NUMERICAL MODELING FOR MECHANICAL AND THERMAL ANALYSIS OF RESIDUAL STRESSES FROM THE WELDING PROCESS

Thiago Vidal Valente, ligoar@gmail.com
Universidade de Brasília

Jorge Luiz de Almeida Ferreira, jorge@unb.br
Universidade de Brasília, Faculdade de Tecnologia – FT, Departamento de Engenharia Mecânica – ENM, Campus Universitário Darcy Ribeiro, Asa Norte, Brasília – DF, CEP 70910-700

Abstract. *It is usual in the construction or maintenance of mechanical elements, to join or repair parts by means of welding processes. . Such processes cause a number of changes in the base material due to the high temperature gradient generated in the process, and produce heat affected zones, (HAZ), which are susceptible to failures. The effect of temperature on material generates a thermo expansion, followed by a subsequent contraction due to cooling. This phenomenon generates a field of residual stresses which is usually responsible for failure fatigue. Therefore it is important to estimate the magnitude of the residual stresses to take control of a failure. The analytical study of such problem is very complex and the corresponding analytical solution is often inexistent in the case of big structures such as a turbine runner. In this work, a numerical analysis method is employed to estimate the problem solution. The finite element software ANSYS was used to model the effects of a welding repair carried out on a Francis turbine runner blade. The method of analysis is of direct type, i.e. built a numerical model of transient process and not a linear input of heat generated by the welding, and has parameters for the variation in thermal properties such as enthalpy and thermal conductivity depending on the temperature. They are also used to the phenomena of convection and radiation conditions as a control for temperature. With this model is obtained the temperature field in the region, which is used as loading for mechanical analysis, which is supported by experimental parameters of stress-strain, modulus of elasticity and coefficient of thermal expansion as a function of temperature. That way you get the residual stresses generated by the process of welding.*

Keywords*: Fatigue, welding, computation analysis and finite element*

1. INTRODUCTION

The process of welding is an excellent tool for engineering, as construction and assembly of components and for repair parts. Its diversity of application is given the benefits described by Masubuchi et al (1980), and flexibility of application in relation to the geometry of the part to be welded, relatively low structural weight, high efficiency of unity, good tightness, low cost, length of project, increased structural performance, among others. But like any process it is clear that it also has disadvantages for use in addition to generating structural commitment, these described by Masubuchi et al (1980) and difficulty of isolation of cracks, the susceptibility of defects from the process itself, as cracks, inclusions, pores appearance of residual stresses and distortions.

One serious consequence of the process of welding is the formation of residual stresses. Their appearance is primarily due to its non-uniform plastic deformation. Such deformations are caused by increase or decrease of temperature in the welded joints, so the hot dilated part suffers a restriction due to the cold that leads to plastic deformation between the parties. When the set starts to cool the hot part that has plastic deformation cannot return to its original form appears as a stress of traction between the deformed and the thermally undisturbed. Therefore the weld in any order of magnitude of residual stresses reaches the limit of flow at some point.

The consequences of the residual stresses become more severe when these are added the heat affected zones (HAZ), these areas are areas that suffer a loss of resistance due to a change of micro structural material in this and the interface between molten metal. Such change occurs when granular growth may cause the migration of an alloying element, thus reducing their resistance. So the combination of these effects in a mechanism under transient may be grounds for failure of primary fatigue which makes the determination of both the field of distribution of residual stresses in its intensity to obtain a better prediction of failure by fatigue.

Various heat treatments are described by Terai, (1978), Masubuchi, (1980) and Micharelis (1996) to reduce the appearance of residual stresses or relief them, but methods are restricted to a specific set of cases due to geometrical and structural constraints, which contributes further to the necessity of obtaining the field of residual stresses. Experimental methods for obtaining the field of tension are generally difficult to use and expensive, but with this development came a new computational tool cheaper and more application that is to use the numerical method of finite elements for modeling of welding. Nomoto & Ueda (1971) were the pioneers in using finite element for the study of residual stresses in welds, considering the effects of changing temperature on the modulus of elasticity of the material, flow stress and coefficient of linear thermal expansion. Already Micharelis & DeBiccari (1997) models used for the plane strain state in a HAZ together with three-dimensional models related to the study of distortions from the welding process. However to obtain the residual stresses behavior is not a trivial process since both thermal and mechanical properties vary with temperature.

