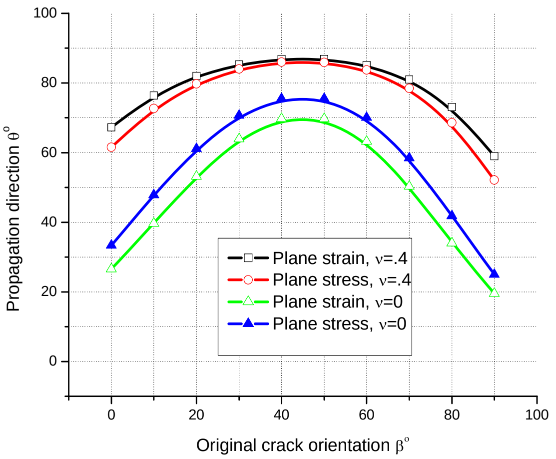

Fig. 10 Propagation direction for bidirectional tension –tension due to heating with bidirectional ratio λ= 1.

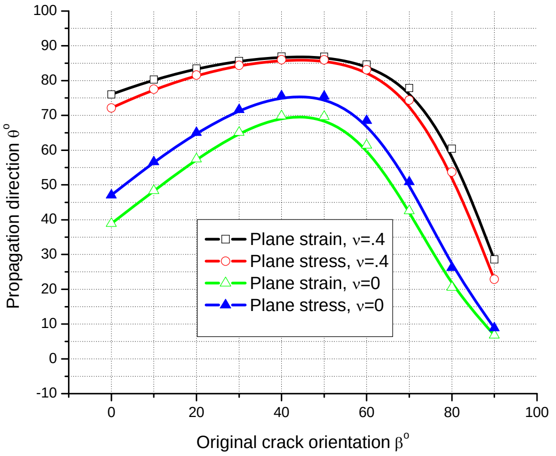

Fig. 11 Propagation direction for tension –tension due to heating rates with bidirectional ratio λ=2.0.

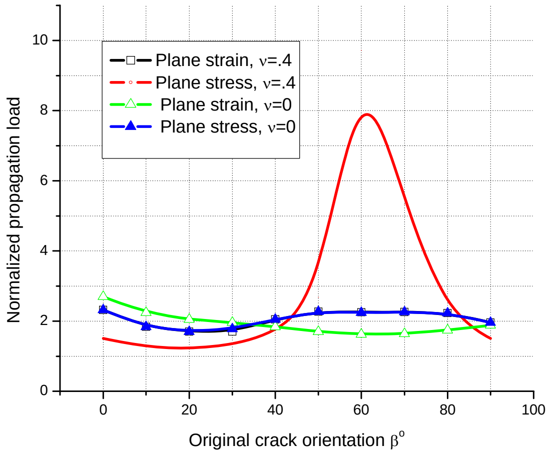

Fig. 12 Propagation load for biaxial tension –tension due to heating with λ=0.5.

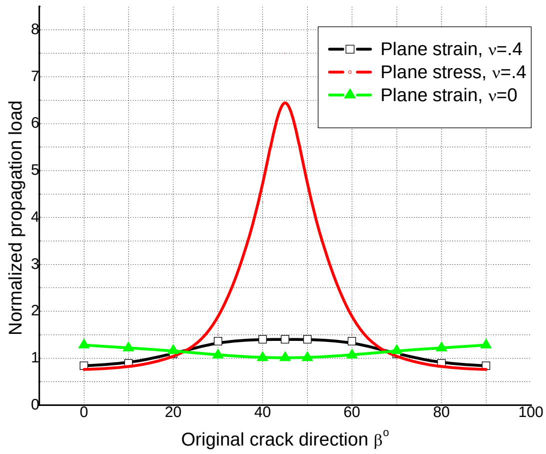

Fig. 13 Propagation load for biaxial tension –tension due to thermal stresses with λ=1.0.

