23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

STUDY ABOUT THE STRESS CONCENTRATION SUSCEPTIBILITY OF THE TIREFOND SCREW APPLIED IN BRAZILIAN RAILROADS

Ana Luiza Soares Cezário
Universidade Federal de Ouro Preto - DEMET-EM, Campus Universitário do Morro do Cruzeiro
analuizasc@yahoo.com.br
Geraldo Lúcio de Faria
Universidade Federal de Ouro Preto - DEMET-EM, Campus Universitário do Morro do Cruzeiro
geraldolfaria@yahoo.com.br
Leonardo Barbosa Godefroid
Universidade Federal de Ouro Preto - DEMET-EM, Campus Universitário do Morro do Cruzeiro
leonardo@demet.em.ufop.br
Luiz Cláudio Cândido
Universidade Federal de Ouro Preto - DEMET-EM, Campus Universitário do Morro do Cruzeiro
candido@em.ufop.br

Abstract. *The Tirefond screw is an important structural component of railroads. It is a fixation component, responsible by the support of the plat fixation, which guarantees the stability of rails. This component is commonly produced in Brazil by hot conformation procedures of low carbon steels. However, with the increasing of transported load per train wheel in last years, this component have been often failing in service. Aiming to understand the effects of screw fillets on mechanical behavior of Tirefond screw, this work present a study about the stress concentration susceptibility of the actual low carbon steel used in this component manufacturing. Chemical analysis were done in a optical emission spectrometry equipment; microstructural analysis were performed in optical and scanning electron microscopes; tension and hardness tests were realized. Specimens submitted to tension tests were machined in two different conditions: with and without a notch in the middle of their utile area. The results showed that the steel used in Brazilian Tirefond screw are a SAE1015 with a very heterogeneous microstructure. The mechanical tests have confirmed that this steel has a high stress concentration susceptibility and this is a dangerous conditions for actual geometry of this component.*

Keywords: *Tirefond Screw, Stress Concentration, Tension Test.*

1. INTRODUCTION

In continental countries, such as Brazil, logistical issues related primarily to the transport of large volumes over long distances are problems that need to be treated with attention. One of the most recommended and effective way is the use of railroads. Aiming to guarantee the rail transport efficiency, it is important, among other things, ensure the integrity of the permanent way and of their structural components (Ildefonso, 2013).

An important structural component of the railway is the *tirefond* screw that is responsible for fastening the plates to sleepers. The support plate has the main function to support and, with the aid of clips, secure the rails. Therefore, if a screw fails and the whole set has a freedom degree to move when a train pass on the rails, they may strongly solicited in flexion loading, which may increase the possibility of fatigue cracks nucleation and growth (Klincevicius, 2011).

The *tirefond* screw used in Brazil is manufactured according to NBR 8497: 08/2008 – railroad (Tirefão) which establishes the conditions and characteristics for its manufacture. Its production is carried out from a round bar of hot rolled steel ABNT1020 with the quality certificate that meets the NBR 8855. However, over the years it has been observed that these screws are very susceptible to fracture in service and an important technological contribution would diagnose the root causes of these failures and propose solutions in order to reduce the incidence of fractures in service of this component. Figure 1 shows pictures of a recurrent mode of fracture in *tirefond* screws. It can be seen that the fracture surface is co-planar with a screw thread which is a natural stress concentrator in the screw structure.

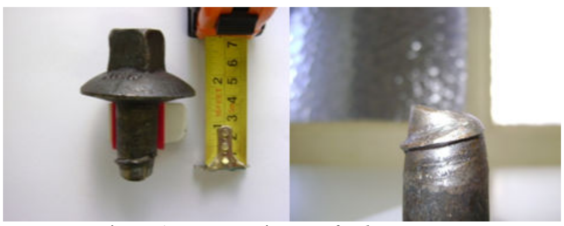


Figure 1 - Fracture in a *tirefond* screw.

The literature reports that most failures in bolts occur under "stress-stress" mode. The bolts are subjected to a preload during their installation and to a cyclic loading in service. These cyclic stresses can cause bolt failures at lower loading levels than its nominal yield strength measured in static conditions (Buda, 1994). Accordingly, the fatigue failure in bolted joints remains a concern, since the failure of a single screw can promote instability and consequent loss of an entire system. They are in the scientific literature, several case studies of mechanical failures related to the fatigue phenomenon in screws. Some authors point out the threads as stress concentrators and preferential regions for the fatigue crack nucleation. Factors that may influence the behavior of the component are the geometric aspects and the sensitivity of the material to the presence of stress concentrators, this assessment that, for simplification, can be made under static loading in order to infer the fatigue behavior (Loganathan *et al*, 2010; Griza *et al*, 2009; Milan *et al*, 2004; Chen *et al*, 2006; Ling *et al*, 2014; Kabche *et al*, 2009; Mackerle *et al*, 2003; Mínguez *et al*, 2006).

