TO	:	Customers
SUBJECT	:	Sub-harmonic vibration stress relief in carbon steel welded joints
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ISSUED BY	:	TAMA INGENIEROS S.A.C.

Research & Development

Sub-harmonic vibration stress relief in carbon steel welded joints.

In 2014 TAMA INGENIEROS S.A.C. aimed to measure the magnitude by which post-weld residual stresses are reduced by the vibratory stress relief process and compare it to the reduction caused by the effect of the stress relief heat treatment.
The method used to determine the residual stresses included the measurement of residual stresses by X-ray diffraction (XRD).
The measurements were performed on two identical specimens subjected to the same welding process and the experimental results reported a reduction in the magnitude of longitudinal tensile residual stresses of up to 85% in the heat treatment stress relief specimen while in the case of the vibration stress relief specimen, a reduction of 35% in residual stresses was found in the center of the weld bead.

1. Residual stress

The temperature changes inherent to steel transformation processes generate residual stresses that in turn lead of adverse effects on the material, the main ones being: dimensional distortions, generation of cracks, alteration in the microstructure of the metal and the hardness near the areas affected by the heat.

Residual welding stresses are produced by plastic and elastic deformations. During the welding process, while the material is heated and melted it attempts to locally stretch, but is restricted by the surrounding cold base metal. This constraint generates local stresses, microscopic deformations, and phase changes that contribute to the creation of residual stresses [1] whose distribution is similar to that shown in Figure 1.

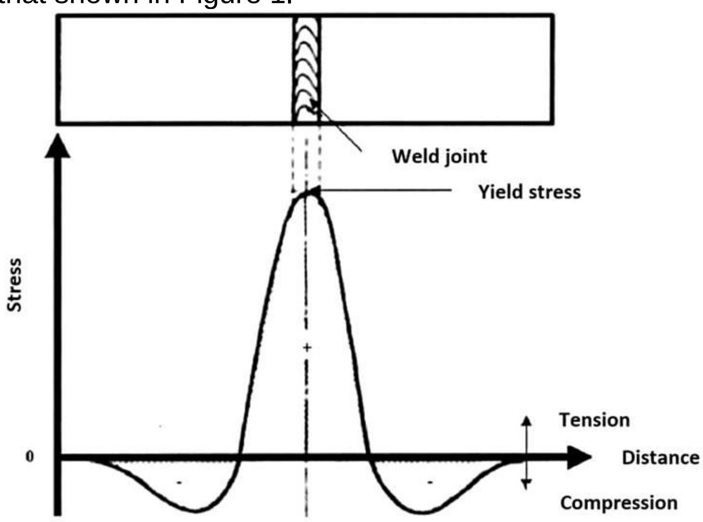


Figure 1: Longitudinal residual stress distribution in a butt joint.
Source: [2]

Hot rolling mill processes also induce residual stresses with magnitude and distribution depending on factors such as material, heat input, heat transfer flow, material thickness, weld type, material clamping, process speed, and others.

2. Stress relief heat treatment

The most used method to reduce the residual stresses is the stress relief heat treatment in which a structure is slowly heated to temperatures above 600°C, then the piece is kept at that temperature for a preset period, during this process the yield point of the base metal is enough lower to plastically relax the material. Although there are alternatives such as portable ceramic blankets and induction heat treatment equipment for post welding heat treatment of large welded structures, some of the disadvantages of this type of stress relief are given by the long process times, the cost and the amount of energy required, the logistic costs of transportation and handling, the alteration of the mechanical properties and the dimensional distortion of the part.

3. Effectiveness of the vibration stress relief method

To answer this question, an experimental process was carried out with carbon steel welded specimens consisting of (a) measuring the effectiveness of the stress relief method in welded specimens, as well as (b) measuring the effectiveness of the stress relief method by heat treatment, and then the quantitative comparison of the results of (a) and (b). Previously, among the different methods available for mechanical vibration stress relief, the subharmonic vibration method was identified.

4. Stress relief by subharmonic vibrations

In this method, the parts are subjected to vibrations with a frequency within the subharmonic zone of the harmonic curve and is based on two principles:

a. The vibrational energy absorbed by an element peaks when it is subjected to vibrations of subharmonic level, i.e. below its natural resonance frequency.
b. The harmonic curve of a part with residual stresses will be shifted to a new frequency when that part is treated by vibration.