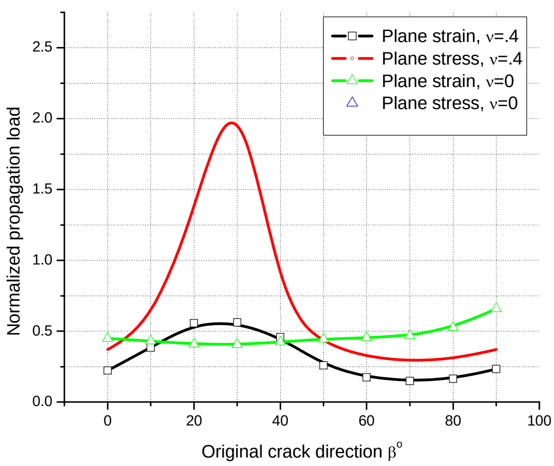

Fig. 14 Propagation load for biaxial tension –tension.

5.6 Heating and cooling effects

Temperature degree of plasma controls the input energy of the coating. It should be enough to make all powders melted without oxidation. It should to avoid a higher input energy than necessary because this will produce more residual energy which will lead to fracture.

On the other hand, the cooling rate should be compatible with the heating rate to avoid more residual stresses since the cooling rate is responsible for the energy dissipation rate. In this case we can minimize the residual energy. The heating produces tri-axial tension stresses on the coating while the cooling produces triaxial compression stresses.

5.7 Cracking surfaces

It is recognized that the irregular surface appears like a zigzag due to the fracture path of the cracks through the bond at the interface between zirconia microstructure grains. The fracture increments and local fracture direction are clear while the global fracture direction of the crack is not affected by this local movement and local direction.

5.8 Fracture direction and fracture load

It is recognized as a special case of the fracture that there are two fracture directions for each crack; one is the global direction and the other is the local direction. Under the triaxial thermal stresses using the Directional fracture theory [8, 9] the fracture directions can be determined globally and locally. Therefore, a new fracture theory is proposed called Global Local fracture theory KR-GL criterion [9] to determine both of the global and local fracture directions for each crack. The global direction should be predicted by the theory while the direction of the local fracture is pre-predicted by the bond direction between the particles of microstructure of zirconia coatings as shown in **Figs. 8-11** for fracture propagation path and **Figs. 12-14** for fracture stresses.

6. Conclusion

This study is newly introduced to explain the philosophy of the branching phenomenon of mixed mode cracks under thermal stresses and producing a unified view for the theoretical and experimental works for this important subject. This research explained the effect and the role of the free stresses on the crack propagation for the first time in the fracture mechanics science.

Now, we can easily understand why some cracks have more than one propagation direction and paths. It introduced the effect of crack inclination angle on the fracture behavior. This study will help researchers in understanding fracture analysis and for good design of materials and structures against fracture and failure.

This research introduces new valuable information about the fracture phenomenon, fracture mechanism and coating characteristics of zirconia coating by gas tunnel plasma spray technology.

It could give us interesting results on the microstructure of zirconia coating as the first time for finding this result to be shown as a very fine three dimensional Honeycomb microstructure with grain size of 200 – 400 nm while the zirconia particles powder particle size is 20 – 60 μm.

It could be recognized that the microstructure controls the fracture behavior of zirconia coating. It could propose a good understanding for the fracture mechanics of the complicated process of de-bonding and body cracking the coating by means of directional fracture Approach [8, 9].

The new proposed version of Directional fracture theory called (KR-GL) Criterion [8] for zirconia coating could predict the crack formation, crack propagation, fracture load, fracture direction, fracture thermal stresses which is triaxial tension for heating and compression for cooling, Input energy, released energy and residual energy. Effects of each of multilayer coating, powder speed and rate, gas speed and rate and substrate speed are predicted.

This research may help in modifying the coating conditions to produce coatings without cracks or with minimum cracks and may help in extending the lifetime of the coating and substrate. It can help in the repair of the coating cracks. Finally, it can help in reducing the coast of the coating as the main target of good economic and safe product.

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