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# AVERAGE THERMAL STRESS IN THE Al+SiC COMPOSITE DUE TO ITS MANUFACTURING PROCESS

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## ABSTRACT

The numerical analyses framework to obtain the average thermal stress in the Al+SiC Composite due to its manufacturing process is presented along with the obtained results. The mixing of Aluminum and SiC powders is done at elevated temperature and the usage is at room temperature. A thermal stress state arises in the composite due to the different thermal expansion coefficients of the materials. Due to the particles size and randomness in the SiC distribution, some sets of models were analyzed and a statistical procedure used to evaluate the average stress state in the composite. In each model the particles position, form and size are randomly generated considering a volumetric ratio (VR) between 20% and 25%, close to an actual composite. The obtained stress field is represented by a certain number of isostress curves, each one weighted by the area it represents. Systematically it was investigated the influence of: (a) the material behavior: linear x non-linear; (b) the carbide particles form: circular x quadrilateral; (c) the number of isostress curves considered in each analysis; and (e) the model size (the number of particles). Each of above analyzed condition produced conclusions to guide the next step. Considering a confidence level of 95%, the average thermal stress value in the studied composite ($20\% \leq VR \leq 25\%$,) is 175 MPa with a standard deviation of 10 MPa. Depending on its usage, this value should be taken into account when evaluating the material strength.

## 1. INTRODUCTION

The studied material is the Al+SiC, a metal matrix composite formed by mixing a powder of aluminum (the metal matrix) with particles of Silicon Carbide (SiC). Typically the mixing is done at elevated temperature (circa 600 ºC) and the usage is at room temperature. So, a thermal stress state arises in the composite due to the different thermal expansion coefficients. Its strength depends, also, on the particle volumetric ratio (VR).

The size of the SiC particles imposes a model that represents a tiny part of the composite. Due to this fact and the randomness in the SiC particle’s size and distribution, for each condition to be verified, a set of models was analyzed and a statistical procedure was used to evaluate the average thermal stress state in the composite.

In the results analysis, the stress field from each model is represented by a certain number of isostress curves, each one weighted by the area it represents. Considering a bar made of this composite, each model can represent its central portion or any portion of a given section along the bar size. The particles position, form and size in each model were randomly generated considering 20% ≤ VR ≤ 25%, close to an actual composite. For robustness of the statistical procedure, at least 20 models were generated in each analysis set but mostly it was used 30 models and, sometimes 40 models.

Systematically it was investigated the influence of several parameters that are important to the stress state as described below (each analyzed condition produced conclusions to guide the next step):

(a) The composite linear x non-linear behavior. The analytical formulation (1) considering intrinsically the linear behavior as well as some numerical linear analyses show very high stresses in the Aluminum, far beyond its yielding level. So, a non-linear stress-strain curve is used for the Aluminum in all subsequent numerical analyses.

(b) The carbide particles form: circular x quadrilateral. Other implicit hypothesis in the analytical formulation is the circular (and regular) form & size for the particles which is unrealistic. Quadrilateral particles with random form and size were also used and confirmed to be more representative.

(c) In the previous analyses it was considered 9 equally spaced isostress curves between the max and the min stress value to represent the thermal stress state. To verify the influence of the number of curves, 09, 20 and 40 curves were considered. The results obtained with 20 and 40 curves show no practical difference, so the remaining analysis results were analyzed using 20 isostress curves to represent the stress field in each model. However, as mentioned and justified in the next set/parameter description, an artifice was used to increase the apparent number of isostress curves to 40 an 80.

(d) The model size: considering the particles average size (L), each model in all previous analysis is a square with a side length of about 10L. To investigate the model size influence in the results, new sets with 20 models each were generated with 20L and 40L size. In these analyses, the isostress percentage distributions show a long tail towards the maximum stress value. Part of this tail can be neglected once the accumulated percentage is ~0% (the part between the max stress and circa its half value). So, the raw results were re-analyzed imposing new maximum stress values to work with: (a) half and (b) one forth of the max stress values. This is equivalent, roughly, to increase (double) the number of isostress curves to 40 and to 80 curves as mentioned above.

