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THE EFFECT OF MECHANICAL VIBRATION ON STRESS RELIEVING OF WELDED JOINTS

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Abstract*. The knowledge of the nature and magnitude of the residual stresses present in mechanical components, as well as techniques that may help reducing the residual stress levels, are very important for several industrial applications. In welding processes there is always residual stresses generation, which will influence the performance of welded structures in service. The present paper analyzes the efficiency of mechanical vibration stress relief process of welded joints of HSLA LNE 380 steel by the GTAW process. The residual stresses were analyzed by X-ray diffraction technique using the $sen^2\psi$ method. An average reduction of 61% in the residual stresses was after application of the high-amplitude sub-resonant frequency.*

Keywords: *Residual stresses, HSLA LNE* 380 *steel, GTAW welding, Vibratory stress relief, X-ray diffraction technique*

1. INTRODUCTION

Welding is the most commonly used manufacturing process for joining metal parts of structures. In particular, the GTAW (Gas Tungsten Arc Welding) process is widely used in various industrial sectors, mainly for the welding of stainless steels and thin sheets, by providing joints with excellent surface finish and mechanical properties. However, during welding, fields of residual stresses are developed, which may cause damage on the component.

The knowledge of the residual stresses state in welded joints is necessary because, depending on the nature and magnitude of these stress fields, they can influence the service life of the welded structures, compromising their performance and, in some cases, leading to rupture of the joints (KANDIL, 2001). It is well established that tensile residual stresses have a deleterious effect on materials as they contribute to the nucleation and propagation of fatigue crack and decrease resistance to stress corrosion crack, while compressive stresses have a beneficial effect (HEINZE *et al.*, 2011; COULES, 2013). In this way, the industries look for techniques capable of minimizing the magnitude of the tensile residual stresses, or even introduce compressive stresses fields in the manufactured components.

There are several methods of residual stress relief in welded joints in order to reduce the tensile residual stresses, to avoid the deleterious effects caused by these stresses and to increase the reliability of the welded joint integrity. Thermal treatments, widely employed, are expensive and often difficult to achieve (COULES, 2013). For this reason, new techniques for stress relief have emerged as an alternative to the existing methods. Vibration stress relief is one of these techniques, which, unlike thermal treatments, has a low cost and application time and does not cause distortions or microstructure changes in the welded joint (KWOFIE, 2009).

In this context, the present work has the objective of carrying out an experimental study of mechanical vibration stress relief in GTAW welded joints of the High Strength and Low Alloy LNE 380 steel, with wide application in the automobile industry.

Two different methods of mechanical vibration were used in this study: resonant and sub-resonant frequencies. This work has the purpose of comparing which method will be most effective in the stress relieving of the LNE 380 steel. Residual stresses were analyzed by X-ray diffraction technique using the $\sin^2\psi$ method.

1.1 Vibratory Stress Relief Treatment

During the vibration stress relief, dynamic stresses imposed on the structure directly affect the residual stress relief. These are combined with the residual stresses and may exceed the material yield strength, inducing plastic microdeformations in parts of the structures, causing reductions of the tensile stress fields near the surfaces, lowering the stress level (RAO *et al*., 2007). According to Rao (2007), residual stresses relief by cyclic loads is mainly affected by: initial magnitude of residual stress; amplitude of the dynamic forces and number of deformation cycles.

The resonant process is achieved by vibrating the body to its natural frequency and large changing loads. To achieve optimal results, constant high cyclic amplitude and accurate frequency should stimulate the cyclic properties of the component. To get higher number of loading patterns, vibrators with high frequency ranges should be used (SHAIKH, 2016).

The sub-resonant vibration, according to Hebel (2001), was developed after using the old approach with resonant vibration presented inconsistent results. In discovering the theory behind the use of vibration energy to optimize the results of stress relief, an advanced procedure replaced the previously used methods.