Figure 2 shows that when a frequency within the sub-harmonic zone is induced, energy absorption for stress relief is maximized as indicated by the larger area within the hysteresis curve. At the frequency of the harmonic peak, the internal energy dissipated drops to zero. For this reason, Hebel [3] warned that the vibratory stress relief at resonant or harmonic peak frequencies should not be applied to prevent damages to the structure with adverse results. The area within the hysteresis loop is the dissipated damping energy and reaches a maximum near the beginning of the harmonic curve, an area known as the Subharmonic Zone [3] and which corresponds to the largest amount of energy dissipated for stress relief.

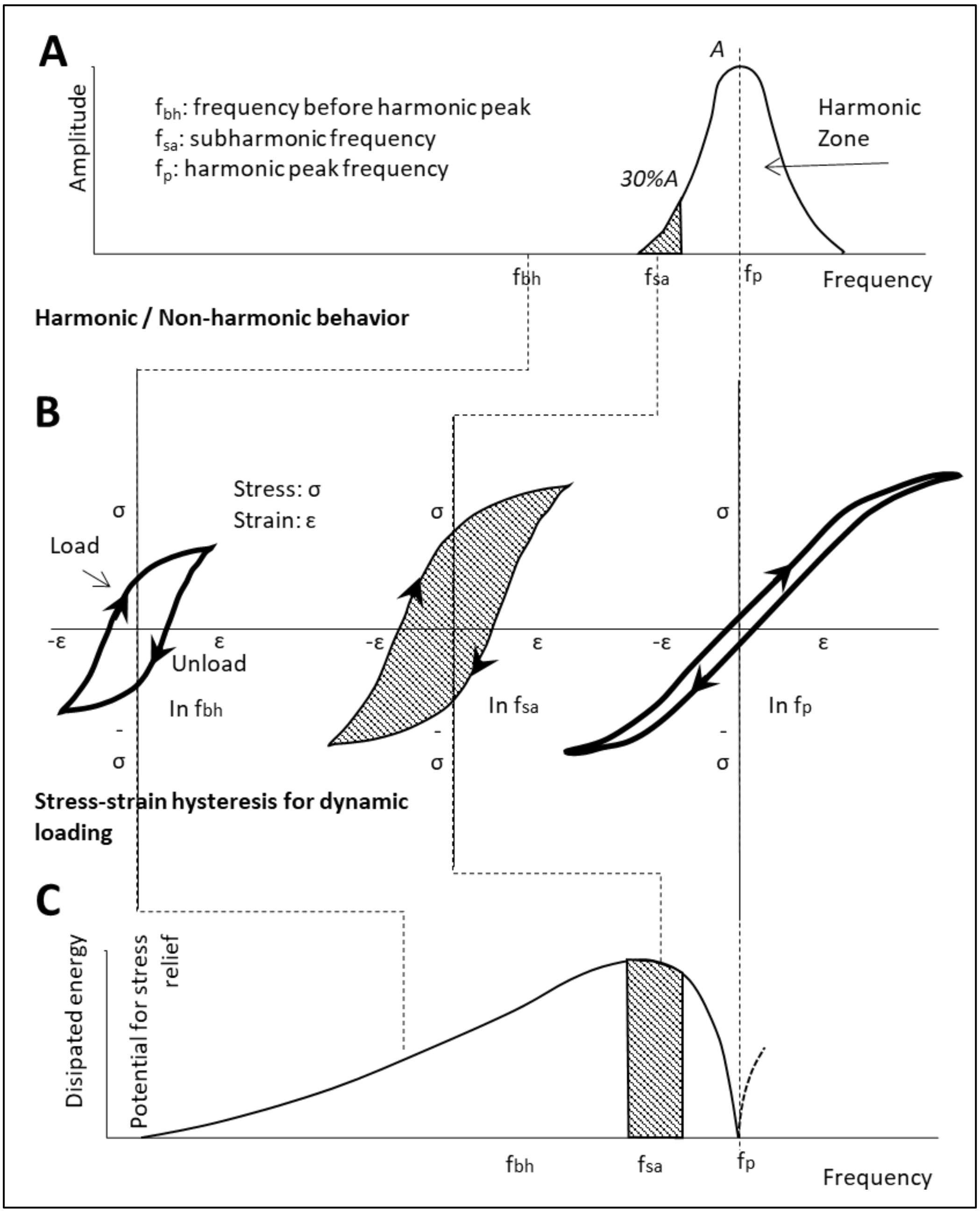


Figure 2: Frequency vs. hysteresis energy dissipation, per cycle.
Source: Hayden, Moffatt & Wolff [4]

On the other hand, all metal bodies have a harmonic frequency. If the part has been subjected to a thermal shock that caused residual stresses during its manufacturing process, the harmonic peak will be placed at a non-natural frequency. Through the application of sub-harmonic vibrations, the component will then neutralize the residual stresses and thus the harmonic peak will shift and remain in a new harmonic frequency. Wong and Johnson [5] stated that the harmonic curve will be shifted as a function of the level of residual stresses present in the object, concluding that the shift in the natural frequency as a result of the presence of residual stresses provides a method for analyzing and demonstrating the effectiveness of the method (Figure 3).

