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INVESTIGATION OF COATING LAYER TO REDUCE THERMAL STRESSES IN STEEL FIBER REINFORCED ALUMINUM METAL MATRIX COMPOSITE

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Abstract-In this study, by using coating layers to reduce thermal stresses in the metal matrix composites with a mismatch in coefficients of thermal expansions of fiber and matrix is investigated. The thermoelastic solutions based on a three cylinder model are deformed. It is shown that the effectiveness of the layer can be defined by the product of its cofficients of thermal expansions and thickness and that a compensating layer with a sufficiently high coefficient of thermal expansions can reduce the thermal stresses in the metal matrix. . In order to verify the results were compared with the finite element method. In this solution, 224 nodes and 44 nine-node isoparametric elements are used. The study is based on a three cylinder model isolating one steel fiber with a coating layer and a aluminum matrix layer. Only monotonic cooling is studied and the variation of the material properties with temperatures is not considered. The results have been presented in graphics.

Key words: Thermal stress, coating layer, stress analysis, finite element analysis

1.INTRODUCTION

The aircraft and automotive industry is showing an increasing interest in materials that are lighter, stronger, and more wear resistant than conventional materials as a means to increase the efficiency and durability of engines. These new materials must retain their superior properties at higher operating temperatures to ensure that the engines meet the stringent economic and environmental requirements. Light metal alloys reinforced with steel fibers, especially aluminum based metal matrix composites are prime candidates for such applications because they can posses properties that meet such demands. However, a thermal mismatch exists between the steel fibers and the aluminum matrix.

The steels having a low coefficient of thermal expansion (CTE) and aluminum has higher values of CTE. This thermal mismatch induces stresses in the composite structure when subjected to temperature change.In many investigation matrix craking has been observed after cooling down from processing temperature to room temperature for brittle matrix materials.

Some investigators have been proposed that the addition of a coating layer between the fiber the matrix can reduce the tensile residual stresses in the matrix to a level which is low enough to avoid matrix craking.

Due to the interest for many engineering areas (especially aircraft and automotive industry) the optimization of coating layers in the design of fiber reinforced metal matrix composites received considerable attention up till now. Ghosn and Bradley [1] have reported optimum interface properties for metal matrix composites. Doghri and Leckie [2] have made elasto-plastic analysis of interface layers for fiber reinforced metal matrix composites. Some numerical parametric studies have been performed in an attempt to determine the material parameters that are most beneficial in reducing thermal stresses. It has been suggested that the optimum coating layer should have a CTE between those of the matrix and fiber, with low allowable modulus and a high layer thickness [3,4]. Okumuş [5]. has made an analysis on effect of coating layer to reduce thermal stresses.

In the present work, simplified elastic analysis has been performed for stainless steel fiber and aluminum metal matrix composite material from ref. [6]. In this study, stainless steel is used as fiber material and aluminum is used as matrix material. Elastic analysis procedure is realized in two steps.

Firstly, elastic analysis is performed assuming that the fiber, matrix and layer materials are isotropic and linearly elastic. In this case, the variation of material properties with temperature is not considered. At second, both the coating layer and the matrix are considered to be elastic-plastic and the temperature dependence of the properties of the three materials is considered. The von Mises theory is used as a yield criterion.

Thermal stress analysis is carried out by using finite element method , and the residual stresses are determined for small deformations.

2.MATHEMATICAL FORMULATION

Steel materials are usually at least three to four times stiffer than the aluminum matrix materials. Hence, it can be assumed that,

$$\frac{E_f}{E_m} >> 1 \quad \text{and} \quad \frac{E_f}{E_L} >> 1 \tag{1}$$

The stress distribution in the matrix and coating layer is governed by the plane strain problem with a fixed inner radius at the fiber interface.

The differential coefficients of thermal expansions of matrix, fiber and coating can be written as,

$$\Delta\alpha_m = \alpha_m - \alpha_f \qquad \text{and} \qquad \Delta\alpha_L = \alpha_L - \alpha_f \tag{2}$$

The stress distribution in the matrix is given by the plane strain solution for a thick walled cylinder subjected to an unknown internal pressure (P), a traction free outer surface, and a temperature change ΔT. Superimposing the solutions given in Ref. [6] for an internal pressure and a temperature change gives the stress distributions in the matrix as follow,

$$\begin{aligned}
\sigma_{rm} &= -p\frac{(R_m/r)^2-1}{(R_m/R_f)^2-1}\\
\sigma_{\theta m} &= p\frac{(R_m/r)^2+1}{(R_m/R_f)^2-1}\\
\sigma_{zm} &= p\frac{2\nu_m}{(R_m/R_f)^2-1}+E_m\Delta\alpha_m\Delta T
\end{aligned} \tag{3}$$

The highest stresses in the matrix occur at the inner surface of the cylinder, $r = R_f$.