The sub-resonant vibration stress relief is based on two fundamental principles: 1) The frequency near the resonance peak should be employed (just before resonance). 2) The curve of the frequency response function will shift to the left during the application of mechanical excitation. When the resonance curve stabilizes to a new position, the relief has been effected. At this point, it is not able to reduce the stress even more.

In the region at the edge of the resonance curve (in other words, the sub-harmonic zone), the ideal frequency for using the vibration energy to stress relieve is located, as shown in Figure 1. The sub-harmonic zone is defined as 1/3 to 1/2 of the lowest portion of the harmonic curve for high strength steels (HEBEL, 2001).

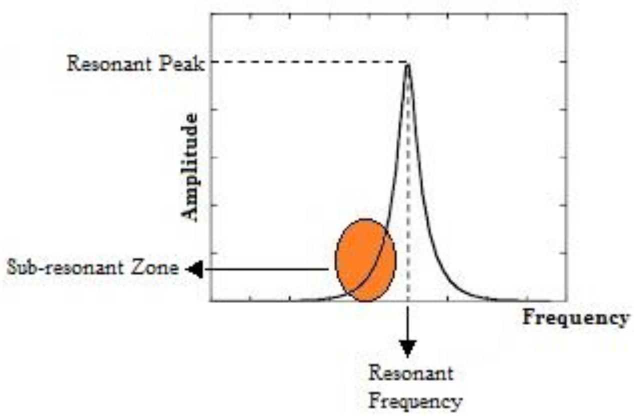

Figure 1: Resonant zone and sub-resonant zone (Source: Adapted from Skinner, 1987).

According to Skinner (1987), the sub-resonant vibration is the one that has the greatest internal energy dissipation capacity. This dissipation translates into greater strain relief.

2. MATERIALS AND METHODS

In the present work the 2.54 mm thick plates of HSLA LNE 380 steel produced by CSN Company was studied. The chemical composition and mechanical properties are shown in Tables 1 and 2, respectively.

Table 1: Chemical composition of LNE 380 steel(% in weight).

C	Mn	P	S	Al	Si	Nb
0.13	1.2	0.03	0.01	0.03	0.15	0.07

Table 2: Mechanical property of LNE-380 steel.

Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
400	500	22

Eight joints were welded with a straight chamfer by the autogenous GTAW process, with variable voltage between 11 and 12 V and direct current of 70 A. EWTh-2 toroidal tungsten electrode with a diameter of 3 mm under pure argon gas protection was used, under 13 L/min of flow rate. The process was carried out with a welding speed of 140 mm/min, producing a heat input of about 0.28 kJ/mm in all samples.

The surface residual stresses were measured by X-ray diffraction using the stress analyzer *XStress 3000*, manufactured by Stresstech (Figure 2), using the $sen^2\psi$ method with CrKα ($\lambda_{CrK\alpha}$ = 2.29092Å) radiation and diffracting the plane (211) of ferrite.

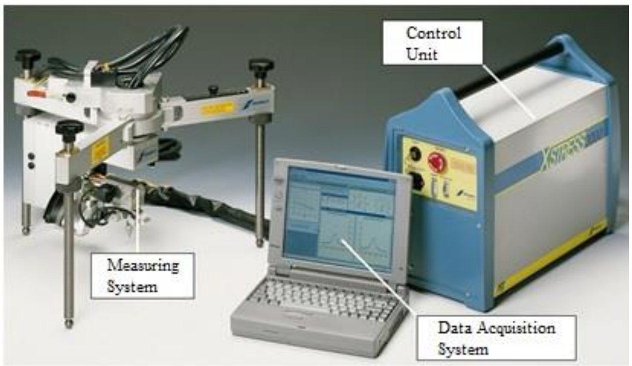

Figure 2: Stress Analyzer XStress 3000.

The vibration tests were performed using shaker from Signal Force Data Physics. One edge was coupled to the shaker and the other was crimped to represent cantilever beam configuration (Figure 3). All vibration tests were performed in 10 minutes.

(a)

(b)

Figure 3: (a) Cantilever beam scheme; (b) Shaker used in the experiment.

