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FAILURE ANALYSIS OF TWO SCREWS USED IN THE FIXING SYSTEM OF BALL MILLS INTERNAL COVERING

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Abstract. *This work presents a study case about the failure analysis of two steel screws, with different geometries, used in the fixing system of industrial ball mills internal covering. This kind of failure has been often occurred in some ball mils installed in Brazil. Two distinct screws, failed in service, were sampled and submitted to standardized procedures of failure analysis. Studies about the screws work conditions, as well as about the material specifications for this application, standardized by international associations, were done. Chemical, macro and microstructural analysis by optical and scanning electronic microscopes, microfractographic analysis and hardness tests were executed in samples of the both studied screws, aiming to determine the failure main causes. Stress concentration factors were calculated in screw threads applying mathematical models proposed by different researchers. The stress concentration factors for static and dynamics loading were compared for the both different geometries. The obtained results showed that screw thread roots are the main stress concentration points in screw structures. This fact was aggravated due to the occurrence of corrosion pitting in these areas caused by its use in an aggressive environment. It was possible to conclude that fatigue cracks have nucleated in these areas of high stress concentration and have growth until a critical size, spreading unsteadily and causing the screws failure.*

Keywords: *Fixing Screws; Ball Mills; Failure Analysis; Fatigue.*

1. INTRODUCTION

The screws, in general, have a great importance in the performance of different kind of machines. The most part of these fastening elements is submitted to cyclic loads that may promote the well known fatigue phenomenon. Fatigue is pointed in technical literature as the main cause of premature failure cases in these elements (Majzoobi et al., 2005). The most part of screw failures occur under tension-tension mode. These elements are submitted to a pre-loading, due to their installation, and to an additional service loading, which is commonly cyclic. These cyclic stresses may cause the screw failure even they have been submitted to stress levels lower than their yield strength (Buda, 1994). As a consequence, the fatigue failure in bolted joints are a constant concern, because the fracture of only one screw may promote, in a short time, the instability and the lost of a complete mechanical system (Nasisrpouri *et al.*, 2011; Loganathan *et al.*, 2010; Griza *et al.*, 2009; Milan *et al.*, 2004; Chen *et al.*, 2006).

Milan et al (2004) investigated the premature failure of various fixation screws made of quenched and tempered SAE 1020 steel. Through the application of macrographic and micrographic analysis, as well, tensile, Charpy and hardness tests, associated with analytical calculus of stress concentration factors (proposed by Neuber models), concluded that high stress levels in screw threads (stress concentrators) during their in service life were the main cause of their fatigue failures.

It is important to highlight that other factors may contribute for the fatigue crack nucleation and growth at screws. Some of them are: superficial defects (corrosion pits); low radius of the thread screw root (minor than predict in project); low material hardness; inadequately fixation of the screw; manufacture defects; bad planed heat treatments or mechanical processing.

The fracture mechanisms as well as the failure mode of screws are described by Chen *et al*. (2006). They showed that at fractured area, where the crack nucleation started in screws from a vapor piping system, there was a flat surface, characterized by the absence of significant plastic strain. The presence of iron oxides, striations at fractured surface and ratchet marks were the main observed evidences of a fatigue failure. In the final detachment, a dark and strained surface was observed, pointing to a ductile final fracture caused by an overload (Nasisrpouri *et al.*, 2011; Loganathan *et al.*, 2010; Griza *et al.*, 2009; Milan *et al.*, 2004; Chen *et al.*, 2006).

The microstructure has a great influence on fatigue behavior of metallic materials. In general, medium carbon and martensitic microalloyed steels have high strength to fatigue crack nucleation, but low resistance to fatigue crack growth. The low carbon steels and the ductile ones have lower strength to fatigue crack nucleation, but low rate of fatigue crack growth (Sankaran *et al.*, 2003a; Sankaran *et al.,* 2003b).

Abrupt changes on component geometry may change the local stress distribution, increasing the stress values. These discontinuities are named stress increasers and the areas where they occur are named stress concentrators. According to Guo *et al.* (2003), superficial cracks which growth from a stress concentration area is the most common cause of fatigue failures.