The von Mises equivalent stress can be written as,

$$\bar{\sigma} = \sqrt{\sigma_r^2 + \sigma_\theta^2 + \sigma_z^2 - \sigma_r\sigma_\theta - \sigma_r\sigma_z - \sigma_\theta\sigma_z} \tag{4}$$

and can be calculated as

$$\bar{\sigma}_m = \left\{ \left[p\frac{C_f}{1-C_f} \right]^2 [3/c_f^2 + 1 - 4\nu_m(1-\nu_m)] - pE_m\Delta\alpha_m\Delta T\frac{C_f}{1-C_f}2[1-2\nu_m] + [E_m\Delta\alpha_m\Delta T]^2 \right\}^{1/2} \tag{5}$$

Where C_f is the fiber volume fraction.
The coating layer is subjected to a pressure in the radial direction resulting from the contact with the matrix

$$\sigma_{rL} = -P \tag{6}$$

The temperature change ΔT introduces stresses in he hoop and longitudinal directions due to the constraint from the fibers. The stresses in the hoop and longitudinal directions are equal and are the sum of the stresses caused by the pressure and the thermal expansion,

$$\sigma_{\theta L} = \sigma_{zL} = -\frac{\nu_L}{1-\nu_L}p + \frac{1}{1-\nu_L}E_L\Delta\alpha_L\Delta T \tag{7}$$

The von Mises equivalent stress in the coating layer is given by following equation,

$$\bar{\sigma}_L = \frac{1}{1-\nu_L}[E_L\Delta\alpha_L\Delta T + (1-2\nu_L)P] \tag{8}$$

The value of P can be found as,

$$P = \frac{(1+\nu_m) - \dfrac{t_L\Delta\alpha_L(1+\nu_L)}{R_f\Delta\alpha_m(1-\nu_L)}}{(1-\nu_m^2)(\dfrac{1+C_f}{1-C_f} + \dfrac{\nu_m}{1-\nu_m}) + \dfrac{t_L E_m}{R_f E_L}(1-\dfrac{2\nu_L^2}{1-\nu_L})} E_m\Delta\alpha_m\Delta T \tag{9}$$

Where C_f is the fiber volume fraction.