From the set of results obtained in the two last steps above, a normal distribution was adopted for the statistical treatment of the thermal stress sets of values aiming to establish the average thermal stress value in the studied composite. So, a confidence interval of 95% around this average value was defined as ±2 times the standard deviation of the distribution. This average stress value should be taken into account when evaluating the material strength once for some usages the thermal stress is important.

## 2. THEORETICAL BACGROUND ON METAL-MATRIX COMPOSITES

The composite material (Aluminum matrix and its disperse phase of Silicon Carbide particles, SiC, referred as Al+SiC) is obtained mixing both materials, reduced to a powder form, heating it at about 600° C and extruding it to form bars. Usually the obtained material is used at room temperature (20°C). So, the combination of the thermal gradient (-580° C), the different thermal expansion coefficients (Aluminum and SiC) and their elasticity modules produces a thermal stress field in the material. Depending upon the material usage (the design guiding standard), this stress state should be evaluated to be combined with the stress that acts on the material due to the applied mechanical loads.

Typically, particles have dimensions about 1 $\mu$m and act in the sense of restrain the Aluminum particles movement. The increase in the composite mechanical strength relies on (a) the restrain that the particles impose to the discordance movement through the material and on (b) the discordance density around the particles. The interaction between the SiC particles and the Aluminum matrix is complex and should be statistically taken into account. Ref. (1, 2) has a deep discussion about composites not reproduced here. An analytical formulation to establish the thermal stress state in the Al+SiC, based on the Eshelby method, dislocation mechanisms and Maxwell-Boltzmann’s distribution, was already developed by Boari in (1) who obtained the composite most probable average thermal stress considering the influence of the volumetric ratio in a linear material.

Besides his analytical work, Boari (1) developed a set of numerical analysis in which the particles were generated on random positions and size, aiming to confirm his analytical results. To stick with the principles (some implicit) of his analytical work, the SiC particles have circular geometry and the materials were both considered to be linear. The statistical treatment of the respective set results, allowed to estimate the most probable average value of thermal stress in the composite material. This numerical value was close to the analytical value, confirming the Boari´s analytical approach also briefly described in (2).

## 3. NUMERICAL ANALYSES – MODELS AND RESULTS

The analyses have shown that the stress values exceed the aluminum yield strength in some points. Modified results and conclusion is expected if one considers, in the analyses, the Aluminum elastic-plastic behavior and, also, the more realistic forma of the SiC particles. So, the analytical results have a limitation for practical usage. To overcome this limitation, new numerical analyses were performed with statistical treatment in their results considering the influence of some factors not taken into account in the analytical work like the particles geometry & size and material behavior and model size as described in the next sections.

To verify the influence of a given parameter in the stresses when the material have already cooled down to 20 ºC (i.e.: $\Delta T = -580$ ºC), as already mentioned, a set of (mostly) 30 models was created. Typical results, in terms of isostress curves were generated using (in the first analyses) 9 curves interpolated by default between the minimum and the maximum value of the Stress Intensity ($SI_{min}$, $SI_{max}$) at $\Delta T = -580$ ºC. Each curve is identified by one specific color which was weighted by the amount of that color among the others defining a ‘frequency’ of that color or stress value. So, for each model/analysis there are 9 values with an associated frequency. The analysis mode stress value, that one with the higher frequency, was adopted. The set of 30 mode values is considered to follow a normal distribution with an average value and a standard deviation. All analysis were performed with the ANSYS program (3).

The figures showing the isostress curves in the composite were generated in the ANSYS general pos-processor (POST1) defining a specific color map with the R(ed), G(reen) and B(lue) values for each color/isostress. A custom program was developed in MATLAB (4) language to analyze the figures and obtain the relative amount of each color (stress level). This program is presented and discussed in (6). The Tresca equivalent stress was chosen to be plotted and used to compare the results from all analyses.

