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EXPERIMENTAL ANALYSIS OF RESIDUAL STRESS RELIEF BY MECHANICAL VIBRATION IN RESISTANCE SPOT WELDING

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Abstract. *The High Strength Low Alloy steels (HSLA), such as the cold-rolled HC420LA, are mostly applied in the automotive industry, especially in vehicle bodywork. The microstructure, which has a low content of alloying elements and added carbon, allows great advantages as high tensile strength, good toughness and weldability. Resistance spot welding (RSW) is known for its rapid application, low cost and easy automation, being then commonly used in the automotive industry. Due to the combined action of shrinkage, heat input and phase transformations that occur during welding operations, residual stresses are generated in the welded joint. These are generated in all manufacturing processes and are produced when regions of a material undergo permanent heterogeneous plastic or elastic deformation, without the presence of any external loads. It is well established that tensile residual stresses have a detrimental effect, as they can add to service loads, contributing to the nucleation and propagation of fatigue cracks. Therefore, new techniques for stress relief have emerged, such as Vibration Stress Relief (VSR), which reduces residual stress through cyclic loading treatments and does not cause distortions or microstructural changes in welded joints, as may occur in heat treatments. The aim of this work was the development of an experimental analyze of the residual stress relief by the mechanical VSR method in the resistance spot welded joints of HC420LA steel. Residual stresses were analyzed by X-ray diffraction technique, by $\sin^2\psi$ method and were correlated to Magnetic Barkhausen Noise (MBN) measurements. This work contributes to a better understanding of VSR techniques applied on resistance spot welded joints. The residual stresses generated in spot welding was quantified and qualified before and after stress relief, and a relationship has been established among the methodologies available for their measurement.*

Keywords: *residual stresses, X-ray diffraction, vibration stress relief, magnetic Barkhausen noise, resistance spot welding.*

1. INTRODUCTION

Resistance spot welding (RSW) is an effective joining technique extensively used in the automotive industry for the purpose of joining metal sheets, owing to its rapidity, cost-effectiveness, and compatibility with automation. This process involves the passage of a high electrical current through the material, which generates a heat input due to its resistance, particularly at the interface of contact. As a consequence, fusion occurs and a weld nugget is formed after solidification (Shah and Liu, 2019). The reliability and mechanical behavior of spot welds represent crucial aspects pertaining to vehicle crashworthiness, as they play an important role in ensuring passenger safety (Das *et al.*, 2023).

Due to the partial melting of materials and the sophisticated thermal-electric-mechanical effect, complex residual stresses are generated. These represents a critical factor that can significantly influence the service life of resistance spot welded joints (Ao *et al.*, 2020). Residual stresses are generated by all manufacturing processes and are produced when regions of a material undergo permanent heterogeneous plastic or elastic deformations, even in the absence of external

loads (Valíček *et al.*, 2019). The presence of residual stresses can either be detrimental or beneficial to materials, depending on their nature, magnitude, and distribution. Tensile residual stress increases the mean stress, thereby deteriorating the fatigue strength and reducing resistance to stress corrosion, whereas compressive residual stress is beneficial. Therefore, it is crucial to comprehend and control residual stress in welded joints for the purpose of evaluating and prolonging the service life of component (Sun and Dilger, 2023).

Conventional methods for relieving residual stress include thermal aging and vibratory stress relief (VSR). Thermal aging, although widely used, is associated with high energy costs, rust scales on the surface, and part deformation. In comparison, VSR technology shows promise as a more advantageous method for residual stress relief due to its low cost, high efficiency, and environmental friendliness (Zhang *et al.*, 2020). VSR involves a motor system with an eccentric weight (referred to as an exciter) placed on the component. The motor is activated by a controller and its speed is adjusted to bring the component into a resonant state. When the vector sum of the residual internal stress and the additional vibratory stress of the component exceeds the yield strength of the material, a slight plastic deformation occurs, thereby relaxing and relieving the residual stress within the component (Xiu *et al.*, 2021).