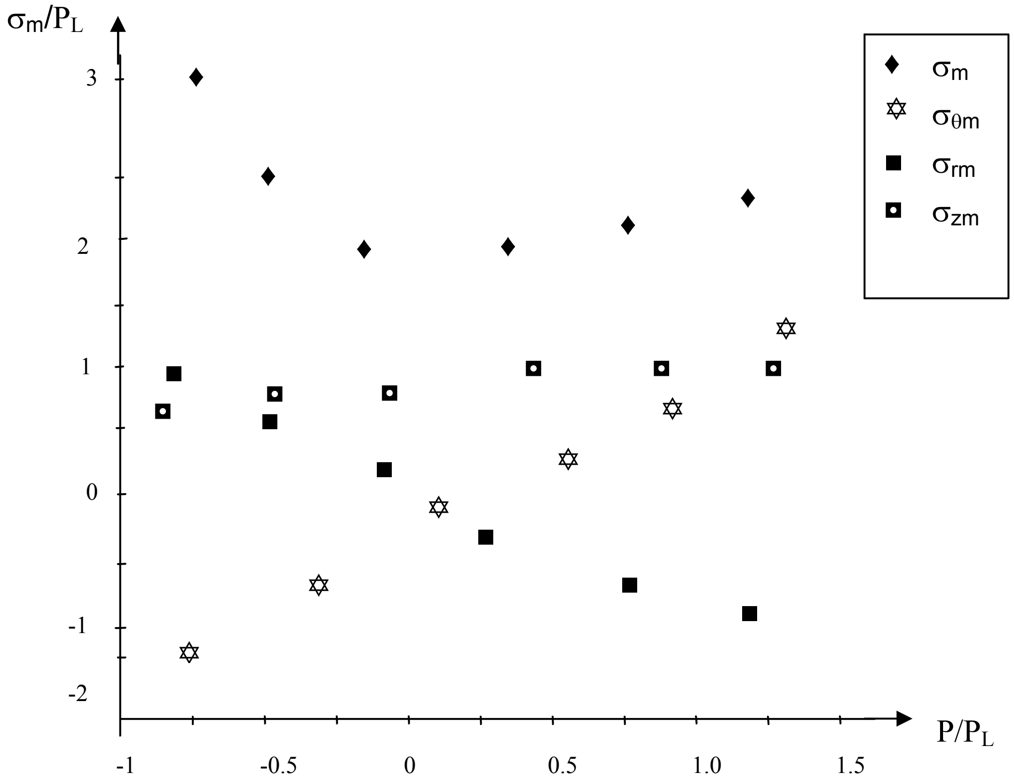

Figure 1. Stresses at the inner radius of the matrix.

($P_L = E_m \Delta\alpha_m \Delta T$)

3.FINITE ELEMENT ANALYSIS

In this work, finite element procedure is employed to calculate the residual stresses and yield strength of the composite laminates. Nine-node elements are used with displacement functions.The stiffness matrix of the composite plate can be obtained by using the minimum potential energy principle. Bending and shear stiffness matrices are,

$$\left|K_b\right| = \int_A \left|B_b\right|^T \left|D_b\right| \left|B_b\right| \, dA$$

$$\left|K_s\right| = \int_A \left|B_s\right|^T \left|D_s\right| \left|B_s\right| \, dA$$

Where ,

$$\left|D_b\right| = \begin{vmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{vmatrix}$$

$$\left|D_s\right| = \begin{vmatrix} k_1^2 & A_{44} & 0 \\ 0 & k_2^2 & A_{55} \end{vmatrix} \qquad (10)$$

$$(A_{ij} , B_{ij} , D_{ij}) = \int_{-h/2}^{h/2} Q_{ij} \ (1,z,z^2) \ dz \ , \qquad (i , j = 1,2,6)$$

$$(A_{44} , A_{55}) = \int_{h/2}^{h/2} (Q_{44} , Q_{55}) \ dz \ .$$

Here, D_b and D_s are the bending and shear parts of the material matrix, respectively. The term A_{45} has been neglected. Because , A_{45} is negligible in comparison with A_{44} and A_{55} . The shear correction factors are given by,

$k_1^2 = k_2^2 = 5/6$ [12].

Since, the calculated stresses do not coincide with the true stresses in a nonlinear problem, the unbalanced nodal forces and the equivalent nodal forces must be calculated. The equivalent nodal point forces corresponding to the element stresses at each iteration can be calculated as follows,

$$\{R\}_{eq.} = \int_{Vol.} \left|B\right|^T \left|\sigma\right| \ dA = \int_{Vol.} \left|B_b\right|^T \left|\sigma_b\right| \ dA + \int_{Vol.} \left|B_s\right|^T \left|\sigma_s\right| \ dA \ . \tag{11}$$

When the equivalent nodal forces are known, the unbalanced nodal forces can be found by,

$$\{R\}_{unbalanced} = \{R\}_{applied} - \{R\}_{equivalent} \tag{12}$$

These unbalanced nodal forces are applied for obtaining increments in the solution and must satisfy the convergence tolerance in a nonlinear analysis. Residual stresses are very important in thermal analysis of metal matrix laminated plates. When the yield point of the laminate is exceeded, the residual stresses occur in laminate plates. The obtained residual stresses can be used to raise the yield strength of the composite plates. In this solution, 224 nodes and 44 nine-node isoparametric elements are used. . In order to obtained more accurate results at the composite , a highly refined mesh was constructed for all region.

