Two-Dimensional Thermo-Mechanical Finite Element Model for Laser Cladding

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Abstract

Temperature and stress fields during Laser Cladding determine, respectively, the microstructure and residual stress induced deformation and crack formation. As laser cladding processes find application in manufacturing, understanding of the temperature and stress fields become crucial for development of the relationship between process parameters and service behavior.

A two-dimensional model of laser cladding is developed, using the finite element software package ABAQUS. It enables an investigation of the temperature field that develops at the center plane of the material. This temperature field provides the input for a thermal stress analysis, for which generalized plane strain was assumed. The goal of the present paper is to perform a quantitative evaluation of the residual stresses that develop at the two-layered material, as a function of process parameters such as scanning speed, laser power and powder feed rate. Results of the model are presented, as applied to cladding of C95600 on AA333.

1. Introduction

1.1 General overview of laser cladding

The purpose of a cladding operation is to deposit one or several layers of a certain material onto a substrate, in such a way that a sound interfacial bond is formed, without significant dilution of one into the other. The goal of this process is to obtain an improvement in surface properties, usually chemical (e.g. corrosion or high temperature oxidation resistance) and/or mechanical (e.g. wear resistance). Other applications include Direct Metal Deposition, In-situ Repair and Rapid Prototyping/Manufacturing.

In laser cladding the beam acts as the heat source. At the laser irradiated zone, the clad material must be brought together with the substrate and these are to undergo melting, so that a metallurgical bond forms between the two materials. For this purpose, one possibility is to preplace the powder on top of the substrate. However, the most common procedure is the blown powder method, in which the cladding material is delivered to the substrate in the form of a powder that is injected into the laser melting pool with the help of a carrier gas.

Insight of the complex phenomena taking place during laser cladding is of great importance in order to effectively control the process and eventually optimize it. Heat and momentum carrying solid particles are transported by an inert gas through a properly designed nozzle and blown into a melting pool. This melt is mainly composed of previously deposited film material, but inevitably some substrate material is also present: in the beginning stages a melt pool has to be formed in the substrate, so that the powder catchment efficiency of the surface is high enough to allow for the formation of a continuous strip of clad material.

After an initial —usually relatively short— transient where composition varies significantly in the clad, the process reaches a steady state. If just slight melting of the substrate occurs, the composition of the coating will be mostly the nominal composition generated at the powder mixing system. In this low dilution case, a good bond between the clad and the substrate can be obtained without significant contamination of substrate alloy elements into the clad, which could be detrimental to the coating performance. Moreover, significant melting of the substrate introduces a certain amount of uncertainty in determining the coating composition. In addition to that, having a melting powder in contact with a melting substrate could lead to the formation of regions of intermediate compositions, e.g. intermetallic compounds, which in turn could be detrimental for the interface mechanical behavior. This problem also arises during the previously mentioned transient initial stage, where composition of the clad is not yet uniform.

It is readily understood that Heat Transfer plays a significant role in the whole process, because the feasibility of a particular cladding operation depends critically on parameters such as absorbed laser power, scanning speed (or: interaction time), and the thermal properties of the clad and substrate, including their melting points. Therefore, modeling efforts have usually focused on obtaining the set of adequate process parameters that lead to cladding. Nevertheless, it is important to address also the matter of the quality of the two-layered material from the viewpoint of its mechanical integrity.

The strong thermal gradients present during laser heating, along with the fact that the two materials usually have different coefficients of thermal expansion, leads to the generation of thermal stresses. Since the yield (flow) stress of the material decreases, in general, with temperature, inelastic deformation will most likely take place. Thus, when the thermal loading is removed, residual stresses remain in the material, concentrated mainly at the interface, which is also the location where defects are more likely to be found (e.g., pores, cracks). A quantitative understanding of these stresses, and how they depend on materials properties and (indirectly) on the process parameters becomes very important.

Therefore, as several events are taking place, simultaneously, involving at least the fields of Mass Transfer, Fluid Flow, Gas Dynamics, Phase Transformations, Deformation Mechanics and Heat Transfer, it is important to develop mathematical models including these phenomena. In this paper we will focus our attention in the latter two, as we will apply the Finite Element Method to the determination of temperature and stress fields in a two-dimensional domain.