Considering that there are few specific studies about the *tirefond* screws used in Brazilian railroads associated with the fact of the screw stand out by presenting many points of stress concentration in its geometry, this study aims to characterize chemically and structurally a type of screw *tirefond* and evaluate the influence of stress concentrators on its mechanical behavior under traction.

2. MATERIALS AND METHODS

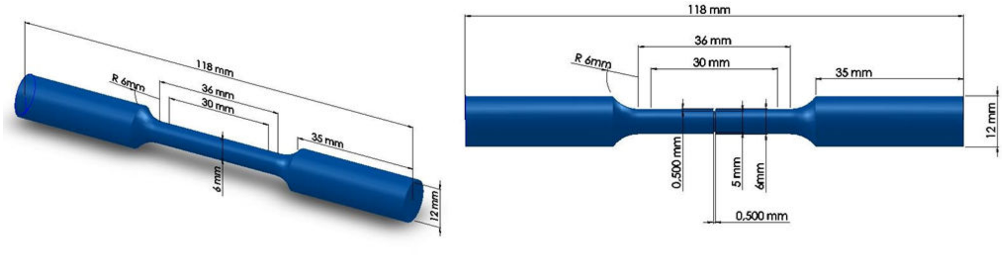
The developed activities in this study were divided into two stages: the first was the chemical, microstructural and mechanical characterization of the *tirefond* screw in its delivery status. The samples of *tirefond* screw, shown in Figure 2, were donated by a company of the logistic segment that has had problems of recurrent failure of this component; the second step consisted in characterizing the effect of the presence of stress concentrators on mechanical behavior under screw traction.

Figure 2 – *Tirefond* screw sample**.**

Chemical characterization was performed with the aid of the technique of optical emission spectrometry. Samples for metallographic preparation and structural characterization procedures were taken to make possible to characterize the longitudinal and the cross section of the screw. The screw was sectioned into three regions: a sample for characterization of the cross section and two for characterization in the longitudinal section. These steps were developed in the Heat Treatments and Optical Microscopy Laboratory (LTM) of the Metallurgical and Materials Engineering Department of Federal University of Ouro Preto.

Vickers (HV) and Brinell (HB) microhardness tests were performed in samples that correspond to the three sampled regions of the *tirefond* screw. The Vickers hardness test was conducted according to ASTM E384 in a digital Pantec microhardness machine, using a load of 10gf and the application time of 10s. The Brinell hardness test was conducted according to ASTM E10, in an Otto Wolpert-Werke universal tester, with an applied load of 187.5kgf and a spherical indenter with 2.5mm diameter (load constant of 30kgf/mm^2).

Tensile tests were performed on test samples without notch and with notch. In this last case, the notch was positioned in the middle of specimen utile area, promoting the decrease of 1mm in their diameters. The samples were standardized according to ASTM E8M. The tests were performed in a universal testing Emic machine. The displacement and strain ($d\mathcal{E}/dt$) rates were 1.8mm/min and $10^{-3}s^{-1}$, respectively. Figure 3 shows schematic drawings of specimens.



(a) (b)

Figure 3 - Schematic drawing of the test specimen (a) without notch and (b) with notch.

The Charpy impact test was performed on test specimens made from *tirefond* screws in its delivery state. The specimens were machined with standardized dimensions according to ASTM E23. The tests were run on Mechanical Testing Laboratory of the Metallurgical and Materials Engineering Department of the Federal University of Ouro Preto in a Jinan Shidai Shyin Instrument pendulum impact machine. To evaluate a possible ductile-brittle transition in the studied material, the tests were performed at different temperatures: -196°C; 0°C; 20°C; 90°C and 280°C.

After carrying out the tensile and impact tests, fractured samples were selected and submitted to fractograpich analysis. Analyses were performed with the aid of a scanning electron microscope (SEM), using a Vega 3 Tescan microscope manufacturer in Nano-Lab Laboratory (REDEMAT).

