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ABSTRACT
An analytical model is developed to predict residual stresses formed during plasma cladding process. This is based on the force and moment balances and misfit strain caused by differential coefficient of thermal expansion (CTE) of substrate and cladding layers during cooling. The model can be implemented by a simple programming. Residual stresses can be predicted from a knowledge of material properties, temperature of substrate and layers and specimen dimensions. Residual stresses are calculated after each layer rather than as a whole. Specific results can be obtained for the distribution of residual stresses within Co-based layers system. The effect of temperature of substrate and layers, the number of layers, the curvature of a composite beam on the residual stresses are discussed. It has been found that the residual stresses decrease with the increase of preheating temperature of substrate and inter-layer temperature of layers. The curvature increase with increasing layer number.

I. INTRODUCTION
The surface cladding techniques can improve wear and corrosion resistance, rather than not change the nature of substrate. Surfacing cladding of substrate has been widely used in aerospace, mining machinery, petrochemical and marine engineering fields.1–12 It is well known that thermal stresses arise from the difference of materials properties, especially, the coefficients of thermal expansion between substrate and cladding layers. When substrate and layers cool down from the cladding temperature to the room temperature, residual stresses are induced. Residual stresses have a strong influence on the properties of layers. It can not only degrade fatigue life and fracture toughness but also lower wear resistance and spallation and delamination resistance.11 The distribution of residual stresses is very complicated, dependent on the geometric parameters of structure and properties of substrate and cladding layers.

Some analytical models for predicting residual stress had been developed and closed-form solutions for multiple coating bonded strips have been derived.7–11 It should be noted that inter-layer temperature is not taken into account in these analytical models. These analyses were mostly based on substrate and layer as a whole during cooling down process. However, inter-layer temperature in multiple plasma cladding process has an important effect on the distribution of residual stress.12 All of these models treat the residual stresses on the premise of overall cooling. This assumption is often unreasonable in some cases. Mainly because there is inter-layer temperature after the first layer of cladding. The inter-layer temperature has an important effect on the subsequent cladding layers.13,14 The effect of inter-layer temperature is taken into account in the present model. So layered cooling is used, rather than overall cooling. At the same time, a continuous solution of residual stress is calculated.

In this paper, an analytical model for predict the residual stress distributions during the plasma cladding process is established. The establishment of model is based on the force and bending moment balance. Classical composite beam bending theory is applied. The model is relatively simple and only incorporates thermal stress
process. Residual stresses are calculated in plasma cladding Co-based alloy system. The effect of parameters (e.g. CTE, Young’s modulus, thickness, temperature of materials and so on) is discussed, trying to find possible approaches for controlling residual stresses induced during plasma cladding process.

II. FORMULATION OF ANALYTICAL MODEL

Cladding system is assumed to be a strip in the analytical model. Only plane stress state in the x-direction is hence discussed. The stresses set up due to CTE mismatch during cooling to room temperature. Residual stresses in multiple layer consist of two contributions, one arising from stress equilibrium due to contraction or expansion and the other coming from moment equilibrium due to bend.\textsuperscript{15,16}

A. Cladding of the first layer

It is assumed that the substrate (plane geometry) is fixed only at one end and is free to bend during plasma cladding process. Consider cladding of the first layer, the total strain of the first layer is equal to that of substrate:

\[ \varepsilon_c = \varepsilon_s, \]  

where the subscripts c and s are cladding layer and substrate, respectively.

The total strain consists of two parts: one arises from temperature strain and the other comes from the bending strain.

\[ \alpha_c(T_0 - T_s) + \frac{F_1}{\delta_1 E_c} = \alpha_s(T_0 - T_s) - \frac{F_1}{\delta_1 E_s}. \]  

The misfit strain due to the difference of CTE sets up a pair of equal and opposite forces, \( F_1 \) (assuming \( \alpha_c > \alpha_s \)). The origin of residual stresses developed during the cooling process (see Fig. 1). Rearranging equation (2), this becomes

\[ F_1 = \frac{\alpha_c(T_0 - T_s)}{\delta_1 E_s} - \frac{\alpha_s(T_0 - T_s)}{\delta_1 E_c}, \]  

Where \( T_p, T_c, \delta_c \) and \( \delta_s \) are the preheating temperature of substrate, cladding temperature of layer, the thickness of substrate, the thickness of layer, respectively.