Table 1. Mechanical Properties of the fiber and matrix materials

	Young's modulus	Thermal expansion coefficient	Poisson's ratio
Fiber	207 GPa	$11x10^{-6}/C^0$	0.30
Matrix	70 GPa	$10.3x10^{-6}/C^0$	0.25

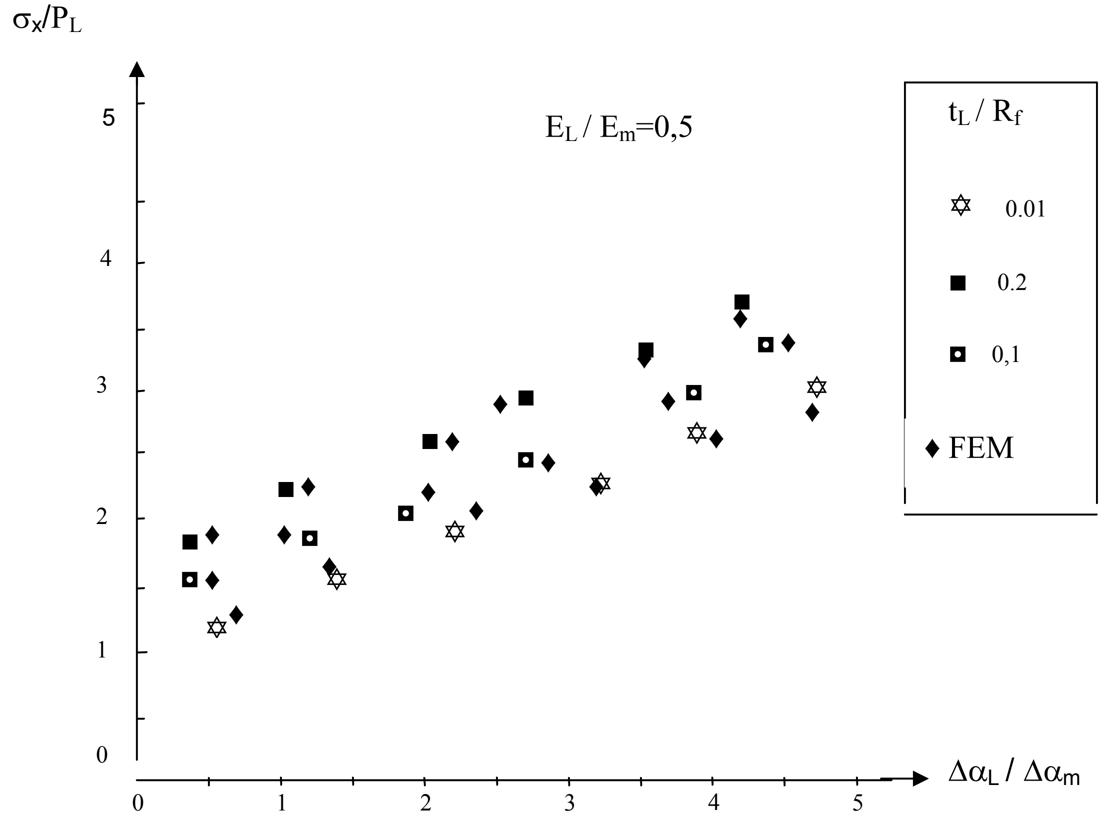

Figure 2. the change of stresses in coating layer.

4. RESULTS AND DISCUSSION

The stresses at the inner radius of the matrix are calculated and results are presented in figure 1. as a function of pressure.
Here, fiber volume fraction for steel is taken 0,5 and poisson's ratio for aluminum matrix is taken 0,25.
As it is seen that a pressure at the interface causes increased tensile stresses in the axial direction that could effect matrix craking. It is also seen that the value of the critical stress for matrix, σ_{cm}, sets an upper limit for the principal stresses ($\sigma_{\theta m}$, σ_{zm}, σ_{rm}) and allowable equivalent stress, σ_{ym} in the matrix sets another limits on the pressure. These conditions clearly shows that an interval exist for the interface pressure so that the failure criteria are not distrupted.
Inspection of equation (9) and figure 1. shows that the von Mises equivalent stress has a minimum for an interface pressure that is close to zero. The pressure P is zero when

$$\frac{\Delta\alpha_L t_L}{\Delta\alpha_m R_f} = (1+\nu_m)\frac{(1-\nu_L)}{(1+\nu_L)} \tag{13}$$

from above equation (13) it can be obtained that the stresses in the matrix are influenced by the parameter $\Delta\alpha_L t_L$. It is seen that a coating layer of available materials with high CTE has the ability of substantially reducing thermal stresses in the matrix.
Stresses in the coating layer is illustrated in figure 2. as a function of the different dimensionless parameters. The deformation of the layer is constrained in the