Many numerical analysis, theoretical studies and experimental investigations, as described by Neuber (1964), Peterson (1974), Dragoni (2013) and others (Majzoobi *et al.*, 2005; Milan *et al.*, 2004; Guo *et al.*, 2003; Pilkey *et al.,* 2008; Meggliorarо *et al.*, 2007) were done aiming to obtain and to understand the applicability of the stress concentration factor (K_t) (relation between the highest real stress at discontinuity and the nominal applied stress). Meggliorarо *et al* (2007) described that the empiric factor notch sensitivity “q”($0 \leq q \leq 1$), was introduced to quantify the difference between the parameter K_t (linear elastic stress concentration factor), and its real effect under fatigue conditions. This effect may be obtained by the fatigue notch stress concentration factor (K_f) that may be calculated by Eq. (1).

$$K_f = 1 + q(K_t - 1) \quad (1)$$

When $q = 0$, so $K_f = 1$ and the material has not a significant notch sensibility under fatigue conditions. If $q = 1$, so $K_f = K_t$ and the material has a complete notch sensibility. Other variables, born from these concepts, were proposed. Majzoobi *et al* (2005) presented a theoretical model to calculate the factor of diameter reduction fatigue stress concentration (K_f^*). This factor, derived from K_f, consider the diameter changes along the screw body. The higher the diameter decreasing rate, the higher the stress concentration at thread root.

In this context, this work executed a failure analysis of two screws applied in ball mills system from a mining company. The both studied screws are commonly used in the fixation system of the internal covering of mill, aiming to contribute with the mechanical wear rate decreasing of the mill steel structure. Macro and microstructural analysis, as well as mechanical characterization procedures were performed on fail screws aiming to understand the main causes of occurrences. Complementary calculus of stress concentration factors were done by the application of different models proposed in scientific literature to understand the influences of geometrical aspects on stress distribution around the threads, as well, to compare the materials notch sensibility used in screws manufacture.

2. MATERIALS AND METHODS

Two screws, with different geometrical characteristics and dimensions, but the both applied in the internal covering of a ball mill, failed in service. The both screws were collected and named as A and B screws. Table 1 and Fig. 1 present the dimensions of the A and B specified by BS1768 standard for this kind of application. Fig. 2 (a) is a picture of a new A screw and its installation components, as well, Fig. 2 (b) is a picture of the failed A screw.

The fractured screws were properly cleaned in a 10%H_2SO_4 aqueous solution during 30s in an ultrasonic vibrator aiming to remove wastes and the thicker oxidized layer from the samples surface. Each of them was submitted to standardized procedures of failure analysis, according to ASM suggestions.

The fractured surfaces were sampled and analyzed with naked eyes. Microfractographic analyses were conducted in a scanning electron microscope. Representative samples were submitted to microstructural analysis by optical and scanning electron microscopes, as well, to hardness tests (average from five measures) and chemical analysis by optic emission spectrometry.

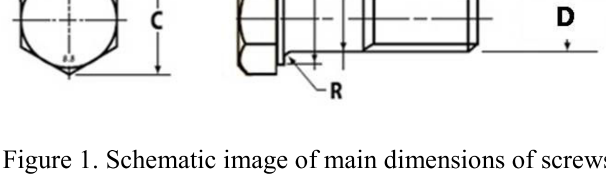


Figure 1. Schematic image of main dimensions of screws.

Table 1. A and B screws dimensions (mm) – adapted from BS1768 standard.

Sample	**D**	**Distance between threads (Pitch)**	**W (max.)**	**C (min.)**	**B (max.)**	**H**	**R (min.)**	**Q (min.)**	**LT**	**L**
A	25.4	3	36	39.9	24	15	0.8	33.6	54	50-280
B	19.05	2	24	26.7	16	10	0.6	22.5	38	25-280