1.2 Modeling of laser cladding: previous efforts

Models of laser cladding developed so far have focused mainly on Heat Transfer, with a few considering also Mass Transfer and Fluid Flow. Weerasinghe and Steen[1] used a 3-D Finite Difference model to calculate the temperature. The circular bead section was modeled as a stepped Cartesian grid. The shadowing effect (attenuation of the laser power at the workpiece due to the gas-powder jet) was considered. Clad dimensions were computed as a function of process parameters, both for single and also for multiple track cases.

Kar and Mazumder[2-4] and Agrawal et al.[5] solved analytically the one-dimensional heat and mass transfer (coupled) equations, for binary systems. The goal was to calculate the composition of the extended solid solution that is formed by rapid cooling. Parametric studies were also included, correlating variables such as laser power, beam radius, traverse speed, clad thickness and film composition, and portions of several non-equilibrium phase diagrams were proposed.

Hoadley and Rappaz[6] used a 2-D Finite Element Model for the calculation of the quasi-steady state temperature field. An idealized problem, in which almost no melting occurs in the substrate, was taken as the basis for defining a successful cladding operation. Mixing was assumed to distribute the powder instantaneously in the melt, which results in a volumetric heat source term associated with the latent heat. The free surface is considered to be an arc of a circle and the temperature of the powder particles is estimated. The calculation procedure involves determination of the laser beam position that is consistent with the requirements of the idealized problem. A parametric study involving laser power, processing speed and clad thickness was included.

Picasso and Hoadley[7] used the Finite Element Method to solve for the stationary heat transfer and fluid flow problem on a 2-D geometry. The model considers the deformation of the gas-liquid interface and the forces associated with the powder injection into the melt pool, and the powder is assumed to melt instantaneously as it hits the liquid surface. Picasso et al.[8] used an iterative procedure, based on a 3-D analytical model for temperature, for obtaining process parameters such as scanning speed and powder feed rate as a function of laser power, beam radius, powder jet geometry and clad height. The shadowing effect and the dependence of the absorption coefficient on the angle of incidence of laser radiation into the melt pool were also considered.

1.3 Proposed approach

The heat conduction equation and deformation mechanics equations are to be solved in a two-dimensional domain, the longitudinal mid-plane of a clad track. It should be noted that this is a rather drastic approximation, as the process is clearly three-dimensional (for instance, the height of clad track is of the same order of magnitude of its half-width). Nevertheless, even a simple finite element model should provide the correct trends for the effect of processing parameters on temperature and stress fields.

It is assumed that the heat transfer problem is independent of the mechanical problem; thus the temperature analysis is performed first and then it is used as an input to the calculation of stress-strain behavior. This is done in a commercial Finite Element Package, ABAQUS[*]. This approach not only takes advantage of the mathematical and geometrical capabilities of the Finite Element Method, but also of the processing and post-processing abilities of the software. For example, a convenient feature is that the temperature calculation is performed, and then the deformation problem is solved in the same mesh, with temperature data that is imported in an automatic way, thus saving the user data transfer procedures.

After an initial —usually very short— transient, the process takes place at quasi-steady state. From the viewpoint of the temperature problem, the natural approach is to study the laser cladding process in an Eulerian reference frame, i.e., fixed to the heat source. Computationally that is more efficient than a Lagrangian coordinate frame (i.e. fixed to the substrate). This is so because, for the Eulerian case, mesh refinement needs only to be performed at a very limited zone (the irradiated part of the top surface), as opposed to having the same degree of refinement for the whole top surface in the Lagrangian case. On the other hand, the deformation problem, which includes inelastic deformation, is usually defined on a Lagrangian basis, because the mechanical behavior of a certain control volume depends on the stress-strain history at that location. Thus, an Eulerian formulation is to be looked for, but that is not readily available, as it is still a matter of research in the field of Computational Mechanics[9]. Therefore, in the present work a Lagrangian procedure was followed.

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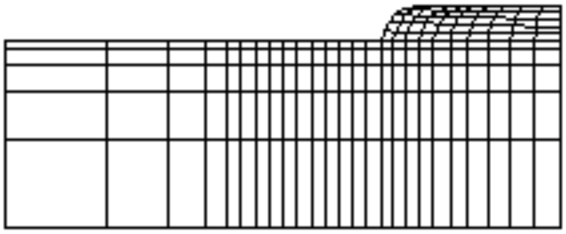
[*] ABAQUS is a trademark of Hibbitt, Karlsson & Sorensen, Inc.



