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# FAILURE ANALYSIS OF A SLEEPER ANCHOR MODEL USED IN BRAZILIAN RAILROADS

**Diego Antônio de Souza Santos**
Universidade Federal de Ouro Preto – DEMET – EM, Campus Universitário do Morro do Cruzeiro, Ouro Preto (MG)
diego.antoniosouza@gmail.com
**Geraldo Lúcio de Faria**
Universidade Federal de Ouro Preto – DEMET – EM, Campus Universitário do Morro do Cruzeiro, Ouro Preto (MG)
geraldolfaria@yahoo.com.br
**Leonardo Barbosa Godefroid**
Universidade Federal de Ouro Preto – DEMET – EM, Campus Universitário do Morro do Cruzeiro, Ouro Preto (MG)
leonardo@demet.em.ufop.br
**Luiz Cláudio Cândido**
Universidade Federal de Ouro Preto – DEMET – EM, Campus Universitário do Morro do Cruzeiro, Ouro Preto (MG)
candido@em.ufop.br

***Abstract.*** *The sleeper anchors are important elements in railroads. They are buried into the ballast, and as the name suggest, they have an anchor function, contributing to the railroads fixation and increasing the railway stiffness. A Brazilian sleeper anchor has been used for many years by many Brazilian companies from the transport business. However, with the increasing of load per train wheel since last years, this model of sleeper anchor have been failing, avoiding the undesired ballast movement and creating a dangerous situation, with imminent risk of accidents. In this context, this work presents a complete failure analysis of this Brazilian sleeper anchor. Chemical, macro and microstructural analysis were done, as well mechanical tests in representative samples of sleeper anchor that have been failing recurrently in Brazilian railroads. An European model, aiming to compare their metallurgical characteristics, were also characterized. The obtained results showed that the studied failure is associated to an overload in Brazilian sleeper anchor. This overload promotes an undesirable plastic strain and the anchor is removed from the ballast. It was possible to conclude that the mechanical properties of Brazilian components do not attend the specifications for the actual load demand in national railways. It was also possible to observe that European sleeper anchors have better metallurgical characteristics than Brazilian one, for this application.*

***Keywords:*** *Railroads, Sleeper Anchor, Failure Analysis.*

## 1. INTRODUCTION

As it comes of a low-cost transport system and considering its use in the transportation of many tons of products over long distances, the railway sector is one of the most efficient transport ways. Due to these characteristics, it is considered as the most promising way for the product transportation in countries with large territory, as Brazil. The success of these ideais depends strongly from the structural integrity of the permanent way. In this context, Brazilian companies, which have the control of important railroads, have been concerned in ensuring the quality of their services, mainly related to the maintenance of railroad components.

The sleeper anchor is one of the elements of the permanent way that is buried in the ballast and, as the name suggests, have the purpose of an anchor, aiding in the fixing of the permanent way and increasing its stiffness, mainly in curved areas, according to Vossloh (2013).

A Brazilian sleeper anchor model has been used for many years by several national companies. However, with the increasing of transported weight per locomotive axle, as well as the traffic speed, this component model has been failing in service, allowing the undesired displacement of the ballast and creating an imminent risk of serious accidents. The Fig. 1 shows a sleeper anchor used in Brazilian permanent ways. The Fig. 2 shows a sleeper anchor plastic strained at the fastener.

According to VLI (2013), the actual national sleeper anchors are made empirically. During the development of this study, a small number of technical and scientific references were obtained about this component. In this context, this work has a great importance to the Brazilian railway sector. This work presents a thorough study of failure analysis of the sleeper anchor model that has been failing in service. A strained sleeper anchor and two new (the same model) were used in this work execution.

Aiming to prevent risks to human life, economic and environmental losses, the failures of structural components are strongly undesirable. According to ASM Handbook (2002), the main causes of the failures in metalic structures are usually related to negligences in the component projects, manufacturing, montage or operation, and also to the not meeting of the material specifications.

According to ASM Handbook (2002), there are four general categories of failures, caused by: overload, fatigue, abrasion or corrosion. Mechanical equipments fail in some of these categories or in a combination of them. A part or the whole structure is considered "failed" if the following conditions happen:

- When the structure is completely flaw;
- When the structure can still be used but is no longer able to perform its function satisfactorily;
- When a serious deterioration makes the structure unsafe to continue to be used.