This work aims to generate a computational model of a real rotor Francis, subjected a process of tungsten inert gas (TIG) weld. This turbine hydroelectric power plant is in phase II of Tucuruí (Eletronorte, 2005) and after a repair and its subsequent use began to appear near the crack repair. In order to understand why the appearance of cracks is proposed, numerical modeling of the turbine to the field of residual stresses, to see whether they are factors for the appearance of cracks.

2. METHODOLOGY OF ANALYSIS

To obtain the field of residual stresses must be done two different type of analysis, a thermal transient in nature that will simulate the process of welding and a static mechanical character which aims to calculate stresses from the thermal loading. The analysis have dependency will need to use combinations of fields that aim to unite various types dependent on a physical solution. This method was validated by Alencar (2007).

In this work was used a type of field combining a sequential, i.e. the first analysis, the heat serves as loading for the second analysis, mechanics, therefore has a strong influence on the second part of the simulation, but the not influence the second part first. In explanatory see Fig 1.

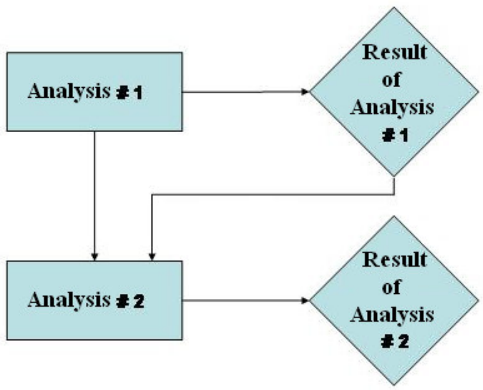

Figure 1. Flow chart for sequential analysis of coupled fields

The simulation, therefore it will be numerically taking into account that the process of welding is done from the TIG process on the basis of the rotor blade material AISI 316L Francis. Is considered for both thermal and mechanical aspects of the temperature dependent, effects of plasticity and strain Hardening the material from experimental data for stress-strain curve as a function of temperature, so a non-linear analysis of the process. The strain Hardening be isotropic and therefore considers that the plastic deformations evolve uniformly.

The analysis by finite element methods is conducted in two steps:

• Thermal analysis transient non-linear is to get the history of global temperature generated during welding. The mesh generated for the thermal analysis is the same for the mechanical analysis.

• The mechanical analysis is then made from the distribution field of temperatures obtained from thermal analysis, which is then subjected to mechanical loading for the modeling.

The analysis will be performed by finite element method, following the first stage of transient heat transfer, shown in Incropera (1992):

$$\rho c\dot{T} = \nabla \cdot k\nabla T \tag{1}$$

Where ρ is the density of the material, c is the specific heat of the material k is the coefficient of thermal conductivity of the material, T is the temperature, the rate of change of temperature and $\nabla = i_1 \frac{\partial}{\partial x_1} + i_2 \frac{\partial}{\partial x_2} + i_3 \frac{\partial}{\partial x_3}$ is the gradient vector in three dimensions. The heat transfer is given by:

$$q_S = -k\nabla T \tag{2}$$

The gradient of temperature is more intense in heat affected zone in the direction perpendicular to the weld. Due to this fact the term mechanical properties have severe changes in small distances, so refinement is needed in the localities of ZTA's, to have a more satisfactory approximation of the effect of the welding.

2.1. Thermal analysis

In thermal analysis, is of fundamental importance to raise the dependencies of physical properties of the material in relation to variation in temperature, because they directly affect the temperature field. The temperature dependence of the transient is generated in the process at certain intervals of time and its difficulty is the fact that the determination of physical properties becomes difficult to measure at high temperatures and is exactly the high temperatures that will be made for thermal analysis, as it is necessary to melt the material. Because it is crucial that a good prediction of physical properties. Equation (3) calculates the temperature in two intervals of time:

$$T(\tau) = T(t-\Delta t) + \frac{\tau}{\Delta t}\left[T(t-\Delta t) - T(t-2\Delta t)\right] \tag{3}$$

Defining g as a coefficient of the material which depends on temperature, i.e. function of T (τ) has been that in a given time t has the following form:

$$g = \frac{1}{\Delta t}\int_{t-\Delta t}^{t} g(T(\tau))d\tau \tag{4}$$

Since it is necessary to obtain two key properties for thermal analysis, the thermal conductivity and enthalpy, both depending on the temperature. These parameters were obtained by Depradeux, (2004) and provided input for the thermal analysis.