Numerous studies have been conducted on vibration stress relief. Mohanty *et al.* (2017) examined the residual stresses induced in AISI 316 austenitic stainless-steel plates welded using a CO₂ laser. Their findings revealed a significant reduction in residual stress, with an average magnitude of 100 MPa. Gao *et al.* (2020) conducted experimental and simulation investigations on the thermal-vibratory stress relief (TVSR) process applied to 7075 aluminum alloy. The results demonstrated that TVSR effectively reduced the residual stress in the aluminum alloy. In a separate study, Xiu *et al.* (2021) investigated the application of vibration stress relief in welding the vacuum vessel of the China Fusion Engineering Test Reactor (CFETR).

X-ray diffraction (XRD) is a well-established technique for analyzing residual stress, which has been widely utilized for over 60 years. One of the advantages of XRD is its ability to determine residual stress without sacrificing the work-piece. The conventional method of tensometry by XRD involves measuring the interplanar spacing and the deformation of the crystalline planes of the material (Shukla, 2020).

Other non-destructive techniques are currently under study and development for assessing residual stresses. Among them is the Magnetic Barkhausen Noise (MBN) method, which originates from the magnetization process of ferromagnetic materials. The modification of the magnetic domain microstructure under the influence of an external magnetic field, generates unpredictable and discontinuous domain wall motions, including successive pinning phases and large amplitude displacements. The MBN signal indirectly reflects this microstructural reorganization and is linked to the material properties. Typically, the MBN measurements are performed using time-independent indicators such as the Root Mean Square (RMS) or the MBN energy (Fagan *et al.*, 2022).

High strength low alloy steels (HSLA) are low carbon and low alloy steels characterized by a microstructure composed of a ferrite matrix containing finely dispersed alloy carbides and ferrite-pearlite aggregates. The exceptional mechanical properties of HSLA steels, including high strength, toughness, and good weldability, have led to a growing demand for these steels in various applications (Singh *et al.*, 2023). Particularly in the automotive sector, HSLA steels have been one of the pioneering high-strength steels (HSS) widely applied, resulting in significant weight reduction and improving material performance properties (Janakiram and Gautam, 2018).

Therefore, the objective of the present work is to investigate the relief of residual stresses in resistance spot welded joints of HSLA steel using vibration stress relief (VSR). For this purpose, the residual stresses will be analyzed using X-ray diffraction (XRD) with the $\sin^2\psi$ method and the RMS_{MBN} were studied before and after the vibration process.

2. MATERIALS AND METHODS

The material selected for this study was the cold rolled HSLA HC420LA steel with the thickness of 2.0 mm, manufactured in accordance with DIN EN 10268. Table 1 and Table 2 show the chemical composition and mechanical properties of the selected material, respectively.

Table 1. Chemical composition of HC420LA steel (max. % by weight).

C	Si	Mn	P	S	Al	Ti	Nb
0.14	0.5	1.6	0.030	0.025	0.015	0.15	0.09

Table 2. Mechanical properties of HC420LA steel.

σ_{LE} (MPa)	σ_{LR} (MPa)	Elongation (%)
420 – 520	470 – 600	17

Four samples were welded using the resistance spot welding process at the Welding Laboratory (LASOL) at CEFET-RJ. The welding parameters are described in Table 3 and the dimensions of the samples are shown in Figure 1.

Table 3. Parameters applied in RSW.

1 st compression cycle	2 nd compression cycle	Welding cycle	Hold cycle	Power (%)	Current (kA)	Pulse	Pressure (bar)
25	10	30	5	65	4 – 10	1	5

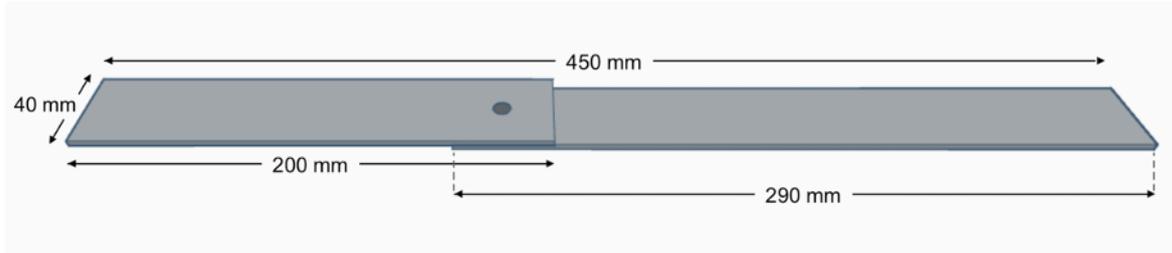


Figure 1. 3D model of welded samples with dimensions.