For comparative purposes, this work also presents the chemical, structural and mechanical characterization of an international sleeper anchor. The sleeper anchor of foreign origin was duly studied by the Technical University of Munich, where it has shown an immediate increase in track stiffness after installation according to Vossloh (2013). Fig. 3 shows a sleeper anchor used in European permanent ways and also characterized in this paper.

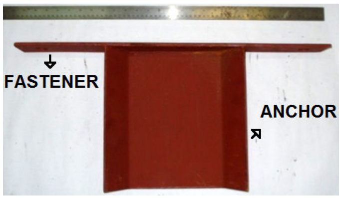


Figure 1. Sleeper Anchor used in Brazilian permanent ways.

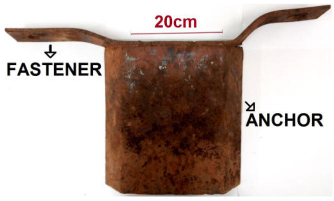


Figure 2. Sleeper Anchor used in Brazilian permanent ways, platic strained in the fastener area.

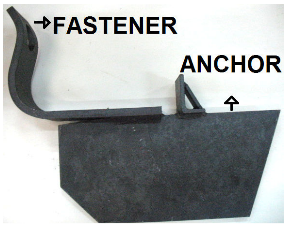


Figure 3. Sleeper anchor used in Europeans permanent ways.

## 2. MATERIALS AND METHODS

The objective of this study was to perform a failure analysis in a sleeper anchor used in Brazilian permanent ways, performing chemical and microstructural analysis, and applying mechanical tests.

A sample of the Brazilian sleeper anchor failed in service as well as two new ones of the same batches were received in the Mechanical Testing Laboratory of DEMET-EM-UFOP for the development of this work. Two new sleeper anchors, used in the European railroads were also received for the execution of microstructural analysis and basic mechanical tests.

Initially, a visual examination of the failed component was performed. Then, representative samples of the anchor and fastener areas were collected for chemical analysis and microstructural characterization. Chemical analyses were performed by optical emission spectrometry and the microstructural characterization was done according to the procedures recommended by ASTM E3-01 (2001).

Then, specimens were machined from the national fasteners and anchors and submitted to basic mechanical tests. Brinell hardness tests were applied following ASTM E10-08 (2008), into a universal tester, Otto Wolpert-Werke manufacturer with an applied load: 187.5kg; a spherical indenter: 2.5mm of diameter; constant of load: 30kg/mm$^2$. For the regions of the welded joints between the anchor and fastener, Vickers hardness tests were performed according to ASTM E384-10 (2010), into a digital Pantec microhardness tester (load: 10gf; application time: 10s).

In tensile tests, the used samples were standardized according to ASTM E8/E8M-09 (2009), differing only in thickness. Tab. 1 presents the thickness of the anchor components and the fasteners of sleeper anchors.

Table 1. Thickness of the anchors and fasteners of the studied sleeper anchors.

| | Brazilian Sleeper Anchor | | European Sleeper Anchor | |
|---|---|---|---|---|
| | Anchor | Fastener | Anchor | Fastener |
| Thickness (mm) | 4.96 | 8.10 | 9.94 | 10.11 |

Following ASTM E23-07 (2007), impact Charpy tests were carried out on specimens with reduced dimensions.
Finally, in order to evaluate the fracture mechanisms in the tested specimens, they were submitted to microfractographic analyses in a scanning electron microscope (SEM). The same experimental procedures were performed on European sleeper anchors, aiming to compare its features with the one used in Brazil.

## 3. RESULTS AND DISCUSSION

### 3.1 VISUAL ANALYSIS

There are a great difference between the dimensions of anchors and fasteners. The thickness of the European component sheets are significant greater than the national ones. In Fig 2, it is possible to observe the occurrence of the recurrent failure in the Brazilian sleeper anchor. The failure consists in a prominent plastic strain in its fastener. The anchor is attached to the fastener by a weld that does not resists and fractures. The failure characteristics, associated with the loading mode, suggest that the fastener was subjected to a compressive overload, generating stress levels that exceed the material yield strength and cause its plastic strain. The welded joint, with low elongation, fractures.