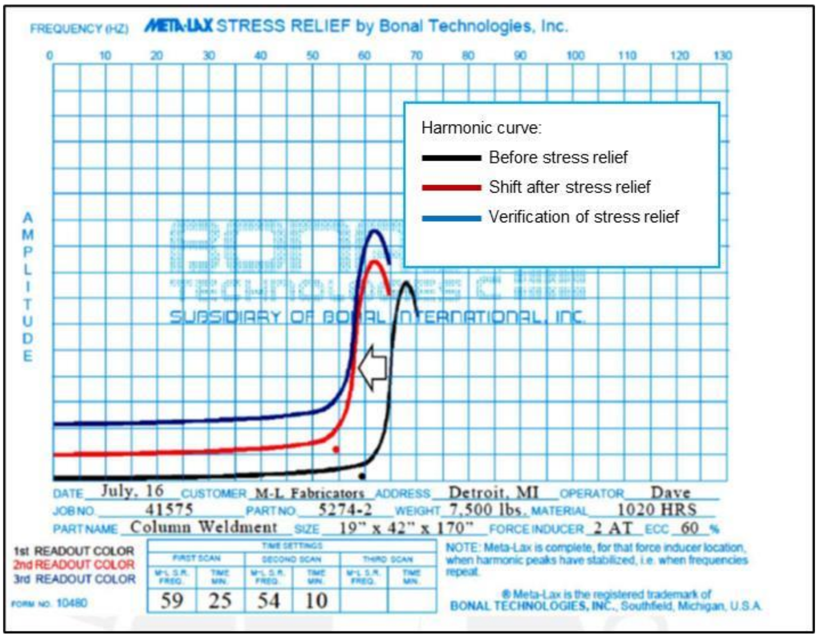


Figure 3: Behavior of the harmonic curve before and after stress relief by subharmonic vibrations.
Source: Bonal Technologies [6]

5. X-Ray Diffraction (XRD)

X-ray diffraction is a versatile, non-destructive technique that measures stresses at macro and microscopic scales. The measurement is made by placing the sample into a diffractometer and exposing it to X-rays that interact with the crystal lattice of the base metal to generate a diffraction pattern. X-rays are generated when electrons with adequate kinetic energy are rapidly decelerated. When an X-ray beam is struck by the surface of a metal crystal, a portion of it is scattered by the layer of atoms on the surface. The unscattered portion enters the second layer of atoms where another fraction is scattered and the remaining portion passes into the third layer (Figure 4). The XRD technique is an indirect measurement technique because what it measures is the deformation interpreted as the variation in the relative interplanar distance between crystalline planes, this deformation causes changes in the lattice spacing from its stress-free value to a new value that depends on the magnitude of the applied stress. A material is stress-free when the value of the interplanar distance is independent of the orientation of these planes with the sample. In contrast, in a material under stress, the deformation will be a function of the orientation of the plane with the stress [7].

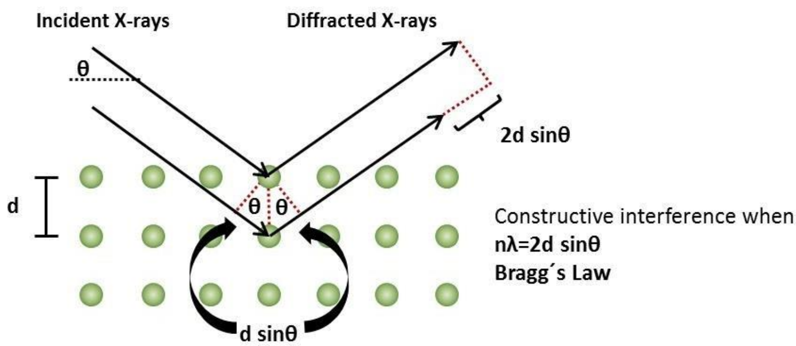


Figure 4: Principle of X-ray diffraction.
Source: Anton Paar [8]

