

## COB-2023-2209

# EVALUATION OF RECOVERY AND RECRYSTALLIZATION INDUCED BY HEAT TREATMENT IN DEFORMED RAILWAY STEEL MICROSTRUCTURE

**Igor Ferreira Passinho Silva**

**Andrei Bavaresco Rezende**

Federal University of Maranhão, UFMA-CCET-CCEM, Avenida dos Portugueses, 1966, CEP 65080-005, São Luís, MA, Brazil

igorferreirapassinhosilva@gmail.com

andrei.rezende@ufma.br

**Abstract.** Railway wheels operate under high load conditions on the contact surface with the rail and exhibit severe grain deformations beneath the contact surface. The railway wheels, after a period of use, are machined via turning process for reprofiling and removing the deformed layer. However, there are works seeking to improve the rail using heat treatments in deformed layer. Based on this aspect of recovery and recrystallization, there is an opportunity to homogenize this deformed layer of the wheel through heat treatments, which could extend the time required for reprofiling and reduce the cutting forces and machined thickness. Thus, this work sought to perform thermal treatments to homogenize the deformed layer induced by twin-disc tests in Class C railway wheel steel. The holding temperatures were 600 and 650 °C with treatment time between 5 and 30 minutes. After heat treatment, the samples were prepared and analyzed by optical microscopy and Vickers hardness measurements. It was observed that the temperature of 650°C resulted in a more effective homogenization and lower hardness values. However, at 600°C, the hardness was slightly higher. Thus, the optimal treatment time was 10 minutes at a temperature of 650°C, demonstrating the homogenization of both hardness and microstructure.

**Keywords:** railway, wheels, heat treatment, hardening.

## 1. INTRODUCTION

The cost of maintaining equipment and machines that are subject to surface contact wear, such as in the railway sector, consumes a large part of the companies' resources. Therefore, there is a constant quest to use the best materials with good resistance to wear and contact fatigue, to increase the useful life of these components and thus reduce the frequency of repairs or replacements (Solano-Alvarez et al., 2014). The components in the railway sector that suffer the most wear are the rails and wheels. Considering that railway companies, in order to increase their competitiveness, expand the load transported by each axle in the wagon, a high investment is necessary to improve the wheel-rail system. Due to the increased volume of cargo, the wheels suffer more impact in maintenance, and consequently require greater reliability and safety for operation, generating high costs (Bôas, 2010).

Following the AAR (Association of American Railroads) standard, Class C wheels are most used for heavy axle loads. Manufacturing can be through forging or casting, using a steel with a medium carbon content composition. Through the composition of the steel alloy, desirable tribological properties can be achieved along with the application of thermomechanical treatments (AAR, 2014). Class C wheels adopt the AAR standard M-107/208, which aims to regulate and certify safety and quality standards, establishing requirements for their chemical composition and manufacture. Due to high axle loads, wheels need good resistance to contact fatigue and high temperatures when braking to avoid the formation and propagation of cracks, especially on the tread (Chaves, 2017).

Just below the raceway surface, significant grain deformations occur in the microstructure (Strey et al., 2021). A multiaxial stress field is generated at the surface and subsurface, cyclically alternating as the body rotates. This stress field increases and accumulates with cycles, potentially exceeding the material's yield strength, causing deformation in the grains just below the raceway surface (Ekberg; Sotkovszki, 2001). With deformation and contact fatigue, cracks emerge, and their propagation and coalescence lead to the development of spalling defects in the wheel, which can also result in the formation of shell defects. Cracks that initiate below the raceway surface propagate to the wheel's surface, leading to flaking or even rim fracture.

Due to wheel wear, the original profile is lost. To maintain their use, they are subjected to a reprofiling process using copying lathes to remove a thin layer and recover the original profile. This process is also important to remove surface defects that affect the performance of the wheel and cause an unsafe operation. The reprofiling process increases the wheel's useful life, and the material removal to recondition the profile is limited to safe operating dimensions. When the

wheel exceeds this dimensional tolerance, they are scrapped. The reprofiling process has a much lower cost compared to replacing the wheels with new sets, but it depends on a good management of the wheel sets lives (Neto, 2006).

