# 538. Influence of vibratory stress relief on residual stresses in weldments and mechanical properties of structural steel joint

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**Abstract.** The welding process can join two similar materials with a bond that has mechanical properties comparable to the original material. Unfortunately, this process induces residual stresses in the weldment, which, if left untreated, can cause distortion of the part, premature fatigue failure or cracking along the weld. A post-weld heat treatment is the traditional method of relieving these stresses, but is costly and a time consuming process. Heat treatment is required for weldments, which have heavy fatigue loading since the post-weld heat treatment reduces the residual stresses in the weldment and generates more uniform mechanical properties. Vibratory stress relief (VSR) techniques could be used to substitute the heat treatment for these types of weldments and save time and money. The purpose of this paper is to provide a brief overview of the generation, measurement, and reduction of residual stresses.
Residual stresses in the weld bead were measured by means of X-ray diffraction, ultrasonic technique and hole drilling methods. In addition, welded specimens were subjected to mechanical testing with purpose of determination of VSR effect on weld and heat-affected zone metal.

**Keywords:** vibration stress relief, residual stresses, ultrasonic stress measurement, X-Ray diffraction, hole-drilling.

## 1. Introduction

The existing methods for relieving welding residual stress are as follows: mechanical, thermal and electromagnetic. The mechanical method may be performed by hammering or vibration. The thermal method consists 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 parts are heated until the yield point of alloy is reduced to the level less than the residual stress level, which in turn causes local plastic distortion, decrease of the residual stress intensity and reduction of hardness.

The vibration method introduces the 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 affects crystalline structure, relieve the stresses and stabilize the pieces without distortion [1, 2].

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

The vibrations used have generally a frequency from 0 to 100 Hz. The vibrator is 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 [4].

## 2. Stress relief by thermal and vibration energy

*Thermal stress relief* (*TSR*). Depending on the shape and size of the piece, the residual stress relief by the heat treatment can be carried out by: - heating the entire piece, or parts of it, in a furnace; - installing a temporary burner into workpiece; - treating the welds one by one by pass of electric current (resistance heating). Heating by exothermic kits, which enjoyed some popularity in the sixties and seventies, was abandoned because it did not produce the expected results [2].

*Vibratory stress relief* (*VSR*) technique, based on the weight of the piece, 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 parent metal 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 [4]. 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 *MMA*, *MAG*, *MIG* and *TIG*. With other welding processes some logistical problems may arise.

## 3. Techniques for measurement of residual stress

Residual stress measurement techniques of different materials can be broadly classified into 3 types: destructive method, semi-destructive method and non-destructive methods [1, 14].

In destructive method a portion of the residually-stressed body is cut away and the resulting deformation of the body is carefully measured with the help of strain gages, then the residual stresses, which existed at the freshly exposed surfaces, before they were thus exposed, can be calculated. This technique, referred to as dissection method, is old but still powerful. The disadvantages of this technique are: the method is very tedious and painstaking, theoretical analysis is difficult and the method is unable to detect residual micro-stresses [11].

Semi-destructive *hole-drilling method* is a widely used method for measuring residual stress. It involves drilling of a hole on the surface of the object being examined, and measurement of strain redistribution that takes place on the surface as a result of the hole. Elasticity theory is used to calculate the residual stresses that existed prior to the drilling. The strains may be measured with strain gages or with photo-elastic coatings mounted on the surface before drilling [3].

Non-destructive methods come in three basic types:

- *X-ray diffraction method* is the most common non-destructive method for evaluating residual stresses. It is based on lattice strains, the changes in the spacing between crystallographic lattice planes, which are caused by stress. The disadvantages of this method are: as the volume of surface material interrogated by x-ray beam is small, and the lattice strain which is measured reflects the combined influence of both micro- and macro-residual stresses acting at that location [10]. In materials having high variation of micro-stress gradients the evaluation of macro-residual stress is not proper. The elastic constants of crystals vary with their orientation so that their calculated values differ substantially from the measured values; measured values are not always available.
- *Ultrasonic method* for evaluating residual stresses is based upon the changes in the velocities of ultrasonic waves due to stress. The disadvantage of this method is: higher order elastic constants are generally required in order to relate ultrasonic velocities to residual stress [12]. These constants which are also dependent on the metallurgical texture must be experimentally determined for a particular material being examined. This method has a limited capability for detecting sharp stress gradients and it has little use for determining residual stress in materials such as plastics, composites and certain non-metallic materials [13].