2.2. Mechanical Analysis

Similarly to what occurs in the thermal analysis, mechanical analysis requires the essential parameters for the analysis of the welding process, which directly influence the values of residual stresses. Due to the high values of temperature generated in the process of join and behavior of mechanical properties data as a function of temperature are obtained experimentally from Depradeux (2004), it is necessary to analyze the modulus of elasticity, coefficient of thermal expansion all depending on the temperature. It is also considered a Poisson coefficient of 0.35.

For strain Hardening multi-linear isotropic material according to the criterion of Von Mises plasticity, a stress-strain curve as a function of temperature was obtained experimentally by Depradeux (2004), as illustrated in Fig. 2. For deflections above 1.5% was considered a behavior of perfect plasticity.

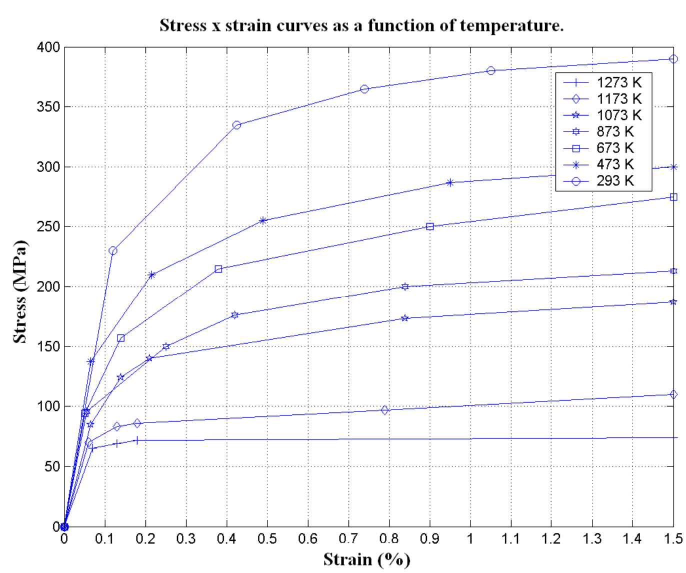

Figure 2. Stress-strain curves as a function of temperature.

2.3 Computational Modeling

It applies the finite element method (FEM) using the commercial program ANSYS ® Multiphysics as a tool for analyzing both mechanical and thermal as ANSYS ® Workbench to build the geometric model of the Francis turbine and for generating the initial mesh . The simulation is on top of a Francis turbine which was designed computationally using technical drawings, and later was a characterization in this specific element, showed in Fig. 3. Used for thermal analysis is a SOLID 87, ten of us in tetrahedral form with a degree of freedom in each node, the temperature, as for the thermal analysis SOLID 92 that has ten of us in tetrahedral form, each with three degrees of freedom has plasticity, stiffness in tension, and most importantly, supports large deflections and traction.

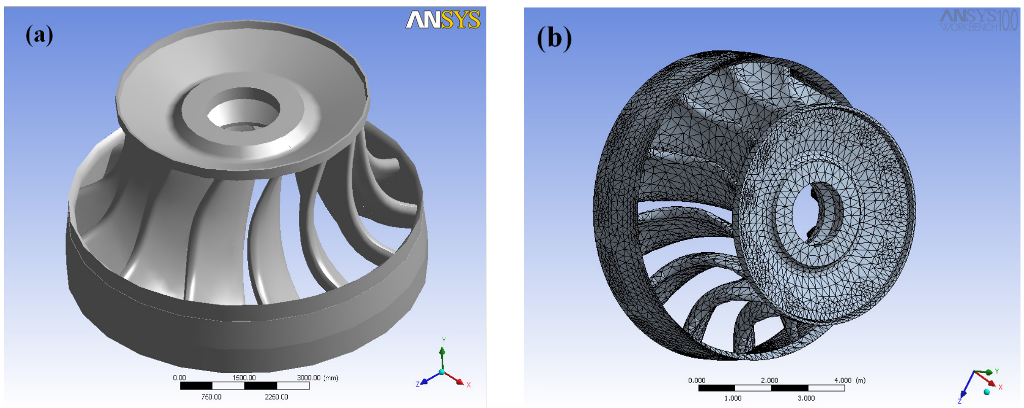

Figure 3. (a) Design of the turbine in ANSYS (b) Turbine characterization in elements.