The grain deformation in the microstructure of the railway wheel resulting from the cyclic stresses of the contact between the wheel and the rail promotes the hardening of the surface layer through cold working. This hardened layer is also achieved in twin-disc tests (Rezende et al., 2021). Strey et al., (2021) observed that discs from twin-disc tests and railway wheels show similar deformed subsurface layer. This deformation generates internal stresses caused by distortion in the crystalline structure of steel, with the energy being stored in the microstructure. The number of point defects and dislocations increases, affecting the grain orientation (Abbaschian and Reed-Hill, 2009).

Heat treatment is a process that involves heating and cooling metals or alloys to achieve specific properties. This may involve changes in the physical, mechanical, and even chemical characteristics of the materials, without altering their shape. The main goal is to increase the product's durability by improving its strength, hardness, ductility, machinability, and formability. Heat treatment can encompass a variety of processes, such as normalization, annealing, and others. (Czerwinski, 2012).

During the annealing heat treatment, the stored strain energy is reduced through the reorganization of the microstructure. As the temperature increases, the cold-worked state becomes progressively more unstable. Eventually, the metal recovers and reverts to a deformation-free condition. The annealing process can be divided into three distinct processes: recovery, recrystallization, and grain growth (Dieter and Bacon, 1986). In recovery, the mechanical properties are partially restored by reducing the strain energy through dislocation movement, the interstices and gaps in the steel are eliminated and undergrain formation occurs (de Oliveira, 2019). In recrystallization, a completely new set of grains is generated. These new crystals form in locations where the lattice strain energy is high, such as at slip-line intersections, deformation twin intersections, and in regions near grain boundaries. Thus, the driving force for recrystallization comes from the energy accumulated during the cold deformation process. (Abbaschian and Reed-Hill, 2009).

Based on the above, the objective of this study is to analyze, through heat treatment, the effects on the microstructure of the deformed layer induced by twin-disc tests, using discs from a class C railway steel wheel. The goal is to understand the results of annealing on the samples under superplastic deformation conditions (such as railway wheels), through recrystallization and recovery. Thus, the aim is to enhance the mechanical strength to reduce maintenance costs, prolonging the service life of railway wheels with a decrease in machining thickness and volume of material removed.

## 2. METHODOLOGY

In this work, samples of class C railway wheel steel discs were used, with composition according to table 1. The discs were submitted to twin-disc tribological test conducted by Rezende et al. (2021). After the tests, the discs were sectioned according to Figure 1. The circumferential sections were annealed in a muffle furnace at temperatures of 600° C and 650° C, with a residence time of 5, 10, 20 and 30 minutes followed by cooling at room temperature. The samples were prepared for a conventional metallographic analysis process.

Table 1. Chemical composition in mass percentage of class C railway steel wheel.

C	Mn	Si	P	S	Cr	Ni	Mo	Al	V	Nb
0.74%	0.74%	0.28%	0.008%	0.023%	0.20%	0.057%	0.02%	0.008%	0.002%	0.002%

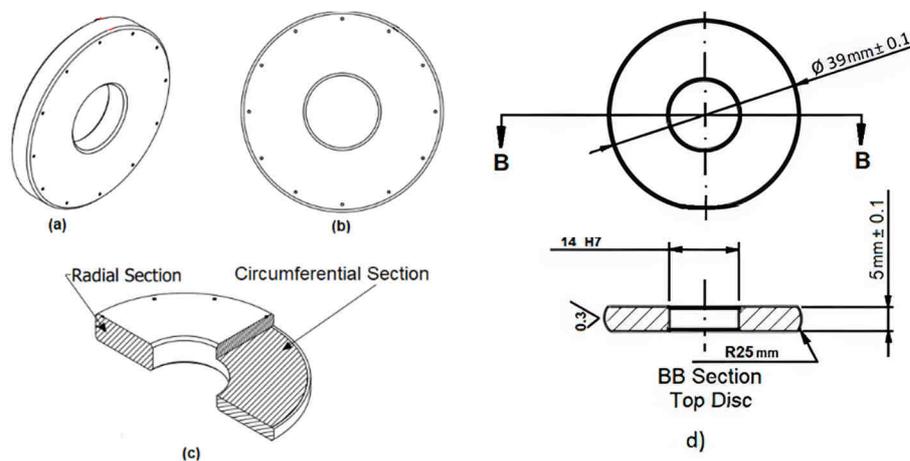


Figure 1. Discs representation: a) isometric perspective; b) frontal view; c) radial section and circumferential section; d) disc dimensions. Adapted from Strey et al., (2021).