## 4. Test specimens and material properties

The specimens were produced from *S355J2* (*LST EN 10025-2*) hot-rolled steel plate of cross-section 140x140x30 *mm*. The specimen size was selected according to limitation of the used measurements technique. The chemical and mechanical properties of *S355J2* grade steel plates are presented in Table 1. Specimens from *S355J2* grade steel were welded by using metal active gas welding process. *ESAB OK Autrod 12.51* welding wire and $CO_2$ shielding gas were used. Chemical composition and mechanical properties of the weld metal are listed in Table 2.

**Table 1.** Mechanical and chemical (%) properties of steel specimens

| $R_m$, *MPa* | $R_e$, *MPa* | $A_5$, % | KV, *J/cm²* | C | Si | Mn | P | S | Fe |
|---|---|---|---|---|---|---|---|---|---|
| 529 | 437 | 30 | 96 (-20°C) | 0.17 | 0.31 | 1.46 | 0.013 | 0.011 | Bal. |

**Table 2.** Mechanical and chemical (%) properties of the weld filler metal

| $R_m$, *MPa* | $R_e$, *MPa* | $A_5$, % | KV, *J/cm²* | C | Si | Mn | P | S | Fe |
|---|---|---|---|---|---|---|---|---|---|
| 520 | 422 | 23 | 131 (-20°C) | 0.16 | 0.8 | 1.2 | 0.013 | 0.011 | Bal. |

**Table 3.** Parameters of VSR treatment during welding

| Force inductor energy level, *kg* | Vibrator unbalance eccentric, % | Harmonic Frequency, *Hz* | SUB-harmonic Frequency, *Hz* | Dwell time after welding, *min* |
|---|---|---|---|---|
| 350 | 35 | 86.6 | 83/84.4 | 15 |

**Table 4.** Parameters of VSR treatment after welding

| Force inductor energy level, *kg* | Vibrator unbalance eccentric, % | Harmonic Frequency, *Hz* | SUB-harmonic Frequency, *Hz* | Dwell time, *min* |
|---|---|---|---|---|
| 350 | 35 | 84.3 | 79.6 | 25 |

**Table 5.** Parameters of welding

| Welding current, *A* | Welding voltage, *V* | Wire feed speed, *m/min* | Welding speed, *cm/min* | Shielding gas rate, *l/min* |
|---|---|---|---|---|
| 230 | 23 | 6 | 16…18 | 16 |

Four specimens were welded from steel *S355J2* plates: at first, without any treatment; second, heat treatment was performed after welding; third, specimen was treated by *VSR* during welding and fourth, *VSR* after welding. The thickness of each plate was 30 mm (Fig. 4). It was necessary to make 14 welding passes to form the normal weld seam (Table 5 and Fig. 4). The total length of welding seam was 140 *mm*. Figs. 4-5 show the structure of the weld seam and indicate the points of stress measurements located on the seam, in the heat-affected zone and outside the weld region. *VSR* treatments were performed using special work-desk (Fig. 1).