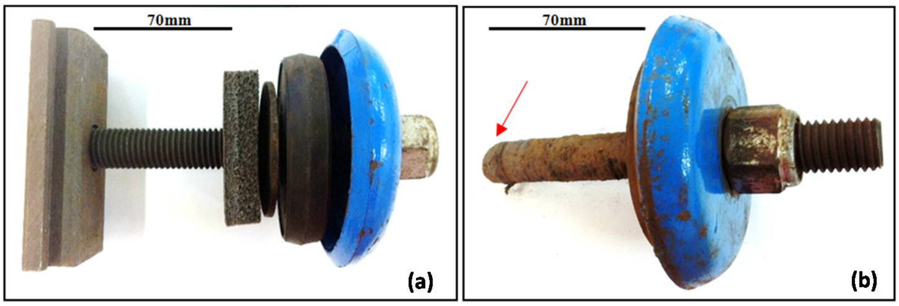


Figure 2. Picture of (a) a new screw used in Ball mill covering system; (b) a failed screw. The red arrow indicates the fractured area.

After the execution of the planed experimental procedures, one representative sample of each screw, was analyzed in an profilometer aiming to determine the real dimensions of failed screws. These measured dimensions were: major diameter (D), minor diameter (d), distance between threads (p), radius of the thread screw root (r) and depth of threads (t).

Applying these collected data, the stress concentration factors (static and dynamic) were calculated for both studied screws. It were used and compared, many fracture mechanics models. Initially, this work proposes to calculate K_t factor, proposed by Neuber (1964), applying Eq. (2). The γ is the load relief coefficient, which is related to the presence of multiple notches, as verified in the screw threads. A model for γ calculations were initially proposed also by Neuber (1964) and the proposed equation was the Eq. (3). Later, Dragoni proposed a change in the model and presented the Eq. (4) with the same objective (Dragoni, 2013).

$$K_t = 1 + 2\left(\frac{t\gamma}{r}\right)^{\frac{1}{2}} \tag{2}$$

$$\gamma = \left(\frac{P}{\pi t}\right) \mathrm{Tgh}\left(\frac{\pi t}{P}\right) \tag{3}$$

$$\gamma = \left(\frac{P}{3\pi t}\right) \mathrm{Tgh}\left(\frac{3\pi t}{P}\right) \tag{4}$$

In this work, the load relief coefficient was calculated by the both presented models by applying the Eqs. (3) and (4). The γ obtained values were substituted in Eq. (2) aiming to calculate the K_t factor, proposed by Neuber (1964). This was done for the both screws. In work sequence, the same obtained values were applied to Norton (2002) master diagram, which allow determining directly the K_t value as a function of r/d and D/d ratios. The static stress concentration factors, obtained by the presented ways, were compared and discussed.

The K_t parameters are geometrical stress concentration factors established for materials static loading mode. However structures as the studied screws, in general, are submitted to dynamics loading mode and the determination of stress concentration factors under fatigue is very important. The K_f factor is a suggested variable which consider beyond the geometrical aspects, the material sensitivity to the notches presence in a dynamic loading mode.

The K_f values, for A and B screws, were calculated by Eqs. (5) and (6) that were proposed by Neuber (1964) and Peterson (1974) respectively. The q parameter is the material notch sensitivity that was calculated by the Eqs. (7) e (8), proposed respectively, by Neuber (1964) and Peterson (1974). The ***a e α*** parameters are constantes that depend of the hardness and tensile strength of the studied materials. These constants were obtained in Neuber (1964) and Peterson (1974) works for A e B screws.

$$K_f = 1 + \frac{K_t + 1}{1 + \sqrt{\frac{a}{r}}} \tag{5}$$

$$K_f = 1 + \frac{K_t + 1}{1 + \frac{\alpha}{r}} \tag{6}$$

$$q = \frac{1}{1+\frac{\sqrt{a}}{\sqrt{r}}} \tag{7}$$

$$q = \frac{1}{1+\frac{a}{r}} \tag{8}$$

The obtained results were evaluated and compared. Through them, it was possible to assess which geometry and what material, between the evaluated (bolts A and B), have the highest stress concentrators, as well as the greater sensitivity to the notches presence. The obtained data were related to the experimental results and the failure cause was pointed.