The samples were mounted with bakelite and subsequently sanded with 5 different grain sizes (300, 600, 1200, 1500, 2000 and 2500). For polishing, alumina in suspension with 1 micrometer granulometry was used. To reveal the microstructure, 2% Nital chemical etching was used for 4 seconds. The microstructure analysis was performed with an Olympus BX51 image analyzer optical microscope. Microstructures were compared using image J software under each treatment condition. A hardness profile on the Vickers scale of the deformed layer was performed using a microdurometer (Shimadzu HMV-2T) with load of 0.3 kg by 15 seconds, and subsequently analyzed in comparison with the images of the microstructure after heat treatment.

### 3. RESULTS AND DISCUSSION

In this section, the results of the metallographic analysis will be presented, including micrographs obtained before and after the heat treatment of the samples, as well as the hardness data obtained for each time and temperature configuration of annealing.

#### 3.1 Metallographic analysis of samples

The micrograph of the untreated sample, at a 200x magnification, reveals a high level of grain deformation near the rolling surface, indicating that the material has undergone work hardening due to the cyclic stresses on the raceway the disc was subjected to. As shown in Figure 2, distortions in the rolling direction of the discs were observed in the microstructure, with elongated grains, signifying the intensity of deformation. There was a significant reduction in the average grain size near the surface, suggesting an increase in dislocation density and the formation of regions with heterogeneous layers.

The results obtained from the micrographs of the samples subjected to twin-disc tribological testing revealed similar characteristics to those observed in the recent study on wheels (Strey et al., 2021). There was a severe hardening on the surface of the disc, with a thickness ranging from 255-270  $\mu\text{m}$ . This surface hardening in the samples occurred due to normal and tangential stresses generated by the contact load and sliding.

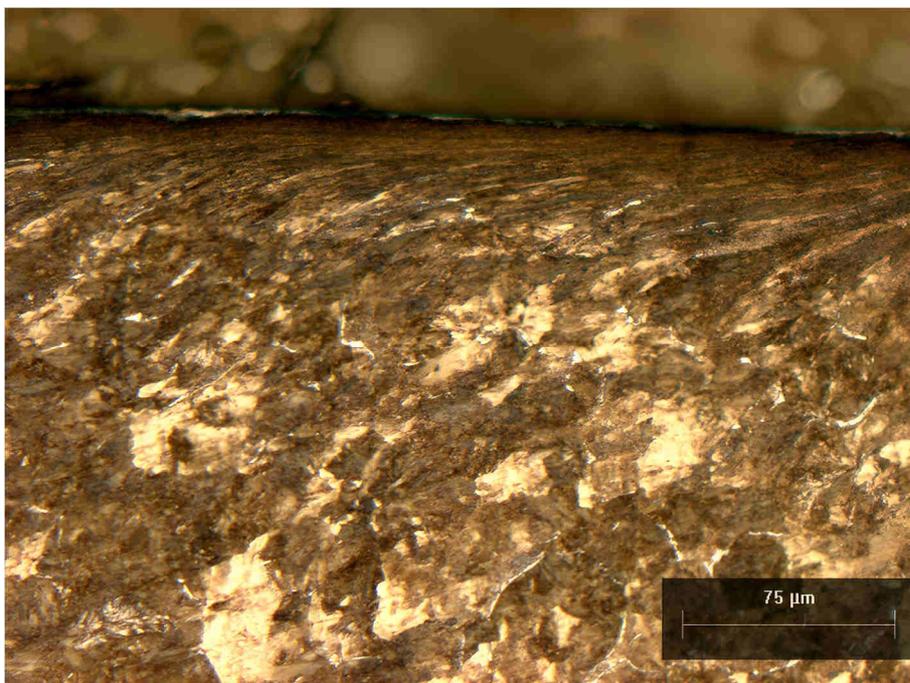


Figure 2. Sample micrograph without heat treatment.