Because of \( \alpha_c > \alpha_s \), a tensile force acts on the cladding layer, while a compressive force of the same magnitude acts on the substrate. This pair of equal and opposite forces forms a couple, then generates a torque of the couple, \( M_1 \), given by

\[ M_1 = F_1 \left( \frac{\delta_s - \delta_c}{2} \right). \]  

However, the torque of the couple generated by the pair of equal and opposite forces, \( F_1 \), should be balanced. Balancing the moment, \( M_1 \), induces a curvature change, \( k_1 - k_0 \).

\[ M_1 = (EI)_1 \left( \frac{1}{\rho_1} - \frac{1}{\rho_0} \right) = (EI)_1 (k_1 - k_0), \]  

Since \( \rho_0 \) tends to infinity, \( k_0 \) tends to zero. So,

\[ M_1 = (EI)_1 k_1. \]  

It is assumed that the coordinates of interface between layer and substrate are zero (\( y = 0 \)). The neutral axis position, \( y_1 \), and the composite beam stiffness, \((EI)_1\), can be expressed as

\[ y_1 = \frac{\delta_s^2 E_s - \delta_c^2 E_c}{2(\delta_s E_s + \delta_c E_c)}, \]  

\[ (EI)_1 = \delta_c E_c \left( \frac{\delta_s^2}{3} - \delta_s y_1 + y_1^2 \right) + \delta_s E_s \left( \frac{\delta_c^2}{3} + \delta_c y_1 + y_1^2 \right). \]

Combining Eq. (3)–(8), \( k_1 \) can be obtained and expressed as

\[ k_1 = \frac{6\delta_c E_c \delta_s E_s (\delta_c + \delta_s) [\alpha_s(T_0 - T_s) - \alpha_c(T_0 - T_s)]}{\delta_s^4 E_s^2 + 4\delta_s^2 E_s \delta_c E_c + 4\delta_c E_s \delta_c E_s + 6\delta_c^2 E_s + \delta_c^4 E_s^2 + \delta_s^4 E_c^2}. \]

Since the model is assumed to be a strip and only has a strain in the x-direction, the net strain in the x-direction can be expressed as

\[ \varepsilon_s E = \sigma_s (1 - \nu), \]  

Then, \( E' = \frac{E}{(1 - \nu)} \).

the effective Young’s modulus value, \( E \), in the above and following equations should be replaced by \( E' \).

As discussed above, the residual strain in the substrate and layers consists of two parts, one strain caused by temperature and the other strain caused by bending. Therefore, residual stress distributions along the y-axis in the x-direction in the substrate and cladding layer can be obtained and expressed as

\[ \sigma_s = -\frac{F_1}{\delta_s} + E_s (k_1 - k_0)(h + y_1) \quad (0 \leq h \leq \delta_s), \]  

\[ \sigma_c = \frac{F_1}{\delta_c} + E_c (k_1 - k_0)(-h + y_1) \quad (0 \leq h \leq \delta_c). \]

As only elastic processes are being considered, the variation of stress along the y-axis of the substrate and the first layer should be linear.
B. Cladding of the $n^{th}$ layer

Fig. 2 shows the schematic model for the generation of residual stress in the $n^{th}$ layer. When the $n^{th}$ layer clads on the $(n-1)^{th}$ layer, the total strain of the $n^{th}$ layer is equal to that of substrate with the $(n-1)$ layer. The calculation of strain is the same as before, the strain equation (Eq. (1)) becomes:

$$\varepsilon_n = \varepsilon_{n-1} - \tau,$$

where $\varepsilon_{n-1}$ and $T_{n-1}$ are the strain and the preheating temperature of substrate with the $(n-1)^{th}$ layer, respectively and then,

$$\varepsilon_n = \varepsilon_{n-1} - \tau,$$

where $\varepsilon_{n-1}$ and $\alpha_{n-1}$ are the equivalent Young's modulus and coefficient of thermal expansion for the substrate with the $(n-1)$ layer (a composite beam), defined by

$$E_{n-1} = \left(\frac{n-1}{n}\right) \frac{E_s}{\delta_c + \delta_c}, \quad (16)$$

$$\alpha_{n-1} = \frac{\alpha_c}{\left((n-1)\delta_c + \delta_c\right)} \left(E_s + \delta_c E_s\right), \quad (17)$$

