Effect of Vibratory Stress Relief on Fatigue Life of S355J2 Steel Welded Joints

Sinem Kacar
HİDROMEK A.Ş., 1.OSB, Sincan, 06935, Ankara, TURKEY
sinem.kacar@hidromek.com.tr

Advanced Manufacturing Technology Research Group, Department of Mechanical Engineering, Gazi University, Celal Bayar Boulevard, 06570, Maltepe, Ankara, TURKEY

Oguzhan Yilmaz
Advanced Manufacturing Technology Research Group, Department of Mechanical Engineering, Gazi University, Celal Bayar Boulevard, 06570, Maltepe, Ankara, TURKEY
oguzhanyilmaz@gazi.edu.tr

This study presents an investigation on Vibratory Stress Relief (VSR) method in order to reduce residual stresses in welded parts. Mechanical properties of the welded parts were compared for the vibratory stress relieved welded parts and non-stress relieved welded parts. Firstly, tensile tests were carried out and then the hardness measurements were accomplished. To investigate the effects of residual stresses on fatigue life, the residual stress values in front and back of the welded plates were measured. Three-point fatigue tests were also performed to show the effectiveness of VSR in terms of fatigue life. It was obtained that the tensile strength and the surface hardness ascended slightly and fatigue life increased about three times and residual stresses on surface decreased after applying the VSR method.

Keywords Fatigue life, residual stress, vibratory stress relief method, welding

1. INTRODUCTION

Welding is one of the primary methods used in joining metallic parts. Welding methods are also used effectively in fabricating of large steel structures such as heavy duty machines, ships, bridges and dams. Strengths and longevity are the most important factors for successes and fulfilment of such structures under high fatigue loads. There might be many reasons that affect the fatigue life in welded structures. The main ones are the residual stresses, surface processing, stress concentration and corrosion effects [1]. Weld zone of the part heats up to the melting temperature during welding. However, the cooling is slower overall in the part in comparison to the heating rate. Hence, the cooling distribution in the welded parts is not homogeneous and structural changes occur during the welding process. While the parts that cooled early have compressive stresses, the parts that cooled later have tensile stresses. As a result, the welding zone is forced to gain tensile stresses through the weld seam direction [2]. In material selection and design, it is very important to know the residual stress distribution in the material to be used, in advance. For this reason, measurement of residual stress is a very common engineering practice today. Tensile stress in structural element is generally destructive, which can cause to early fatigue failure and stress corrosion cracking and it could be the main cause. Compressive residual stresses are generally useful because of propagation of fatigue cracks, increase wear and corrosion resistance [3].

Destructive and non-destructive residual stress measurement methods are used for a long time. On of the effective residual stress measurement method is Magnetic Barkhausen Noise method and this method has become more important today in terms of quick and reliable results, portability and easy of use. Barkhausen noise method is based on the principal of analysing a magnetic noise generated by a ferromagnetic material during magnetization. A measurement is made through probes which can be specially prepared according to the material geometry. Measurement values are based on magnetic parameter (MP). Calibration curves are used to find real residual stress value. Generally, tensile residual stresses in the material increase the MP values while the compressive residual stresses decrease MP values [3].

Generally, welding fatigue improvement methods are studied in two main categories as welding geometry improvement and residual stress relief.