Figure 3 presents the micrographs of the material subjected to the heat treatment at 600°C. For holding times of 5 and 10 minutes in the furnace, a progressive reduction in plastic deformation can be observed in Figure 3 (a) and (b) at a magnification of 100x. The grains tend to realign and take on a more rounded shape, suggesting the beginning of the recovery process. Clearer grain boundaries start to form, indicating possible partial recrystallization. However, the microstructure still retains some characteristics of the initial deformation.

As the heat treatment time increases to 20 and 30 minutes at 600°C (Figure 3 (c) and (d)), the results of recovery and recrystallization become more pronounced, reducing the effects of plastic deformation on the grains.

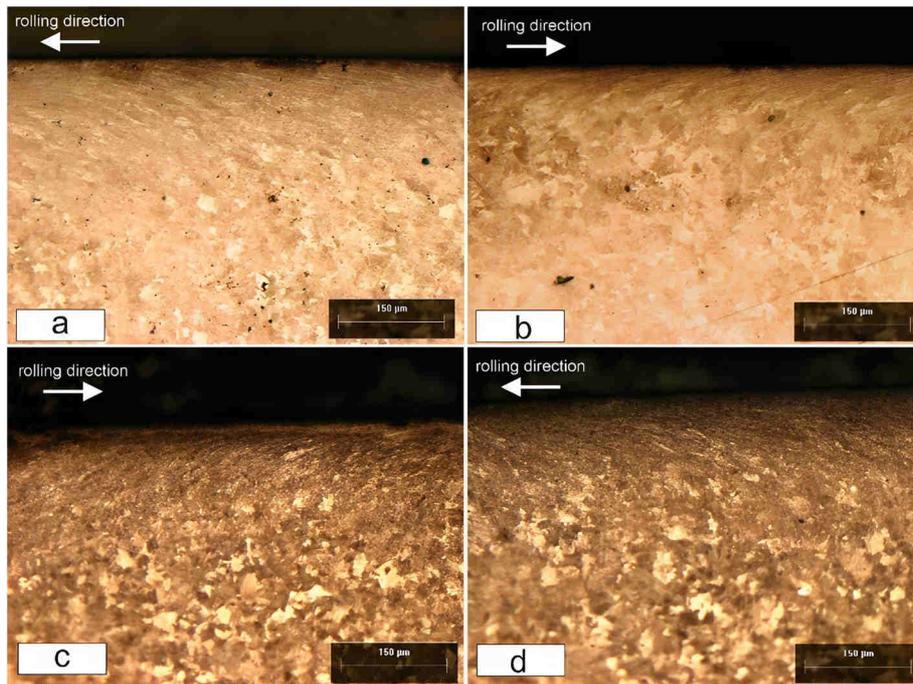


Figure 3. Micrograph of Heat Treatment at 600°C. (a) 5 min, (b) 10 min, (c) 20 min and (d) 30 min.

Figure 4 presents the micrographs of the material subjected to heat treatment at 650°C. For times of 5 and 10 minutes (Figure 4 (a) and (b)), a higher rate of recovery and recrystallization is observed compared to the samples treated at 600°C for the same residence time. The microstructure exhibits a higher proportion of recrystallized grains, but it is still possible to notice significant grain deformation. The effects of plastic deformation on the grains are reduced, indicating a higher effectiveness of the heat treatment at higher temperatures.