### 3.2 CHEMICAL ANALYSIS

Tab. 2 and Tab. 3 show the chemical compositions of the national and international anchors and fasteners, respectively.

Table 2. Chemical composition (wt%) of the anchor and fastener of national sleeper anchor.

| Components | C | Mn | P | S | Si |
|---|---|---|---|---|---|
| Anchor | 0.047 | 0.244 | 0.017 | 0.015 | 0.003 |
| Fastener | 0.166 | 0.672 | 0.011 | 0.006 | 0.132 |

Table 3. Chemical composition (wt%) of the anchor and fastener of international sleeper anchor.

| Components | C | Mn | P | S | Si | Ni | Cr | Cu | N |
|---|---|---|---|---|---|---|---|---|---|
| Anchor | 0.056 | 0.762 | 0.013 | 0.013 | 0.018 | 0.030 | 0.032 | 0.058 | 0.004 |
| Fastener | 0.500 | 0.712 | 0.010 | 0.002 | 1.556 | 0.071 | 0.095 | 0.203 | 0.005 |

The steels used in national sleeper anchors (fastener and anchor) are common carbon steels, as well as the steel used in international anchor, but the international fastener has a typical chemical composition of a spring steel (Peng *et al,* 2010).
Analyzing the chemical compositions of the anchors shown in Tab. 2 and Tab. 3, it is possible to observe a great difference in Mn content, which may implies in better mechanical properties for the international component. Whereas the C content is similar, the highest Mn content implies higher equivalent C, improving properties, for example the steel hardenability, according to Herring (2015).
Regarding the chemical composition of fasteners shown in Tab. 2 and Tab. 3, it is noticeable significant differences in C and Si contents. The highest C content associated with the highest Si content in the international fastener may provide a good rate between their mechanical strength and ductility (CIMM, 2015).

### 3.3 STRUCTURAL CHARACTERIZATION

#### 3.3.1 CHARACTERIZATION OF INCLUSIONS

To evaluate the level and morphology of inclusions present in the studied steels, samples were analyzed by optical microscopy before the chemical etching. Fig. 4 shows obtained images from national and international anchor components.
It is possible to observe that the highest inclusion levels are in anchors area of both components, national and international. Due to the inclusion morphologies, according to ASTM E45-13 (2013), it is possible to affirm that they are constituted by globular oxide.

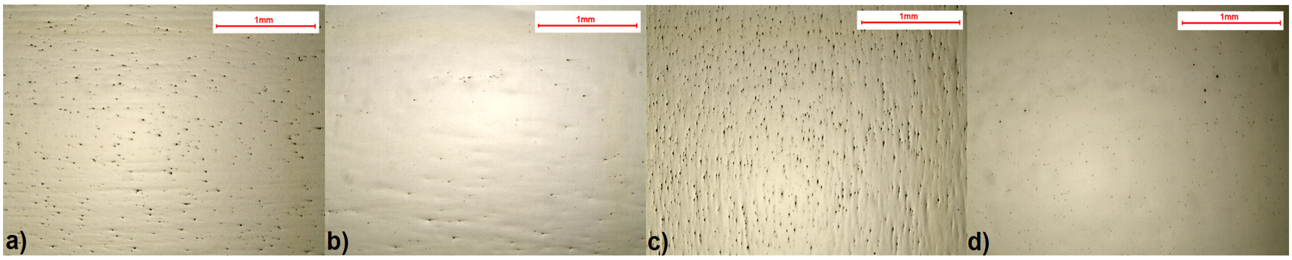


Figure 4. National sleeper anchor: a) Anchor; b) Fastener. International sleeper anchor: c) Anchor; d) Fastener. Magnification: 40x.

### 3.3.2 MICROSTRUCTURAL CHARACTERIZATION

Aiming to evaluate the microstructures of the different parts of the sleeper anchors, representative samples were metallographically prepared and analyzed by optical microscopy. For the microstructural analysis of the anchor and the fastener of studied sleeper anchors, images were obtained with magnification of 400x, after chemical etching with Nital 2%. Fig. 5 presents the obtained micrographs from national and international sleeper anchor parts.