### 3.1. Material Properties, Load and Model Boundary Conditions

The main material properties adopted in all analyses are shown in Table 1. To take into account the Aluminum non-linear behavior the same stress x strain curve shown in Fig. 1 was adopted for the all non-linear analyses.

**Table 1: Adopted material properties**

| Property | Aluminum | SiC |
|---|---|---|
| Elasticity modulus | $E_a$ =73 GPa | $E_S$ = 450 GPa |
| Specific mass | $\gamma_a$ = 2800 $Kg/m^3$ | $\gamma_S$ = 3200 $Kg/m^3$ |
| Thermal dilatation coefficient | $\alpha_a$ = 23.6 $10^{-6}$ $ºC^{-1}$ | $\alpha_S$ = 4.0 $10^{-6}$ $ºC^{-1}$ |
| Poisson's ratio | $\mu_a$ = 0.33 | $\mu_s$ = 0.17 |
| Transversal elastic modulus | $G_a$ = 27.4 GPa | $G_S$ = 192 GPa |

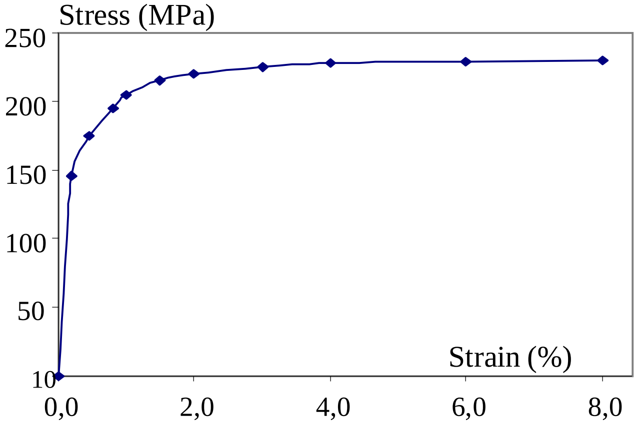


**Figure 1: Stress x strain curve adopted for the Aluminum.**

As boundary conditions, in each model/analyses, the nodes along the Y=0 coordinate were restrained in the Y direction while the nodes along the X=0 coordinate had their X direction restrained. The only load is a uniform temperature (varying from 600 ºC to 20 ºC) applied in the model in several steps, due to the Aluminum non-linear behavior, that simulates the cooling process regardless of the time. The time influence is considered irrelevant once the uniform final 20 ºC temperature is attained. So, in other words, it is assumed the cooling process takes a long time.

### 3.2. Influence of the Material Behavior – Linear x Non-Linear

To verify the influence of the composite (actually, the Aluminum) linear x non-linear behavior in the stresses when the material have already cooled down to 20 ºC (i.e.: ΔT = -580 ºC) as already mentioned, a set of about 25 models were created. For this comparison the VR value was allowed to range from 18% to 35%. Only round particles were created in random position and sizes. One should remember that, when adopting linear behavior for the Aluminum only the Elastic Modulus need be defined instead of stress x strain curve.

Fig. 2 summarizes the obtained results using 9 isostress curves to characterize the thermal stress field in the composite. As one can see, when using the linear behavior the stresses are far beyond the Aluminum yielding value and even greater than the maximum value in the Al stress x strain curve. However, these results compare well with the analytical ones. By other hand, when using the non-linear behavior the maximum stress values have a dramatic reduction (as expected). Also, the average (avg) stresses and the mode one have almost the same value and due to this fact the mode stress was adopted to represent the composite thermal stress state.