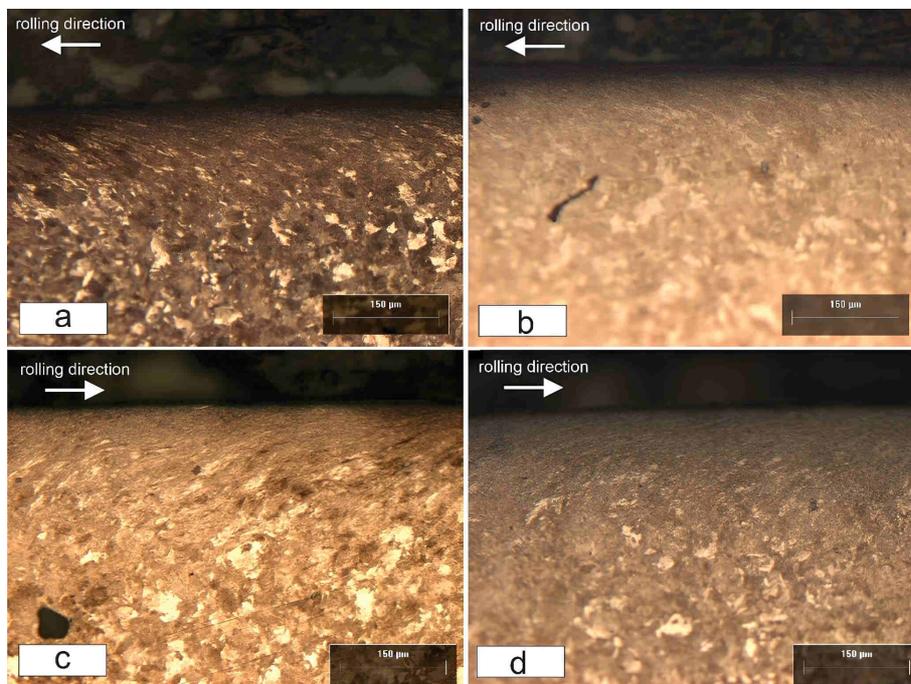


Figure 4. Micrograph of Heat Treatment at 650°C. (a) 5 min, (b) 10 min, (c) 20 min and (d) 30 min.

The redistribution of atoms to form new crystalline structures is a fundamental process of atomic diffusion. Diffusion in crystals is explained in terms of vacancies, assuming that vacancies move through the lattice. With increasing

temperature, there is a higher rate of atomic movement, leading to a higher rate of recrystallization due to the rapid redistribution of atoms (Abbaschian and Reed-Hill, 2009).

### 3.2 Hardness measurement analysis

The combination of micrograph analysis and hardness measurements is crucial for a comprehensive understanding of the evolution of the deformed layer after annealing. By measuring hardness in the heat-treated samples, it was possible to obtain information about the material's strength and its ability to recover and recrystallize. Samples with higher and lower hardness in the deformed layer were identified, indicating the presence of regions that have not yet been fully homogenized for certain temperature and furnace residence time.

Figure 5 and 6 present the hardness measurements below the rolling track of the samples treated at 600 and 650 °C, respectively. A hardness profile of the untreated sample was also plotted. In Figure 4, it was observed that the heat treatment reduced the hardness for all residence times at 600 °C. From 5 minutes of residence, the hardness was very similar. The samples exhibit good homogeneity in the hardness of the deformed layer. While the hardness values in the untreated layer show considerable variation, with differences of up to 60 HV between measurements, the hardness values of the thermally treated samples have less variation.

In Figure 5, there is a tendency for the hardness of the untreated sample to have higher values at shorter distances from the rolling surface. These values are consistent with Figure 1, where the microstructure shows a deformed layer with elongated ferrite and cementite grains compared to the core of the sample. As the depth increases from the surface, hardness results show lower values since the microstructure did not undergo plastic deformation beyond a depth of 140 μm.

When compared the hardness with the micrographs (Figure 2), even though the deformed layer maintained some deformation aspect after the heat treatment, it is clear that there was a homogenization of the less hardened parts and that the entire layer has not yet been finished. It is also important to note that the hardness has been practically restored. Therefore, this remaining deformed grains orientation does not mean that the treatment was not effective, as the hardness reduced considerably. In terms of microstructure hardness homogenization, the sample subjected to 600°C with a 30-minute furnace residence time achieved better results, with hardness values not being too low. The microstructure, as shown in Figure 2 (d), underwent more recrystallization and, consequently, exhibited a lower dislocation density.