3. RESULTS AND DISCUSSION

For simulation of seam weld was selected only one region between the strap and the rotor blade, this area is applied to input of heat, but to make the simulation more close to reality, it should be applied in a transient, i.e. input of heat walks the length of cord to both the welding region was divided into eight smaller areas with the same amount of elements, this is done to have a homogeneity in the heat inserted in each region, since all that is primary that the areas of the cord to reach the solder melting temperature of the material, which is around 1400 ° C. The eight areas were decided because of the time and amount of welding set of steps that makes the simulation, the time is 40 s for the seam weld, then for each area of the heat input will be 5 s. The Figure 4 shows the welding cord.

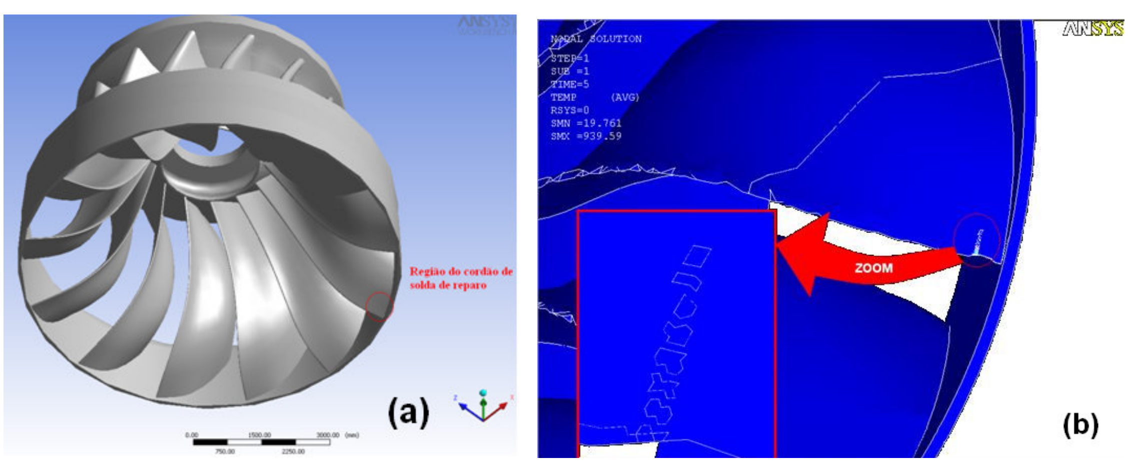

Figure 4. (a) Region of the welding cord. (b) Division of the cord in 8 areas.

Because the area of interest for the cord to be well below solder compared to the whole and because the temperatures are high and the magnitude is small at times make it necessary for the refinement of the mesh elements, because elements can cause a very large high gradient of temperature in a small space that generated the results masked. The refinement rather is generated in three different stages, the refinement to become smoother, i.e. without any sudden direction of the elements, which could lead to risk the reliability of results. Therefore the first stage of refinement will be done in a wider area and will reduce up to a region near the seam weld; this effect is shown in Fig. 5.

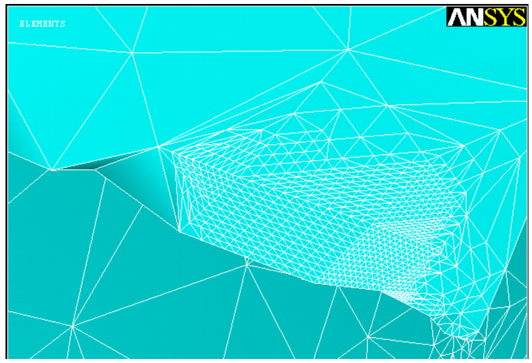

Figure 5. Progressive refinement.

3.1 Obtaining the gradient of temperature

It is common in the welding process starts with pre-heating a part to avoid a thermal shock in the play and generate weakening of the crystalline structure of metal. In order to simulate this effect the region of the blade has a heating until a temperature about 150 ° C then be applied to the input of heat, Fig. 6.