A strain hardening assay was performed in steel bars of SAE 1015 steel cold drawn until the desired strains and then tested in tensile tests. The yield strength values and the total elongation were measured and analyzed as a function of the degree of deformation.

3. RESULTS AND DISCUSSION

3.1 Chemical Analysis

The chemical composition of the studied *tirefond* screw is presented in Table 1.

Table 1 - Chemical composition of *tirefond* screw (weight %).

C	Mn	P	S	Si	Ni	Cr
0.141	0.503	0.016	0.0244	0.117	0.036	0.058
Mo	**Al**	**Cu**	**B**	**Ti**	**N**	**Sn**
0.005	0.003	0.168	0.0003	0.0006	0.0073	0.0122

It is possible to note that the studied steel is a low-carbon steel, without any significant additions of alloying elements. It presents a ttypical composition of a ABNT 1015 carbon steel, therefore it do not meets the NBR 8497 chemical specifications for *tirefond* screw manufacturing.

3.2 Microstructural Characterization

Figures 4 and 5 present the microstructure of the *tirefond* screw in longitudinal section.

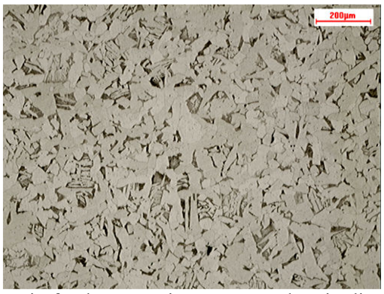


Figure 4 – Tirefond screw microstructure; longitudinal section; Nital 2% - 100x.

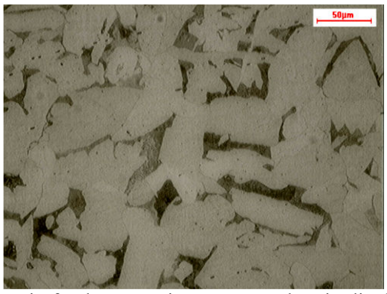


Figure 5 - Tirefond screw microstructure; longitudinal section; Nital 2% - 400x.

The screw microstructure is predominantly composed of ferrite with a significant amount of pearlite. The ferrite grains have a heterogeneous morphology (plates and strips), indicating that this material was hot worked and cooled with a high cooling rate, probably associated to a air forced or oil immersion cooling.

3.3 Hardness tests

From the Brinell hardness tests performed in cross and in longitudinal sections of *tirefond* screw, it was possible to calculate the average hardness that is 120HB in both studied sections.

In Vickers hardness (HV) tests, executed in the cross section of the screw, the average hardness values are in the range of 125HV to 175HV. This variation is mainly due to the fact that the constituent, in which the hardness was measured, sometimes was pearlite (harder) and sometimes was ferrite (lower hardness). It is possible to observe, by the graph in Figure 6, that there was no significant difference in the hardness values measured in central regions and ate screw threads. This is probably a result of the manufacturing process where the screw is heated to 1100°C and then strained in the austenitic field, therefore, during cooling the primary ferrite and pearlite nucleate and grow from the deformed austenite, with no evidence of banding or strain hardened zones along the screw.

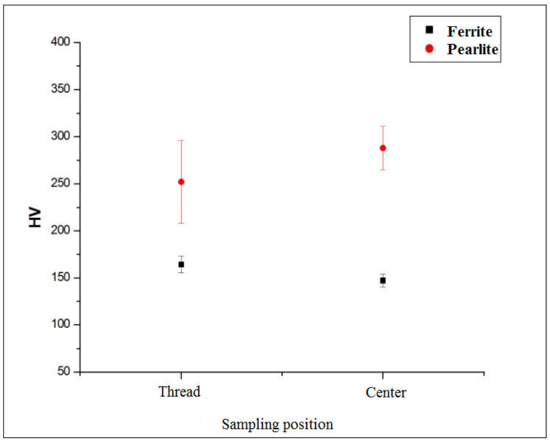


Figure 6 – Vickers microhardness in longitudinal section of *tirefond* screw.

3.4 Tensile Tests

From the tensile tests performed on specimens without and with a notch, it was possible to build engineering comparative curves as shown in Figure 7, where the abscissa shows the strain (%) and the ordinate axis presents the uniaxial stress (MPa).