Residual stress relieving methods increase the fatigue life by transforming the tensile stresses in the regions where the cracks are likely to occur to compressive stresses [4]. Heat treatment emerges as the most effective method for eliminating residual stresses for many years. However, the researchers have been searching for different methods for stress relieving due to some limitation of heat treatment such as high cost, time consuming and inconveniency for every material [5]. Vibratory stress relief (VSR) has emerged as an alternative method in the last 60 years. Nowadays, it is applied in many industrial fields such as manufacturing, molding industry, automotive industry and ships industry [6]. It is based on the principle that it applies vibrations at resonance frequency or near resonance frequency to the work piece and vibrated part absorbs the energy that will reduce residual stresses of the part [7]. It is aimed that dislocations enter a regular state with absorbed vibratory energy. So that residual stresses are expected to decrease. VSR method has been used in previous studies in different materials, shape, size and weld. In many studies, it was examined that residual stress descended when VSR applied after welding process with different percentage. Moreover, it is also seen VSR increased the strength of the parts by means of tensile and yield points, but shifting rate is not very high. Material damping capability, applied frequency and externally applied dynamic force are essential and variable; effectiveness of application can vary on each material and structure. Time saving, low cost, low distortion, and applicable for large-scale parts are the advantages of the VSR method over other stress relieving processes. A major limitation of VSR, however, is the lack of thorough understanding of the phenomenon, resulting in a lack of confidence in the broad application of the process. Without this understanding it is difficult for engineers and manufacturing managers to determine when, where and how the VSR process can be effectively applied and especially where fatigue is of major concerns [7]. In 2009, theoretically the mathematical modeling of vibration stress relief was theorized. But it was expressed that the obtained results by experimental studies need to be compared to empirical expressions in this model [7]. In 2003, the influence of VSR effect on the Ck 35 steel shaft used in shipbuilding was examined. Different mechanical tests were applied to investigate the variation of mechanical properties of the part within the scope of the study [8]. In another study in 2003, the effects of VSR on low-alloyed high-strength welded steels and also the change in residual stresses distribution on welded plate were investigated [9]. Although there are some papers about effect of vibration stress relief method on residual stress and the change of mechanical properties (hardness and strength), there are only a few of papers about effect of vibration stress relief method on fatigue life. But it is known that this process will improve fatigue life because of decrease residual stress and increase toughness of material. This paper presents the results of the test of vibration stress relieving of S355J2 steel. Mechanical properties' differences and residual stress change were investigated between vibration stress relief welded parts and non-stress relief welded parts and the effect of this method on the fatigue life was studied.

2. EXPERIMENTAL PROSEDURE

In this section, materials, test equipments, conducted tests, and the selected test parameters used in this work are introduced.

2.1. Materials

In this study, S355J2 steel formerly known St52-3 was used as a test material since it is widely used in the metal construction industry. The chemical compositions and mechanical properties of S355J2 steel declared by the manufacturer are shown in Table 1 and Table 2.

Table 1. Chemical compositions of S355J2 steel.

Standard Designation		Chemical Composition					
Standard	Quality	C	Mn	P	S	Si	Cu
EN 10025-2	S355J2	0.20	1.6	0.025	0.025	0.55	0.55

Table 2. Mechanical properties of S355J2 steel.

Yield Strength (N/mm^2)	Tensile Strength (N/mm2)	Elongation (%) min.
355	470-630	20

2.2. Test Specimens

Separate plates were prepared for tensile, fatigue, hardness and residual stress measurement tests. Specimen thickness was chosen as 10 mm. To ensure that all of the test specimens had the same characteristics. The large specimens were first welded and then the test specimens were sampled from the large specimens. Dimension of large specimens was 600mm X 225mm X 10mm, Figure 1. Metal active gas (MAG) welding was used during the joining process of the steel plates. Welding parameters are shown in the Table 3. One pass weld was made considering thickness of the plate. After welding process, grinding process was not performed on the plate root section in order to avoid residual stresses change. MAG welding process for residual stress and hardness measurement samples can be seen in Figure 2. In order to minimize the residual stress change in fatigue and tensile test

Table 3. Welding parameters of test samples.

Welding Travel Speed (cm/dk)	Welding Wire Speed (m/dk)	Welding Current (A)	Welding Voltage (V)
25	10	270-280	17-28

samples, during laser cut 8 mm clearance was given from edge of every sample. Then samples were processed to their exact size according to standard.