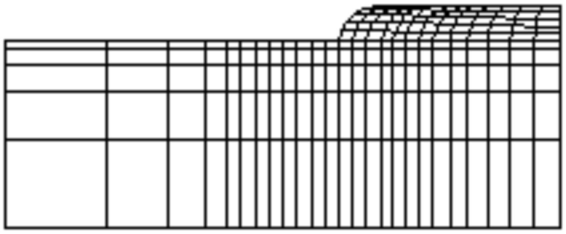


Figure 1. Initial Finite Element Mesh.

Figure 2. Element generation: three columns of clad elements were generated at the clad edge.

In the cladding process mass is constantly being added to the workpiece; this event needs to be simulated in the Lagrangian procedure. That was accomplished by means of successive discrete addition of new elements to the computational domain (figs. 1 and 2), as was done before in the case of welding[10]. These elements are generated at room temperature, so their addition will have a cooling effect on the pre-existing melt pool. There will be a heat redistribution period, which is usually very short as compared with the time elapsed between two element generation procedures. This is done in accord with the assumption that the clad powder gets melted as it hits the liquid metal, with the advantage that the cooling effect of the powder on the whole melt pool is handled by means of heat conduction —that is, in a way which is consistent with conservation of energy. Some preplaced clad material is considered in the computational domain, corresponding to the experimental procedure of preplacing some powder to enhance coupling of laser energy to the workpiece. The moving heat source starts its movement with its center still at the top of the preplaced clad material; subsequent element generation is only allowed to occur if some melting of the substrate has taken place (fig. 3). As for deformation, the generated elements are strain and stress free.

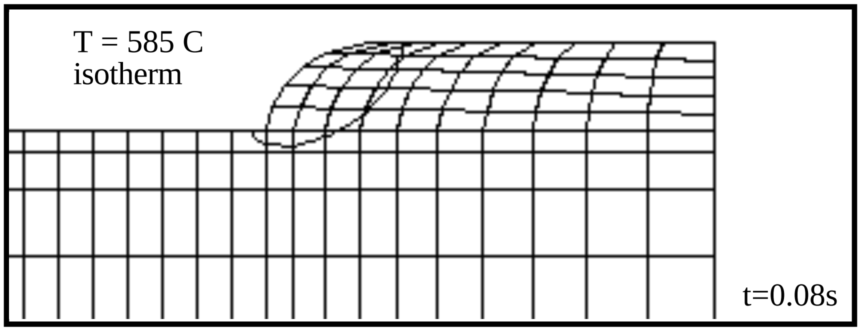


Figure 3. Isotherm corresponding to the substrate liquidus temperature.

2. Modeling

2.1 Heat Transfer modeling

The laser beam is gaussian in shape and results are generated for fixed values of absorbed power during each computer run. This is an approximation, because the amount of energy imparted to the workpiece varies with time. Nevertheless, since the process is taking place at steady-state for the most part, one can assume that an average absorptivity can be defined. This value can be calculated —for each particular experimental setup— by calibrating the model with the help of experimental results. Then the total power, which is an important process parameter, can be easily accessed. Of course, a complete description of the total process absorptivity should include the dependencies of the surface absorptivities (clad and substrate) on temperature and angle of incidence, plus the losses associated with the beam focusing optics and also from the interaction between the beam and the traveling particles. The latter results in a shadowing effect, in which the clad material particles partially block laser irradiation of the melt pool. To account for this, one needs to know particle size, shape and distribution in the jet; a full discussion should include energy absorption at each particle and also account for multiple reflections between particles and from particles to the melt pool. This has been discussed in some of the previously mentioned references and also by Marsden et al[11].

Likewise, the total amount of mass added in each step, which corresponds to the generated elements, is always the same. This corresponds to assuming a constant average catchment efficiency throughout the process. It is known that this parameter (the ratio between the total mass of particles that get incorporated in the melt pool per unit time and the nominal feed rate) varies throughout the process, increasing from zero (at the time the substrate begins to melt) to a steady state value, as it depends on the melt pool size, other parameters remaining the same. The steady state value can be accessed by knowing the nominal feed rate, the processing time and the weight increase of the workpiece. For a study of the dependence of catchment efficiency on process parameters, see ref. 12. The generated elements all conform to a circular geometry. The (dynamic) contact angle was taken as a constant.

We consider the radiation boundary condition for all surfaces except for the bottom substrate surface. Also included is the convective boundary condition. A higher value of the heat transfer coefficient was taken at the melt pool (during irradiation), consistent with the presence of forced convection, associated with the powder carrier gas; on the rest of the domain surface, natural convection was assumed. Typical values were considered; a more complete procedure should involve calculation of Nusselt numbers for a particular experimental setup.

