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Residual Stress Analysis of Laser-cladded Al/Si Coatings onto Aluminium Alloy Substrates

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ABSTRACT

Surface properties of aluminium alloys (particularly hardness, elastic modulus and wear resistance) can be significantly improved by laser cladding. This high energy process causes thermal stresses, which lead to the appearance of residual stresses and substrate distortions. In this study, laser cladding was applied to a 5052 aluminium alloy using a cw Nd:YAG laser and coaxial injection of Al 50Si powders. Residual stresses were quantified by X-ray diffraction and by sample strain measurements. The differences in the results obtained by these two methods highlighted the influence of the heat-affected zone (HAZ) underlying the coating. A model of three strain domains has explained these differences: the coating, the HAZ and the substrate. Experiments identified an optimal treatment speed, leading to maximum compression stresses, which improve hardness and wear resistance. Moreover, at a certain fixed speed, thermal stresses balanced each other in the sample leaving the substrate undistorted.

1.0 INTRODUCTION

Aluminium alloys offer considerable advantages in mechanical construction, particularly because of their light weight and corrosion resistance. However, their tribological characteristics are mediocre. This weakness can be corrected by a surface laser treatment that does not affect the overall properties of the material. The laser cladding process (Fig. 1.a) involves coating a surface with a material of a different nature. The metal being deposited in powdered form is carried by an inert gas, then injected coaxially or laterally into the laser beam. The energy produced by the beam is then distributed between the powder stream and the material so as to melt the particles in flight and the surface of the material. As the sample is moved under the laser beam, a clad is generated (Fig. 1.a) and the juxtaposition of several clads produces a coating on the surface. A slight dilution in the surface results in a perfect metallurgic bond.

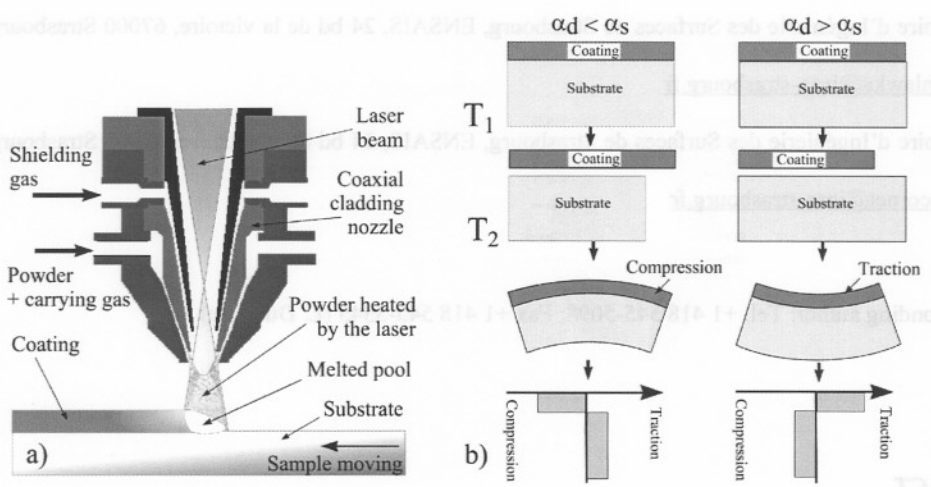

Figure 1: a) Laser cladding process using coaxial injection of powders, b) Influence of coefficients of thermal expansion (CTE) on the residual stresses (α_d: CTE of the coating, α_s: CTE of the substrate, T_2: temperature during the treatment, T_1: room temperature).

As with other high energy surface treatments, laser cladding creates thermal stresses that can result in residual stresses and eventually distort the sample. According to Sue *et al.*, [1], the residual stresses can be modelled as per Eq. 1, using the sum of intrinsic and thermal stresses. The intrinsic stresses correspond to the structural modifications of the material during treatment: diffusion, enlargement of the grains and variation in the dislocation density. In the case of laser cladding, a high energy process, thermal stresses predominate. They are generated by the difference in contraction during cooling between the coating and the substrate. As can be seen in Fig. 1.b, the coating has the same dimension as the substrate during treatment (temperature T_2). During

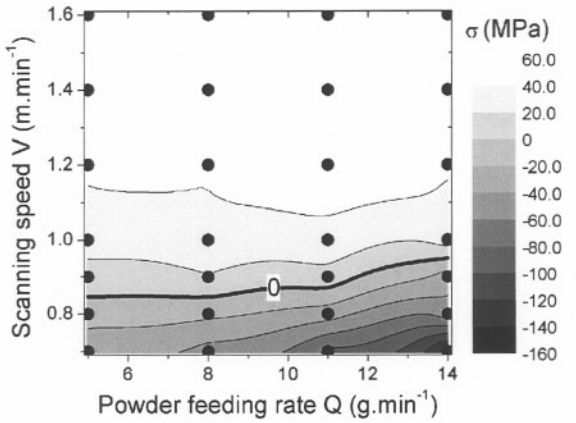

Figure 2: Residual stress measurements in the coatings (MPa) using the strain method. Influence operating parameters: scanning speed (V) and powder feed rate (Q).