3. RESULTS AND DISCUSSION

3.1. Chemical Analysis

The Tab.2 presents the chemical composition of the steels used in A and B screws manufacture. It is possible to notice that the studied steels have completely distinct chemical compositions. The A steel has a lower carbon content than B, as well as the highest Mn, Si and Cr contents. It is possible to affirm that A steel has chemical characteristics that characterizes it as a spring steel. However, the B steel is a typical carbon steel with characteristics that meet the SAE 1045 specifications. These observed differences are strongly significant and have a great influence on microstructure and mechanical properties of screws.

Table 2. Chemical analysis of A and B screws (% weight).

Sample	C	Mn	P	S	Si	Ni	Cr	Mo	Al	Cu	Ti
A	0.318	1.176	0.011	0.001	1.487	0.116	1.233	0.027	0.026	0.248	0.036
B	0.456	0.765	0.021	0.025	0.204	0.003	0.016	-	0.017	-	0.001

3.2. Dimensional Analysis

The Tab. 3 presents the measured dimensions of the studied screws (profilometer measurements). It is noticed that screws have significant differences between their dimensions, mainly between their diameters and radius of the thread roots. Comparing Tab.3 with specified values BS1768 presented in Tab.1, it is possible to affirm that the A screw attends the dimensional specifications. However, the B one presented the radius of the thread root considerably higher and diameter smaller that specified.

Table 3. Measured dimensions of the A and B screws (profilometer measurements) (mm).

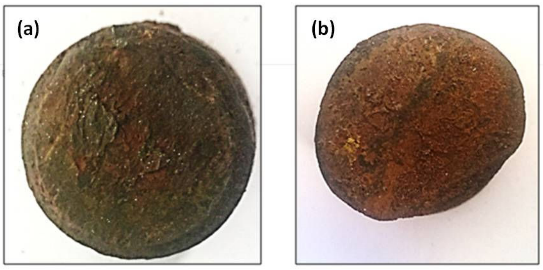
Sizes	A	B
Major diameter	25.00	17.80
Minor diameter	21.10	14.85
Distance between threads (Pitch)	3.176	2.532
Radius of the thread screw root	0.449	0.296
Depth of threads	1.995	1.504

3.3. Macrofractographic Analysis

Figure 3(a) and 3(b) present the fractured surfaces of A and B screws respectively. It is possible to observe an intense oxidation of the both surfaces, pointing to the concerning that the studied screws were bad conserved before the beginning of the sampling procedure. The severe oxidation state initially hides some possible evidences of fractures causes. However, with a critical observation, it is possible to note the flat aspect of the fracture surfaces, as well, specific deformed regions, suggesting a localized plastic strain.

Chen *et al.* (2006) described in their works that similar aspects were observed in their failure screws. According to them, the flat area would be associated to the stable growth of fatigue cracks and the deformed region associated to the plastic strain that caused the final rupture. In this context, it is supposed that screws failure was not caused by an overload during their utilization, but due to a fatigue crack nucleation and growth, until a final rupture with a significant plastic strain, mainly is screw B.

Fig.3. Fracture surface of (a) A screw; (b) B screw.



3.4. Microstructural Analysis

Specimens from the both screws were submitted to a standardized metalographic procedures (sanding, polishing and etching with Nital 2%wt) and so characterized by optical microscopy (OM) and scanning electron microscopy (SEM). Fig 4 (a,b) presents de microstructure of A screw, as well as the Fig. 4(c,d) shows the microstructure of B screw. It is possible to observe that the microstructures of studied screws are completely different. The A screw are mainly constituted by tempered martensite, with a significant amount of faceted inclusions, supposed to be some kind of carbides. The B screw is mainly constituted by pearlite with a significant amount of proeutectoide ferrite. The observed microstructures are in accordance with the chemical composition of A and B steels and with the suppositions that A screw is made of a spring steel and B screw made of a common carbon steel.

The differences in material microstructures, related to their distinct chemical composition and their heat treatment history, are responsible for their specific mechanical properties. This relation between chemical composition, microstructure and mechanical properties of steels used in screws manufacture is well described in Sankaram *et al* (2003a) works about high and low cycle fatigue of low carbon and microalloyed steels. They showed that the fatigue crack nucleation and growth are strongly influenced by microstructure. According to them, ferrite-pearlite structures have a longer fatigue life than martensitic ones.