3. RESULTS AND DISCUSSION

Natural frequencies were established numerically. The numerical result was obtained using ANSYS software 18.2 for geometric modeling and finite element analysis, resulting in the flexural vibration modes of the cantilever beam. The numerical solution of the vibration modes are shown in Figure 4.

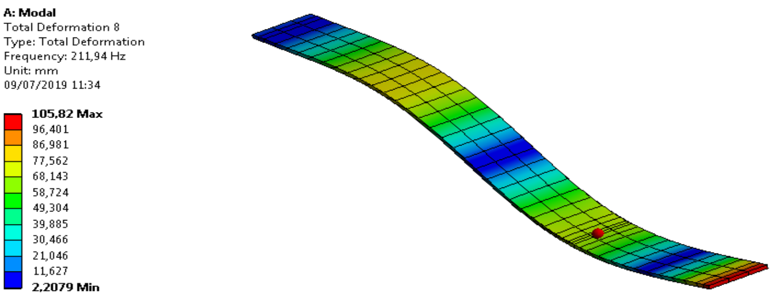

Figure 4: Total displacement of the 3rd natural frequency.

The third mode of vibration was selected to perform the stress relief of the sample. As shown in Figure 4, indicated by a red ball, the weld bead appears at the crest of the wave motion, generating a high total displacement at this point. This displacement contributes to elastic microdeformation in the bead, and consequently will probably reduce the stresses of the welded joint. Table 3 below shows the difference between experimental and numerical results of the third natural frequency of the cantilever beam.

Table 3: Difference between experimental and numerical results.

Natural Frequency	Numerical	Experimental	Error (%)
3rd harmonic	211.94 Hz	215 Hz	1.4

To further elucidate what has been done, when the frequency of excitation employed in the vibration test match the third natural frequency of the system, this parameter will be called "resonant". The other parameter used was the 3rd sub-resonant frequency which corresponds to 1/3 of the response transmissibility imposed by the 3rd resonance in the body. Regarding acceleration amplitude, the parameters used were 0.3g for low level and 0.8g for high level.

The two parameters already mentioned are expressed in Eq. 1 (a(t) = harmonic acceleration equation). These are the amplitude "B" and the frequency "ω".

$$a(t) = -\omega^2 A \cos(\omega t + \theta) = B \cos(\omega t + \theta) \quad (1)$$

The residual stresses were analyzed in two steps. The first one was to measure residual stresses after welding. The second stage presents the residual stress values of the samples after the mechanical vibration, analyzing the efficiency of the technique and the influence of different test parameters on the obtained results.

In Figure 5, the parameters used in the experiment are exposed according to the flowchart. There is variation of the dynamic input amplitude acceleration and the type of frequency used.