3.2 Stress Measurement Using XRD

The measurements of longitudinal and shearing stresses carried out by XRD as a function of scanning spe presented on Fig. 3. Measurements were taken through the depth of each coating at 0.1 mm intervals do the interface with the substrate. The powder feed rate was set at an intermediate rate of 11 g.min^{-1}. scanning speed evolved from 0.8 to 1.6 min^{-1}.

cooling to room temperature T_1, the substrate contracts more than does the coating (case where the coefficient of thermal expansion (CTE) of the coating is less than that of the substrate: $\alpha_d < \alpha_s$) resulting in compression stresses in the coating. Conversely, where $\alpha_d > \alpha_s$, the coating is in tension since the substrate contracts less than does the clad. This phenomenon can be modelled using Eq. 2 [1].

$$\sigma_t = \sigma_i + \sigma_{th} \quad (1) \qquad \sigma_{th} = (\alpha_d - \alpha_s)(T_2 - T_1)\frac{E_d}{(1-\upsilon_d)} \quad (2)$$

[Eq. 1]: σ_t global stress, σ_i intrinsic stresses, σ_{th} thermal stresses.

[Eq. 2]: α_d: CTE of the coating, α_s: CTE of the substrate, E_d and ν_d : Young modulus and Poisson coefficient of the coating, T_1 room temperature, T_2 temperature during treatment.

The residual stresses have a critical influence on the behaviour and the lifespan of mechanical parts. Along with external stresses, they serve to modify the real value of the applied load. Consequently, with the recent development of laser cladding, it was essential to understand these phenomena. Also, by controlling residual stresses it is possible to limit the distortion of samples after treatment and to increase the compressive stress in coating in order to increase the hardness and wear resistance. This article therefore presents the influence of the main treatment parameters (scanning speed and powder feed rate) on the range of residual stresses. These stresses were measured using two different techniques: the strain method and XRD.

2.0 EXPERIMENTAL PROCEDURE

The cladding was carried out using a cw 2000 W Nd:YAG laser with a wavelength of 1.064 μm and 1 mm diameter optical fibre. The Nd:YAG laser was chosen based on the fact that the aluminium substrate has an absorption coefficient at this wavelength twice that of the CO_2 laser [2]. A 300 mm focal length lens was used to focus the beam. The operating parameters used were as follows: laser power of 1700 W on the workpiece, 2.7 mm diameter circular beam on the sample with an energy density of 300 $W.mm^{-2}$. The laser beam was maintained in the vertical, whereas the surface of the substrate was inclined 5° to the horizontal. Normal incidence was not used to avoid the risk of beam reflection that could damage the optical fibre. The composition of the powder used was Al 50Si (wt.%) with a granulometry between 45 and 90 μm. These coatings were the subject of a metallographic study conducted by Pei *et al.* [3]. The powder was injected at rates varying from 5 to 14 $g.min^{-1}$ depending upon the coating, using argon at 1 bar pressure and a flow rate of 3 $l.min^{-1}$. The samples were placed on a X-Y stage that moved under the beam at scanning speeds varying from 0.7 to 1.6 $m.min^{-1}$. The

substrates were made from a commercial aluminium alloy 5052 (Al + 3 wt.% Mg) and measured 75 x 8 x 6 mm^3. We chose this non-hardenable alloy in order to minimise the intrinsic stresses and to analyse particularly the effects of thermal stresses (see Eq. 1). Surfaces to be clad were abraded with grade 120 SiC paper then cleaned with acetone. The samples were then annealed at 150°C for 24 hours to relax the residual stresses from rolling and present a homogenous microstructure. The laser cladding was then produced over the entire length of the substrate.