The standard transient 2-D nonlinear heat conduction equation with no source term is solved (latent heat effect was not considered). A more complete study should include convection in the melt pool, as it influences the overall heat and mass transfer (including mixing, which affects the composition of the melt and consequently its properties). Nevertheless, the error involved in not taking convection into account generally decreases with increasing thermal conductivity; in many cases, considering conduction only can still provide a good idea on how the process parameters affect the temperature field. On the other hand, it can be argued that, from the deformation calculation standpoint, the location of the solid-liquid (S-L) interface is more important than the details of the temperature field inside the melt pool, as this is essentially a stress-free zone.

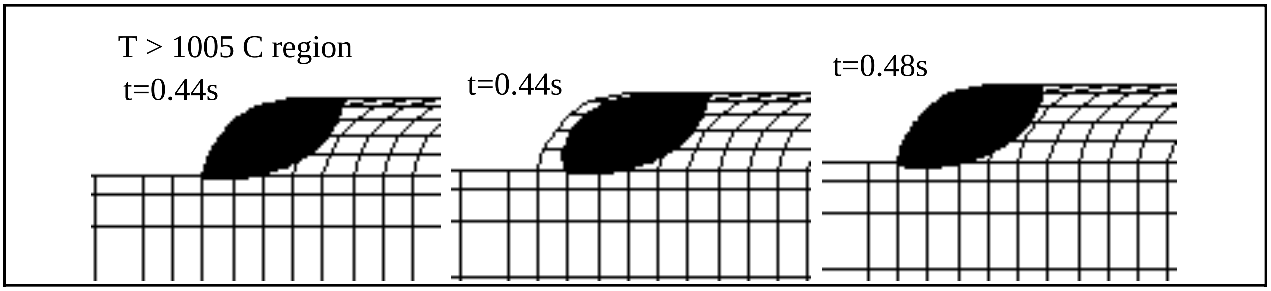


Figure 4-6. Clad melt pool: immediately before mesh generation, immediately after and then, again, before a new mesh generation procedure. The temperature field conforms to the requirement that the clad material liquidus isotherm spans from top to bottom of the clad -but not lower than that. Figs. 4 and 6 show that a steady state has almost been attained.

Therefore, emphasis will be placed more on the location of the S-L interface as it conforms with the overall mass transfer. Namely, at steady state, the liquidus isotherm of the clad material has to completely span from the bottom to the top of the clad layer (this is depicted in figs. 4-6, which also illustrate the behavior of the temperature field during the process of mesh generation). If in a computer run this condition is not achieved, this means that the available laser energy is not enough to produce a clad layer of the previously assumed thickness. Therefore, in keeping the same clad height (which, for a given speed, corresponds to a certain powder feed rate), the power and/or scanning speed has to be adjusted accordingly. On the other hand, if this isotherm drops considerably to the substrate, that would mean that the clad layer would become diluted, so parameters should be adjusted. This iterative process should continue, until a limit condition is satisfied. The limit condition imposed is that the lowest point of the clad material liquidus isotherm is located at the clad-substrate interface, a procedure considered by Hoadley and Rappaz[6]. In that case, the set of process parameters is taken as one that leads to a possible cladding operation (as long as the liquidus isotherm still hits the top surface of the clad region). In this way, a parametric study can be undertaken, in such a way that a region of successful cladding can be defined in the {absorbed power, absorbed feed rate, scanning speed} parameter space, for a certain experimental setup (i. e. optical and powder delivery systems) and clad-substrate materials.

2.2 Thermal stresses modeling

As the clad and substrate are heated, thermal strain will develop in the material. This field will not be uniform because: a) the temperature is not uniform; b) clad and substrate have, in general, different values for the thermal expansion coefficient. Stresses in the elastic domain will be generated and, most likely, conditions for inelastic deformation will become present, as the flow stress decreases markedly with temperature, while the elastic moduli are not expected to undergo such a sharp drop. When the thermal load is removed, permanent deformation will result in residual stresses, mostly concentrated at the clad-substrate interface.

We assume that the local strain is due to thermal expansion and plastic deformation only, so we are not considering other possible sources of transformation strain, such as the one arising from phase transformations, for example. No external loads are applied, and one of the extreme nodes in the bottom surface is considered to have zero displacement in the longitudinal direction, while the other is fully constrained. This is done to prevent rigid body motion of the domain.