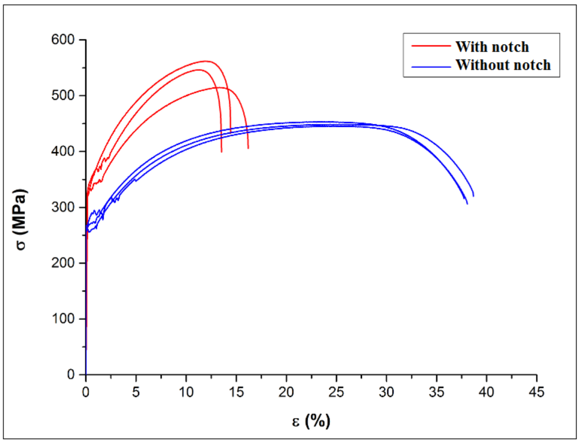


Figure 7 - Comparative curves of tensile tests for specimens without and with notch.

The comparative curves of tensile tests shows significant differences regarding the ductility and strength parameters between notched and not notched specimens. It is possible to observe that the notched specimen presented the highest yield strength and the lowest ductility. Table 2 shows a comparison between important mechanical parameters measured in tensile tests for notched and not notched specimens.

Table 2 - Tensile test parameters.

Parameters	Without notch	With notch
Yield point σ_{ys}	262.5 MPa	325 MPa
Tensile strength σ_{ts}	450 MPa	540 MPa
Total strain (ε)	38%	15%
Reduction of area (R.A.)	65%	43%

Regarding σ_{ys}, it is noted that the notched specimen have a higher value when compared with the specimen without notch. This difference is explained mainly by the stress concentrator presence which increases significantly the stress in its vicinity. These stress concentration areas meets the maximum stress value along the specimen diameter during the elastic straining. These regions may reach and initially exceed the material yield strength. However, in areas distant from the stress concentrators, a large volume of material is still in the elastic strain regime. As the load is being applied there is a tendency of equalization of stresses, thereby causing the material to an outlet at a lower loading level (strength), but with corresponding higher stresses, damaging the material ductility (Peterson, 1974).

Specific values of maximum stress in the critical section are determined by advanced mathematical experimental methods or techniques that employ the theory of elasticity. The results of this investigation are provided in graphical form. The stress concentration factor (K) is defined as the ratio between the maximum and the average stresses (nominal) acting on the smaller specimen cross section (Hibbeler 2004).

The ultimate linear stress of the not notched specimen is 260MPa. Considering its initial diameter equal to the useful area D = 6mm and the possibility of putting a notch fit for the diameter d = 5 mm (as done in the experiment), it is possible to calculate the ratio D/d = 1.2. By using the curves shown by NORTON (2002), it was possible to obtain the curve that determines the factor of static stress concentration as a function of the ratio r/d wherein r is the slot curvature radius. The Figure 8 presents the obtained results. For a notch radius r=0.5mm, the r/d rate is 0.1 and the approximate static stress concentration factor is k = 2.1.

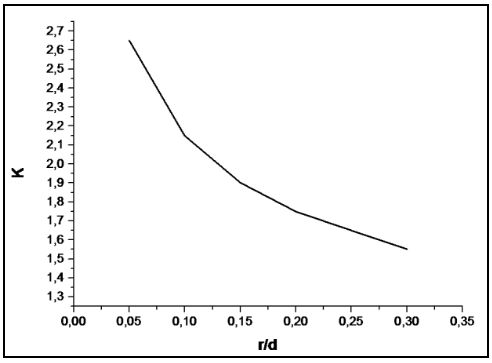


Figure 8 – Stress concentration as function of the notch r/d ratio for D/d = 1.2.

After these analyses, it is noticed that the used steel for *tirefond* screw manufacturing is very sensitive to the presence of stress concentrator presence under static loading. It is supposed that under cyclic loading, this fact may be aggravated because the screw threads will probably work as preferential points for fatigue crack nucleation.

Figure 9 shows the curve of the strain hardening test for a SAE 1015 steel used in the *tirefond* screw manufacturing. It is observed that there is a significant increasing of the yield and tensile strengths with the steel straining. Therefore, replacing the hot rolling of screw threads by a cold rolling may be feasible, since this steel demonstrates good ability to strain hardening. This change in the process can increase significantly the steel's yield strength in the screw surface.