The strain method consisted in measuring sample distortion after laser cladding and calculating overall stresses in the coating using Eq. 3. This technique was used by Tomlinson *et al.* [4] on different aluminium surface alloys produced by laser (Al-Fe and Al-Cu alloys). In our case, sample distortion was measured using an extended field confocal microscope [5] with vertical resolution of ± 0.01 µm and lateral resolution of ± 2 µm. The sampling step was 5 µm in X direction. The strain and curvature radius of the sample were then approximated by a parabolic equation. The elastic modulus of the coating E_d and substrate E_s were set respectively at 89 and 69 GPa [6]. Moments of inertia I_d and I_s were calculated for each sample according to the dimensions of the coating. Each result represented the average of measurements conducted on 3 samples. A similar approach was used by Teixeira *et al.* [7] in the case of residual stress measurements in PVD coatings.

$$\sigma_d = -\frac{(E_s I_s + E_d I_d)y}{\left(I_d + \frac{E_s}{E_d} I_s\right)R} \qquad (3)$$

[Eq. 3]: σ_d: stress in the coating, E_s and E_d: Young modulus of the substrate and the coating, y and R: strain and radius of the sample after laser cladding, I_s and I_d: moments of inertia of the substrate and the coating.

In order to measure stresses in the depth of coatings, the clads were electrolytically polished with perchloric acid to successively remove material. This method has previously been used on laser surface alloys [8, 9]. Stress was measured along the clad length for the {311} crystal plane of aluminium using a chrome anode (λ = 0.2291 nm) and a Siemens D5000 diffractometer. We studied the diffraction peak located at 139.339° (oscillation ± 1°, duration 6 min) [10]. The configuration worked on Ω mode and included a linear detector with a 16° view angle and a 1 mm diameter circular slit.

3.0 RESULTS

3.1 Stress Measurements Using the Strain Method

Scanning speeds of 0.7 to 1.6 $m.min^{-1}$ and powder feed rates of 5 to 14 $g.min^{-1}$ were used, with experimental limits set according to the morphology of the clads obtained. For values less than 0.7 $m.min^{-1}$ (scanning speed) or 5 $g.min^{-1}$ (powder feed rate), clads showed excessive and inconsistent dilution. For scanning speeds greater than 1.6 $m.min^{-1}$ or powder feed rates greater than 14 $g.min^{-1}$, the energy was not sufficient to ensure dilution and the metallic bond between the coating and the substrate. Fig. 2 shows the stress measurements using the strain method, with each point representing one speed/flow pair analysed. The level of residual stress is shown by contour curves and evolves between -160 and 60 MPa. Distortions associated with these stresses correspond to those in Fig. 1.b: samples with a convex form show a compressive state in the clad and conversely samples with a concave form result from tension in the clad.

The following phenomena can be observed:

(i) Results obtained using the strain method disagree with the model in Fig. 1.b. In our case, the CTE of the coating ($\alpha_d = 14.10^{-6}$ $m.m^{-1}.K^{-1}$ [6]) is less than that of the substrate ($\alpha_s = 24.10^{-6}$ $m.m^{-1}.K^{-1}$ [6]). Therefore, according to Fig. 1.b, all coatings should be in compression and should show signs of convex distortion, regardless of operating parameters.

(ii) Residual stresses increase when the scanning speed increases, moving from a compressive to a tension state. For example, for a rate of 8 $g.min^{-1}$, the coating is in compression (σ_d = -48MPa) at V = 0.7 $m.min^{-1}$ and in tension (σ_d = 58 MPa) at V = 1.6 $m.min^{-1}$.

(iii) For low scanning speeds ($V \leq 0.8$ $m.min^{-1}$), residual compressive stresses increase enormously when the powder feed rate increases. For V = 0.7 $m.min^{-1}$ and Q = 14 $g.min^{-1}$, the maximum is -151 MPa, corresponding to a substantial compressive stress for aluminium (yield strength of 150 MPa).

(iv) For a speed of approximately 0.9 $m.min^{-1}$, samples show no distortion, with a zero residual stress level in the coating (black level curve in Fig. 2).

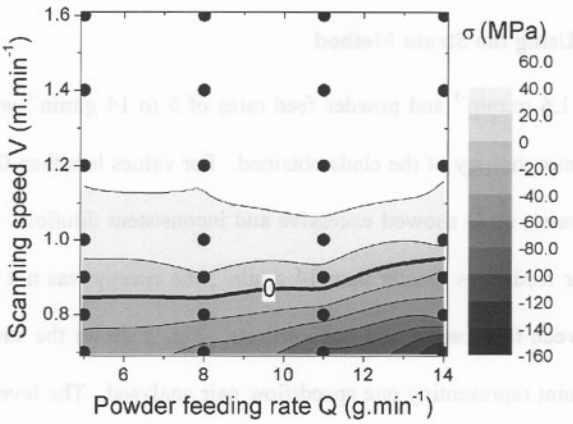

Figure 2: Residual stress measurements in the coatings (MPa) using the strain method. Influence of the operating parameters: scanning speed (V) and powder feed rate (Q).