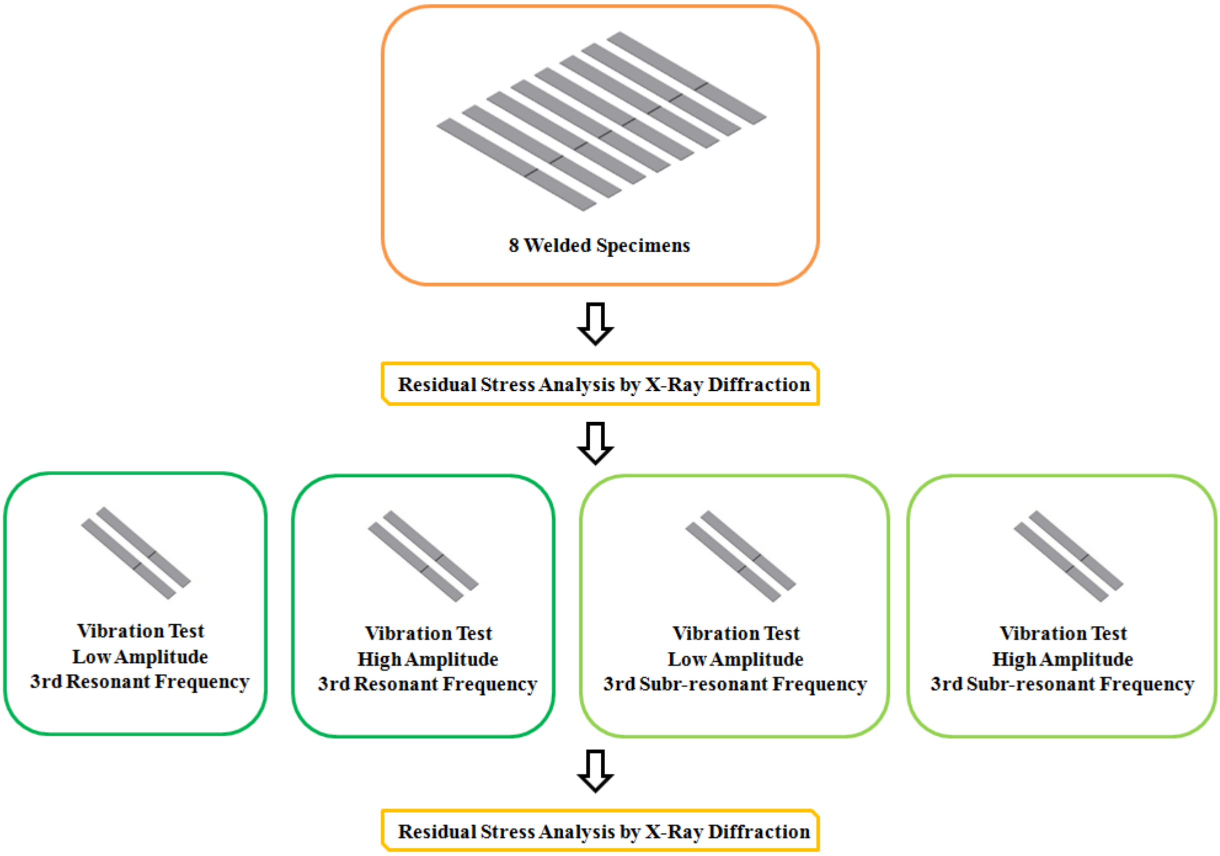

Figure 5: Selected mechanical vibration parameters.

Tables 4 and 5 below show the residual stresses measured in the region of weld bead after welding, and Figure 6 shows the residual stress relief of each specimen, which is calculated as Eq. 2.

$$\text{stress relief}(\%) = \frac{After\ vibration - After\ welding}{After\ welding} \tag{2}$$

Table 4: Longitudinal stress relief results.

Selected Parameters	Specimen	Longitudinal Stress (MPa) After Welding	Longitudinal Stress (MPa) After Vibration	Residual Stress Reduction (MPa)
Resonant Frequency / Low Amplitude	1 face	360 ± 10	315 ± 10	45
	1 root	170 ± 12	134 ± 12	36
	2 face	300 ± 11	240 ± 13	60
	2 root	260 ± 11	210 ± 1	50
Resonant Frequency / High Amplitude	3 face	300 ± 12	210 ± 10	90
	3 root	150± 3	100 ± 09	50
	4 face	190 ± 10	110 ± 10	80
	4 root	220 ± 12	145 ± 10	75
Sub-resonant Frequency / Low Amplitude	5 face	260 ± 4	180 ± 3	80
	5 root	190 ± 10	130 ± 10	60
	6 face	240 ± 4	160 ± 10	80
	6 root	115 ± 10	100 ± 10	15
Sub-resonant Frequency / High Amplitude	7 face	250 ± 11	80 ± 11	170
	7 root	145 ± 12	50 ± 10	95
	8 face	285 ± 10	120 ± 10	165
	8 root	220 ± 8	80 ± 10	140