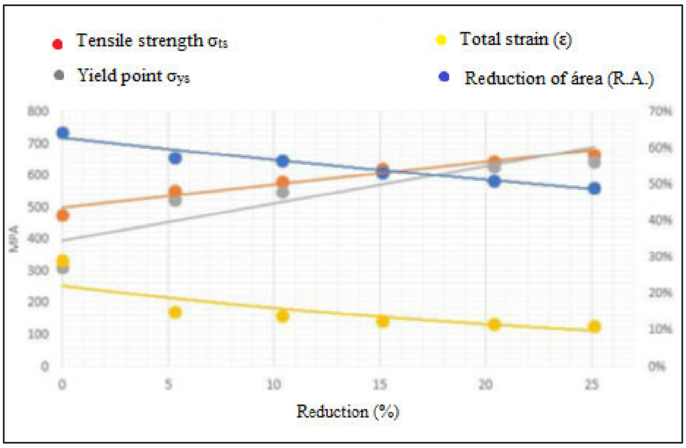


Figure 9 – Strain hardening curve of SAE1015 steel.

3.5 Charpy impact tests

Figure 10 shows the curve of the impact toughness versus temperature obtained in the Charpy impact tests.

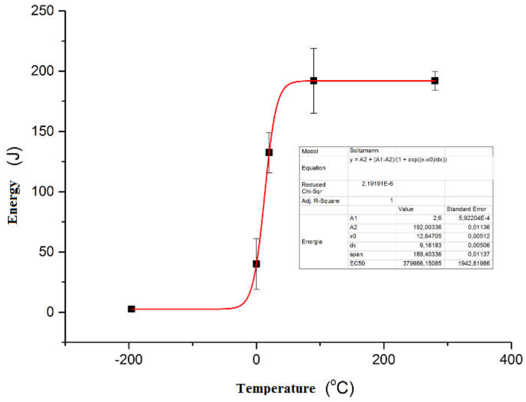


Figure 10 – Results of Charpy impact tests.

Based on the obtained values, it was possible to make a nonlinear fit of experimental data, according to the Boltzmann equation (1), whose parameters A1, A2, x0 and dx are respectively 2.6; 192; 12.8; 9.2.

$$y = A2 + (A1 - A2) / (1 + \exp((x-x0) / dx)) \quad (1)$$

From the obtained curve, it is noted that the lower temperature, the lower the absorbed energy, as well as the specimen temperature rises, its absorbed energy increases. Thus, it can be said that materials with low service temperatures tend to have a brittle behavior, since its mechanical strength significantly increases and the impact toughness decreases, while the materials with higher service temperatures tend to have a ductile behavior. The *tirefond* screw ductile-brittle transition occurs between 0°C and 25°C. At a temperature below 0°C, the screw may present a dangerously brittle behavior.

3.6 Fractography

Through scanning electron microscopy technique (SEM), fractographic analyses were performed in the specimens submitted to tensile tests. Figure 11 shows a comparative picture of the fractured regions of the notched and not nothced specimens.

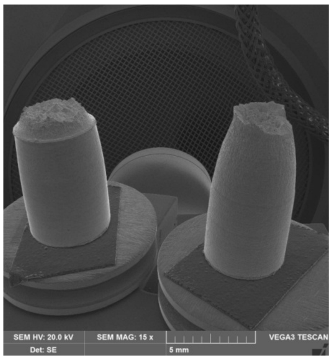


Figure 11 – Comparison between the fractured surfaces of notched and not notched specimens - tensile test - 15x.

It is observed that the not notched specimen presented the highest necking effect. Figures 12 and 13 present, respectively, images from fractured surfaces of not notched and notched specimens respectively. The fractography of without notch and notched specimens showed significant amounts of *dimples*, featuring fractures such as ductile.

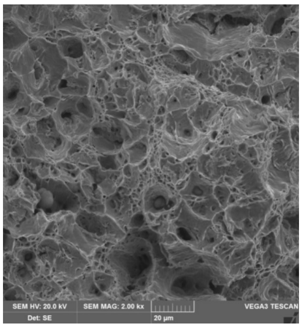


Figure 12 – Not notched specimen fractography - 2000x.

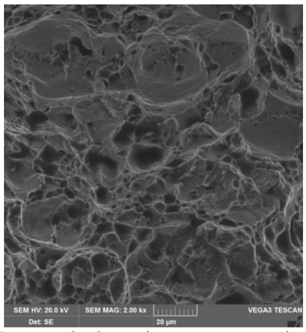


Figure 13 – Notched specimen Fractography - 2000x.

4. CONCLUSIONS

The *tirefond* screw is manufactured of a low carbon steel and has a microstructure mainly constituted of ferrite and pearlite. The ferrite presents plate morphology with random directions due to the manufacturing process (ABNT 1015 steel hot forming).