longitudinal direction so that tensile stresses increase in the layer. The stress in the coating layer is dependent on the layer modulus (E_L/E_m) and CTE, $\Delta\alpha_L/\Delta\alpha_m$, but the influence of the layer thickness t_L/R_f on the stress in the coating layer is not significant. This result indicates that the influence of the constrained thermal expansions on the stress is more significant for coating layer and it is also displayed that stress in the coating layer is weakly dependent on the interface pressure. It can be deduced from figure 2. that it is more prefer to have a thick layer and a moderate high layer CTE than a thin layer and a high CTE in order to obtain stress reduction in the matrix and to prevent high tensile stresses in the coating layer.
The influence of the young's modulus (E_L) and the CTE (α_L) and the thickness (t_L) on the reduction of the residual stresses in the matrix are obtained. For this purpose the fiber and the matrix mechanical properties are given in table 1. The fiber volume fraction is taken as,

$$C_f = \left(\frac{R_f}{R_m}\right)^2 = 38 \tag{14}$$

The mechanical properties of the fiber and the matrix were kept constant and the range of coating layer parameters was chosen as follows:

For E_L, 50 Gpa$<E_L<$500 Gpa

For α_L, $5\mathrm{x}10^{-6}/C^0 < \alpha_L < 25\mathrm{x}10^{-6}/C^0$

For $\frac{t_L}{R_f}$, $0.03 < \frac{t_L}{R_f} < 0.3$

The poisson's ratio of the coating layer was kept constant ν_L=0.3.
Figure 3. displays the layer CTE effect on the stresses in the matrix. In this case, young's modulus E_L and thickness t_L was kept fixed for each calculations. The results show that the matrix equivalent stress $\bar{\sigma}_m$ decreases considerably as α_L increases. However as showed in figure 3., the equivalent stresses reach a minimum value (about α_L=24) after this minimum value they increase again with increasing α_L. Results also show that the decrease of σ_m is more pronounced if the fixed thickness t_L is high. Results pointed out that the addition of the interface coating layer does reduce the residual stresses in the matrix.
Influence of he young's modulus of the coating layer is presented in figure 4. in the case that the layer CTE and thickness t_L was kept fixed for each calculations. It is seen that in the range 60 GPa-200 GPa, the value of young's modulus of the layer is relatively insensitive on the matrix stresses. After the 200 GPa point the value of E_L has more effect on matrix stresses until 450 GPa. It is shown that if α_L is big value from $10\mathrm{x}10^{-6}/c^0$ value the increase of E_L may reduce the stress in the matrix.
If α_L value is small from $10\mathrm{x}10^{-6}/C^0$ value, the effect of E_L on the stresses has no significant.

Influence of the thickness on the stresses in the matrix is given in figure 5. It is seen that stresses in the matrix is decrease while the thickness of the layer is increase. In this case, E_L and α_L was kept fixed for each calculations.

In all the cases the analysis it was shown that the important layer parameter which affected the matrix stress is $\Delta\alpha_L t_L$.