Table 5: Transversal stress relief results

Selected Parameters	Specimen	Transversal Stress (MPa) After Welding	Transversal Stress (MPa) After Vibration	Residual Stress Reduction (MPa)
Resonant Frequency / Low Amplitude	1 face	220 ± 7	175 ± 11	45
	1 root	240 ± 12	186 ± 10	54
	2 face	245 ± 15	190 ± 12	55
	2 root	150 ± 11	125 ± 20	25
Resonant Frequency / High Amplitude	3 face	170 ± 10	100 ± 10	70
	3 root	55 ± 6	55 ± 10	0
	4 face	190 ± 2	105 ± 12	85
	4 root	220 ± 11	130 ± 11	90
Sub-resonant Frequency / Low Amplitude	5 face	145 ± 7	90 ± 10	55
	5 root	110 ± 10	100 ± 7	10
	6 face	160 ± 6	90 ± 10	70
	6 root	330 ± 10	260 ± 10	70
Sub-resonant Frequency / High Amplitude	7 face	170 ± 11	60 ± 9	110
	7 root	170 ± 6	65 ± 10	110
	8 face	130 ± 12	60 ± 8	70
	8 root	205 ± 10	100 ± 8	105

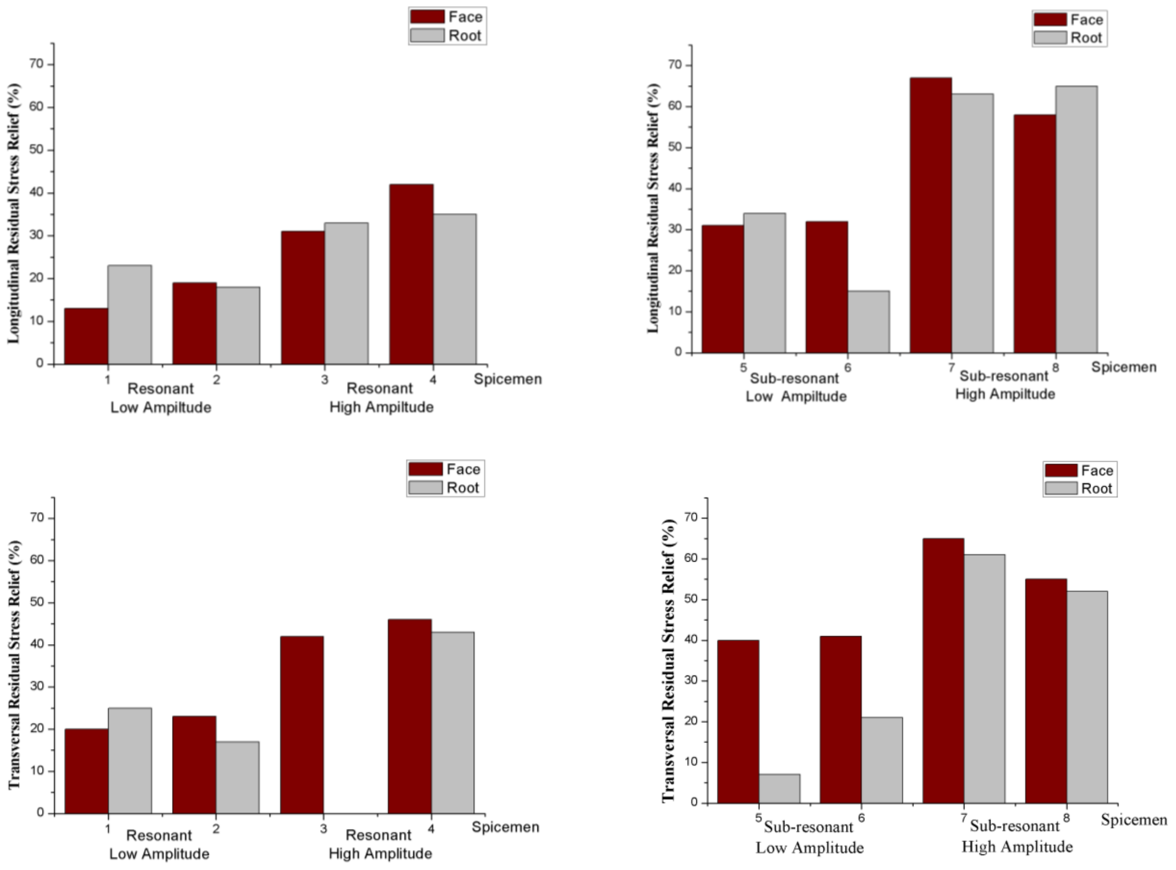

Figure 6: Residual stress relaxation after vibration treatment (%).