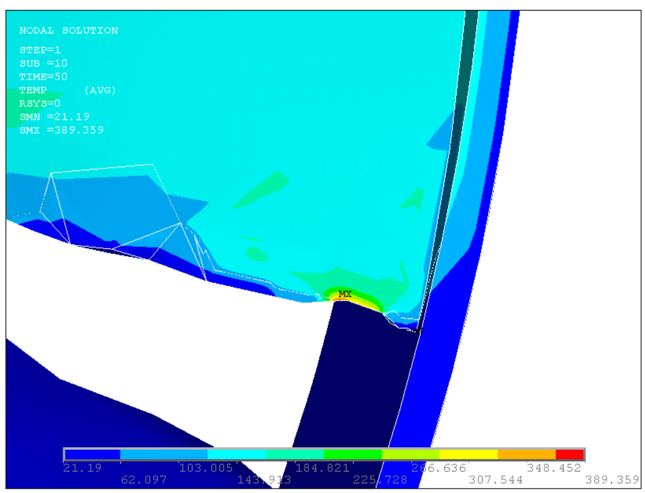

Figure 6. Pre-heating.

The input of heat occurs in a homogeneous, is the entry of heat in each region are equal and worth $2x10^4$ Watt, which was subsequently divided by an approximate average area of each region of the solder, in the form of a circle of radius $2x10^{-3}$ meters so each region has reached the melting point of the material, as seen in Fig. 7.

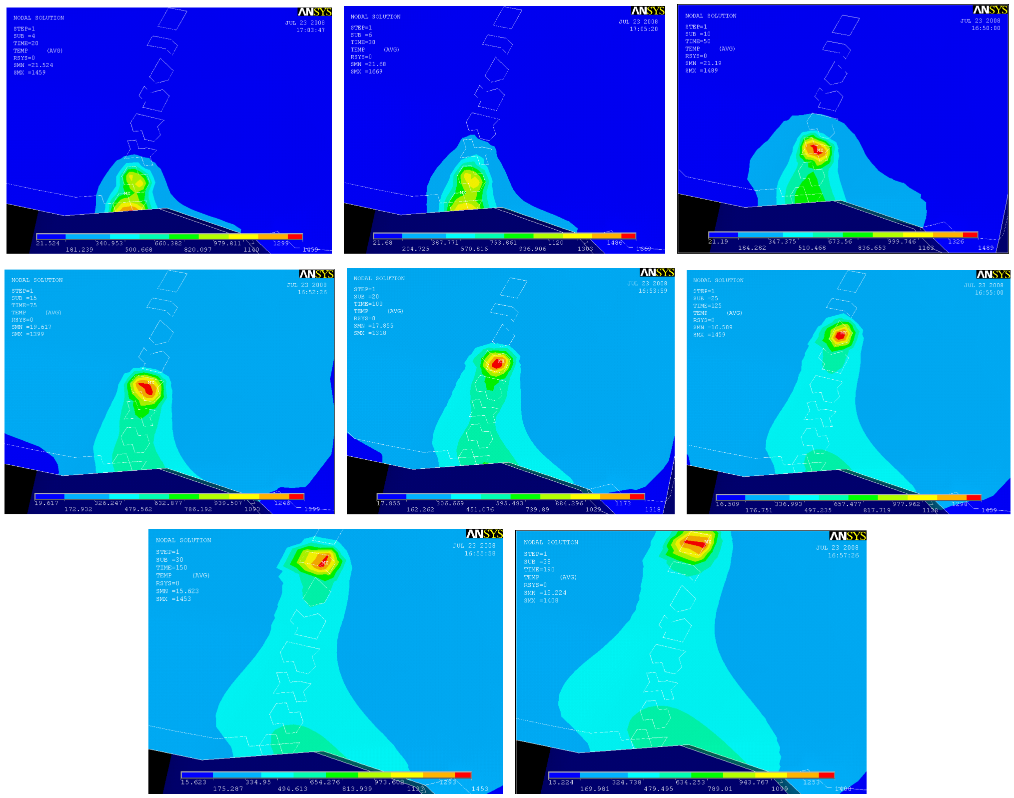

Figure 7. Input of heat in each region of the cordon of soldiers.

After temperature increase it is expected to play important cool to put it into operation, so it was time to apply a cooling that caused due to convection between the turbine and the environment to 22 ° C and the heat conduction pro remainder of the turbine. For the application of radiation assumed an emissivity of 0.75, which is consistent for steel alloy. To demonstrate the entry of heat and cooling of the piece, was raised a graph, shown in Fig. 8, containing the eight areas and the rise and fall of temperature against time, it was stipulated a maximum time of 300 seconds.