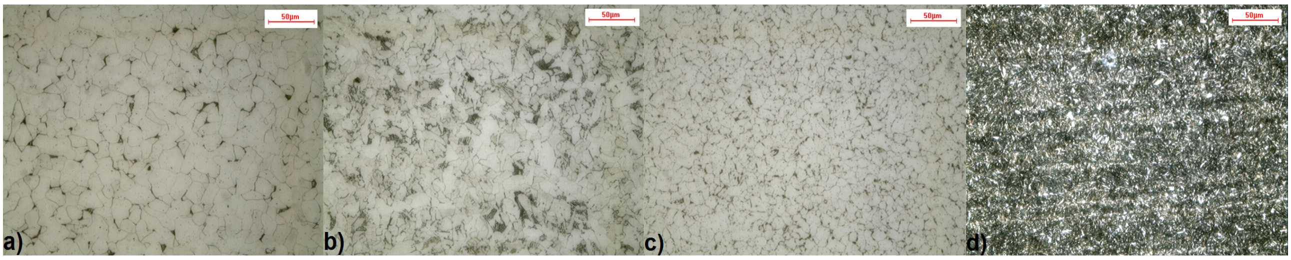


Figure 5. Microstructure of national sleeper anchor: a) Anchor; b) Fastener. Microstructure of international sleeper anchor: c) Anchor; d) Fastener. Magnification: 400x. Cheamical etching: Nital 2%.

Comparing the microstructures of the anchors, it is possible to observe that both are mainly composed of primary ferrite and small fraction of pearlite, typical microstructures of normalized low carbon steel, which is consistent with the chemical compositions of these parts. However, the international anchor presented smaller ferritic grain, which may lead to higher hardness and mechanical strength (Lee and Tomar 2014; Zepter 2007).

Comparing the microstructures of the fasteners, it was seen that the national sleeper anchor also presented structure mainly constituted of ferrite with small fraction of pearlite. This microstructure is also in accordance with expectations for normalized low carbon steel. However, the fastener of the international anchor presented a martensitic microstructure, indicating that this material was undergone to the quenching and tempering heat treatments. This observation, coupled with the chemical composition of steel, reinforces the hypothesis that the fasteners of European component is made of a spring-steel type. The martensitic microstructure provides this component good mechanical strength, probably much higher than the national fastener.

Microstructural analyzes were also performed on the welded joint areas (joint fastener-anchor) for both sleeper anchors. Fig. 6 shows micrographs obtained from national and international sleeper anchor taken in welded areas. For The microstructures of the both anchors and of the fastener of national component were revealed after chemical etching with 2% Nital, but the weld microstructure of the international fastener were just revealed with Villela reactive (2g of picric acid, 100ml of ethanol and 5ml of hydrochloric acid).

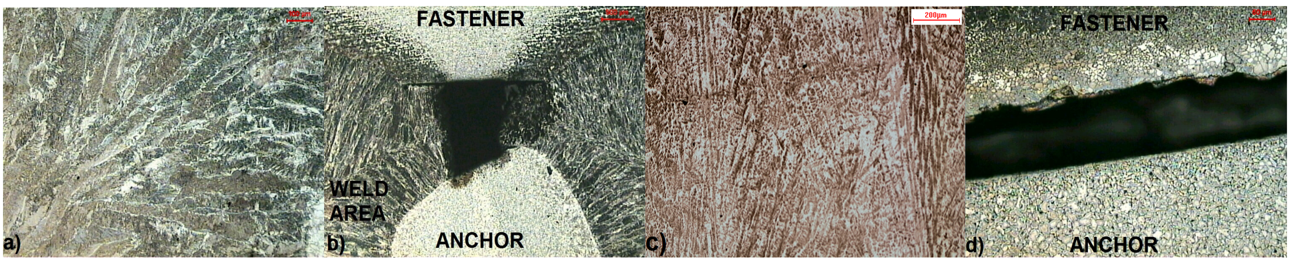


Figure 6. Microstructure of national sleeper anchor: a) weld region - Nital 2%; b) welded joint region - Nital 2%. Microstructure of international sleeper anchor: c) weld region - Villela; d) welded joint region - Nital 2%.