After the $n^{th}$ layer is cladding, the force $F_n$ acting on the composite beam is composed of two forces: $F_{nc}$ acting on the $(n-1)$ layers and $F_n$ acting on the substrate. The last layer and the substrate with $(n-1)$ layers are subjected to the same strain.

$$F_n = F_{nc} + F_n$$

The force $F_n$ acts on the neutral axis of composite beam ($y_{n-1}$). The force, $F_{nc}$, acting on the substrate is equal to

$$F_{nc} = \delta_c E_c \left(\frac{F_n}{(n-1)\delta_c} + \delta_c E_c\right), \quad (18)$$

Similarly, the force, $F_{nc}$, acting on the layer is

$$F_{nc} = \delta_c E_c \left(\frac{F_n}{(n-1)\delta_c} + \delta_c E_c\right), \quad (19)$$

The force, $F_n$, acting on the last layer is a tensile force, but the force, $F_n$ ($F_{mc}$ and $F_{nc}$), acting on the substrate with the $(n-1)$ layers is a compressive force. The pair of equal and opposite forces, $F_n$, sets up a moment, $M_n$, given by

$$M_n = F_n \left(n - \frac{1}{2}\right) \delta_c - y_{n-1}, \quad (20)$$

Where $y_{n-1}$ is the neutral axis of composite beam. Balancing the moment, $M_n$, induces a curvature change, $k_n - k_{n-1}$, which is equal to

$$k_n - k_{n-1} = \frac{M_n}{(EI)_n}, \quad (21)$$

and then,

$$F_n \left(n - \frac{1}{2}\right) \delta_c - y_{n-1} = (EI)_n (k_n - k_{n-1}), \quad (22)$$

where $(EI)_n$ and $y_{n-1}$ can be calculated from

$$(EI)_n = (n\delta_c) E_{c} \left(\frac{(n\delta_c)^2}{3} - (n\delta_c) y_{n-1} + y_{n-1}^2\right) + \delta_c E_{c} \left(\frac{\delta_c^2}{3} + \delta_c y_{n} + y_{n}^2\right), \quad (23)$$

$$y_{n} = \frac{(n\delta_c)^2 E_{c} - \delta_c^2 E_{c}}{2(n\delta_c E_{c} + \delta_c E_{c})}. \quad (24)$$

As previously, the residual stress is made of two parts, one arising from temperature and the other coming from bending. Residual stress distributions along the y-axis in the x-direction of the substrate are given by

$$\sigma_y = \sum_{i=1}^{n} \left(-\frac{F_i E_s}{(i-1)\delta_c} + \frac{E_s}{\rho_i} (h + y)\right) \quad (0 \leq h \leq \delta_c), \quad (25)$$

Residual stress distribution of the $j^{th}$ cladding layer can be calculated from

$$\sigma_y = \sum_{i=1}^{n} \left(-\frac{F_i E_s}{(i-1)\delta_c} + \frac{E_s}{\rho_i} (h + y)\right) \quad ((j-1)\delta_c \leq h < j\delta_c \quad and \quad j < n), \quad (26)$$

$$\sigma_y = \sum_{i=1}^{n} \left(-\frac{F_i E_s}{(i-1)\delta_c} + \frac{E_s}{\rho_i} (h + y)\right) \quad ((j-1)\delta_c \leq h < j\delta_c \quad and \quad j = n), \quad (27)$$

where the subscript, $j$, denotes the layer number and ranges from 1 to $n$. It is noted that the last layer (the $n^{th}$ layer) is only subjected to one
force action but the other layers (from 1 to \((n-1)\)th) and substrate suffer from a lot of force.

C. Verification

With the absence of published experimental, the FEM model has been established to verification the accuracy of analytical solutions. The FEM and analytical data shown in Fig. 3 were compared with the results of the numerical simulation analysis.

From the Fig. 3, there is consistency in base metal and the first layer data between FEM data and analytical data, but there is also data deviation on the third layer. The main reason may be due to the lack of enough accurate material properties data during the welding, especially the data of high temperature. Anyway, the analytical predictions agree well with most of FEM data. Thus, the present analytical model in this paper could predict the residual stress of multiple layers by plasma cladding process.