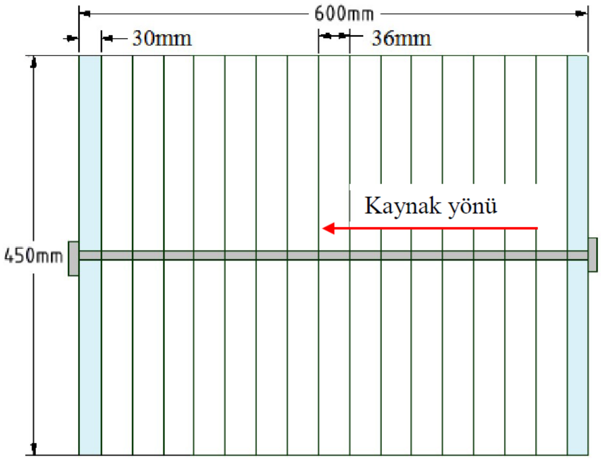

Fig. 1. Fatigue test samples from welded plate

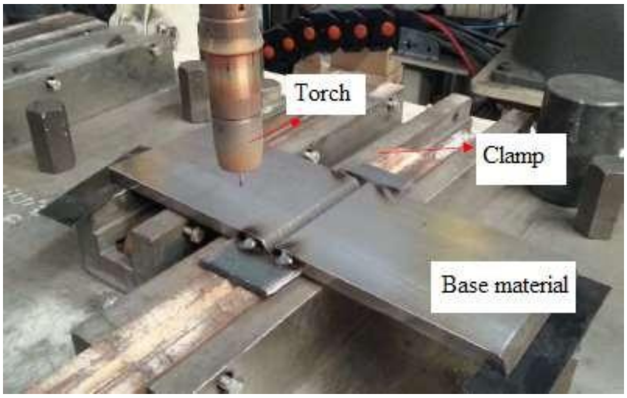

Fig. 2. Welding procedure – Residual stress measurement sample

All mechanical tests have been carried out in accordance with standards in laboratories with accreditation certificate. Tensile samples produced according to TS 287-EN 895 standard as shown in Figure 3. Tensile tests were carried out on Zwick tensile test device with a load capacity of 250 kN in university laboratory. Vibratory stress relief process was then applied to three samples of the six samples. Hardness measurements were accomplished according to Standard Brinell Hardness Method and the measurement position and direction are shown in Figure 4 and Figure 5. During the measurement DHT 100 hardness tester device was used. The measurements were taken at approximately 1 mm intervals perpendicular to the welding cross-section along a line from the full mid-axis of the welded plate. Hardness values were taken from both the front and back surfaces of the welded plate. Residual stress measurements were made according to Magnetic Barkhausen method with Stress Tech Microscan 500-2 test device and three samples were used. 125 Hz sinusial magnetic field was used during Magnetic barkhausen noise measurement, which was adjusted according to S355J2 steel. The collected Barkhausen signals were [illegible]-200 kHz range and amplified by 10 dB. Position and direction of the collected values are seen in Figure 4 and Figure 5. Fatigue tests are carried out to determine the fatigue strength of materials exposed to dynamic loads. During the tests MST 322 Test Frame was used. In this study, three-point bending fatigue tests were performed. Before the fatigue tests, static bending test was conducted and four different loads were determined. The sample used in the fatigue and bending test is shown in Figure 6.

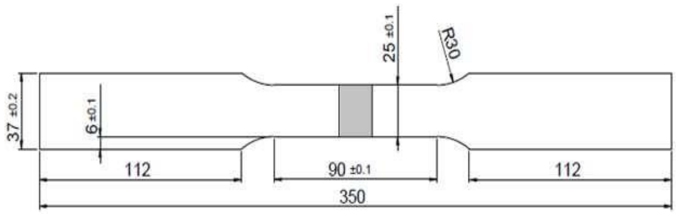

Fig. 3. Tensile test sample (dimensions are in mm)

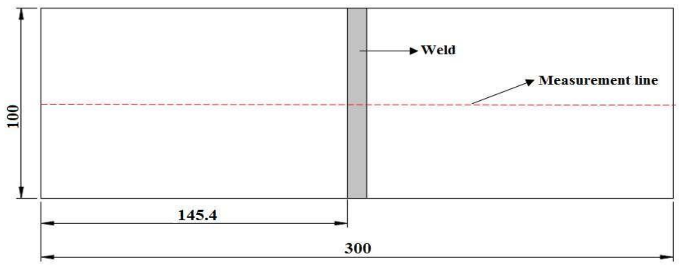

Fig. 4. Hardness and residual stress measurement test sample (dimensions are in mm)

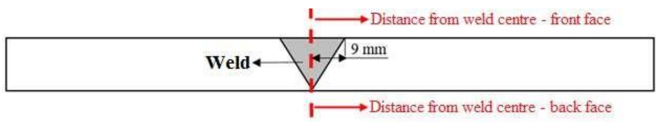

Fig. 5. Welded plate front and back face measurement positions

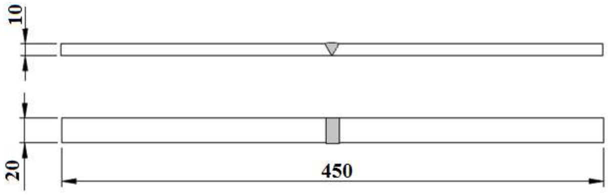

Fig. 6. Fatigue and bending test sample (dimensions are in mm)