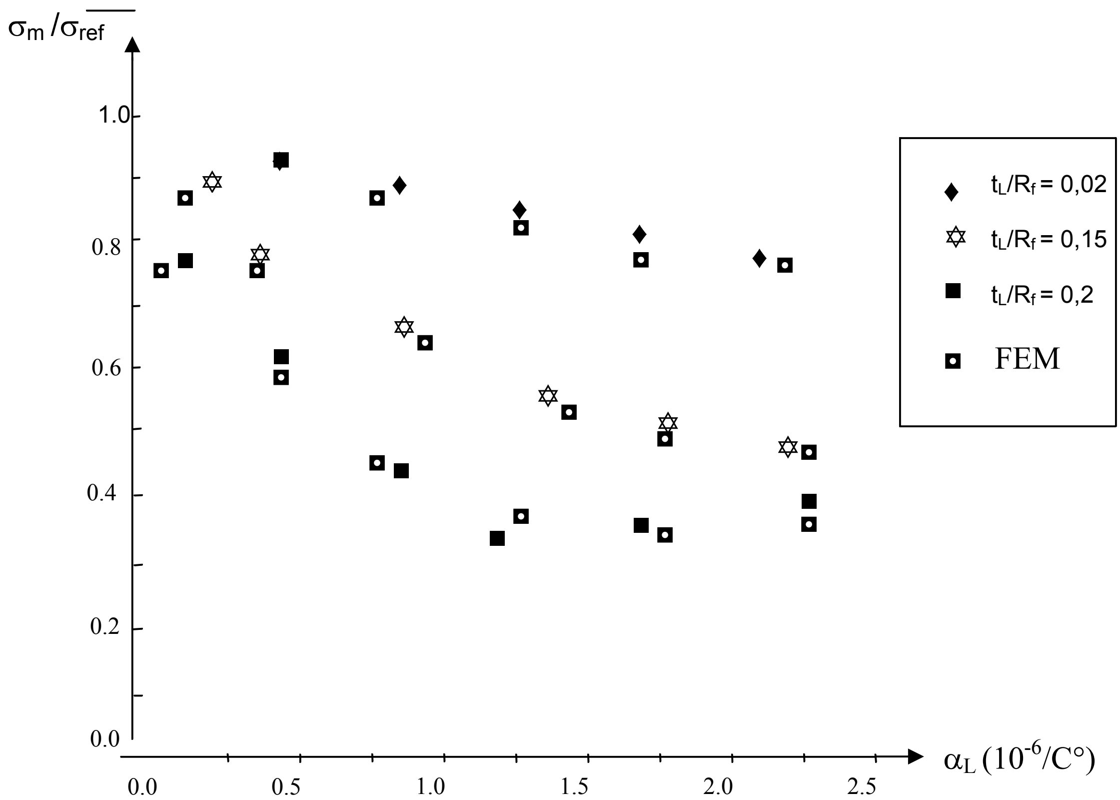

Figure 3. Effect of the layer CTE on the stresses in the matrix.

5.CONCLUSIONS

In the present study, thermal stresses analysis is carried out for cylindirical composite material.Metal matrix composites reinforced with stainless steel fibers are attractive because of their high specific stiffness and strength. Advantage can be taken from the high temperature strength of stainless steel fibers and the ductily of the aluminum metal matrix to produce a composite with superior combined properties. However a thermal mismatch exist between the fiber and the matrix. This thermal mismatch induces stress in the composite when subjected to temperature change. This stresses may cause matrix craking which have been observed in many application.

It has been proposed that the addition of the coating layer between the fiber and the matrix can reduce the tensile residual stresses which may prevent matrix craking.

Based on this study, the following results were obtained.

1. A high coating layer with a sufficiently high CTE has an influence on the reducing thermal stresses in the matrix.
2. While using the coating layer between the matrix and the fiber it should be noted that the young's modulus of the coating layer has not to be very low.
3. If young's modulus of the coating layer is taken in a certain range, the coating layer performance is defined by the product of its CTE and thickness.

4. If the coating layer has high young's modulus, it may create high stresses in the matrix
5. The thermal mismatch between the fiber and the matrix has to be taken up by the coating layer.
6. The influence of the layer properties on the axial stress in the matrix is not much important.