Regarding the Brinell hardness values, it is possible to conclude that the material is homogeneous. The average Brinell hardness in the longitudinal and in the cross sections converges to 120HB. The Vickers microhardness tests performed both in the central and in the threads areas, also indicate homogeneity along the screw.

Regarding the tensile test results, the presence of the notch, which is a stress concentrator, causes the increasing of the material yield and tensile strengths, but the decreasing of the ductility. Therefore, it can be said that the steel used in screw manufacturing is strongly sensitive to the presence of stress concentrators when demanded in static loading. The decrease in ductility can affect its ability to resist the crack growth when in service under cyclic loading. This may cause the component premature rupture.

In the impact test, it was observed that the *tirefond* screw has a lower impact resistance when exercising their function at low temperatures, whereas at higher temperatures its impact toughness is increased. At room temperature, the studied steel absorbed energy is 132J.

In fractographic analyses, it was found the presence of *dimples* that characterize the fractures, both in the absence or presence of stress concentrator, as ductile.

The actual used steel in the *tirefond* screw manufacturing is strongly sensitive to the presence of stress concentrators which significantly reduces its ductility. In this context it is suggested that further studies should be developed in order to decrease the stress concentration intensity in the *tirefond* screw project, or to suggest another material with higher mechanical strength and, if possible, less sensitive to the presence of stress concentrators, for this application.

5. ACKNOWLEDGMENT

The authors thank the VLI - FCA by screws donation to carry out the present work and CNPq for the financial support.

6. REFERENCES

Chen, H., Tsang, P., Hwang, S., 2006.*Failure Analysis of Bolts on an End Flange of a Steam Pipe.* Engineerin Failure Analysis, v. 13, p.656-668.

Griza, S., Bertoni, F., Zanon, G., 2009.*Fatigue in engine connecting rod bolt due to forming laps.*Engineering Failure Analysis, v. 16, p.1542-1548.

Hibbeler, R.C., 2004.*Resistência dos Materiais.*5.ed. São Paulo: Pearson Prentice Hall. 670p.

Ildefonso, J. S., 2013.*Proposta de um Sistema de Gerência para Vias Férreas Brasileiras.* Tese apresentada à Escola de Engenharia de São Carlos, da Universidade de São Paulo, como parte dos requisitos para a obtenção do Título de Doutor em Ciências no Programa de Pós-Graduação em Transportes. 199p.

Kabche, J.P., Pacheco, M.R., Thesi, I., 2009. *Finite Element Analysis of a Locked Bolt With an Initial Crack*. Mechanics of Solids, Structures and Fluids, v. 11, p.39-45.

Klincevicius, M. G. Y.,2011.*Estudo de Propriedades, de Tensões e do Comportamento Mecânico de Lastros Ferroviários*. Dissertação apresentada à Escola Politécnica da Universidade de São Paulo para obtenção do Título de Mestre em Engenharia. 172p.

Ling, L., Rong, W., 2014. *Failure analysis on fracture of worm gear connecting bolts.Engineering Failure Analysis,* v. 36, p. 439-446.

Loganathan, T.M., Purbolaksono, J., Inayat-Husain, J.I., 2010.*Pitting Corrosion of Triggering Initial Fractures of Palm Oil Screw Press Machine Shafts*.Engineering Failure Analysis, v. 17, p.1086-1093.

Mackerle, J., 2003. *Finite element analysis of fastening and joining: A bibliography*. International Journal of Pressure Vessels and Piping, v. 80, p.253-271.

Milan, M.T., Spinelli, D., Bose Filho, W.W., 2004. *Failure Analysis of a SAE4340 Steel Locking Bolt.*Engineering Failure Analysis, v. 11, p. 915-924.

Mínguez, J.M., Vogwell, J., 2006.*Effect of torque tightening on the fatigue strength of bolted joints.* Engineering Failure Analysis, v. 13, p.1410-1421.

Norton, R.L. *Machine design—an integrated approach*, 2ª ed. Prentice-Hall, New Jersey, USA.Oh,Y.J.; Lee, B.S.; Hong, J.H., 2002. *The Effect of Non-Metallic Inclusions on the Fracture Toughness Master Curve in High Copper Reactor Pressure Vessel Welds*.Journal Of Nuclear Materials, v. 301, p.108-117.

Peterson R.E., 1974. *Stress concentration factors*. Wiley.

7. RESPONSIBILITY NOTICE

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