III. RESULTS AND DISCUSSION

Once the material physical and chemical properties and geometry of substrate and individual layer are identified, the implement of the analytical model is fairly straightforward. The selection of the number of layers can be changed. It should be noted that the model only considers elastic processes. The study of the effect of inelastic processes such as yielding or creep on residual stresses could be found in the other literature.19–21 Moreover, the present model does not take account of the variation of material properties with temperature, except thermal expansion coefficient. So if the properties of materials vary considerably with temperature or the cladding temperature is very high, the accuracy of predicting result is affected. A cladding Co-based system is studied in order to illustrate the use of the analytical model. The properties required for the present analytical model are listed in Table I. It is important to note that in all cases the values of properties at room temperature are used in the analytical model. The temperature dependence of parameters does not be taken into account.

The substrate and the layers are assumed to be stress-free at a room or cladding temperature. But the preheating temperature of substrate is not equal to the cladding temperature. The same as above, the cladding temperature after the cladding \((n-1)\)th layer is not equal to the cladding temperature of the \(n\)th layer. It is assumed that the cladding temperature is 1000°C and the temperature after the cladding is \(T_{s(n-1)}\). The temperature difference (inter-layer temperature) is \((1000°C-T_{s(n-1)})\). And the room temperature is assumed to be 20°C.

![Residual Stress Distribution](image)

**A. Effect of the number of layer on residual stress distribution**

Fig. 4 shows the effect of the number of layer, \(n\), on residual stress distribution. From the Fig. 4, it can be seen that a different magnitude of tensile or compressive force are generated due to a large CTE mismatch between substrate and layers. The stress in all layers are always tensile because of the lower CTE of layer. The stress at the top of the substrate (the interface between substrate and layers) is compressive force, but the stress at the bottom of the substrate is tensile force. It also should be noted that residual stresses are all calculated from the bottom to the top faces of substrate and each layer. In this figure, it can be seen that the number of layer, \(n\), has an impact on the residual stress distribution. The stress distribution and level in the substrate and layers are significantly different with the change of the number of layer. When \(n\) is equal to 1, the stress at the cladding layer surface is less tensile than that at the interface between substrate and the 1th cladding layer. Slope is negative, showing a negative stress gradient. The stresses in the substrate are always compressive because it has lower coefficient of thermal expansion than the cladding layers. There is only a little difference between the stress at the top and at the bottom of substrate. The stress in the substrate and layer is linearly distributed.

As the number of cladding layers increases, when \(n\) is equal to 2 or 3, the larger difference between the stress at the top and at the bottom of substrate is predicted. The slope is getting bigger and bigger (a negative stress gradient). It should be noted that a negative

| Material | Thickness (mm) | Young’s modulus (GPa) | Poisson’s ratio | CTE \((10^{-6}/K)\) | Temperature (K) |
|----------|----------------|-----------------------|----------------|-----------------|----------------|
| Co-based | 2              | 207                   | 0.3            | 11.3            | 1573           |
| Ti6Al4V  | 20             | 106                   | 0.3            | 8.6             | 773            |
stress gradient is generated within each cladding layer. However, the total trend of layer stress is rising from the bottom to the top face of the cladding layers, showing a positive stress gradient. And the effect of a negative stress gradient on the total stress trend is getting smaller and smaller with the increasing of the number of cladding layers.

From Fig. 4, it is also can be seen that the stress of the first layer in two-layer system is lower than that of the first layer in one-layer system. Likewise, the stress of the second layer in three-layer system is lower than that of the second layer in two-layer system. It is largely due to the decrease of tensile component in the multiple cladding layers.

The effect of the number of cladding layer on curvature is shown in Fig. 5. it can be seen that the curvature becomes larger with the increase of the number of cladding layers. However, it should be noted that the slope of curvature is getting smaller. The more the number of cladding layers, the greater the overall stiffness of the substrate. In fact, considering the cost and the residual stress, it is clear that the appropriate number of layers is very important.

B. Effect of inter-layer temperature on residual stress distribution

The inter-layer temperature during plasma cladding process is the main factor that affects the residual stress level and distribution in the substrate and layers. The effect of different inter-layer temperature (i.e. 373K, 673K, 1073K) is investigated in the present model. Fig. 6 shows the stress distribution with two cladding layers at different inter-layer temperature.

It can be seen that with the increase of inter-layer temperature, the amplitude of residual stress in the substrate and cladding layers decreases gradually. Moreover, the slope of substrate and layer is getting smaller. From Fig. 7, the curvature decreases linearly and deformation is smaller as the temperature increase. Therefore, during the plasma cladding process, improving properly the inter-temperature (including substrate preheating temperature) is conducive to reducing the residual stress after cooling.