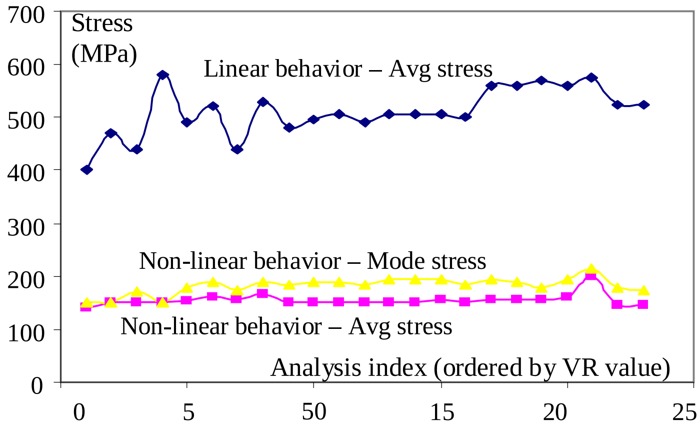


**Figure 2. Results comparison – Linear x Non-linear Aluminum Behavior**

### 3.3. Influence of the Particles Form and Number of Isostress Curves

The quadrilateral form is more realistic as one can see from Fig. 3 which is a Scanning Electronic Microscopy (SEM) photo of a sample of this composite with 590x magnification (7). In this figure one can see the 'natural' irregularity (or randomness) in the particle distribution, form and size. (The small black areas in the figure represent some $Mg_2Si$ areas not considered in this work.)

To analyze the influence of the SiC particles form in the results, two set of 30 models each were analyzed; one set with circular particles and the other one with quadrilateral particles. All of them with position, size and form randomly generated. The volumetric ratio was in the range 20% ≤ VR ≤ 25%. Also, at the same, it was analyzed the influence of the number of isostress curves used to define the thermal stress field in each model.

The initial figure pos-processing was done using 9 curves, as done previously, for both sets. Typical results can be seen in Fig. 4(a) for round particles. For the results from the quadrilateral particles, where there are more stress concentration due to the irregular form of the particles with sharp angles, it was observed larger stress range, which can reach until four times the stress range from the round particles. Due to this fact the basic results from the numerical analyses were post-processed three times to generate images: (a) using 9 isostress curves, like in Fig. 4(a), (b) using 20 isostress curves, like in Fig. 4(b), and (c) using 40 isostress curves.

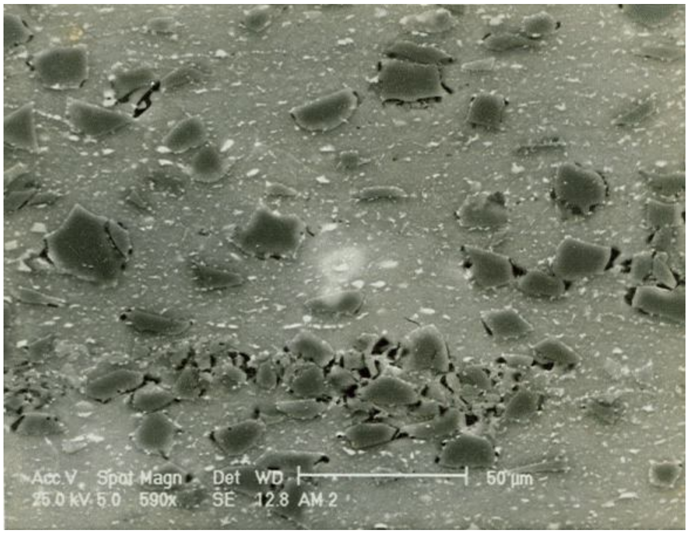
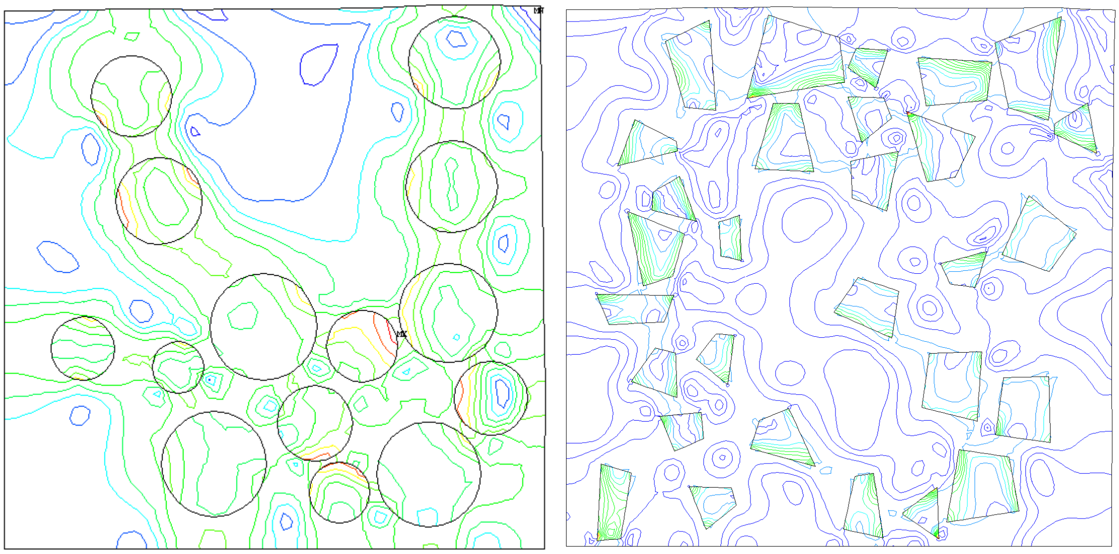


