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STRESS RELIEF OF WELDS BY HEAT TREATMENT AND VIBRATION: A COMPARISON BETWEEN THE TWO METHODS.

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ABSTRACT

Although not yet accepted officially by the American pressure vessels and piping design and construction codes, which continue to require that stress relief of welds be done by heating, the stress relief by vibration has gained considerable popularity over the last several years.
The scope of this article is to make a description of the vibration method, the theoretical principles upon which it is based, its operational procedures and the present "state of the art".
The article is complemented by an experimental section. Three pieces of pipe were welded, one of which was left "as welded", the second was stress relieved by heating and the third one was stress relieved by vibration. Several coupons were cut off the pipes, to be submitted to tensile, impact, hardness tests and metallurgical analysis.
Finally, the results of the tests are presented, a comparison is made among them and the authors' conclusion is discussed.

Key words: residual stress, stress relief, heat treatment, vibration method

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1. INTRODUCTION

The existing methods for relieving residual stress from welds are: mechanical, heat and electromagnetic.

The mechanical method may be performed by hammering or vibration. The heat method consist of heating the whole welded piece or each weld, one by one. The electromagnetic method uses the electromagnetic hammer technique.

In the heat treatment the part is heated until the yield point is reduced to less than the residual stress, which in turn causes local plastic distortion, decrease of the residual stress intensity and reduction of hardness.

The vibration method introduces energy into the part by means of vibrations. For the stressed atomic structure there is no difference between the energy introduced through heat and the energy introduced through vibrations. The applied energy reorganizes the crystalline structure, relieving stress and stabilizing the piece, without distortion.

This process is especially useful for stress relieving of big structures, for which the cost of treatment by electrical means would be high, and for parts with severe dimensional tolerances, in which heat treatment could cause distortions that would exceed them.

The vibrators generally used have a frequency band of 0 to 100 Hz. They are connected to the structure, which should be supported on rubber blocks. Frequency is gradually increased until the first resonance is reached. This resonance is maintained for a specific period of time and then the frequency is increased again until the second resonance is reached and so on.

2. SOURCES OF RESIDUAL STRESS

Residual stress in welds is produced by localized metal tensions occurring immediately after welding, which are:

a) Contraction stress. This is the main source of residual stress. It takes place during the cooling of the welded areas, which have undergone non uniform heating.

b) Stress due to higher surface cooling. When a weld cools down the surface cools faster than the inside, even if this cooling occurs in still air. The greater the thickness, the more stress is generated.

c) Stress due to phase transformation. It occurs due to the transformation of austenite (face centered cube, fcc) to ferrite (body centered cube, bcc), that causes an increase in volume to which the base metal is opposed.

The three types of residual stress usually take place at the same time. Experience proves that the individual effects of each one can be linearly superposed.[1]

3. EFFECTS OF RESIDUAL STRESS ON WELDS

Among others, the effects of residual stress on welded parts are the following:

a) Residual stress is added to the load the weld has been designed to support, which can lead to the collapse of the material.

b) Reduction of stress corrosion resistance. The regions submitted to elastic tensile stress may suffer localized corrosion in aggressive environments.

c) Risk of cracks. All cracking mechanisms are affected by residual stress and distortion caused by localized heating. .

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[1] Silveira. José Paulo et. al: Tensoes residuais e deformaçoes em soldagem, page 2.15

4. STRESS RELIEF BY HEAT TREATMENT

Depending on the shape and size of the piece, heat treatment for residual stress relief can be carried out by heating the entire piece, or parts of it, in a furnace; or transforming it in a combustion chamber by installing a temporary burner into it, or treating the welds one by one by means of electric resistances. Heating by exothermic kits, which enjoyed some popularity in the sixties and seventies, was abandoned because it did not produce the expected results.

5. STRESS RELIEF BY VIBRATION (VSR)

Based on the weight of the piece, the VSR method introduces into it high amplitude and low frequency vibrations for a given period of time. This relieves residual stress without distortion or alteration of tensile strength, yield point or resistance to fatigue, and the static equilibrium is restored.

The most efficient vibrations are the resonant ones, because in the resonance frequency vibrations stress is better distributed, if compared with sub-resonant frequency.

Low frequency vibrations carry high amplitude energy and are very efficient in the significant decrease of peak residual stress in metallic parts and welds. The equipment usually employed consists of a sturdy vibrator of variable speed which is attached to the piece and an electronic control panel. Both are mounted into a portable cabinet.

Also attached to the piece is an accelerometer that detects vibrations and transmits a signal to the control panel. The resonance point is then determined and displayed on a dial. If the vibrator is equipped with a recorder, a chart can also be obtained.

The point of resonance is attained by varying the frequency of the vibrator until the proper one is reached. Two minutes is the average time required to reach the resonance frequency. At this point, vibration is maintained for a given time, depending on the weight of the piece and its intended application. The time may range from ten minutes to an hour or more, but if it is exceeded, the piece will not suffer any damage due to fatigue or loss of tensile strength.

If structures are very big, long or have open spaces, it may be necessary to apply the procedure in several points.