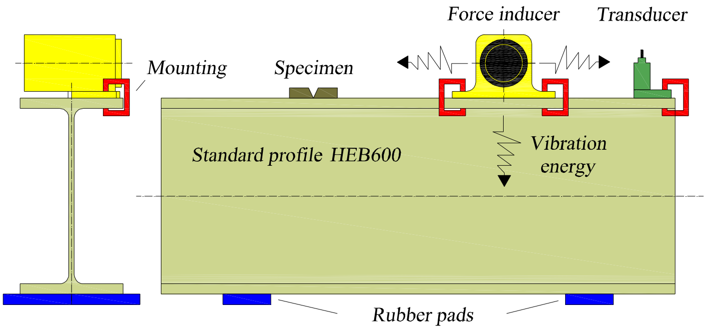


**Fig. 1.** Work-desk for *VSR* treatment

*VSR* treatment charts (Fig. 2 and Fig. 3) are a curve of data displaying the response of a workpiece to vibration both before (1) and after (2) treatment, and can include data collected during the actual treatment. Treatment charts include plots of both the workpiece acceleration and vibrator input power, each represented along its own vertical Y-axis, with the common X-axis of vibrator frequency.

Vibrational conditioning relaxation process uses a sinusoidal vibration waveform. Force inducer induces energy to create vibration amplitude that is below the harmonic amplitude. A dwell time and working frequency depending on the component's strength, elastic modulus, and size, is maintained to allow internal stresses to redistribute and balance themselves. Vibration energy is induced into and absorbed by the metal at a frequency just below the peak [4]. This is the proper frequency for best results, because vibrating at the peak amplitude frequency may causes plastic deformation and fatigue.

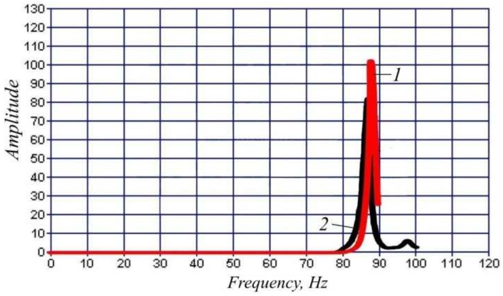


**Fig. 2.** Curve of VSR during welding

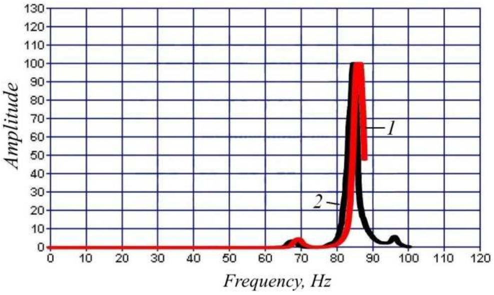


**Fig. 3.** Curve of VSR after welding

## 5. Experimental process, results and discussion

The longitudinal residual stresses were measured with ultrasonic method at each point accordingly (Fig. 5). Combinative hole drilling and digital speckle pattern interferometry (*HD/DSPI*) measurements were carried out from weld center to one side only. X-Ray diffraction measurements were made on the middle of seam.