The residual stresses on the surface of weld bead were very heterogeneous. All of them were tensile stresses in the heat affected zone, varying from 54 MPa to 360 MPa. The longitudinal residual stresses presented higher stress levels than the transversal stresses. As shown in Figure 6, the sub-resonant frequency produced, on average, a 61% relief in the welded joint, and also resulted in maximum relaxation of 67% after vibration by 10 minutes.

Statistical calculations were performed with intention of reducing systematic error. Since mechanical vibration stress relief is less effective for points containing reduced residual stress level (RAO *et al.*, 2007), residual stresses below 150 MPa were disregarded in the calculation. The statistical method ANOVA of two factors with two levels each was performed. The dependent variable is the residual stress reduction.

Tables 6 and 7 indicate if the longitudinal and the transversal residual stresses respect the basic premises for the ANOVA. The results for normality tests of residuals and homogeneity of variances, both for the longitudinal and transversal residual stresses, presented p-value higher than 0.05, qualifying the experiment to perform the analysis of variances.

Table 6: Normality test of residuals and homoscedasticity for longitudinal residual stresses.

Normailty test of residuals	p-value	Homoscedasticity	p-value
Lilliefors	0.052	Cochran C, Bartlett	0.6649

Table 7: Normality test of residuals and homoscedasticity for transversal residual stresses.

Normailty test of residuals	p-value	Homoscedasticity	p-value
Lilliefors	0.20	Cochran C, Bartlett	0,4339
Shapiro-Wilk	0.5162		

Thus, in Table 8 and Figure 7, the influence of different applied frequencies and amplitudes used in the experiments on longitudinal residual stress behavior was verified, as well as the interaction effect between the two parameters mentioned. Table 9 shows the same Analysis of Variance calculations for the transversal direction.

Table 8: Longitudinal residual stress ANOVA.

Effect	Sum of Squares	p-value
Applied Frequency	7475	0.000013
Amplitude	10413.5	0.000004
Applied Frequency x Amplitude	1912.7	0.001418
Error	674	

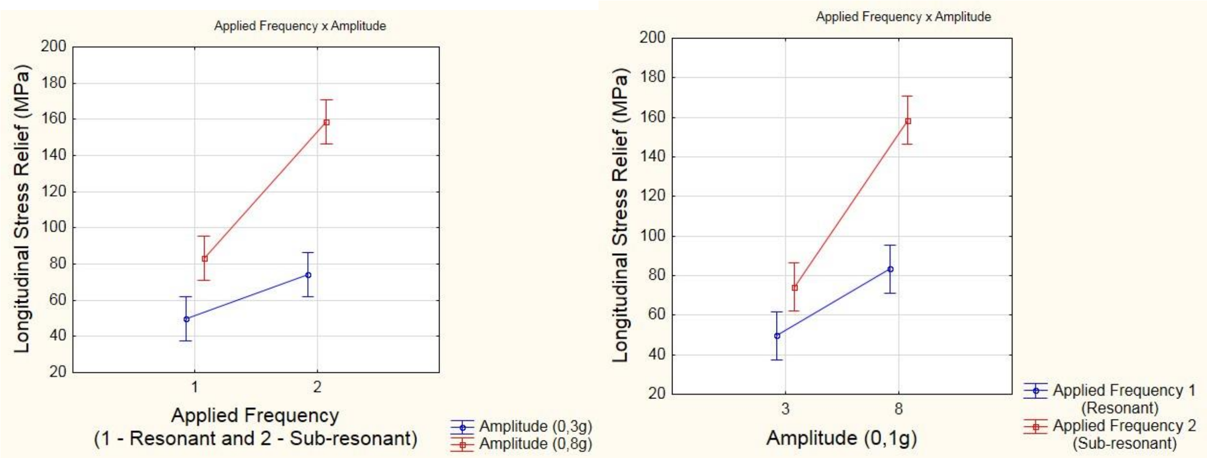

Figure 7: Interaction effect between Applied Frequency and Amplitude in Longitudinal Stress Relief.