Some equipment carries out the vibration process automatically. Vibration is maintained for 15 minutes, in a sequence of three different selected frequencies, each lasting five minutes. This setting is efficient to treat pieces weighing up to ten tons. For pieces weighing more than ten tons two consecutive 15 minute periods can be used, without the piece suffering any harm.

Two simple rules should be followed for all applications:

a) Support the piece in the best possible manner, isolating it from the floor or rigid structures, thus leaving it free to vibrate.

b) The vibrator should be directly connected to the piece, in order to transfer the entire vibratory energy generated.

The method can be used on a wide range of ferrous and nonferrous metals, including carbon and stainless steel, cast iron, aluminum, titanium etc., in a large variety of shapes. Sizes can vary from small welded parts, shafts and gears, to large welded and machined steel structures. However, it presents some limitations: it is not efficient for extruded, cold worked and precipitation hardened materials.

One of the most important benefits of the use of the VSR method is its capacity to relieve stress at any point of the manufacturing process, such as after machining, snagging, drilling or grinding. In welded parts, stress relief can be performed during welding, which is very useful to prevent concentration of residual stress that may cause warping of the piece. The method is especially compatible with SMAW, GMAW and GTAW welding processes, popularly known as stick electrode, MIG and TIG. With other welding processes some logistical problems may arise.

6. MEASURING THE EXTENT OF STRESS RELIEF

Until recently there was no reliable method for the precise measurement of residual stress, that not only originated from welding, but also from forging, cold drawing and other types of metal working. Now, with the use of diffractometry with x-rays, the problem has been solved.

In the past, the only way of checking if residual stress had been reduced to an acceptable level was by analogy with hardness. It is a well known fact that materials get harder when submitted to stress. Experience acquired over the years, upon which the applicable standards are still based, demonstrated that if the hardness measured after stress relief had been performed was lower than a given empiric value, the treatment had been successful.

This condition was especially important if the weld was to be in contact with corrosive environments, as is the case of the chemical industry. It is well known that, depending on the environment, metals show less corrosion resistance if submitted to residual stress.[2]

This fact is taken into account in ASME/ANSI B 31 Code for Pressure Piping. Section B 31.3, which is used in process industries such as oil refineries and chemical plants, states the maximum allowable hardness in welds after stress relief. This requirement does not exist in Section B 31.1, which is used in power plants, where the possibility of corrosion is much less.

Until very recently, diffractometry by x-rays presented a serious operational problem. The equipment was too large to be taken to the point of use, and in many cases the weld could not be taken to the equipment. This situation has been overcome by the development of equipment small enough to be moved from one place to another. The applicable codes, however, continue to consider Hardness as the parameter ruling the approval of stress relief, and this is why we have adopted it in the Experimental Section.

7. EXPERIMENTAL SECTION

The experimental part of this study consisted in comparing the results of stress relief performed by heating and by vibration on welds made on the same material, ASTM A 106 grade B carbon steel, whose chemical composition is shown in Table 1. Three 4 inch diameter, schedule 40 pieces of pipe were welded with the weld located in the middle. The first piece was not submitted to any type of treatment, the second was submitted to heat treatment and the third to VSR. The electrode used was E-6010 for the first pass and E-7018 for the rest. After the welding and before treatment the pipes were machined to eliminate the weld reinforcement, i.e., to have a flush outer pipe surface.

Table 1: Chemical composition of ASTM A-106 grade B steel

Elements	%
Carbon	0,30 max
Manganese	0,29 - 1,06
Phosphorus	0,035 max
Sulfur	0,035 max
Silicon	0,10 max

7.1. Heat Treatment

The heat treatment was carried out in the oven of the Metallurgical Laboratory of Mackenzie School of Engineering, according to Standard ASME / ANSI B 31.3. The heating took place at a

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[2] Silveira, José Paulo et al.: Op. cit., page 4.13

maximum speed of 315 ºC / h until the soak temperature of 650 ºC was reached, at which point the pipe was kept for 30 additional minutes. Then, the oven was switched off and allowed to cool with the pipe in it.

7.2. Vibration Stress Relief

A company in the city of Sao Paulo that owns equipment for VSR kindly offered its help, performing the treatment on the sample pipe. The treatment was made according to the equipment's Instruction Manual. The pipe was firmly secured and the frequency of vibration was gradually increased until resonance was reached and maintained for ten minutes. Then, the vibrator was switched off.

7.3. Tensile test

All tests were carried out according to Standard API 1104 guidelines.
Three specimens were cut, one from each pipe, having the dimensions indicated in Table 2. The specimens were clamped in the Amsler machine of the Material Testing Laboratory of Mackenzie School of Engineering, taking them to rupture. The loading rate was 600 N/s (~60 kgf/s). In all cases rupture occurred in the base metal and not in the welds or HAZ. Table 3 shows the information resulting from the tests.

Table 2: Dimensions of specimens before tests.