2.3. Application of Vibratory Stress Relief Process

Vibratory stress relief system has three parts, which are force producer (vibrating machine), transducer, control, and accelerometer. During vibration stress relief process manual system Meta-Lax 2020 was used as a vibration machine. First samples were fixed to table. The locations where the samples are fixed are positioned according to the impact area determined by the manufacturer according to the capacity of the device. Resonance frequency of the complete structure including table and test specimens was determined by the device. Resonance frequency, the most effective frequency level to reduce residual stresses. After the test samples (parts) were shaken with the force generating part. By taking continuous measurement with the accelerometer from the test part, the part is constantly vibrated at desired frequency. Structure is vibrated at the same frequency value with transducer and control sections. Figure 7 and Figure 8 show VSR working cycle and VSR application example. In this work, all the test specimens were vibrated at 90 Hz for about half an hour.

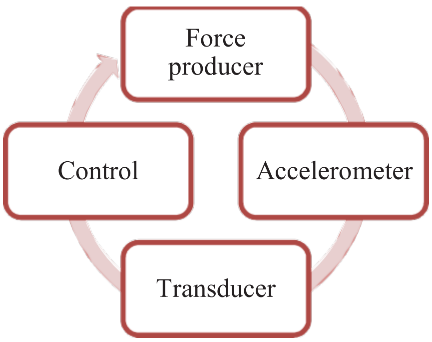

Fig. 7. Vibration stress relief working cycle

3. RESULTS AND DISCUSSIONS

3.1. Mechanical Test Results

Numeric results of the tensile tests of three as-welded parts and three vibratory treated specimens are shown in Table 4 and Table 5, respectively. The tensile test results show that the vibration stress relief did not reduce neither yield strength nor tensile strength. On the other hand, it is known that the thermal stress relieving decreases tensile and yield point [10-11]. It is also observed that the vibratory stress relief nearly does not chance the material strength property and even improves elasticity modulus and tensile strength. Elasticity modulus measures substance's resistance to being deformed elastically when stress is applied to it. According to average results of three sample, this value increased from 197.6 GPa to 211.6 GPa so the toughness of the test part grew at about 7.1%. Because of the vibration energy absorption during the treatment, the bonds between the irregular state atoms became stronger and as a result of the strengthening of the bonds, the modulus of elasticity increased.

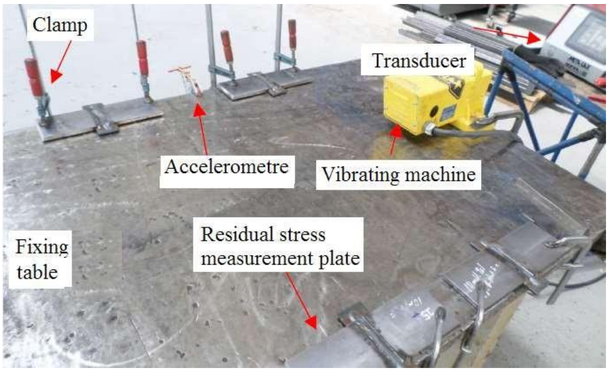

Fig. 8. Fatigue and bending test sample

Table 4. Tensile tests result of as-welded specimens

Sample No	Yield Strength (MPa)	Tensile Strength (MPa)	Elasticity Modulus (GPa)
1	398	555	196
2	386	551	200
3	410	548	197
Average	398	551.3	197.6

Table 5. Tensile tests results of vibratory treated specimens

Sample No	Yield Strength (MPa)	Tensile Strength (MPa)	Elasticity Modulus (GPa)
1	412	552	216
2	393	556	218
3	409	555	201
Average	404.6	554.3	211.6

Brinell hardness method was used to measure the hardness change after the vibratory treatment. Hardness measurement plate was used as shown in Figure 4. As a result of the hardness measurements, the collected values showed that the applied vibratory stress relief process after welding increased harnesses on both sides of the test part. The front and back face results can be seen in Figure 9 and Figure 10, respectively. At the front face, 13 mm from weld center 1 HB enhanced while 6 HB rise was measured at 24 mm from weld center. As for back face, 5 HB and 15 HB change were seen at 9 mm and 13 mm from the weld center, respectively. When looking at the graphs in general, the variation in hardness values near the weld is less, while the hardness values in the regions farther from the weld are greater. The reason for this could be the grain size and they type of microstructure change in the heat-affected zone [10]. Other reason might be the local work hardening during the vibration stress relief process.