**Figure 3. Al+SiC particles (SEM photo) (7)**



(a) 9 isostress curves
$(SI_{min}, SI_{max}) = (23.8, 327)$ MPa

(b) 20 isostress curves
$SI_{min}, SI_{max}) = (27.3, 883)$ MPa

**Figure 4. Typical Stress Distributions (Round and Quadrilateral particles)**

### 3.3.1. The number of isostress curves

The calculated composite thermal stress range changed as the number of isostress curves changed toward a ‘converged’ value as the number of isostress increased. Using 9 curves the average value for the mode stresses from each model was found to be ~160 MPa with standard deviation of ~15 MPa. When 20 and 40 curves were used these values were, respectively: 175 and 180 MPa (average) with, 10 and 5 MPa of standard deviation. These results show clearly, that there no practical difference between the average mode stress obtained using 20 or 40 isostress curves to characterize the thermal stress field in the composite.

### 3.3.1. The form of the carbide particles

To establish the average value of the thermal stress value in the composite, considering the round and the quadrilateral particles, it was used the results obtained from the post-processing images (like in Fig. 4) with 20 curves to characterize the stress field in one givel model. After the processing of the images with the isostress curves to obtain the respective mode value and applying the statistics in the set of 30 mode values, assuming a normal distribution, the results are summarized in Table 2.