3.2 Stress Measurement Using XRD

The measurements of longitudinal and shearing stresses carried out by XRD as a function of scanning speed are presented on Fig. 3. Measurements were taken through the depth of each coating at 0.1 mm intervals down to the interface with the substrate. The powder feed rate was set at an intermediate rate of 11 $g.min^{-1}$. The scanning speed evolved from 0.8 to 1.6 min^{-1}.

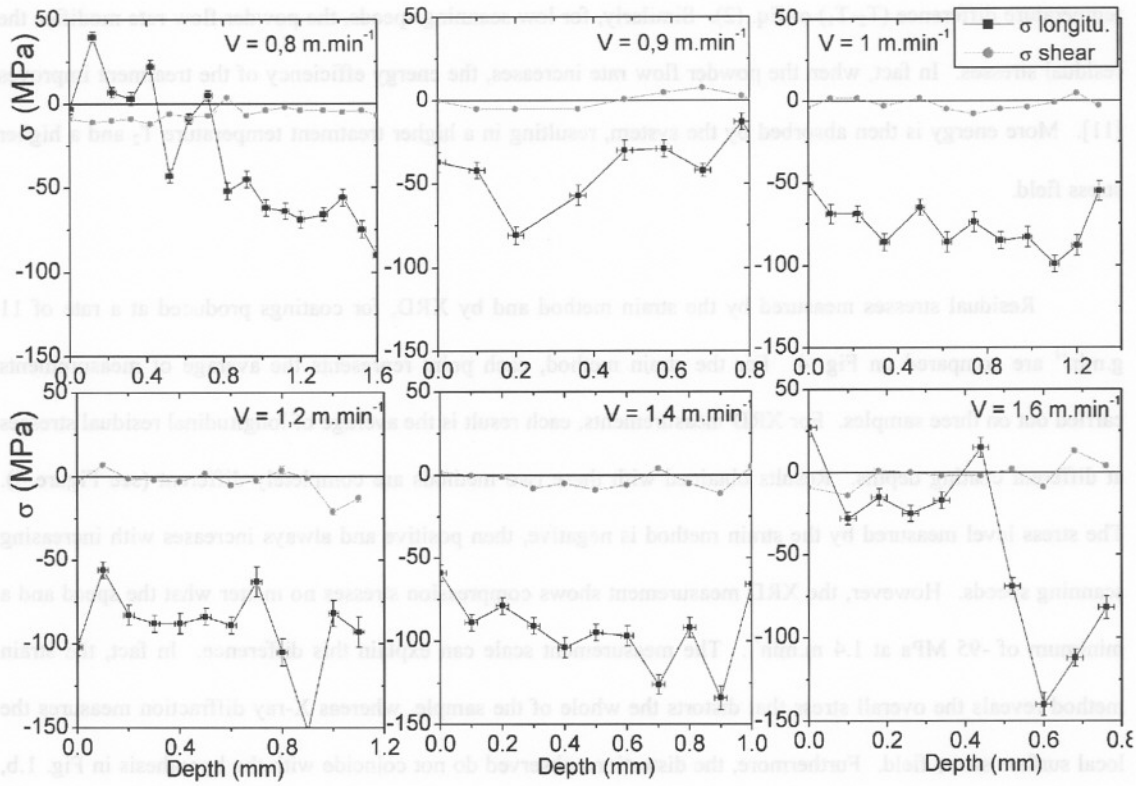

Figure 3: Residual stress measurements in the coating depth using XRD. Influence of the scanning speed (constant feeding rate of 11g.min^{-1}).

The following phenomena can be observed:

(i) The level of residual longitudinal stresses is relatively stable and always negative in the coating. Whatever the scanning speed, the cladding is systematically in compression. This observation agrees with the model of Fig. 1.b. Also, since shearing stresses are always nil, this phenomenon supports the model of linear stresses used in Eq. 3.

(ii) The average residual stress level increases with increasing scanning speed. It evolves by approximately -30 to -110 MPa for speeds of 0.8 to 1.4 m.min^{-1}. However, a decrease is observed on the surface of coating conducted at 1.6 m.min^{-1}.