Metallography by optical microscopy, employing a 2% Nital chemical etching solution, was conducted to examine the microstructure of the material prior to and following welding. The analysis focused on the longitudinal section of the weld spot to determine the dimensions of the nugget, the heat-affected zone, and the extent of plate melting.

Residual stresses were measured, before and after VSR, at the nugget center by X-ray diffraction using the $\sin^2\psi$ method at the Stress Analysis Laboratory (LAT) of Universidade Federal Fluminense (UFF). The X-ray stress analyzer, XStress3000 from Stresstech, as shown in Figure 2, was employed for this analysis made in longitudinal direction with achieved accuracy of approximately 15 MPa. The XTronic V1-0 Standard software (stresstechgroup.com) was used for the residual stress calculation. The experimental parameters utilized are listed in Table 4.

Table 4. Stress analyzer calibration parameters.

Collimator diameter	2 mm
Incidence angle 2θ	156.42°
Inclination angles ψ [°]	0; 18; 27; 33; 45
Radiation	CrK α
Wave-length λ [Å]	2.29092
Diffraction plane	[2 1 1]
Electric current	6.7 mA
Voltage	30 kV

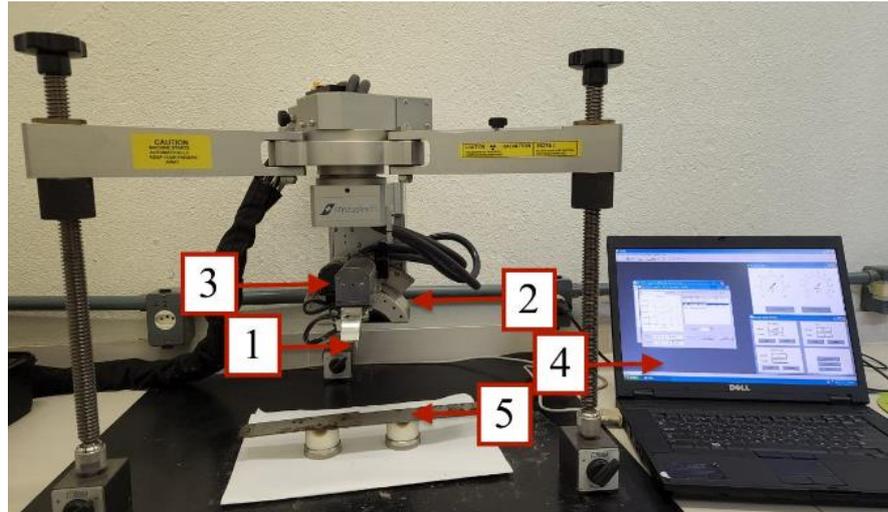


Figure 2. XStress3000 stress analyzer: 1) collimator; 2) goniometer; 3) X-ray tube; 4) software; 5) sample. (LAT/UFF).

The MBN was analyzed in the center of the nugget, in the longitudinal direction, with an excitation frequency of 10 Hz and excitation amplitude of 2.5V. The results were processed in MATLAB software to obtain effective RMS values.

To implement the VSR technique, the specimens were affixed to a shaker system, which was linked to a function generator and an amplifier. This arrangement allowed for the controlled vibration of the samples at specific frequencies and amplitudes, enabling the desired stress relief. Sensors were strategically placed on the samples to measure the acceleration near to the weld nugget. Prior to the vibration process, resonant frequencies were studied through simulations and the second resonant mode were applied to half of the samples, as well as a sub-resonant frequency to the other half. The parameters utilized in the process are vibrating time of 10 minutes, acceleration of 10 m/s^2 and frequency of 34 Hz and 52 Hz for samples A and B and samples C and D, respectively. The Figure 3 shows how the experiment was performed.