**Table 2: Round x Quadrilateral Particles Comparison**

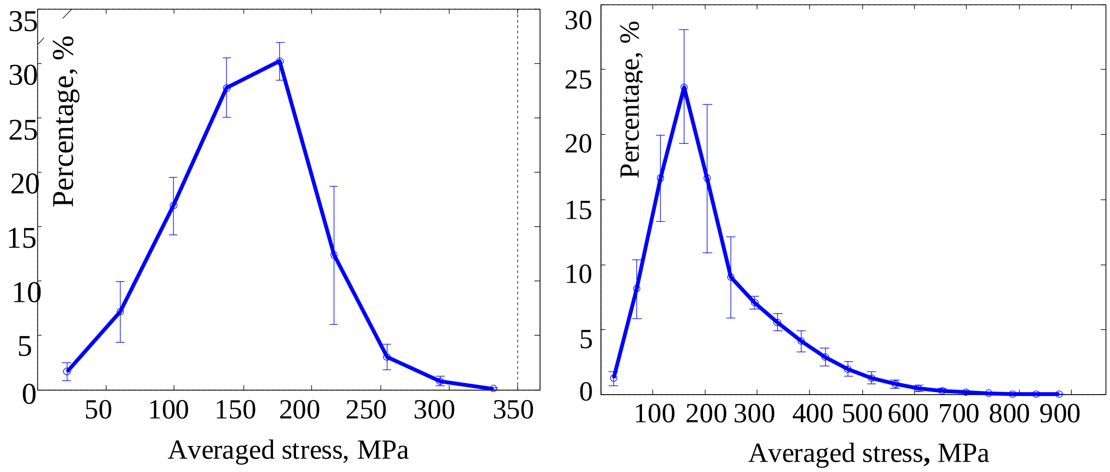
| Particle form | Avg mode value (MPa) | Standard deviation (MPa) |
|---|---|---|
| Round | 172 | 13 |
| Quadrilateral | 181 | 6.5 |

Considering the nature of the analyses: different form of particles (round and quadrilateral), randomness in the round particles (size & position) and in the quadrilateral particles (size, form & position), the above results can be seen as very coherent. The composite models with quadrilateral particles are considered more representatives once the particles geometries are more generic then the circular ones.

In a normal distribution, a range of ±2 times the standard deviation around the average value encompass about 95% of the whole ‘universe’. Taking this as a confidence range/value, and considering the results associated with the quadrilateral form, it is possible to say that the thermal stress in the Al+SiC composite is within 155 MPa and 195 MPa (average value of 175 MPa, and a standard deviation of 10 MPa).

Also, analyzing the results, it was observed a strong influence of the number of isostress curves (9, 20 and 40) in the stress values distribution even if the average or mode value are almost the same, as can be seem in Fig. 5, for 9 and 20 curves. In this figure, the percentages of each isostress curve index (all the first isostress values, all the second ones, etc.) were averaged and the bar represents the respective standard deviations. (These averaged values and std dev are different from those presented above.) As can be seen from the Fig. 5, the mode values are almost the same but the curve associated with 20 isostress values have a very low representative tail over high stress values. A more pronounced behavior occurs with the equivalent curve for 40 isostress values.

These curves show that the very high stress values in the composite (in the SiC particles) has a very little, sometimes a null, influence over the desired result (the mode value). This will be more explored in the next section when the influence of the model size will be analyzed.



(a) 9 isostress curves

(b) 20 isostress curves

**Figure 5. Frequency associated with the Averaged Stress Values**

### 3.4. Model Size: 10L, 20L and 40L

In all models used in the previous analyses/results it was assumed it represents a slice of square cross section geometry, whose side length is about 10 times (10L) the particles average size (L). As principle, the thermal stress depends on the thermal gradient, it is not the absolute value of the particles and models that matters, but its relative size. However, a doubt remains: as we have a model that mixes two materials (a matrix with disperse particles), the appropriate size of the model or how many times the side length should be greater than the average particles size (L). Or, in other words, how many SiC particles should be considered disperse in the Aluminum matrix to satisfy the principle above mentioned.

So, two new sets were generated with 20 models in each set: one with 20L and the other with 40L as the size of the each model length. In both sets we have 20% ≤ VR ≤ 25%.Typical results from both model set with 20L and 40L always at ΔT=-580 °C, the last step in the non-linear numerical analysis, as done in all previous results, are shown in Fig. 6 where one can depict the (also typical) meshes for each set. The average size of the particles is the same of all previous analysis so is the whole model that has increased with the correspondent increasing in the number of particles.

The results (figures/images) were obtained with 20 isostress curves, as done before, using the ANSYS default values. However, considering that the maximum values of stress are too high it implies a wide stress range associated to each curve/value of isostress. The representativeness of these very high stress values is none once their percentage distributions show systematically a stronger asymmetry and a tail longer than that in Fig. 5b.