The microstructure of the weld region of the national sleeper anchor, shown in Figure 6-a, presented the microstructure with herringbone appearance, with acicular and a significant amount of grain boundary ferrite, resulting from the solidification process. The material relatively fast solidification prevents the complete diffusion of C, gaining strength and higher hardness due to distortions of the crystalline material lattice. According to the technical literature, the presence of the grain boundary ferrite may decrease the joint toughness (Bhole *et al*, 2006; Crawford and Baker, 1991).

The weld region of international sleeper anchor, shown in Figure 6-c, also presented the microstructure with herringbone appearance but with a significant higher amount of acicular ferrite, which guarantee higher toughness. This structure was revealed just after etching by Villela, this fact evidence that the weld metal probably consists of an alloyed steel (Bhole *et al*, 2006; Crawford and Baker, 1991).

The welded regions of both sleeper anchors presented some voids due to problems occurred during the welding process. The observed voids are potential stress concentrators that, for a static load or under fatigue conditions, can promote the studied component premature failure. However, it is noticeable that the weld quality in national sleeper anchor is worse than the European.

### 3.4 HARDNESS TESTS

#### 3.4.1 BRINELL HARDNESS

Fig. 7 presents the Brinell hardness of each part of the studied anchors. It is possible to observe that the international fastener is the component with the highest hardness, while the others did not present significant differences between them (100HB-125HB). This variation can be explained by differences in chemical compositions and microstructure parts.

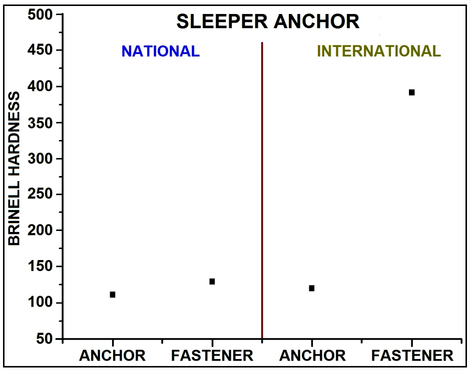


Figure 7. Brinell hardness of each part of the studied anchors.

#### 3.4.2 VICKERS MICROHARDNESS

Fig. 8 and Fig. 9 show Vickers microhardness (HV) profiles. The Fig. 8 presents the profile which leaves the weld area trough the anchor region and returns to the weld region. Fig. 9 shows the hardness profile from the weld area until the fastener, both for the national sleeper anchor. The Fig. 10 and Fig. 11 show HV profiles with similar organization to those shown in Figures 8 and 9, however, they refer to the international sleeper anchor. The x-axis show the distance between measured points (mm).

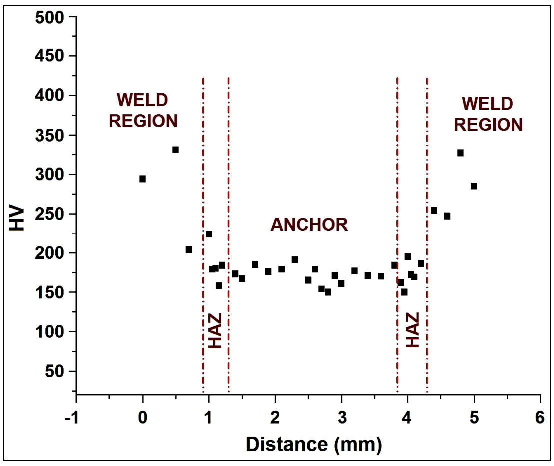


Figure 8. HV profile in the transition welding / anchor / welding - National sleeper anchor.

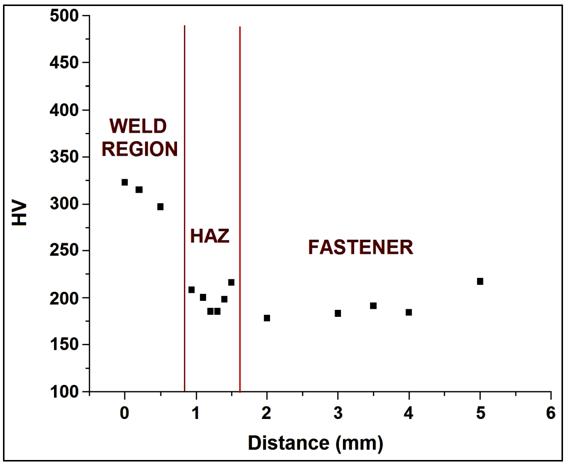


Figure 9. HV profile in the transition welding / fastener - National sleeper anchor.