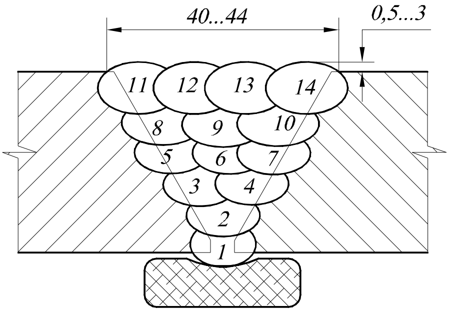


**Fig. 4.** Preparation of joint edge, welding succession and dimensions

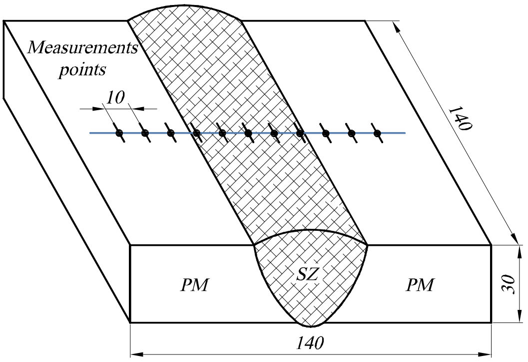


**Fig. 5.** Displacement of residual stress measurement points on specimen surface

The ultrasonic longitudinal residual stresses measurements were made with a transmitter-receiver transducer generating longitudinal waves. The transducer axis was parallel to weld axis. Ultrasonic travel time is taken on 10 *mm* spaced points (Fig. 5). The residual stresses measured by this ultrasonic method were localized in 7…10 *mm* deepness from top side. Measurements were integrated on a 137 *mm* length. The metallurgical texture was taken into account through a double calibration i.e. in parent and weld metal, when acoustic-elastic constants were determined. The influence of texture was estimated to 16 %. The residual stress distributions in the as-welded test plates (without any stress relief treatment) indicate a maximum tensile stress on the weld axis (Fig. 6), reaching a value of 335 *MPa* in the *S355J2* steel joint.

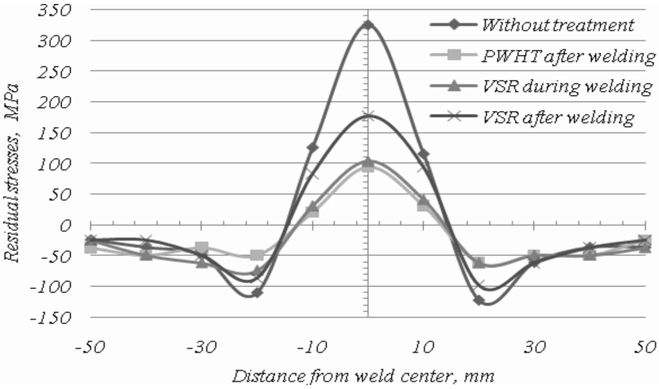


**Fig. 6.** Distribution of longitudinal residual stresses in specimens by ultrasonic technique

Digital speckle pattern interferometry has been successfully used for several years in many applications in the field of experimental mechanics for measurements of mechanical stresses. Two sets of images are grabbed, one in the reference loading stage and the other in the final relaxing stage. A phase pattern is computed for each stage and the phase difference is calculated for each pixel of the image. After some image processing, the displacement field between the two loading configurations is computed for the whole image. From spatial derivatives of that, the strains can be computed and then, the stresses can be determined.

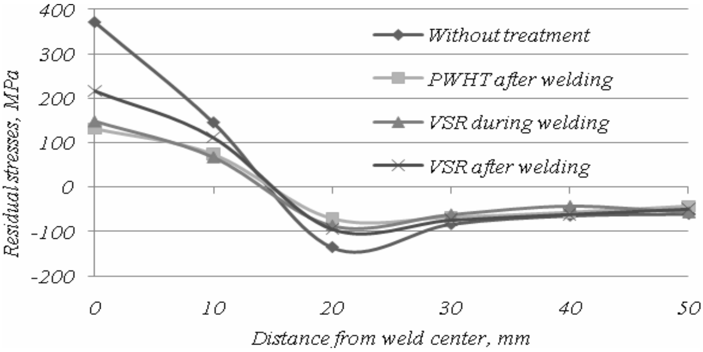


**Fig. 7.** Distribution of longitudinal residual stresses in specimens by *HD/DSPI* technique

In laboratory environment *HD/DSPI* device was very practical and easy to use. The time necessary to measure residual stresses is about ten times faster than what is required when strain gauges rosettes are used. Almost no surface preparation is required. The acquisition and processing time is very short [5]. However, some experience and measurement skills are necessary at the current development stage to successfully measure residual stresses.

Research, performed by using combinative *HD/DSPI* technique demonstrates that maximal residual stresses relieve was higher than normal steel *S355J2* yield stresses. It was also determined that vibration energy used during welding reduced residual stresses peak more than 2.5 times. *VSR* after welding reduced peak of residual stresses about 42 %.