No evidences of cold work were observed in screw microstructures. This suggests that in screws manufacture processes, they were hot formed or heat treated after the forming procedures. Fig. 5 presents a qualitative chemical analysis (SEM-EDS) of inclusions present in A and B steels. The A steel has a high amount of faceted inclusions, where the Ti content highlights. In this context, it is possible to affirm that these inclusions are titanium carbides. The B steel presents elongated inclusions with high S and Mn contents; therefore they are manganese sulfide inclusions.

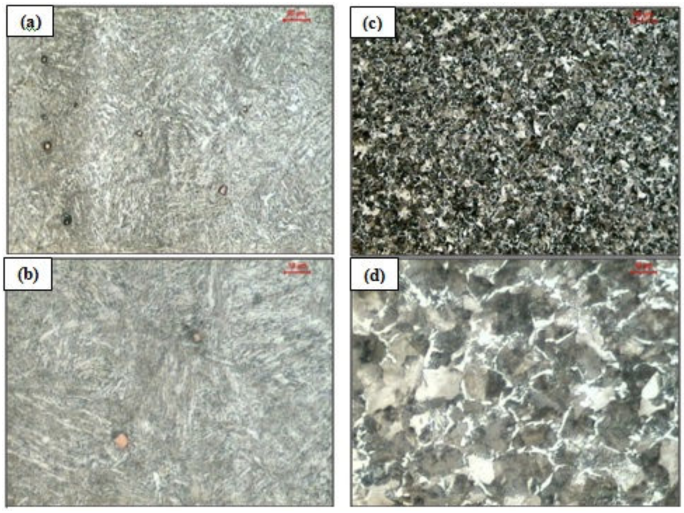


Fig.4. Microstructures of (a,b) A screw; (c,d) B screw – OM – Nital 2%.

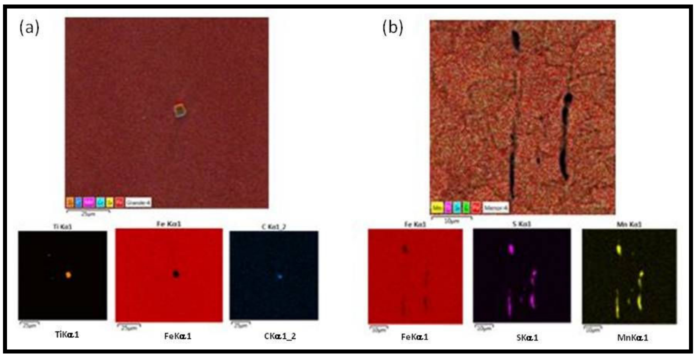


Fig.5. EDS chemical analysis of inclusions in (a) screw A; (b) screw B.

3.5. Hardness and Stress Concentration Factors

The A (quenched and tempered steel) and B (normalized steel) screws presented, respectively, average hardness of 70HRA (362HB) and 62HRA (243HB). This difference was expected due to the differences in chemical compositions and microstructures. According to BS718 standard, it is possible to affirm that A screw is out of specification, because its hardness is 13.5% higher than the established maximum value. The B screw attends the hardness specification. Throw the hardness measurements it was possible to calculate the screws tensile strength. The A and B tensile strengths were, respectively, 1196MPa and 786MPa.

The Tab. 4 presents the calculated values of load relief coefficients (γ). It is possible to observe that this parameter, related to the geometrical aspects of the screw threads, are higher in B screw for the both tested models. Using the determined γ values, the K_t parameters were calculated and presented in Tab. 5. The B screw presented the highest values of stress concentration factors. This result indicates that the geometrical configuration of the B screw is more severe than A one. This is mainly associated with minor values of the distance between B screw threads and of the radius of B screw thread root.

The Tab. 6 presents the Neuber and Peterson constants determined for A and B screws. These values were applied to the q and K_f calculus. The Tab. 7 and Tab. 8 present, respectively, the q and K_f obtained values. The B screw presented the lowest notch sensitivity, in all tested models. This can be explained due to its softer and ductile microstructure. In this scenario, although the B screw had presented the highest K_t, it presented the lowest K_f. The A steel (tempered martensite), which has the highest notch sensitivity, presented the highest K_f factor, as expected.