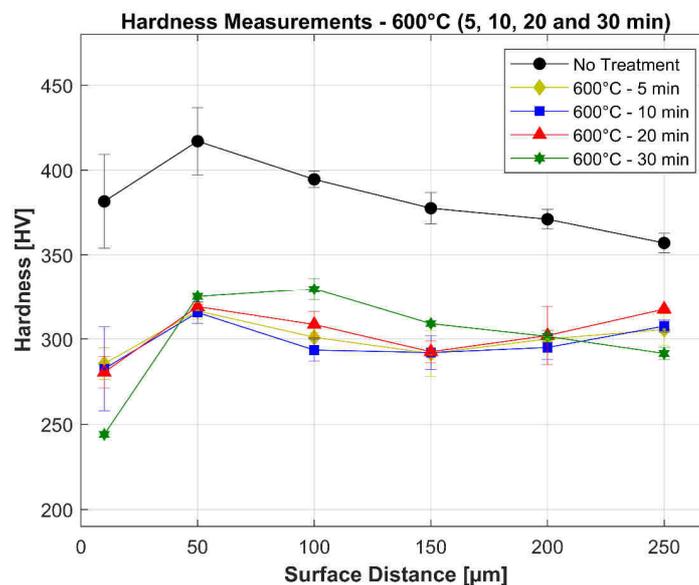


Figure 5. Hardness measurements after heat treatment at a temperature of 600°C.

For the temperature of 650°C, as shown in Figure 6, it was observed that the hardness decreased in thermally treated samples as the furnace time increased. This result indicates a higher degree of recovery in the deformed layer compared to 600°C for the same furnace time. As the temperature is higher, the energy available for atomic movement increases, leading to the annihilation of dislocation lines and a reduction in hardness. In the sample treated at 650°C for 30 minutes, the hardness values were lower, with the central region reaching a hardness of 274 HV, a difference of 120 HV compared to the central region of the untreated sample. Figure 2 (d) shows that the grains appear less elongated and distorted compared to the untreated sample, explaining the lower hardness.

In this configuration, with 10 minutes at 650°C, the hardness was already homogenized. The annealing heat treatment reduced the hardness of the layer more evenly along the distance from the surface, and the core of the sample remained at 308 HV.

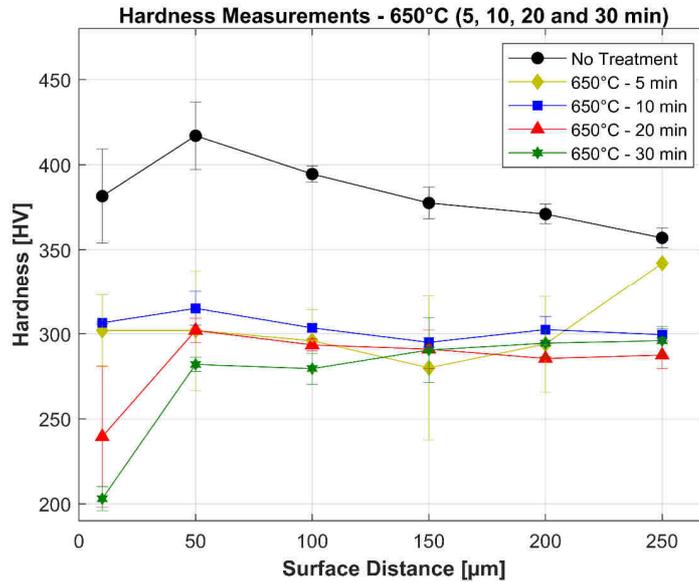


Figure 6. Hardness measurements after heat treatment at a temperature of 650°C.

According to the standard (AAR, 2014), new Class C steel wheels must meet minimum hardness values both in the core and on the surface. For the wheel core, the minimum required hardness is 306 HV, while on the surface, the minimum hardness is 330 HV, as shown in Table 2. When these requirements are compared with the untreated samples, it is observed that the measured hardness in the wheel core is 357 HV, which is above the standard requirement. Considering that after the heat treatments, the condition of 650°C and 10 minutes presented an average hardness of 308 HV, this treatment maintain the microstructure above the required of 306 HV. The same is valid for the condition of 600°C and 30 minutes.

Table 2. Hardness comparison according to AAR standard and sample without heat treatment.

Class C steel (AAR M-107) Hardness (HV) - 60 mm depth	Sample without thermal treatment at the core (HV)	Class C steel (AAR M-107) Surface Hardness (HV)	Sample without thermal treatment (HV) - surface
306	357	330	401

Through the analysis of micrographs and hardness results, it was found that the sample treated at 650°C for 10 minutes exhibited a more homogeneous hardness distribution in relation to the distance from the surface, indicating a more effective recrystallization process. Furthermore, the average hardness in this sample exceeded the minimum requirements specified by the AAR standard for new wheels.