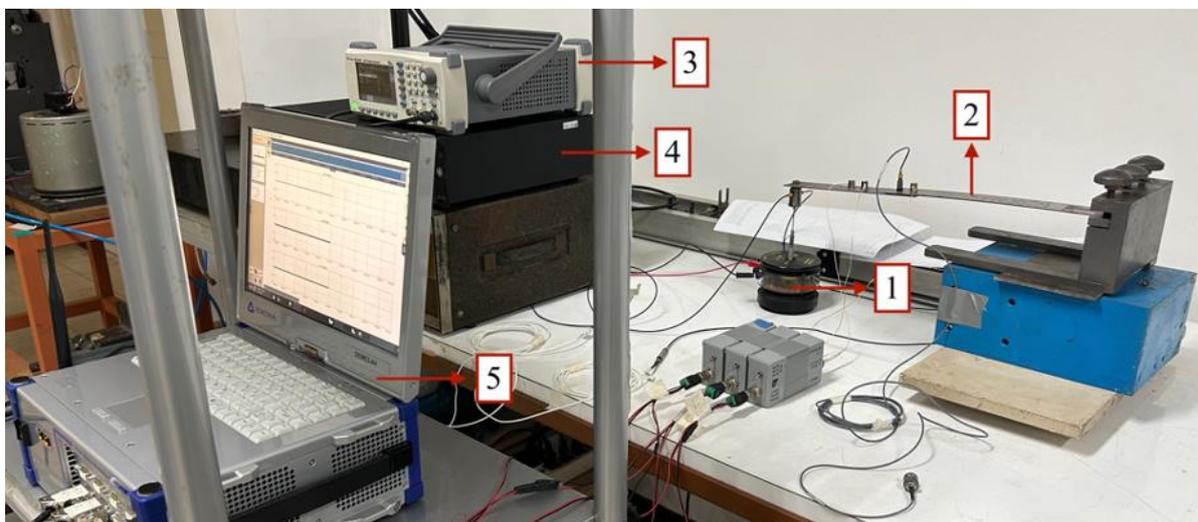


Figure 3. Assembly scheme of vibration stress relief process: 1) shaker; 2) analyzed sample; 3) function generator; 4) amplifier; 5) software. (LAVI/COPPE-UFRJ).

3. RESULTS AND DISCUSSION

The microstructure of the sample, both as-received and after welding, was examined using optical microscopy, as presented in Figure 4. The micrographs reveal the characteristic ferritic microstructure of the steel, along with grain elongation observed in the nugget and the heat-affected zone.