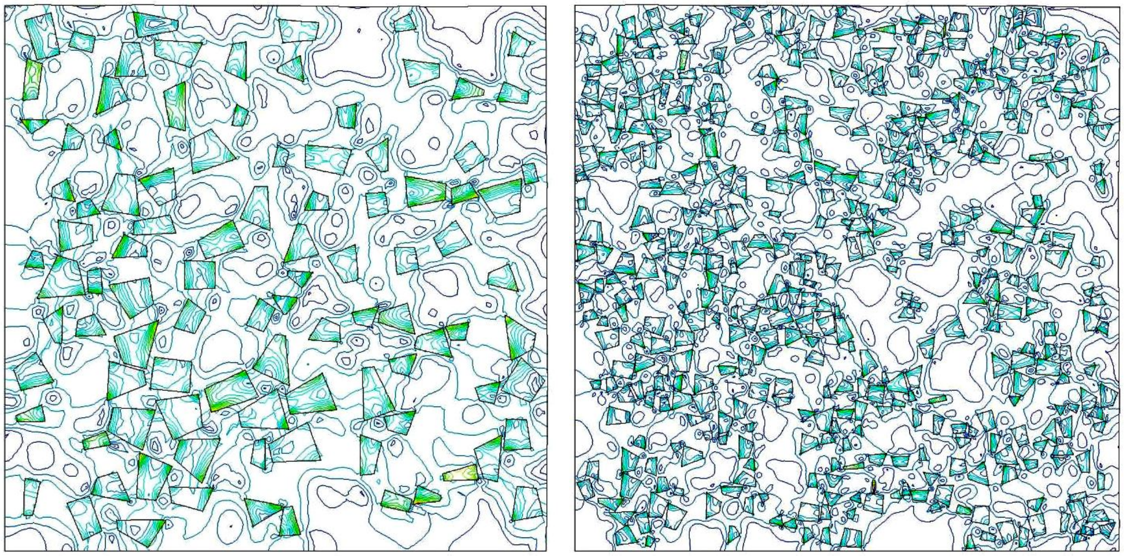
In the previous analysis (Fig. 5b) the higher stress value is around 900 MPa and in these new analyses the maximum is around 1200 MPa, always found in the composite particles. So, part of the tail that can be neglected choosing an appropriated cutting value that represents a lost in the accumulated percentage ~0%.

So, after the initial analysis of the results it was found appropriated to re-process the raw analyses generating new figures of iso-stress cutting the non-representative tail of the asymmetric percentages distribution at 650 MPa. This represents a loss in the accumulated percentage that is less than 1%. So, this procedure will have no influence on the average stress or in the mode stress values and it is equivalent, roughly, to double the number of isostress curves to from 20 to 40 curves.

Figure 7 shows the (new) stress distributions imposing $SI_{max}$ = 650 MPa, typical for the 20L and the 40L models.