The constitutive model takes a very simple elastic-ideal plastic behavior, where the yield stress decreases with temperature, tending to zero as the liquidus temperature is approached. A more complete model should include phenomena such as hardening and creep, but it is believed that even such a simple model can capture the essentials of the relevant sequence of events, namely, thermal expansion, plastic deformation, followed by dissimilar contraction, resulting in residual stresses.

For stress-strain behavior, generalized plane strain was assumed (a state that allows for strains to be defined in the transverse direction, although in a limited way; still, this should produce better results than the plane strain or plane stress assumptions, as the thermal strain is essentially triaxial in nature). For plasticity, the Von Mises criterion (with no hardening) was utilized.

2.3 Numerical solution

Finite Element equations were solved for temperature and displacements, using suitable elements corresponding to the above mentioned assumptions[13]. Four-node isoparametric elements were utilized. Simulations were performed, using a 263-node, 225-element mesh, for the following conditions:

Materials: Cladding of Cu alloy C95600 on Al alloy AA333 (substrate).
Nominal power: 2100 W, average absorptivity 10%.
Scanning speed: 12.5 mm/s.
Beam radius (at $1/e^2$): 1 mm.
Substrate height: 6.67 mm.
Clad height: 1.29 mm.
Contact angle: 80°.
Nominal feed rate: 0.22 g/s.

Table 1

These parameters relate to real processing conditions. Materials properties can be found on Table 2. Whenever possible, the variation of the properties with temperature was included, such that the nonlinearities associated with the temperature field could be accounted for.

3. Results and discussion

The plastic strain magnitude $\mathrm{PEMAG} = \sqrt{\frac{2}{3}\varepsilon_{ij}^{p}\varepsilon_{ij}^{p}}$ plot (after cooling) shows that plastic deformation occurs at regions that undergo melting and solidification (fig. 8). This results in residual stresses, as can be seen from the stress field in the longitudinal direction, S11, where we note that compressive stresses are predominant in the clad, whereas tensile stresses develop on the substrate (fig. 9). This is to be expected[22]: during cooling, the substrate has the tendency to contract more than the film, because the value of the thermal expansion coefficient is higher in the aluminum alloy than in the copper alloy (the fact that the temperature decreases with depth somehow tends to diminish this tendency). Since the film imposes some constraint into the substrate, the latter won't contract as much as if it was alone. Thus a tensile stress field is present at the substrate, whereas a corresponding compressive field is found at the film. The displaced mesh plot shows some shrinkage in the clad region, which is associated with compressive plastic strain (fig. 10). Nevertheless, its exact value is not to be taken as rigorous, because of the simplifications of the constitutive model. Besides that, the initial size of the generated elements was taken as the same as the corresponding preplaced elements, which is a reasonable but not a strictly necessary assumption.

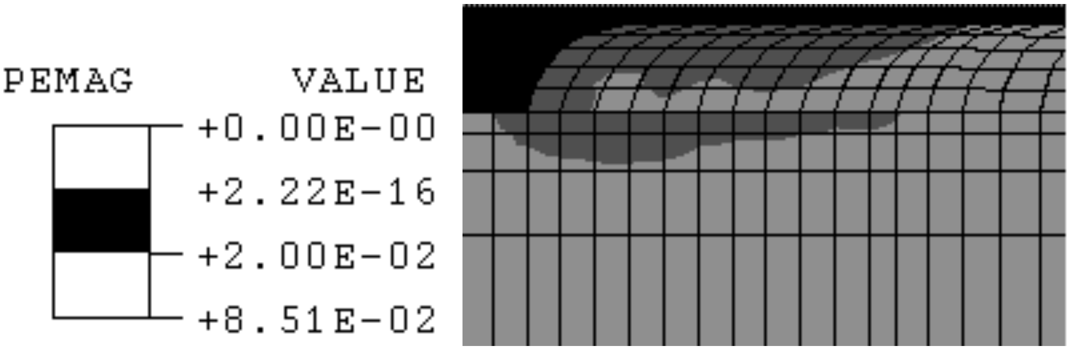


Figure 8. Plastic strain occurs in locations where melting took place. The dark gray zone corresponds to: PEMAG > 0.02