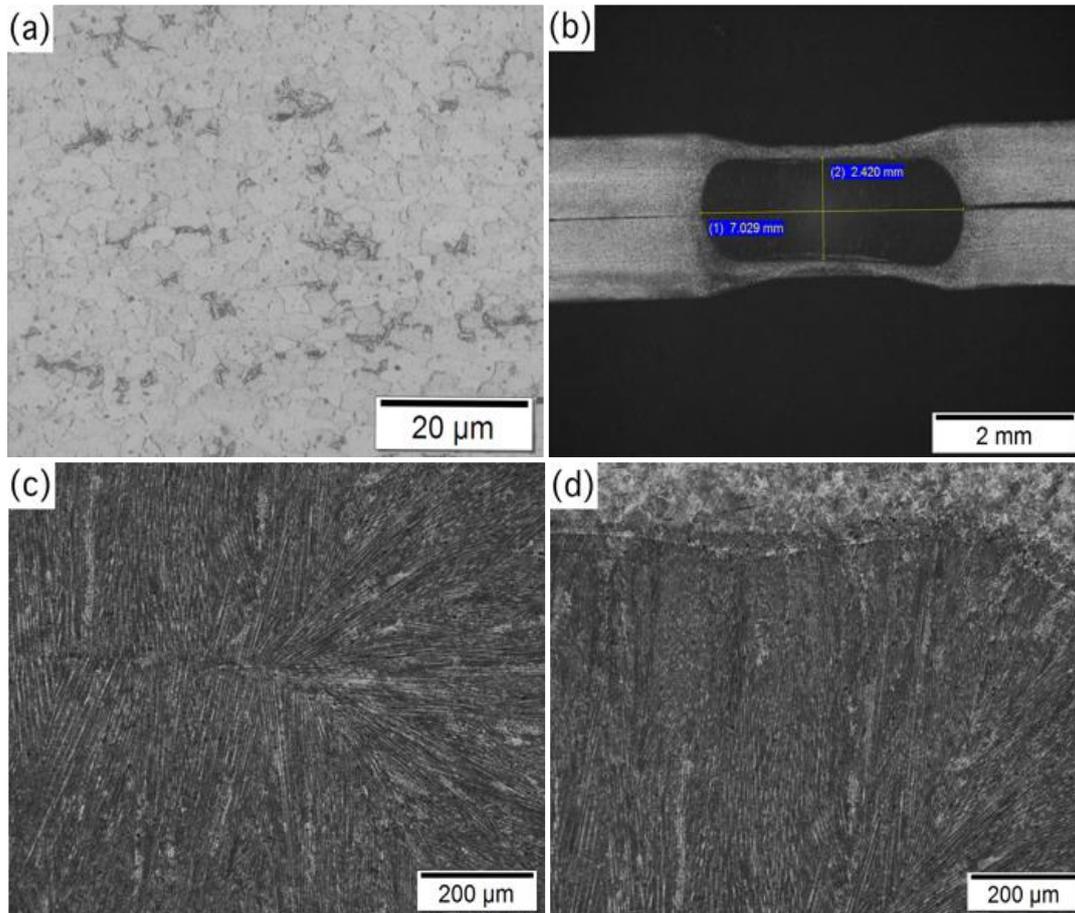


Figure 4. Microstructure of HC420LA steel, (a) as received; (b) nugget with dimensions; (c) melting point of the plates; (d) heat affected zone.

The results of residual stresses (RS) measured by X-ray diffraction before and after the vibration stress relief process, along with the percentage of stress relief (SR), are presented in Table 5. Figure 5 illustrates the corresponding graphical representation of these results.

Table 5. Residual stresses before and after welding and percentage of stress relief.

Samples	RS before vibration (MPa)	RS after vibration (MPa)	Percent SR (%)
A	110 ±1	55 ±1	50
B	240 ±9	140 ±5	42
C	230 ±8	120 ±1	48
D	240 ±2	200 ±1	17

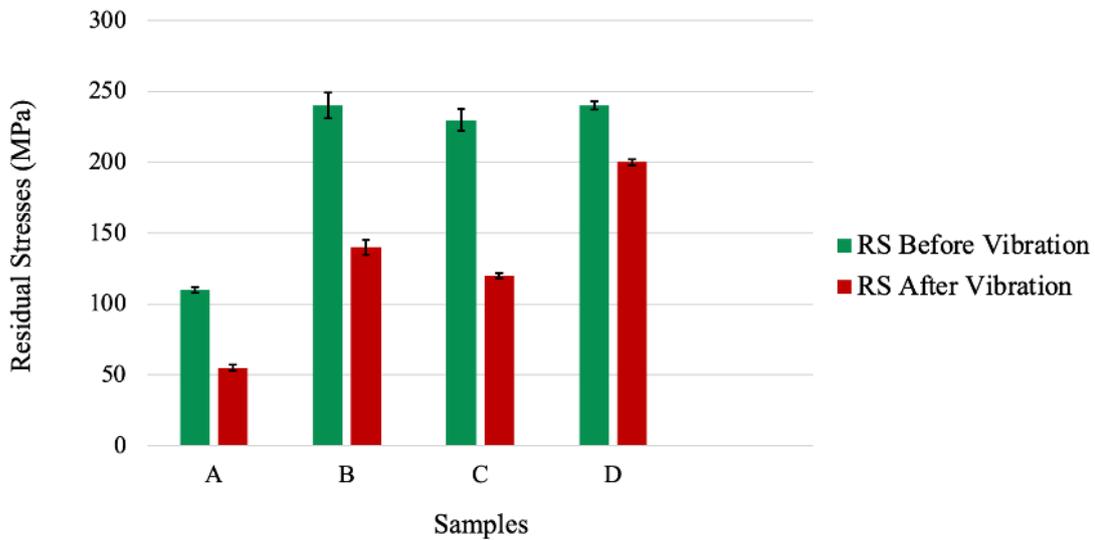


Figure 5. Graphical representation of residual stresses before and after vibration stress relief.