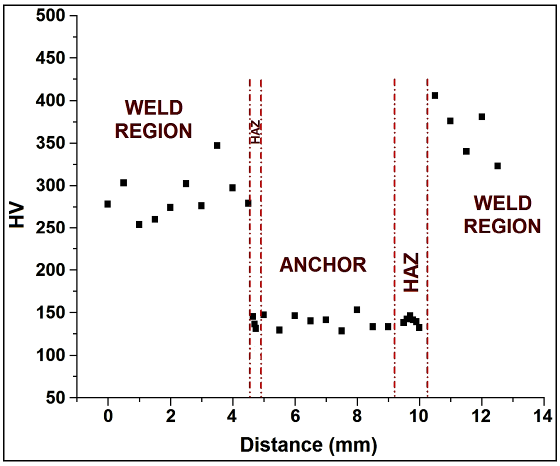


Figure 10. HV profile in the transition welding / anchor / welding - International sleeper anchor.

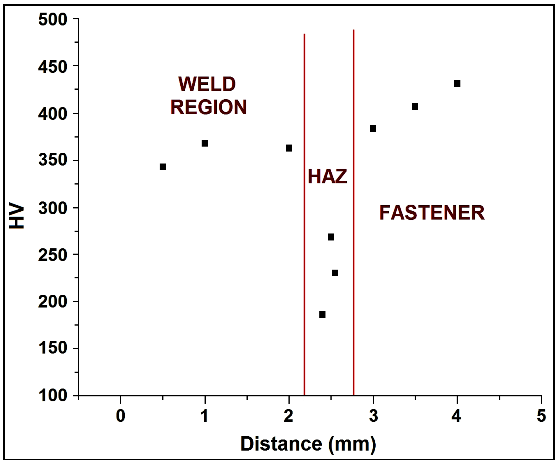


Figure 11. HV profile in the transition welding / fastener - International sleeper anchor.

Figures 8-10 show a tendency towards microhardness profiles: the weld region presented the higher hardness values compared to the heat affected zone (HAZ). These results are consistent with the analyzed microstructures.

Figure 11 shows a larger value of HV for the international fastener region and a smaller value for the HAZ. The highest microhardness presented by the fastener region is in accordance to the martensitic microstructure and analyzed by chemical analysis. There was a region of decarburization and ferritic grain growth in the HAZ region, thus explaining the lower value of hardness in this area.

### 3.5 TENSILE TESTS

Table 4 shows the mean values of yield strength ($\sigma$ys) (MPa) and tensile strength ($\sigma$ts) (MPa), with their standard deviations, for anchors and fasteners from both studied sleeper anchors.

Table 4. Yield strength ($\sigma$ys) and tensile strength ($\sigma$ts) of each part of the studied anchors.

| | Brazilian Sleeper Anchor | | European Sleeper Anchor | |
|---|---|---|---|---|
| | Anchor | Fastener | Anchor | Fastener |
| $\sigma$ys (MPa) | 276 ± 1 | 226 ± 2 | 274 ± 2 | 1124 ± 5 |
| $\sigma$ts (MPa) | 354 ± 2 | 313 ± 3 | 380 ± 5 | 1263 ± 7 |

Regarding $\sigma$ys and $\sigma$ts, it was observed that the national fastener and both anchors did not show significant differences. However, the international fastener highlights due its highest yield and tensile strengths. This result may be explained due to its tempered martensite microstructure.

The undesirable plastic strain of the national fastener (Fig. 2) is related to its low yield strength. This characteristic in association with its low thickness, much minor than the presented by the European fastener, did not meet the necessary conditions to support the applied loading during the train passage.