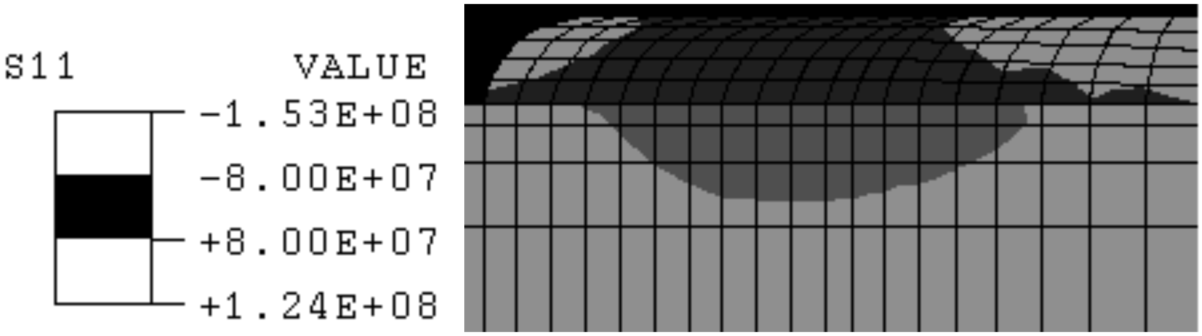


Figure 9. Stress in the longitudinal direction. Stress changes abruptly at the interface, from tension (dark gray) to compression (darker gray). This is not a problem, because displacements are the variables that have to be continuous throughout the domain, not stresses or strains.

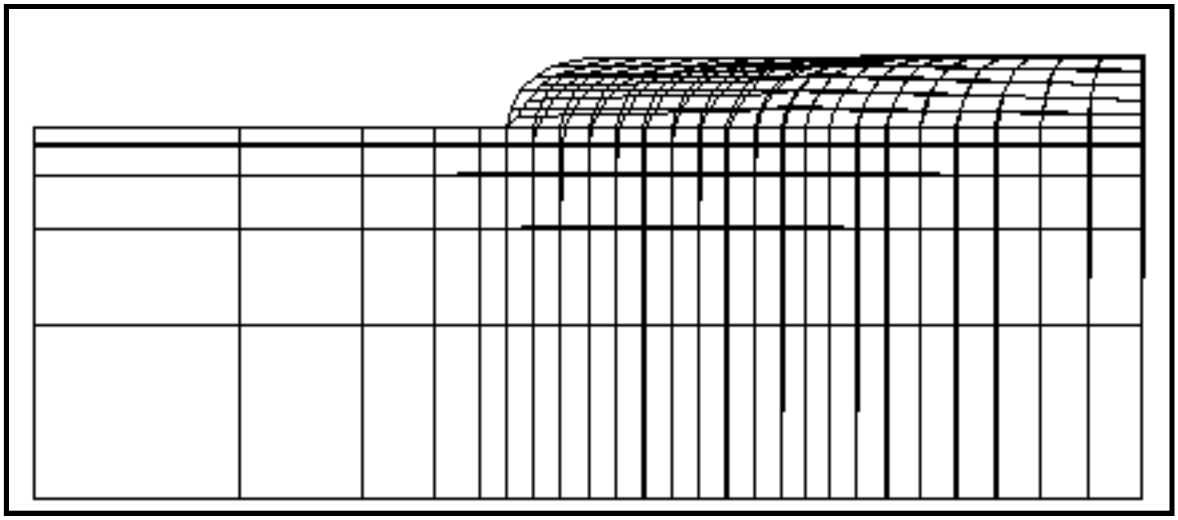


Figure 10. Displaced mesh plot (along with initial mesh).

4. Conclusions

1. A two-dimensional thermo-mechanical finite element model was developed, and applied to the cladding of C95600 on AA333. Since the film has a lower coefficient of thermal expansion than the substrate, the latter was found to be predominantly in tension and the former in compression.

2. The maximum values found for the longitudinal stress are, for both materials, about 65% of the yield stress at room temperature.

3. Stresses are concentrated at the interface between the clad and the substrate.

4. Although the material models that were utilized are simple, the Finite Element model that was developed is still expected to provide reasonable insight into the stress fields that develop in laser cladding. This can be a very useful tool, for instance, in predicting failure behavior of laser cladded materials.

5. This model can also be used in the following way: a parametric study based on the temperature field can be undertaken, in order to define ranges of process parameters that are expected to lead to successful cladding operations. Then, within those ranges, values of parameters (e.g. laser power and scanning speed) that minimize the residual stresses can be determined. The stresses are expected to depend indirectly on the process parameters through their dependence, e.g., on total plastic strain (which depends on interaction time) and thermal strain (which depends on the temperature distribution).

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