Table 4. Calculated values of load relief coefficients (γ).

γ values	**Neuber Model**	**Dragoni Model**
A Screw	0.49	0.17
B Screw	0.51	0.18

Table 5. Calculated values of static stress concentration factors (K_t).

Applied Model	**A**	**B**
Neuber (γ) – Neuber (Kt)	3.99	4.22
Dragoni (γ) – Neuber (Kt)	2.77	2.90
Norton	3.70	3.78

Table 6. Determined Neuber and Peterson constants.

Constants	**A**	**B**
Neuber ($a^{1/2}$)	0.0265	0.1333
Peterson (α)	0.0664	0.1474

Table 7. Calculated values of notch sensitivity parameters (q).

Applied Model	**A**	**B**
Neuber	0.83	0.67
Peterson	0.87	0.67
Dragoni	0.85	0.67

Table 8. Calculated values of fatigue stress concentration factors (K_f).

Applied Model	A	B
Neuber (γ) – Neuber (Kt) – K_f	3.51	3.16
Dragoni (γ) – Neuber (Kt) - K_f	2.47	2.27
Norton - K_f	3.37	2.86

3.6. Microfractographic Analysis

Fig. 6 presents SEM images from fractured surfaces from A and B screws. It is possible to observe, for both screws, flat surfaces with small rungs at their edges. This may indicate that corrosion pits had been formed during their utilization and an increasing of stress concentration factors could contribute to the fatigue crack nucleation. At B screw were noticed plastic strain signals at final rupture area due to its highest ductility. However, at A screw, which has high mechanical strength and low ductility, these signals were not verified.

Sankaram et al (2001) had explained in their work that fatigue crack may nucleate at corrosion pits and growth with high rates in corrosive environments, decreasing the fatigue life of material. Due to the significant flat surface extension, it was supposed that during their utilization, the screws were submitted to low loading levels.

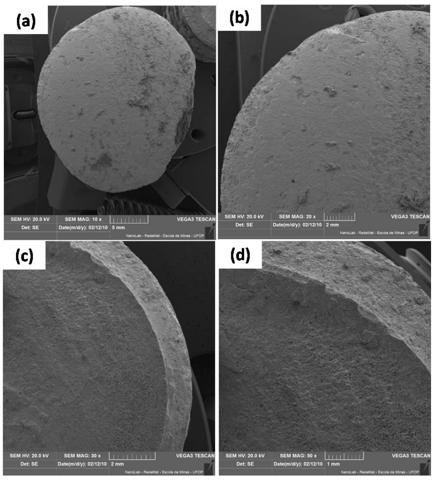


Figure 6. Fracture surfaces of A (c e d) e B (a e b) screws - SEM.

4. CONCLUSIONS

The studied screws are manufactured by different steels. The A steel is a spring steel, mainly constituted by tempered martensite with a high amount of titanium carbide inclusions. The B steel is a common carbon steel, around SAE1045, mainly constituted by ferrite-pearlite, with a significant amount of oxide and manganese sulfide inclusions.

The both studied screws have geometrical aspects that implies in high stress concentration in screw thread roots. The A screw did not meet the BS718 standard, because it attends the dimensional specifications, but its hardness is higher than the maximum specified. The B screw did not meet the BS718 standard, because he has the minor diameter smaller than the specified. However its hardness is accordance with expected.

The A screw has the lowest values of γ and K_t. However, due to its microstructure, it has the highest notch sensitivity (q) and under fatigue conditions it presents the highest K_f, been more susceptible to fatigue failure than B screw. Although the B screw presents the highest K_t (more severe geometrical configuration), it has the lowest K_f. This can be explained due to its softer and ductile microstructure which promotes lower notch sensitivity.

The both studied screws failed by fatigue phenomenon. Natural stress concentrators associated with corrosion pits occurrence, were the main factors that had created severe conditions that allowed fatigue crack nucleation and growth, leading the screws to a final and ductile fracture. The large extension of the flat surface indicates that, probably the fatigue failure, in both cases, occurred under low loading levels.