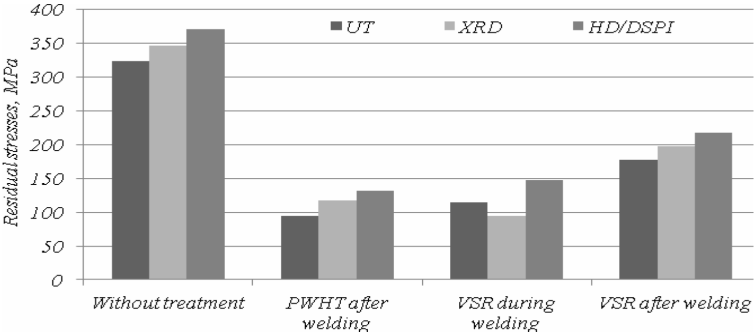


**Fig. 8.** Peak of longitudinal residual stresses in welded specimens, using different methods

X-Ray diffraction measurements were conducted with a portable X-ray apparatus *PROTO iXRD*. *Cr-*$K_\alpha$ radiation and (*BCC, hkl-211*) reflections were used to study residual stress distribution in weld region. The depth of the measurements was 50…100 $\mu m$ on the specimen surface.

The analysis of X-ray diffraction indicates that *VSR* during welding reduced peak of residual stresses more than 3.5 times. It also revealed that *VSR* after welding reduced residual stresses peak more than 40 % in the specimen.

Tensile test were performed according to requirements of standard *LST EN 895* [6]. Analysis of the mechanical properties indicates that *VSR* does not have negative effect on the joint strength, in contrast to thermal stresses relieves. Elongation results outweigh minimal requirements by 20 %. It was also established that *VSR* during welding enlarges plasticity of the joint by not changing strength properties.

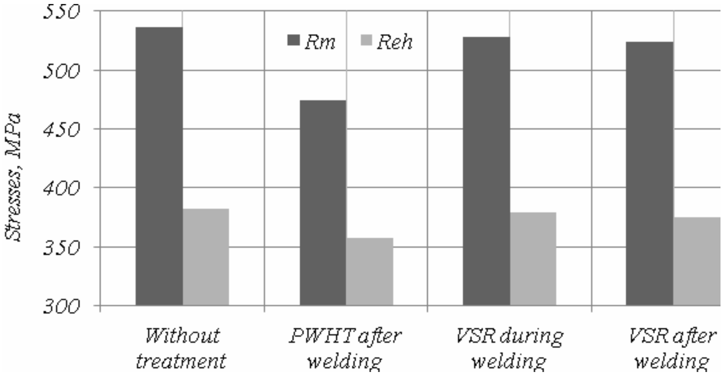


**Fig. 9.** Tensile test results

According to *LST EN 875* recommendations [7] impact strength analysis was performed for two different zones: weld metal and heat-affected zone. Temperature for all tests was -30 °C. For weld metal and *HAZ* impact strength study *VWT 0/1* and *VHT 1/1* specimen types were used respectively. Test results (Fig. 10) demonstrate that impact strength of specimens without treatment is the least of all specimens, but exceed minimum value of impact strength (33.8 *J/cm*$^2$) according *LST EN 10025-2* standard [9], when test temperature is -30 °C. In addition, analysis indicates that *VSR* after welding does not change weld metal and *HAZ* impact strength. Vibratory stresses relieve during welding and *PWHT* increase weld metal and *HAZ* impact strength.