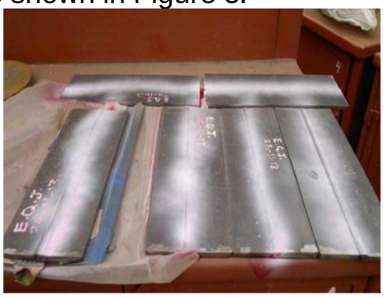
6. Experimental procedure for stress relief

In TAMA INGENIEROS an experimental procedure was carried out to demonstrate the effectiveness of stress relief by subharmonic vibrations, which is outlined in the research "Stress relief by subharmonic vibrations in welded carbon steel joints" [9] described in the following summary:

a. Cutting, welding and labeling of six ASTM A36 carbon steel welded specimens of 9.5 mm x 150 mm x 400 mm (marked 9ST1, 9ST2, 9TT1, 9TT2, 9AV1 and 9AV2) where ST: No treatment, TT: Stress relief heat treatment, AV: Stress relief treatment by subharmonic vibrations.
b. Dimensional inspection and nondestructive (NDT) liquid penetrant testing.
c. Packing and air shipment to the X-ray diffraction measurement laboratory of specimens 9AV2 and 9TT2.
d. Electropolishing to 0.5 mm depth to remove the surface layer of material in the laboratory.
e. Selection and identification of residual stress measurement points on each specimen.
f. XRD measurement of as-welded residual stresses at a number of points aligned transversely to the weld bead.
g. Packing and return air shipment to TAMA INGENIEROS S.A.C. workshop in Lima, Peru.
h. Sub-harmonic vibration stress relief of specimen 9AV2 at TAMA INGENIEROS S.A.C. workshop.
i. Heat treatment Stress relief of specimen 9TT2 by a local supplier.
j. Packing and second air shipment of specimens 9AV2 and 9TT2 to the X-ray diffraction measurement laboratory.
k. Post-treatment residual stress measurement test at the same locations as initially measured (step e).
l. Analysis and results comparison before and after both treatments.

Main steps of the process are shown in Figure 5.

Cutting, welding and labeling



Dimensional inspection and NDT

Sub-harmonic vibration stress relief

Electropolishing to 0.5 mm depth

X-ray diffraction

Figure 5: Experimental procedure.

7. Results

The results of the residual stress measurements in both specimens -before and after treatments- revealed that in the center of the weld joint of the specimen that was subharmonically vibrated, the tensile residual stresses were 29 ksi and 19 ksi before and after the stress relief process, respectively, that is, a 34.5% reduction in the magnitude of the residual stresses was obtained. In the case of the heat-treated specimen, at the same location, tensile residual stresses of 26 ksi and 4 ksi were measured before and after the stress relief process, which represents a reduction of 84.6% in the magnitude of the residual stresses, as shown in Figure 6.

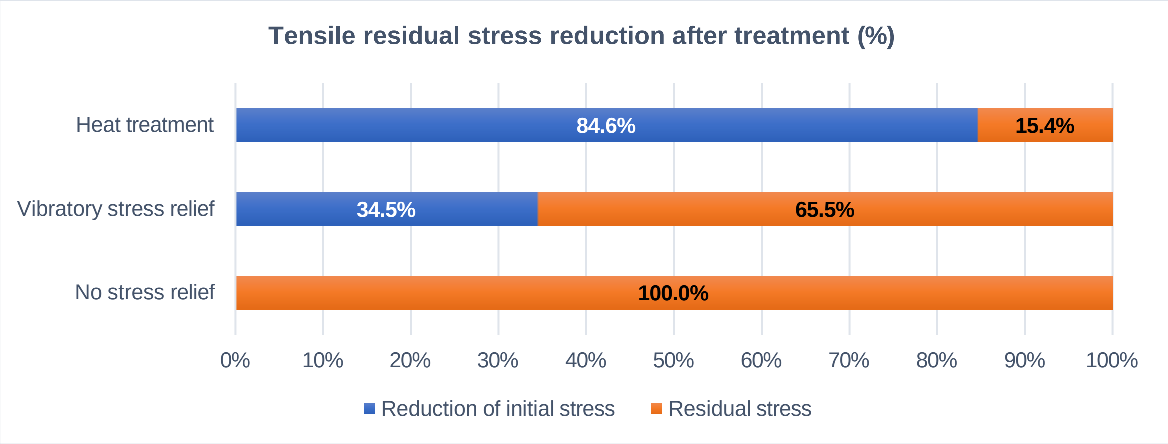


Figure 6: Transverse tensile residual stress reduction measured at the center of the joint of heat-treated and subharmonic vibration stress relieved specimens.