### 3.6 CHARPY IMPACT TEST

Tab. 5 presents the absorbed energy for each part of the national and the international sleep anchors. It is important to highlights that the presented values were obtained for reduced size specimens (ASTM E23)

Table 5. Energy absorbed in impact (Charpy) of anchors and fasteners of sleeper anchors at 20°C.

| | Brazilian Sleeper Anchor | | European Sleeper Anchor | |
|---|---|---|---|---|
| | Anchor | Fastener | Anchor | Fastener |
| Energy (J) | 30.6 ± 0.6 | 29.4 ± 0.8 | 33 ± 1 | 6.2 ± 0.4 |

From the obtained results, it is possible to observe that there were no significant differences between the national and international anchors and the fastener of national sleeper anchor. The international fastener presented the lowest absorbed energy, which is in accordance with its martensitic microstructure.

### 3.7 FRACTOGRAPHY

Fig. 2 presents the microfractographic images obtained from the fractured surfaces of the specimens submitted to the tensile tests. The fracture surface of the national and international anchors and the fracture surface of the national fastener present significant amount of dimples, indicating that these components presented a ductile behavior on tensile test. The international fastener presented a semi-ductile behavior. The presence of delaminations and very small and disperse microavoids reinforces this affirmation.

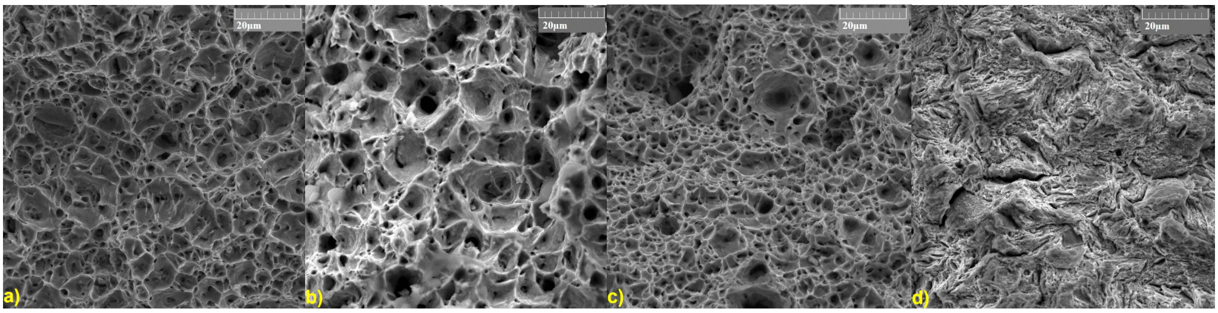


Figure 12. Fractography of national sleeper anchor: a) Anchor; b) Fastener. Fractography of international sleeper anchor: c) Anchor; d) Fastener. 3000x. (tensile tests).

## 4. CONCLUSIONS

In visual analysis it was observed that the service failure of the national sleeper anchor is related to an undesired plastic strain in its fastener. The intense deformation promoted the displacement of the sleeper anchor of ballast and the fracture of the welded fastener-anchor joint, making the component unusable.

The anchor and fastener of national sleeper anchor are manufactured from standard low carbon steels that were precariously welded. Considering the low yield strength of steel used in the national fastener manufacturing and the imposed level of loading during its service, it can be said that the thickness of the used sheets are poorly dimensioned for this type of application.

Comparing the microstructural characteristics and basic mechanical properties of national with European sleeper anchor, it is clear that the most significant difference is related to fasteners. The European fastener has a considerably higher thickness, even though the used steel has the highest yield strength (more than three times larger than the national fastener).

It is suggested that changes should be made in the manufacturing project of national sleeper anchor: the first concerns the selection of materials. Knowing that the national fastener is failing due to a compressive overload and that it is not possible to avoid this type of event during its use, it is suggested the change of the national fastener steel. It is suggested the utilization of a higher-strength steel, as well as the resize of the sheet thickness in function of the loading levels in the railways; the second concerns the welding process that should be done with greater quality control, with attention especially to the homogeneity of the weld and microstructural constituents; the third and last relates to the sleeper anchor installing on the way. There was observed that the fastener when attached to two sleepers may be strongly requested under compression. In this context, it should be evaluate the possibility of modifying the component design to allow its installation in each sleeper individually.

## 5. ACKNOWLEDGEMENTS

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## 7. RESPONSIBILITY NOTICE