Dimensions	No treatment	VSR	Heat treatment
Width, mm	25,3	25,3	25,3
Length, mm	225,0	225,0	225,0
Thickness, mm	6,25	6,25	6,40
Gage length (L_0), mm	125,0	125,0	125,0

Table 3: Tests results

Measurements	No treatment	VSR	Heat treatment
Yield load kN (kgf)	52,0 (5300)	52,0 (5300)	44,9 (4580)
Maximum load, kN (kgf)	74,7 (7620)	75,9 (7746)	68,6 (7000)
Rupture load kN (kgf)	60,2 (6140)	61,8 (6300)	53,9 (5500)
Gage length (L_f), mm	148,4	148,4	153,9

The tensile tests calculations are shown on Table 4

Table 4: Tensile tests calculations

Parameter	No treatment	VSR	Heat treatment
Yield point MPa (kgf/cm^2)	328,7 (3352)	328,7 (3352)	277,4 (2829)
Maximum stress MPa (kgf/cm^2)	472,6 (4819)	480,4 (4899)	423,9 (4323)
Ultimate tensile stress MPa (kgf/cm^2)	380,8 (3883)	390,7 (3984)	333,1 (3397)
Elongation (%)	18,76	18,74	23,12

7.4 Impact Test

The specimens for the impact test had the same dimensions as those of the tensile test with the addition of two lateral notches on the welding bead, as required by Standard API 1104. The three specimens were submitted to impact test in the Charpy machine, at room temperature, with a 30 kg hammer. None of the specimens broke. Results are shown in Table 5.

Table 5: Impact Test

	No treatment	VSR	Heat treatment
Energy absorbed kJ (kgf.m)	284,4 (29)	285,4 (29,1)	285,2 (29,08)

7.5 Brinell Hardness

Brinell hardness was measured on the three coupons, with a 10 mm diameter ball and a load of 3.000 kgf (~30.000 kN). The sizes of the impressions and their corresponding hardness are shown on Table 6.

Table 6: Brinell Hardness

	No treatment	VSR	Heat treatment
Indentation diameter, mm	4,10	4,53	4,45
BHN hardness	217	178	183

7.6. Metallography

After being polished, the specimens were attacked with nital for nearly 5 seconds and their microstructures observed in the metallographic microscope. The results are outlined below.
As expected, the micrographs of the original base metal show an alignment of grains, indicating that the material was manufactured by hot rolling.
The weld is basically constituted by ferrite with a dendritic arrangement due to the high temperature it supported during the welding process. As carbon also exists, the dark part visible in the micrographs is probably perlite.
On the interface of the weld with the HAZ, dark perlite grains are visible, with ferrite around the grains, forming a net around the perlite. The closer the perlite grains are to the weld the bigger is their size, because they were exposed to higher temperatures than the ones farther.
It was also observed that neither the vibration method nor the heat treatment alter the original metallographic structure of the material.

8. CONCLUSIONS

First, it is noted that while the specimens that had been heat treated showed a decrease in tensile strength and an increase in elongation, as was to be expected, the vibration method practically does not alter those values, for it does not temper, normalize or anneal nor does it modify the mechanical properties of the material.[3]
Second, the energies absorbed in the impact test are practically the same. None of the specimens broke, indicating that the welded material is ductile because it has a considerable amount of ferrite, as can be observed in the micrographs. The decrease in hardness resulting from both treatments was similar, indicating an effective reduction in residual stress.

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[3] Stress Relief Engineering Co.: Resonant vibration method for reducing residual stresses in welded or machined fabrications, page 5.

The conclusion that could be reached would be that heat and vibration methods are equivalent for practical purposes. The authors agree, however, that a test conducted with only one sample piece treated with each method is not sufficiently representative to reach valid conclusions. Nonetheless, the authors believe that the preliminary conclusion of this paper can encourage other researchers to seriously consider further investigation of the vibration method of stress relief.

The fact that the American standards, widely used not only in the U.S.A. but also in many other countries, do not formally accept vibratory stress relief, raised certain doubts regarding this method. However, the method could be used with a specific piece of material, not designed and/or manufactured according to those standards. It is the case, for example, of the supporting structure of paper machines, called *Beloit machine* in the paper industry slang. As the structure makes part of the machine itself, the welds do not need to follow standard AWS D.1, as would be the case of the structural steel of a football stadium. Consequently, the machine manufacturer is free to choose the stress relief method most convenient for him, provided that the final quality of the product is maintained. In the case of the Beloit machines, the reason for the choice is clear: the machine must be installed within severe level tolerances and stress relief by heat could produce distortions that, even if very small, would exceed the mentioned tolerances. Relief by vibration, on the other hand, does not introduce dimensional changes in the parts.[4]

In some cases, stress relief by vibration may be used as a more convenient option to heat treatment, as for example when the piece is too big to be transported and placed in a furnace. In these cases, the possibility of carrying out the stress relief on site with no need to move the piece is a clear advantage. An example would be a petrochemical tower.

On the other hand, pieces in big quantities and easy to handle, such as prefabricated piping sections, may be conveniently heat treated in batches in a furnace.

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[4] Stress Relief Engineering Co.: Op. cit., page 5