8. Conclusions

- Given the difference between the magnitudes of residual stress reduction, stress relief by sub-harmonic vibrations cannot be considered as an alternative to heat treatment, however, it is possible to recommend the application of this method as a complement to heat treatment. Should for any reason the application of heat treatment be necessary due to the modification of mechanical properties, it is recommended to apply subharmonic vibrations before the heat treatment to reduce dimensional distortions that usually occur during the heating process.
- On the other hand, its application is recommended in structures or components that are subject to fatigue stresses in order to reduce the risk of premature cracking. In this field, TAMA INGENIEROS has a wide experience in stress relieving by means of sub-harmonic vibrations to components such as pump bases, structures for vibrating screens, SAG and ball mill components, trommel rings for the mining industry and tundishes for continuous casting, rollers and refrigerated ducts for the steel industry.
- The cost per kilogram of stress relief treatment by sub-harmonic vibration was found to be almost one-sixth of the cost per kilogram of furnace heat treatment, as shown in Figure 7.

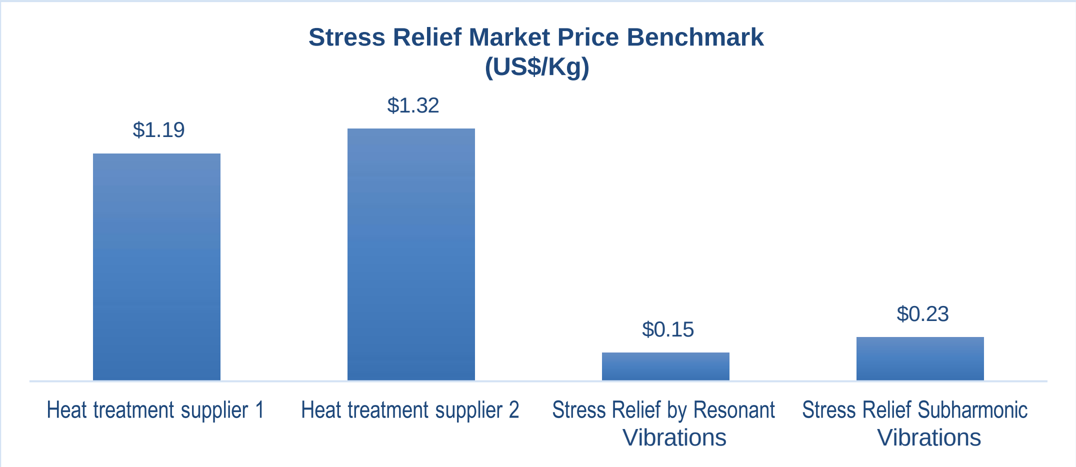


Figure 7. Market prices of Stress Relief services (US$/kg) in nominal US$ for 2014 [9].
Notes:
(*) Heat treatment price for a welded frame 1034 mm (L) x 1341mm (W) x 325 mm (H), 450Kg, Material: A-36.
(**) Price of Resonant Vibration Stress Relief for frame 2745 (L) x 1422 (W) x 1310 (H) MM, 1479 Kg, Material A-36, as obtained by market quotations, in nominal US$ for 2014.
(***) Estimated cost of Stress Relief through sub-harmonic vibrations.

Further benefits of vibration stress relief for these applications are given by the lower emission of greenhouse gases: 0.85 kg of CO2 emissions can be generated for each hour of thermal stress relief heat treatment considering thermal losses [10], while 0.23 kg of CO2 emissions can be generated with a heat blanket, compared to 0.13 kg of CO2 emitted by the 5/8 HP vibration inducer electric motor [10], according to Table 1.

Table 1. Greenhouse gas emissions comparison chart

Energy consumption	Emission factor		Qty		GHG (KG CO_2)
LPG furnace (kg)	2.96	CO2 kg / GLP kg*	0.29	kg GLP/hr	0.85
Theoretical electric blanket consumption (kWh)	0.267	CO2 kg /kWh**	0.85	kw.hr	0.23
Vibration inducer electric motor (kWh)	0.267	CO2 kg/kWh***	0.47	kw.hr	0.13

Sources: (*) [11], (**) [10], (***)[9]

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