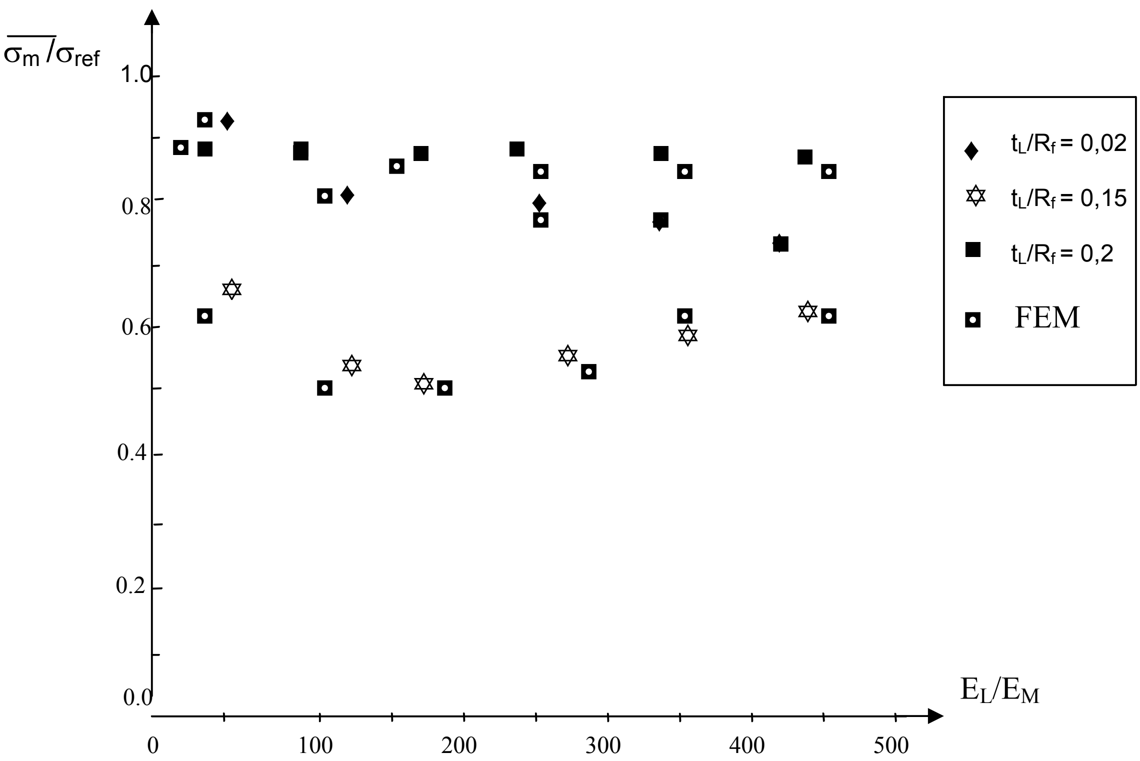

Figure 4. Influence of the layer young's modulus on the stresses in the matr

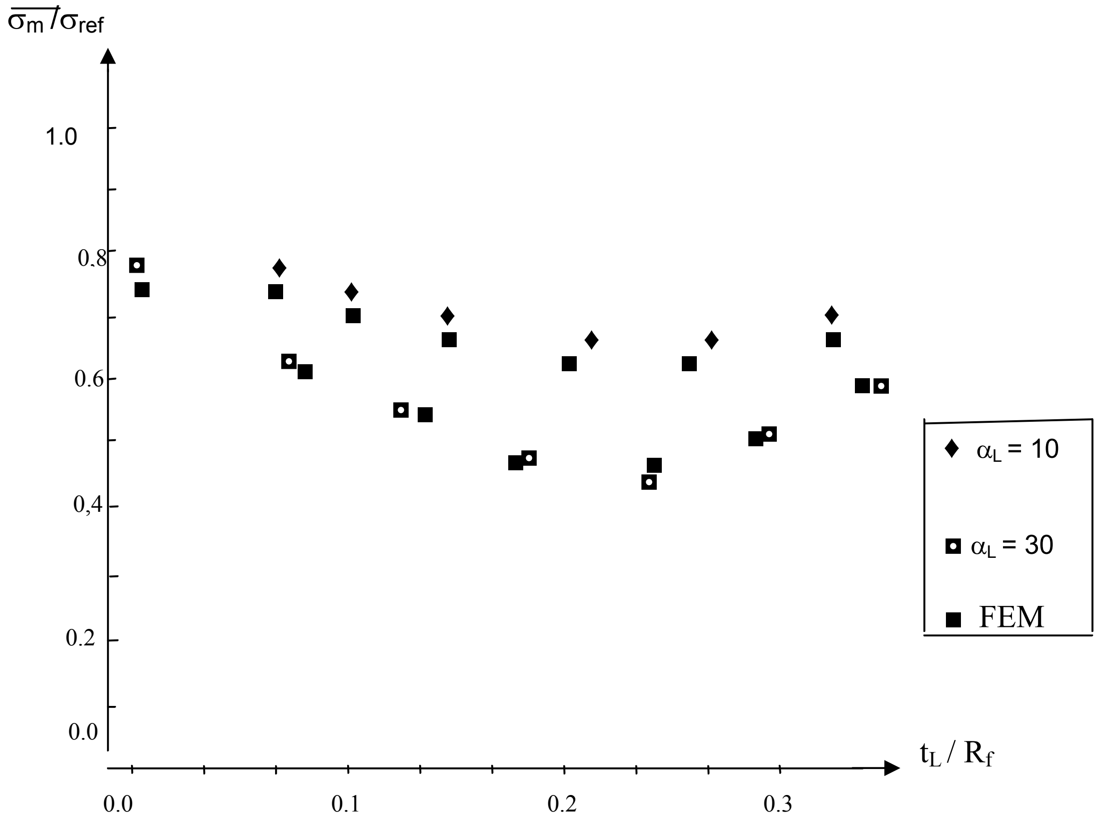

Figure 5. Effect of the layer thickness on the stresses in the matrix

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