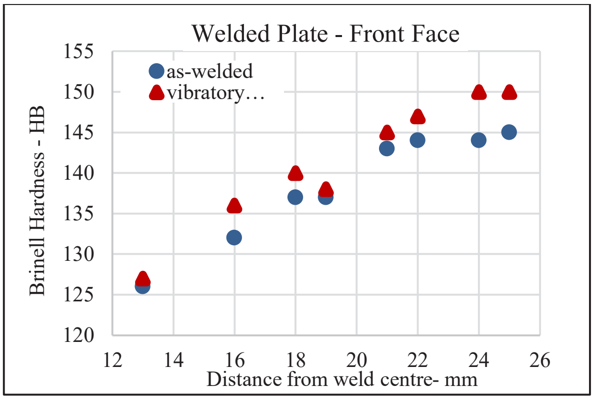

Fig. 9. Welded plate front face hardness value

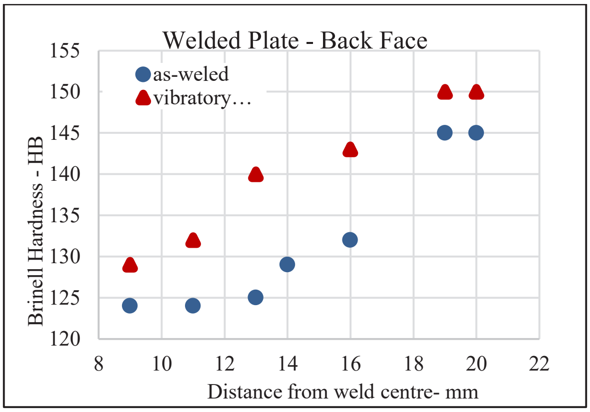

Fig. 10. Welded plate back face hardness value

There is a direct relationship between the hardness values and the tensile strength of the material. It shows that when the hardness value of the part rises, the value of tensile strength increases. Therefore, the increase in hardness value according to test results is in good agreement with the increase in yield and tensile strength. Before the fatigue tests, first static three point bending test was performed according to the standard. The yield point of the material was determined during the static bending test. The forces to be applied in the fatigue tests were determined. In Figure 11, the static three-point test results can be seen. The point where the plastic deformation starts is 2.4 kN and the displacement value corresponding to this load is 1 mm. In that case, it is obvious that the test material is ductile and no fracture occurred during test.

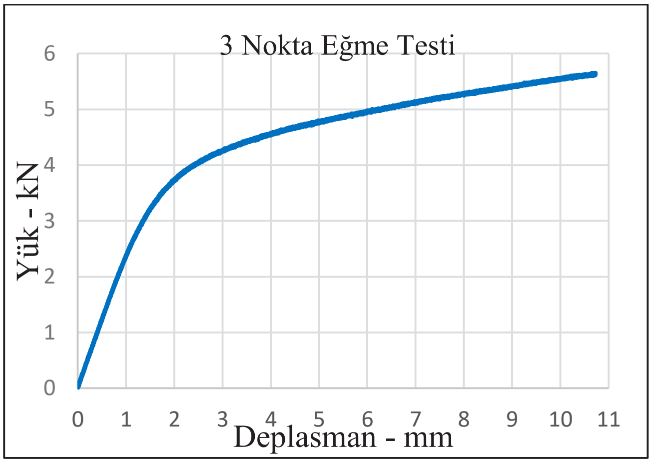

Fig. 11. Three-point bending test results

3.2. Residual Stress Relief Measurement Results

To investigate the effects of residual stresses on fatigue life, residual stress changes of front and back of the welded plates were measured by Magnetic Barkhausen Method. These measurements are based on magnetic parameter (MP). Calibration curves, which is specific for each material, must be used to find stress value. Since calibration curve determination for used material requires a comprehensive, long and time-consuming study, residual stresses were compared as MP value and percental decreases were determined in this study. Residual stress change results for three samples on the front and back of the welded plate are examined in Figure 12 to Figure 17. The curves obtained from front and back face are generally similar to those of previous studies in the literature [3]. After vibratory stress relief process, the decreases in residual stress values with different percentages on both front and back face were examined. Residual stresses descent after vibratory treatment where the similar results were seen in similar studies but for different materials [8, 12, 14, 15]. The amount of reduction in residual stress change depending upon the application point of vibration, applied frequency, amplitude and the damping capability of the applied material [7]. It is considered that during VSR practice due to vibration energy plastic deformation may occur and therefore residual stresses have decreased on samples surfaces. At front face for 1st sample, the residual stress of welded plate decreased from 125 MP to 110 MP with 12% improvement and 20% reduction at the back face near the weld zone.