It is possible to suggest that, aiming to improve the fatigue behavior of these components, it is very important to adequate the dimensional aspects of the screws, adjusting them to promote the decreasing of stress concentration factors. As it is not possible to change the loading profile of the screws, it is essential to guarantee that the applied steels have a low notch sensitivity and high strength to fatigue crack nucleation.

5. REFERENCES

ASM Handbook, 1992. *Failure Analysis and Prevention*, ASM International, Materials Park, v.11.

Buda J., 1994. *Why Bolts Fail*. Machine Design, v. 66, p. 85.

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.

Delagnes, D., Lamesle, P., Mathon, M.H., Mebarki, N., Levaillant, C., 2005. *Influence of Silicon Content on the Precipitation of Secondary Carbides and Fatigue Properties of a 5%Cr Tempered Martensitic Steel. Materials Science & Engineering*, v. 394, p. 435-444.

Dragoni, E. and Castagnetti, D., 2013. *Stress Concentrations in Periodic Notches: A Critical Investigation of Neuber's Method*. Materials Science & Technology, v.44, p.364-371.

Dragoni, E., 1997. *Effect of Thread Pitch on the Fatigue Strength of Steel Bolts.* Proceedings Institution of Mechanical Engineers, v. 211, pp.591-600.

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.

Guo W., Shen H., Li H., 2003. *Stress Intensity Factors for Elliptical Surface Cracks in Round Bars With Different Stress Coefficient*. International Journal of Fatigue, v.25, p.733-741.

Hoeppner, D.W., 1979. *Model for prediction of fatigue lives based upon a pitting corrosion fatigue process.* ASTM Special Technical Publication, v. 675, p.841-870.

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.

Majzoobi, G. H., Farrahi, G. H., Habibi, N., 2005. *Experimental Evaluation of the Effect of Thread Pitch on Fatigue Life of Bolts.* International Journal of Fatigue, v. 27, p.189-196.

Meggioraro, M.A., Miranda, A. C. Q., Castro, J. T. P., 2007. *Short Crack Threshold Estimates to Predict Notch Sensitivity Factors in Fatigue.* International Journal of Fatigue, v.29, p.2022-2031.

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.

Murakami, Y., 2012. *Material Defects as the Basis of Fatigue Design.* International Journal of Fatigue, v. 41, p. 2-10,

Nasisrpouri, F., Alizadeh, H., Hosseingholizadeh, M., 2011. *Failure Analysis of a Carbon Steel Screw Under the Service in the Presence of Hydrogen Sulphide*. Engineering Failure Analysis, v. 18, p.2316-2323.

Neuber H., 1964. *Theory of notch stress: Principles for Exact Calculation of Strength with Reference to Structure Form and Materials*. WashigtonDC, USA: Office of technical Services, Department of commerce.

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.

Pedersen,N.L., 2013. *Optimization of bolt thread stress concentrations.* Archive of Applied Mechanics v.83,p.1-14.

Pilkey, W.D., Pilkey D.F., 2008. *Peterson's stress concentration factors*. Wiley, 3rd edition, New York.

Sankaran, S., SubramanyaSarma, V., Padmanabhan, K.A., Jaeger, G., Koethe. A., 2003a. *High Cycle Fatigue Behaviour of a Multiphase Microalloyed Medium Carbon Steel: a Comparison BetweenFerrite–Pearlite and Tempered Martensite Microstructures*. Materials Science & Engineering, v. 362, p. 249-256.

Sankaran, S. SubramanyaSarma, V., Padmanabhan.K.A., 2003b. *Low Cycle Fatigue Behavior of a Multiphase Microalloyed Medium Carbon Steel: Comparison Between Ferrite–Pearlite andQuenched and Tempered Microstructures.* Materials Science & Engineering, v.345, p.328-335.

Sankaram, K. K., Perez, R., Jata, K. V., 2001. *Effects of pitting corrosion on the fatigue behavior of aluminum alloy 7075-T6: modeling and experimental studies.* Materials Science & Engineering, v.297, p.223-229.

Shigley, J.E., Mischke, C.R., Budynas, R.G. *Mechanical Engineering Design*, 7th ed. Mcgraw-Hill, New York, USA, p.328-329.

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