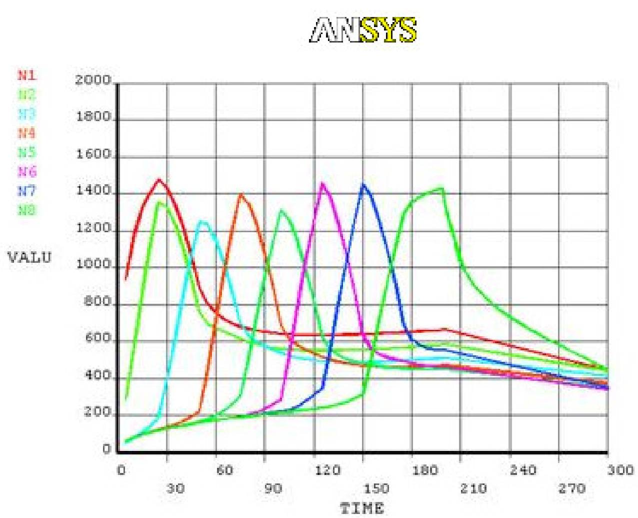

Figure 8. Graph of heating and cooling of the cordon of soldiers.

3.2 Obtaining the residual stresses

To obtain the residual stresses the model must be analyzed statically, so your movement should be restricted and if the turbine is of a rigid, i.e. no movement between them, so just restrict any part of the structure. Thus apply the temperature gradient generated as static loading. The residual stresses obtained comprise only a small part of the blade, however a relatively large area when compared to the size of the seam weld, and this shows the residual stresses are distributed through the material, which is in agreement with reality. The average magnitude of tension in the area around the loading of 151 MPa, however there is a very small area where the stress is maximum, that occurs at the edge of the blade, which is well justified due to the effect of concentration of stress in edges, then the residual stress is around 271 MPa, and a point very requested in the turbine when it is in operation. These data can be seen in Fig. 9.

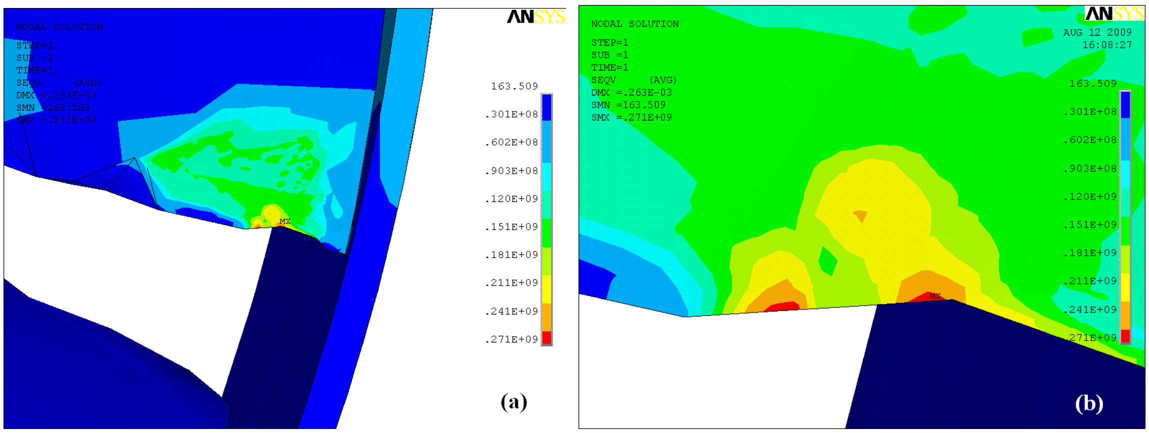

Figure 9. (a) Field of residual stresses (Von Mises). (b) Approximation of the field of tension.

To better visualize the influence of plastic deformation in the development of residual stresses were built 4 different graphs showing the evolution of these two variables over time, and so as to influence a change in another. Was chosen a remote area in the field of residual stresses, whose magnitude is minimal and it is approximate to an area where the magnitude of residual stresses is close to the maximum. Figure 10 shows regions of magnitudes lower, as the Fig. 11 shows regions with high magnitude.