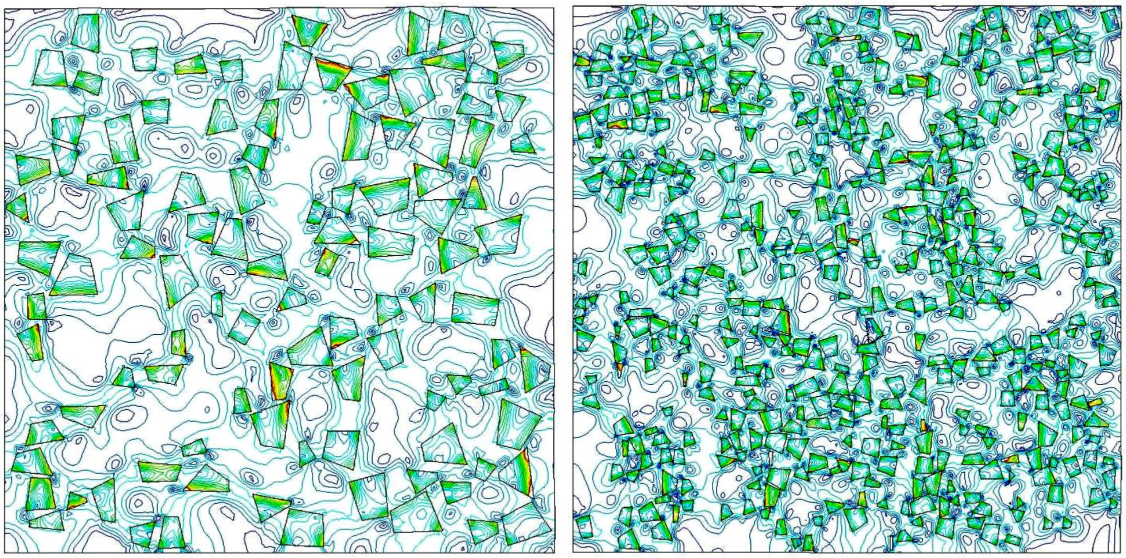
Using the same statistical procedure already adopted in the previous analysis, for both sets of 20L and 40L models, it was found the value of 161 MPa as the most probable thermal stress value, with null dispersion. This value can be considered to stick with the previous section results.

Note: A second reprocessing of the raw results was done considering, this time, the stress cutting value set to 330 MPa (results not shown). This represents a small influence on the average stress (not used in this work), less than 5% of accumulated percentage, and a lesser influence on the mode stress. This approach is equivalent, roughly, to double the number of isostress curves to 80 curves. Using this approach, a most probable thermal stress value of 172 MPa was found also with null dispersion. This value is very near the ones obtained in the previous section. This discussion as well these results were already presented elsewhere (5).



(a) ($SI_{min}$, $SI_{max}$) = (31.8, 1210) MPa (b) $SI_{min}$, $SI_{max}$) = (32.4, 1230) MPa

**Figure 6. Typical (Initial) Stress Distributions: (a) 20L and (b) 40L models**



(a) ($SI_{min}$, $SI_{max}$) = (30.0, 650) MPa (b) $SI_{min}$, $SI_{max}$) = (30.0, 650) MPa

**Figure 7. Typical (Re-processed) Stress Distributions: (a) 20L and (b) 40L models**

## 4. CONCLUSIONS

The work presented the adopted the methodology and obtained results of a systematic study using numerical analysis to obtain the average thermal stress value in an specific metal matrix composite, the Al+SiC. The particles were created with random size, form and position. In all created set of models, regardless of the analyzed parameter, the volumetric ratio (VR) is in the range: $20\% \leq VR \leq 25\%$, near the value of an actual composite. The influence of several parameters was investigated: (a) the material behavior (linear x non-linear), (b) the carbide particles form (circular x quadrilateral), the number of isostress curves (9, 20 and 40) considered in post-processing phase of each analysis, and the model size (10L, 20L and 40L). Each of above analyzed condition produced conclusions to guide the next step. To have a statistical relevant group of values at least 20 models (sometimes, 30 and 40 models) were analyzed in each set.

Considering a confidence interval of 95% as defined: a range of ±2 times the standard deviation around the average value, the average thermal stress value in the studied composite is 175 MPa with a standard deviation of 10 MPa. This average thermal stress value is due the manufacturing cooling process of the composite (obtained by mixing and extrusion of the materials at 600 °C and considering its use temperature at 20 °C). it should be taken into account when evaluating the material strength once for some usages the thermal stress is important.

As the results have shown, due to their random size and shape some particles can experience strong stress gradients. This could lead them to brittle fracture. However, most of them are confined by the ductile surrounding material which turns more unlikely their fracture. Even so, the overall results remain once the stress redistribution will be localized.

## ACKNOWLEDGMENTS

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