As shown in Table 8, the main effects Amplitude and Applied Frequency as well as the interaction effect between both were_significant. Increasing the amplitude produces a greater stress relief at both frequencies. This is in agreement with Yang *et al*. (2009) that said load amplitude is the key parameter that reduces weld residual stress.

The Applied Frequency x Amplitude interaction effect is pronounced when it combines the sub-resonance and the high amplitude. For nonresonant vibration stress relief, load amplitude should be proper otherwise residual stress cannot be reduced (YANG *et al*.,2009). For the sub-resonant frequency, the amplitude increase further improved the efficacy of the stress relief.

The sub-resonant frequency was more efficient when compared to the resonant frequency in both amplitudes. This is in agreement with the results of Skinner (1987). Accordingly, the hysteresis loop from a cyclic loading rate with frequency coinciding with a sub-resonant frequency has a larger width. In this way, larger microdeformations are produced, being responsible for the relaxation of the internal stresses.

Table 9: Transversal residual stress ANOVA.

Effect	Sum of Squares	p-value
Applied Frequency	892.69	0.006616
Amplitude	4275.19	0.000045
Applied Frequency x Amplitude	35.02	0.491784
Error	910.5	

As shown in Table 9 above, the main effects Amplitude and Applied Frequency were significant in transversal stress relief. As previously mentioned, greater amplitudes of acceleration and the application of the sub-resonant frequency provided a better stress relief.

In this study, the correlation between the stress relief and the natural frequency variation of the system (welded joint) was performed. This has a scientific relevance because if the resonance peak of the sample shift to the left (decrease in the natural frequency) in the plotted FRF (Frequency Response Function) curve, this represents a proof of residual stress relief (HEBEL, 2001). Therefore, the natural frequency measurement before and after the test becomes an auxiliary method of stress relief evaluation.

Table 10 shows the variation of the natural frequency related to the mean stress relief obtained on the face of the weld bead. Figure 8 shows an example of the natural frequency shift occurring in sample 7 after the vibration treatment, where Δf = [frequency after treatment - frequency before treatment].

Table 10: Natural frequency variation according to the residual stress variation.

Specimen	Natural Frequency Variation (Hz)	Mean Variation of Face Weld Residual Stress (MPa)
1	0.5	45
2	0.9	55
3	0	80
4	-0.48	85
5	0.47	68
6	0	75
7	-2.48	140
8	-1	120