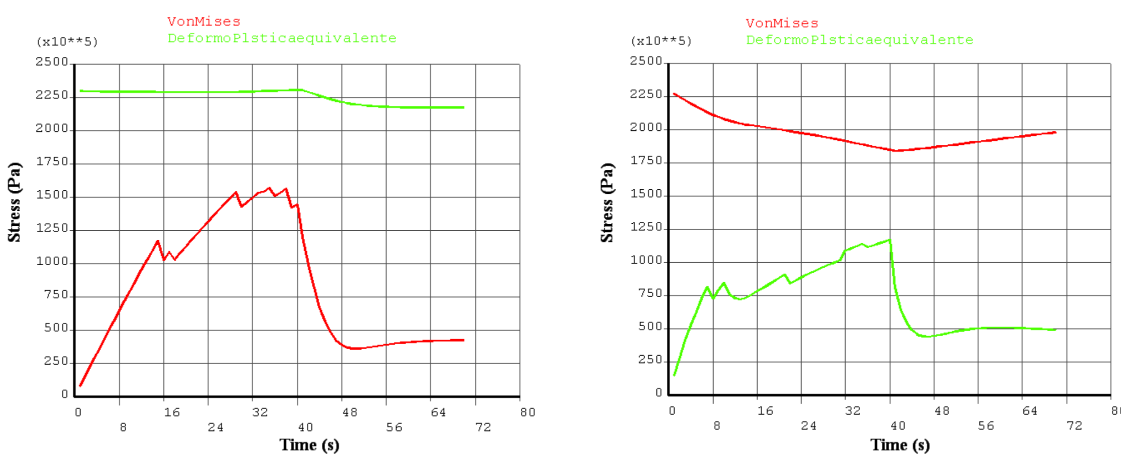

Figure 10. More remote regions in the field of tension.

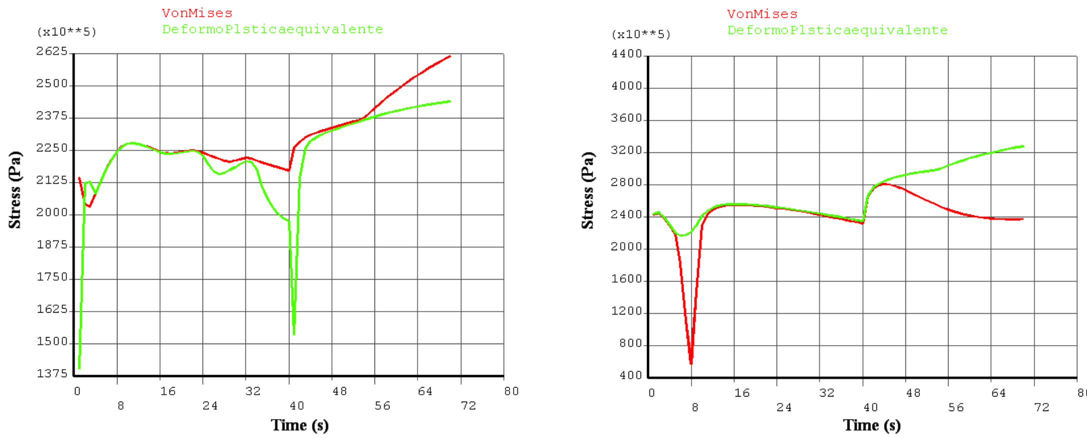

Figure 11. Regions with high magnitude of strain.

As expected and seen in the literature the residual stress generated in a thermal cycle is associated with plastic deformations, which is evident in the graphs shown in Fig (11), since the curve of Von Mises intend to monitor the effects generated by the equivalent plastic strain and where the magnitude of residual stress is near the maximum, the second graph of Figure (11), we see a behavior very close to the curves, and the sometimes difficult to differentiate one from the other. Already a Fig. 10 shows that in regions distant from the appearance of residual stresses is not directly affected by plastic deformation, but because of tension created in the epicenter of the field of residual stresses, which is expected when a metal material pulled, and that is why the tensions are lower.

Von Mises stress of the show only the magnitude of residual stresses but not the sign of the displays, to verify that the residual stresses are tensions real traction and therefore more harmful to the tension-compression as described in the phenomenon of the appearance of residual stresses, is constructed a graph, shown in Fig. 12 containing the three major point of tension within the field of residual stresses near the maximum stress.