The results demonstrate that the residual stresses measured at the center of the welded nuggets are considerably tensile in all samples. Furthermore, a significant reduction in residual stresses in all analyzed samples, averaging 40%. Additionally, it is noteworthy that the highest stress relief of 50% was observed in sample A and the lowest stress relief of 17% was measured in sample D. By calculating the average percentage of residual stress relief for samples A and B, where the sub-resonant frequency was employed, a relief of 46% was obtained. On the other hand, for samples C and D, where the resonant frequency was utilized, the average relief was 32%. These results may indicate that the application of sub-resonant frequencies for vibration stress relief may be more effective, which, however, would require further experiments to confirm this hypothesis.

These findings are consistent with the results obtained by Chuvas *et al.* (2016), who investigated the relief of residual stresses in welded joints through mechanical vibrations. Their study reported reductions in residual stresses of approximately 40% in the longitudinal direction and 20% in the transversal direction. In another case, similarities were identified with the findings of Zhang *et al.* (2020), who successfully relieved the residual stress in an aluminum alloy plate through ultrasonic vibratory stress relief (UVSR) treatment, resulting in an observed reduction ratio of 57%.

The results for magnetic Barkhausen noise, expressed in terms of RMS_{MBN} values, are presented in Table 6. Additionally, Figure 6 illustrates the corresponding graphical representation obtained from the measurements conducted before and after the VSR process.

Table 6. RMS_{MBN} before and after welding and percentage of stress relief.

Samples	RMS before vibration	RMS after vibration
A	0.0579 ± 0.0009	0.1124 ± 0.0024
B	0.0673 ± 0.0011	0.0992 ± 0.0014
C	0.0618 ± 0.0009	0.0992 ± 0.0014
D	0.0585 ± 0.0009	0.1031 ± 0.0019

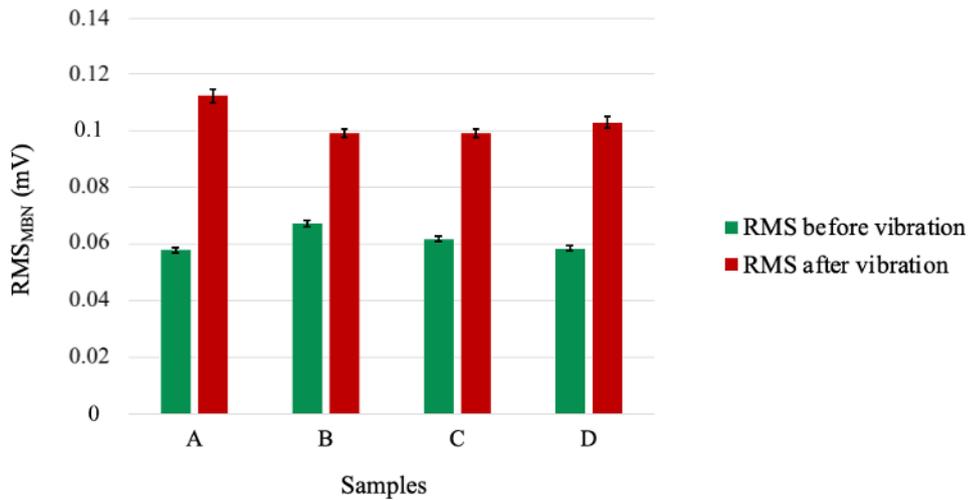


Figure 6. Graphical representation of RMS_{MBN} before and after vibration stress relief.

Considering the residual stress values obtained by X-ray diffraction, it is successfully achieved a relationship between the residual stress measurements and RMS_{MBN} values. It is notable that the techniques have an inverse relationship, which means that the lower the measured residual stress, the higher the values of RMS_{MBN}. Figure 7 exhibit the relation between those two results obtained. The graphics show the mean values for RMS_{MBN} and residual stresses before and after VSR.