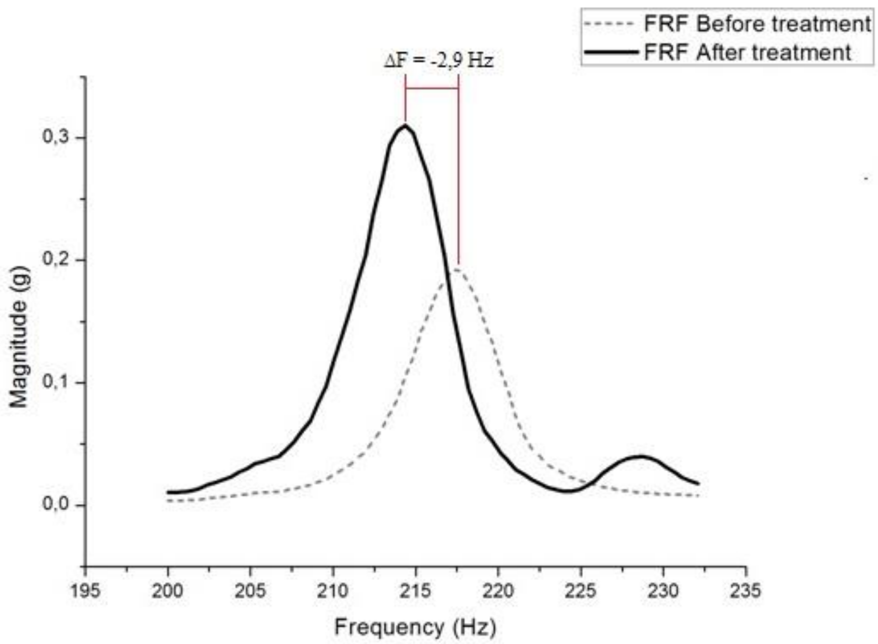

Figure 8: Maximum natural frequency variation (specimen 7).

The Figure 9 shows the linear regression equation between stress reduction and natural frequency variantion. The objective of the extraction of this curve is to predict how much the natural frequency displacement corresponds to the absolute value of stress reduction.

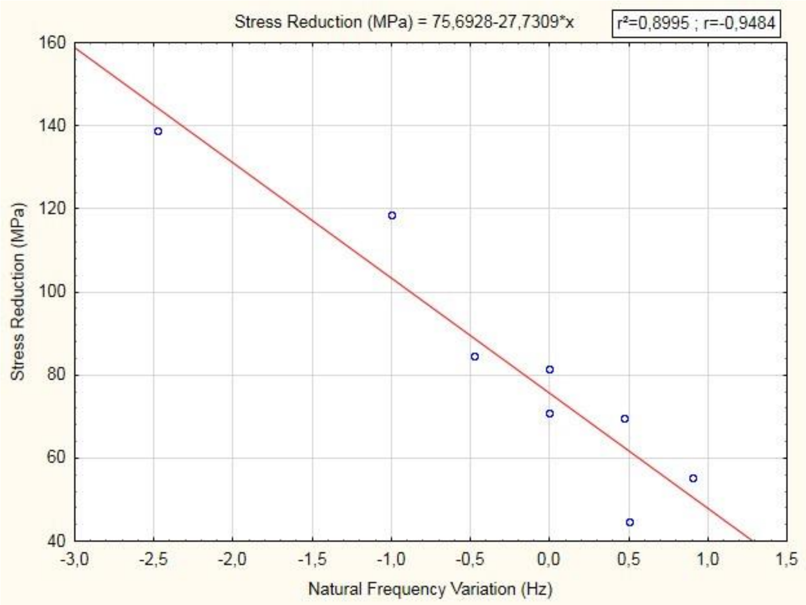

Figure 9: Regression equation between Stress Reduction VS Natural Frequency Variantion.

These two variables have a great correlation between them (R = -0.9484), denoting the greater the natural frequency reduction, the greater will be the stress relief. What is noticed in this curve is that when the natural frequency of the sample decreases by 1Hz, there will probably be a residual stress reduction of around 100MPa. The equation representing this relation between **Δσ x Δf** is expressed in Eq. 3.

$$\Delta\sigma=75{,}7-27{,}7(\Delta f) \quad (3)$$

4. CONCLUSIONS

The present work, whose objective was the study of stress relief by mechanical vibrations in welded joints of LNE 380 steel, allows the following conclusions:

1) The residual stresses on the surface of weld bead were very heterogeneous. All of them were tensile stresses in the heat affected zone, varying from 360MPa to 54MPa.

2) The main effect of load amplitude and frequency applied were significant.

3) The sub-resonant frequency was the one that obtained the best results. Combining the application of the sub-resonant frequency with the high amplitude of acceleration, there will be an optimization of the stress relaxation results, achieving a maximum stress relief percentage of 67% in longitudinal direction.

4) The curve corresponding to the relationship between Δσ and Δf of LNE 380 steel welded joint showed that the reduction of 1Hz indicates a relief near 100MPa. This curve is only valid for initial magnitude of residual stress greater than 150MPa.

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