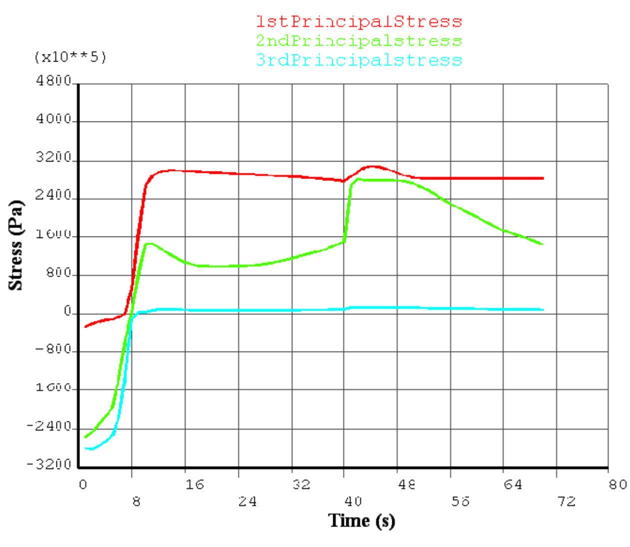

Figure 12. Tensions in the main field of residual stresses.

As expected the graph shows that at the beginning of the process of welding the stresses are compressive in nature due to expansion of the metal, and the tension is sufficient to plastically deform the metal, with the gradual cooling of the weld region of note is the increase in tension until it becomes traction, which is the contraction of the material and pull it generates due to the fact that material cannot return its original form because of plastic deformation.

4. CONCLUSIONS

In computational studies it is important that the simulation of the problem or event presents a similarity with what occurs in real cases, and this study was able to show results that accompany the phenomena generated by the welding process, were identified as cited by the graphs, the simulation of the problem tends to show results close to the real, thus validating the study. As seen, despite the region of the cord of a small welding residual stresses in the field covered an area greater than the stress magnitude has the order of 200MPa, high enough to cause the fracture by fatigue, when the rotor enters into arrangements, this is an important factor to predict the effects of fatigue on the turbine. The next step would be using this field of residual stresses as a condition of entry into a simulation of fatigue in order to obtain coefficients and verify the precise damage to the field of stress from a welding process. Another interesting thing to do is a simulation with measures that can alleviate the field of stress and verify that generate better results.

5. ACKNOWLEDGEMENTS

This project was supported by Centrais Elétricas do Norte do Brasil S.A. – Eletronorte, UnB and Finatec. These supports are gratefully acknowledged. And I thank the GAMMA group and my supervisor Jorge Luiz for the help

6. REFERENCES

Alencar, Cristiano A., 2007, **Modelagem Numérica para Análise Térmica e Mecânica de Tensões Residuais Resultantes do processo de soldagem-Fase I**, Projeto de Graduação, Departamento de Engenharia Mecânica, Universidade de Brasília.

Depradeux, L. **Simulation Numerique du Soudage – Acier 316L – Validation sur Cas Tests de Complexite Croissante**, Ph.D Thesis, Ecole Doctorale des Sciences de L'Ingenieur de Lyon, L'Institut National des Sciences Appliquees (INSA) – Lyon, 2004.

Fujita, Y. and Nomoto, T. **Studies of thermal stresses in welding with special reference to weld cracking.** In First International Symposium on *Cracking and Fracture in Welds*, Tokyo, November 1971, 12 pp.

Incropera, F.P., Witt, D.P., **Fundamentos de Transferência de Calor de Massa,** 3ª Edição, Rio de Janeiro, Brasil. LTC – Livros Técnicos e Científicos Editora S.A., 1992.

Masubuchi, K. Analysis of Welded Structures. **Residual Stresses, Distorcion and their Consequences.** First Edition, New York, E.U.A., Pergamon Press Ltd, 1980.

Michaleris, P. and DeBiccari, A., 1997. **Prediction of Welding Distortion**, *Welding Journal*,76(4), 172s-180s.

Michaleris, P., Sun, X., **Finite element analysis of thermal tensioning techniques mitigating weld buckling distorcion,** The Pennsylvania State University, University Park, PA; Battelle Columbus, OH.

Terai, K., 1978. **Study on prevention of welding deformation in thin-skin plate structures.** Kawasaki Technical Review, no. 61, pp. 61-66.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.