(iii) The greatest average compression stress (σ_d = -95 MPa) is observed for a speed of 1.4 m.min^{-1}.

4.0 DISCUSSION

According to the previous observations, the scanning speed influences the field of residual stresses. This phenomenon can be explained by the energy input that varies according to the speed used, thus modifying the

temperature difference (T_2-T_1) of Eq. (2). Similarly, for low scanning speeds, the powder flow rate modifies the residual stresses. In fact, when the powder flow rate increases, the energy efficiency of the treatment improves [11]. More energy is then absorbed by the system, resulting in a higher treatment temperature T_2 and a higher stress field.

Residual stresses measured by the strain method and by XRD, for coatings produced at a rate of 11 g.min^{-1} are compared on Fig. 4. For the strain method, each point represents the average of measurements carried out on three samples. For XRD measurements, each result is the average of longitudinal residual stresses at different coating depths. Results obtained with these two methods are completely different (see Figure 4). The stress level measured by the strain method is negative, then positive and always increases with increasing scanning speeds. However, the XRD measurement shows compression stresses no matter what the speed and a minimum of -95 MPa at 1.4 m.min^{-1}. The measurement scale can explain this difference. In fact, the strain method reveals the overall stress that distorts the whole of the sample, whereas X-ray diffraction measures the local surface stress field. Furthermore, the distortions observed do not coincide with the hypothesis in Fig. 1.b, namely a convex distortion for $\alpha_d < \alpha_s$.

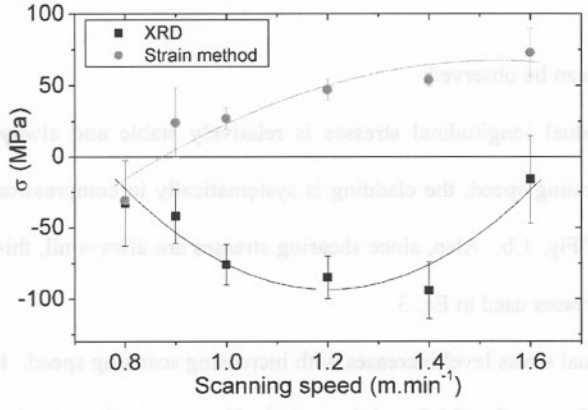

Figure 4: Comparison of the residual stress measurements obtained by the strain method and XRD in the coatings (constant feeding rate of 11 g.min^{-1}).

These results support the introduction of the block model proposed by Pilloz *et al.* [12]. In addition to the coating and the substrate, the authors take into account the Heat Affected Zone (HAZ) in evaluating the operation (see Fig. 5). This zone corresponds to the part of the sample significantly affected by the heat cycle of the treatment. In the case of aluminium, the HAZ reaches a critical temperature beyond which the material is

subject to plastic distortions due to thermomechanical effects. The substrate thus corresponds to the zone where the thermal effects of the process are negligible (we will assume that the temperature of the block remains equal to the room temperature T_1). Fig. 5 illustrates this principle for various speeds and for a coating with a lower CTE than the substrate ($\alpha_d < \alpha_s$).