The promising results of the thermal treatment at 650°C for 10 minutes and 600°C for 30 minutes offer optimistic prospects for improving wheel maintenance, increasing their lifespan, and reducing cutting forces and material removal volume during the reprofiling process (Neto, 2006). Based on these results, it is possible to design a way to apply heat treatment to wheels before the machining process. It is important to highlight that this work was an exploratory regarding the effect of temperature on the deformed layer. Therefore, a twin-disc test disc was used. Its continuation is to apply heat treatment to real wheels to check the influence and have a more specific overview.

#### 4. CONCLUSION

Based on the results obtained from the annealing heat treatment of class C steel discs used in the twin-disc test, whose rolling track presented a deformed layer with a hardness above 400 HV, the following conclusions are presented:

Micrographs revealed the presence of intense plastic deformation in the untreated sample, with distortions indicating the extent of deformation. The heat treatment at 600°C for 30 minutes proved to be effective in the recovery and

recrystallization of the microstructure, with a progressive reduction in the effects of deformation on the grains without a significant decrease in hardness.

The heat treatment at 650°C for 10 minutes showed promising results, with a more homogeneous microstructure and a more uniform distribution of hardness, with an average hardness value within standard requirements. These results indicate a higher degree of microstructural recovery and recrystallization.

A longer residence time in the furnace with a lower temperature also produces the desirable effect of reducing hardness and homogenizing the deformed layer. However, the bulk hardness dropped significantly in some points.

## 5. ACKNOWLEDGEMENTS

The authors thank the Foundation for the Support of Research and Scientific and Technological Development of Maranhão (FAPEMA), under grant number 10005/22 and the Federal University of Maranhão for the financial support.

## 6. REFERENCES

- AAR – Association of American Railroad. *M-107/M-208: Manual of Standards and Recommended Practices Wheels and Axles - Section G*. Washington, 2014.
- Abbaschian, R., & Reed-Hill, R. E. (2009). *Physical metallurgy principles-SI version*. Cengage Learning.
- Bôas, R. L. V. (2010). *Desenvolvimento de aço microligado para rodas ferroviárias* (Doctoral dissertation, Dissertação (Mestrado)—Universidade Estadual de Campinas).
- Chaves, A.P.G., 2017. *Rodas ferroviárias: análise, microestrutura e propostas de melhoria*. Ph.D. thesis, Universidade de São Paulo.
- Czerwinski, F. (Ed.). (2012). *Heat treatment: Conventional and novel Applications*. BoD—Books on Demand.
- Dieter, G.E. & Bacon, D. (1976). *Metalurgia mecânica* (Vol. 3, pp. 43-53). Nova York: McGraw-Hill.
- de Oliveira, D. A., & Fraga, F. E. N. (2019). Influência do tempo de recozimento sobre a recristalização e tenacidade ao impacto de um aço baixo carbono. *Revista Eletrônica de Engenharia Elétrica e Engenharia Mecânica*, 1(1), 235-244.
- Ekberg, A., & Sotkovszki, P. (2001). Anisotropy and rolling contact fatigue of railway wheels. *International journal of fatigue*, 23(1), 29-43.
- Neto, A. L. (2006). O Desgaste de Rodas e o Processo de Reperfilamento. *Monografia apresentada ao Curso de Especialização em Transporte Ferroviário de Carga do Instituto Militar de Engenharia*.
- Rezende, A. B., Fonseca, S. T., Miranda, R. S., Fernandes, F. M., Grijalba, F. A. F., Farina, P. F. S., & Mei, P. R. (2021). Effect of niobium and molybdenum addition on the wear resistance and the rolling contact fatigue of railway wheels. *Wear*, 466, 203571.
- Solano-Alvarez, W., Pickering, E. J., & Bhadeshia, H. K. D. H. (2014). Degradation of nanostructured bainitic steel under rolling contact fatigue. *Materials Science and Engineering: A*, 617, 156-164.
- Strey, N. F., Rezende, A. B., da Silva Miranda, R., da Fonseca, S. T., Mei, P. R., & Scandian, C. (2021). Comparison of rolling contact fatigue damage between railway wheels and twin-disc test specimens. *Tribology International*, 160, 107037.

## 7. RESPONSIBILITY NOTICE

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