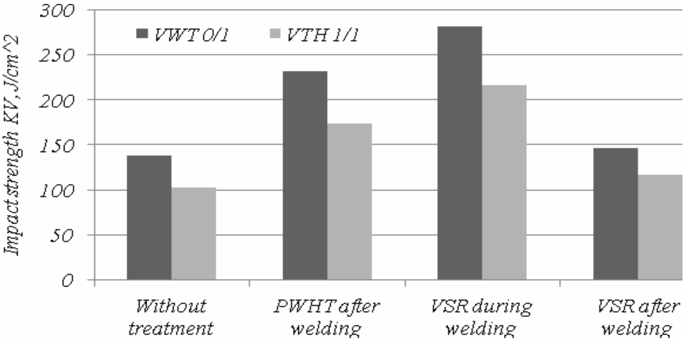
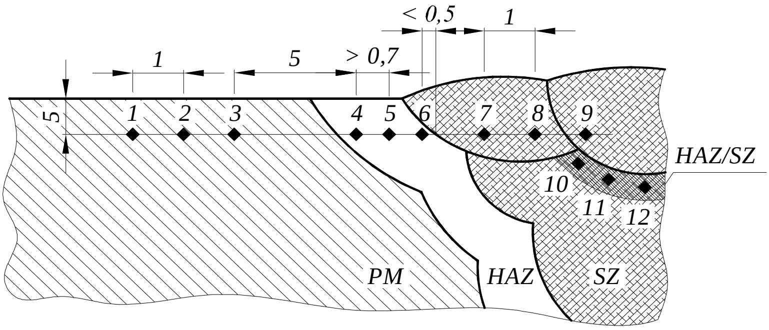


**Fig. 10.** Impact strength test results

In micro-hardness tests universal *Zwick/Roell ZHU 2.5* electronic hardness tester was used, applying technique described in standard *LST EN 1043-2* [8]. Four measurement areas were made: parent metal, *HAZ*, weld metal and *HAZ* between welds (*HAZ/SZ*). Thereby 12 measurements were carried out for each specimen. Micro-hardness test results are given in Fig. 11.



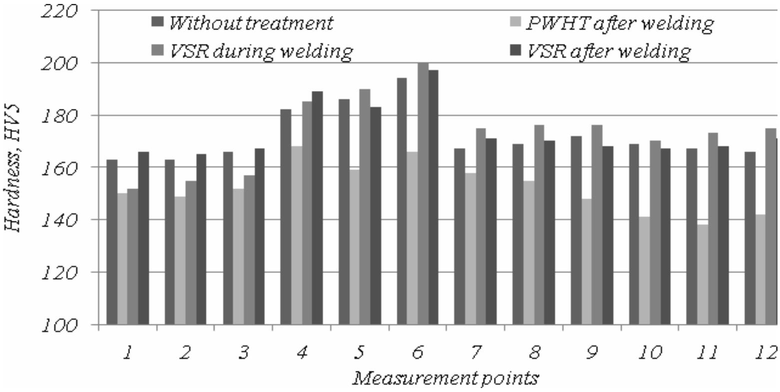


**Fig. 11.** Distribution of hardness in specimens

Hardness tests revealed that vibratory energy does no affect parent metal, weld and *HAZ* hardness. Maximum hardness value in *HAZ* near the melting line was 200 *HV*. The minimum hardness values estimated in welded metal was about 175 *HV*. Thermal stress relieve reduced the hardness of the weld significantly. Minimum hardness value in *HAZ* between welds was 141 *HV*.

## 6. Conclusions

- Vibratory treatment during welding or after welding effectively reduces residuals stresses of welded joints until safe level. Results of *VSR* during welding is analogous to thermal stress relief technique, therefore *VSR* method for carbon structural steel treatment is more effective considering work and energy inputs.
- According to comparison of residual stresses peaks (Fig. 7) it is posible to state that vibratory relieve during welding reduces residual stresses on average by 60 % and vibratory relieve after welding reduces residual streses - on average by 40 %.
- This paper confirms the potential of the longitudinal ultrasonic waves to accurately evaluate welding residual stresses, if all the sample microstructures are taken into account.
- Analysis of mechanical properties demonstrated that *VSR* after welding does not have any fundamental influence on material strength, ductility and hardness characteristics. Joint properties remain unaltered after vibratory treatment as without any treatment but residual stresses decrease.
- Thermal residual stress relieving increases plasticity of welded joint, but simultaneously diminishes its strength and hardness. The treated joint becomes less resistant to fatigue, static and dynamic loads as well as less friction-proof.

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