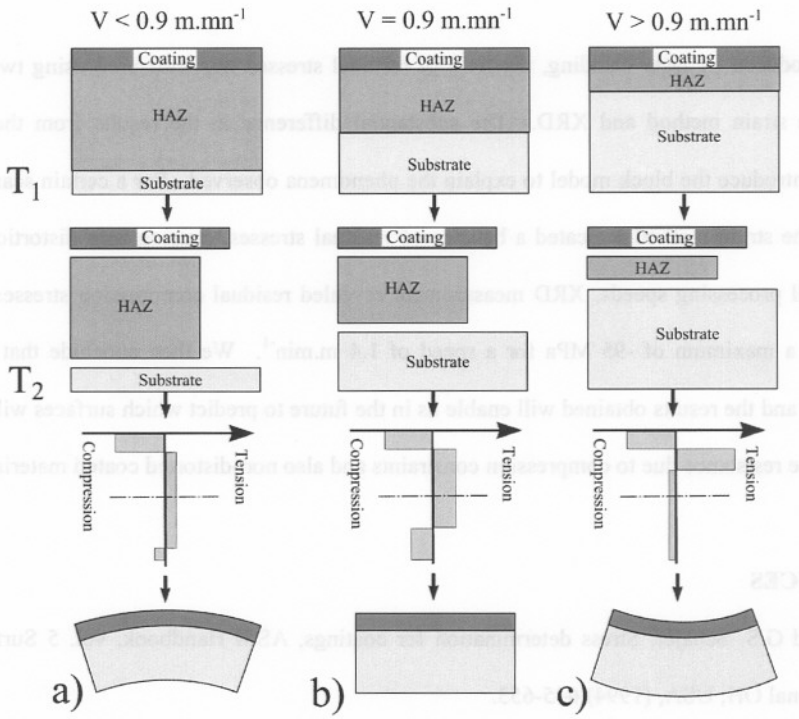

Figure 5: Hypothesis of the stress field in the samples as function of the scanning speed: block model with $\alpha_d < \alpha_s$.

Going from T_2 to T_1, the coating therefore contracts less than the HAZ whereas the substrate expected to remain at the same temperature is not subject to expansion. The coating and the substrate are thus always in compression and the HAZ in tension.

(i) For a slow scanning speed ($V < 0.9$ m.min^{-1} in our case), the HAZ is relatively deep, resulting in an overall state of compression above the average line of the sample and a convex distortion (Fig. 5.a).

(ii) For a rapid scanning speed ($V > 0.9$ m.min^{-1}), the HAZ is not widespread. The upper part of the sample is entirely in tension and therefore presents a concave distortion (Fig. 5.c).

(iii) For an intermediate scanning speed ($V = 0.9$ m.min^{-1}), the field of stresses is balanced through the depth of the sample, resulting in no sample distortion (Fig. 5.c).

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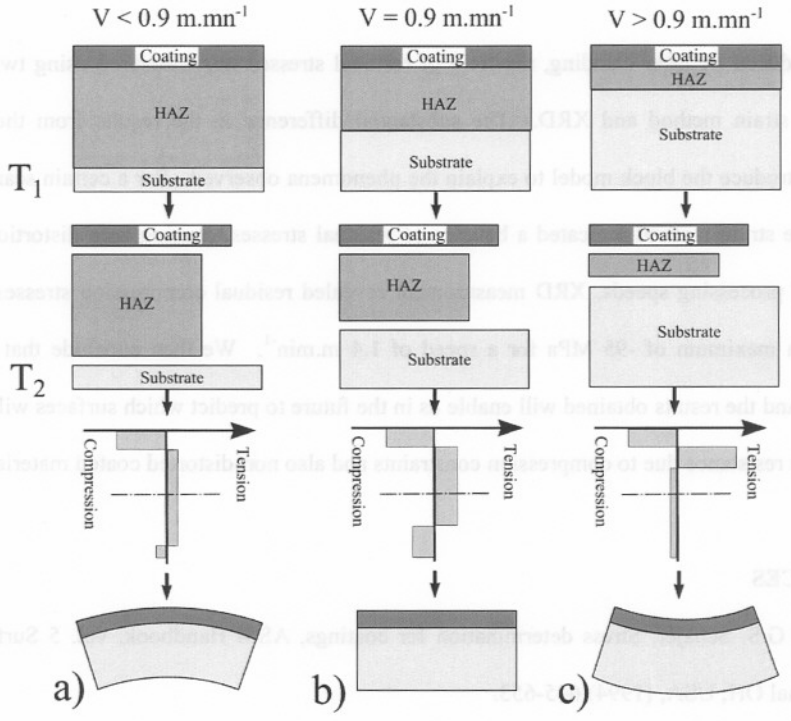

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(iii) For an intermediate scanning speed ($V = 0.9$ m.min^{-1}), the field of stresses is balanced through the depth of the sample, resulting in no sample distortion (Fig. 5.c).

The block model thus provides an explanation for the divergent phenomena observed using the strain method and XRD.

5.0 CONCLUSION

In the clads produced by laser cladding, the field of residual stresses was measured using two complimentary techniques: the strain method and XRD. The substantial difference in the results from the two techniques allowed us to introduce the block model to explain the phenomena observed. For a certain scanning speed (V = 0.9 $m.min^{-1}$), the strain method indicated a balance of residual stresses, causing zero distortion of the sample. Likewise for all processing speeds, XRD measurement revealed residual compression stresses in the coatings, which reached a maximum of -95 MPa for a speed of 1.4 $m.min^{-1}$. We then conclude that the methods are complimentary and the results obtained will enable us in the future to predict which surfaces will show improved wear and fatigue resistance due to compression constraints and also non-distorted coated materials.

6.0 REFERENCES

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