C. Effect of $\delta$ and $E$ on residual stress distribution

Studies have shown cladding layer thickness has an important effect on stress distributions. The case of single-layer cladding layer system can be used to illustrate the effect of thickness of layer and elastic modulus on the residual stress distribution in substrate and layer. The results are shown in Fig. 8 and Fig. 9, in the case of the inter-temperature, $T_m=773K$. The other parameters of single-layer cladding layer system are the same as those in Section III A. The parameters $\varphi$ and $\eta$ are defined as, respectively,

$$\varphi = \frac{\delta_c}{\delta_s} \quad \text{and} \quad \eta = \frac{E_c}{E_s}$$

It can be seen that the greater the amplitude of stress variation is predicted with the increase of $\varphi$. This may be attributed to
the stress redistribution in substrate when the thickness of layer is larger. With further increasing the thickness of cladding layer, the stress at the top of cladding layer change from tensile to compressive. From Eq. (21–24), it should be noted that with increasing the thickness of cladding layer, the curvature increases and bending strain also increases. When $\delta_c$ is far less than $\delta_s$, the curvature is very small and bending strain has no effect on total strain. However, the thin layer will lead to the large tensile stress, and cracks and failure are easily generated. In the otherwise, the thick layer will result in the large curvature, and layer materials are wasted.

Although the tensile stress in the cladding layer decreases when the layer thickness increases, the compressive stress in the substrate increases. It should be seen that with the thickness of layer increasing, tensile stress in the cladding layer is not always decreasing. For instance, when $\varphi = 0.3$ or $\varphi = 0.5$, the tensile stress in the layer is minimal. While, when $\varphi = 0.7$ or $\varphi = 1.0$, the tensile stress increase greatly. Hence, it can be concluded that the appropriate layer thickness is important.

Fig. 9 shows that elastic modulus is an important parameter that influences the stress distributions. With the increase of $\eta$, the stress is increasing. For instance, when $\eta = 0.2$, the stress of substrate and cladding layer is several tens of MPa. However, when $\eta = 2.0$, the stress is as high as hundreds of MPa. Therefore, it can be drawn that the bending effect is enhanced with increasing coating to substrate elastic modulus ratio.

D. Effect of CTE on residual stress distribution

As can be seen from Fig. 10, the residual stress distribution in the substrate and cladding layer is very sensitive to the difference in the CTE between substrate and layer, compared to other factors that
affect the residual stress. In the case, assuming $\alpha_c \geq \alpha_i$, the parameter $y$ is defined as

$$y = \frac{\alpha_c}{\alpha_i}$$

When the ratio of CTE of layer to substrate rise from 1.0 to 2.0, the variation of the residual stress in the substrate and layer is as high as hundreds of MPa. However, the variation is relative to temperature of substrate and layer. From Eq. (15), it can be seen that the effect of the change of CTE on residual stress is coupled with the reduction of the temperature. So the layers of CTE-matching materials should be employed to reduce the stresses, otherwise, it will lead to cracking and failure.

IV. CONCLUSIONS

Plasma cladding technology is widely used in engineering field. However, the performance of cladding layer is strongly influenced by residual stress. In this paper, an analytical model based on force and moment balances has been developed to predict the residual stress distributions in plasma cladding layer systems. This model is simple, but clearly explains the process of generating residual stress. With the analytical model, residual stress distributions can be predicted directly from a knowledge of material properties, temperature of substrate and layers and specimen dimensions.

Residual stresses are calculated after each layer addition rather than for multiple layers as a whole. Specific results can be obtained for the distribution of residual stresses within Co-based layers systems. However, the model could be applied not only to plasma cladding systems, but also to other cladding systems. At the construction site, the model provides an effective guidance during the cladding process, and the model could be applied not only to plasma cladding systems, but also to other cladding systems. At the construction site, the model provides an effective guidance during the cladding process, and the model could be applied not only to plasma cladding systems, but also to other cladding systems.

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NOMENCLATURE

- $E$ (Pa): Young’s modulus
- $F$ (N): force
- $\alpha$ ($K^{-1}$): coefficient of thermal expansion
- $\delta$ (m): thickness
- $k$ ($m^{-1}$): curvature
- $\nu$: Poisson’s ratio
- $\sigma$ (Pa): stress
- $T$ (K): temperature
- $\varepsilon$: strain
- $n$: number of layers
- $y$: neutral axis position relative to the interface (between substrate and the first layer)

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