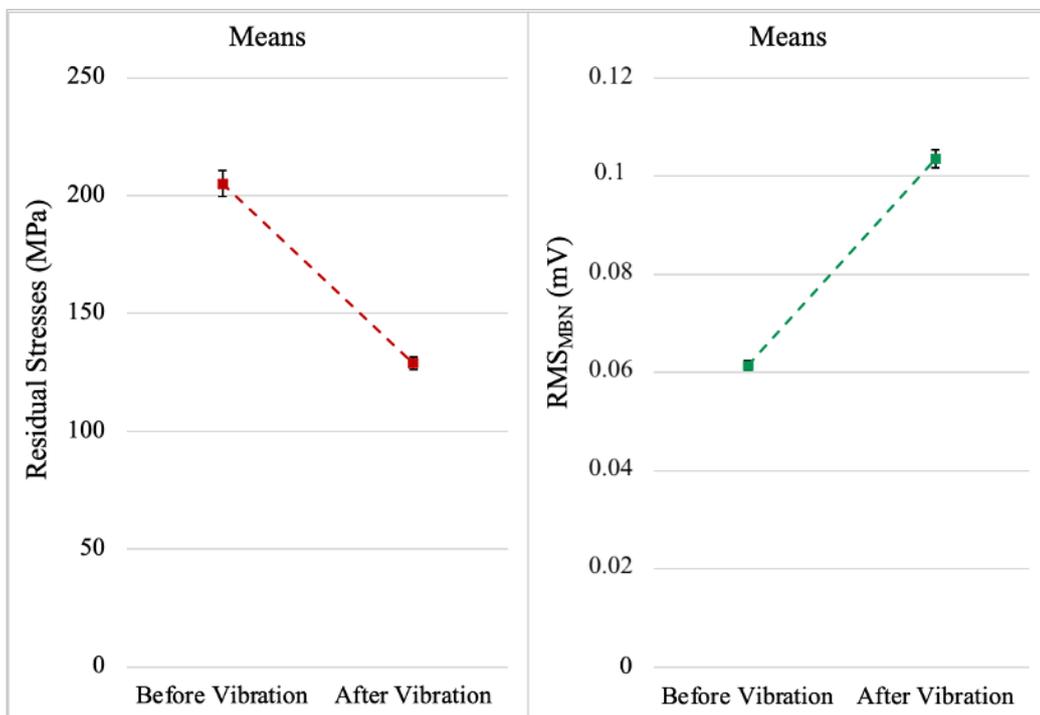


Figure 7. Graphical representation of relationship between RMS_{MBN} and residual stresses before and after VSR.

Analyzing Figure 7, it can be commented that the residual stresses relief resulting from the mechanical vibration treatment may have probably reorganized the dislocations present in the material, in such a way that the lower tensile residual stresses resulted in higher RMB values. This result aligns with the existing literature, as demonstrated by Souza *et al.* (2022), who evaluate the residual stresses generated in quenching and tempering heat treatments at different temperatures of AISI 4340 steel, comparing the results with MBN. They state that other factors affect the results obtained through the MBN technique, due to the combined effect of residual stress and microstructure, which requires careful pre-calibration and verification procedures to obtain reliable quantitative results.

4. CONCLUSION

The conducted study leads to the following conclusion:

- [1] Resistance spot welding of HC420LA steel results in predominantly tensile and high residual stresses, which can have an impact on the service life of the material and should be taken into consideration during joint design.
- [2] The application of vibration stress relief technic to the resistance spot welded joints effectively relaxation the residual stresses, with an average reduction of 40%.
- [3] The correlation between residual stresses determined via X-ray diffraction and the root mean square (RMS) values derived from magnetic Barkhausen noise exhibits a good association, which is inversely proportional, in the case of spot welded and vibrated samples of HC420LA steel.
- [4] The magnetic Barkhausen noise (MBN) technique exhibits substantial potential as a diagnostic tool to qualify the nature of residual stresses induced by resistance spot welding and vibration stress relief in steel specimens.

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