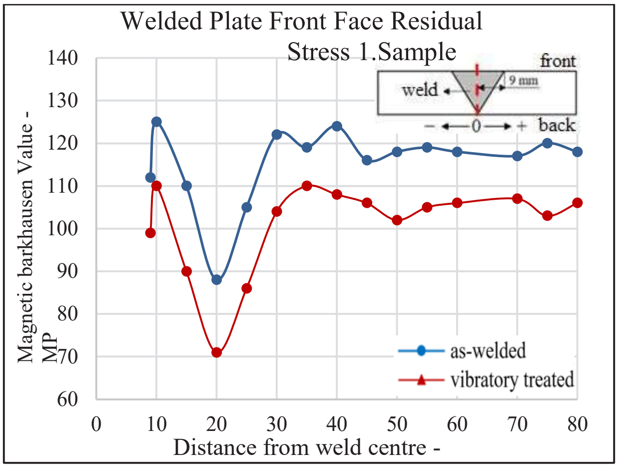

Fig. 12. Welded plate front face residual stress – 1. Sample

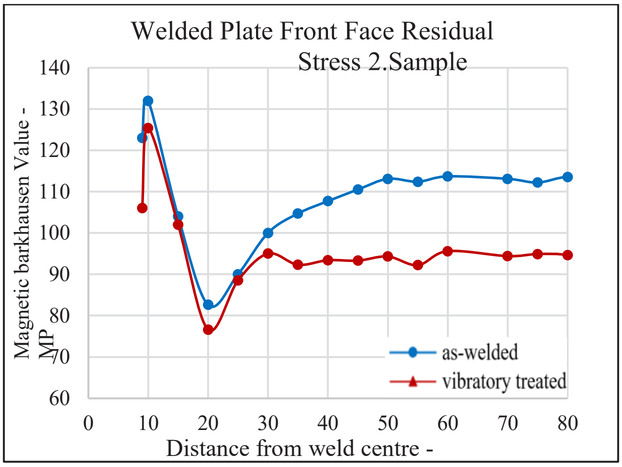

Fig. 13. Welded plate front face residual stress – 2. Sample

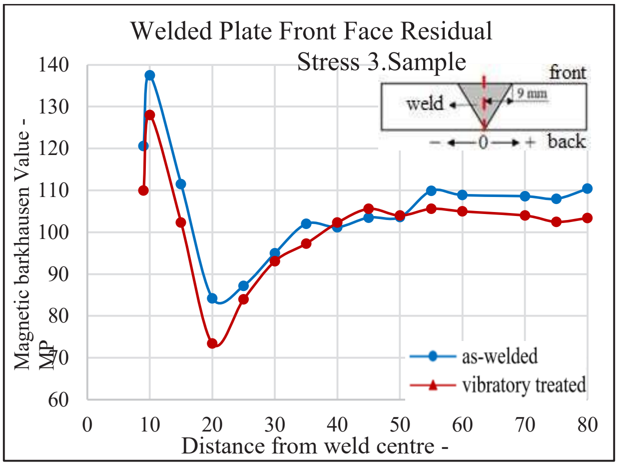

Fig. 14. Welded plate front face residual stress – 3. Sample

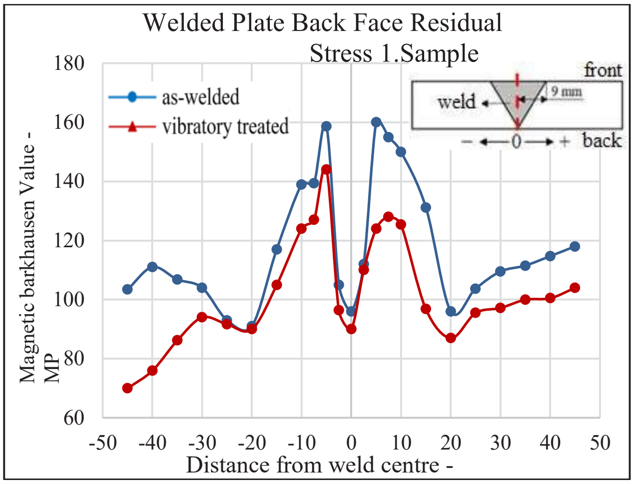

Fig. 15. Welded plate back face residual stress – 1. Sample

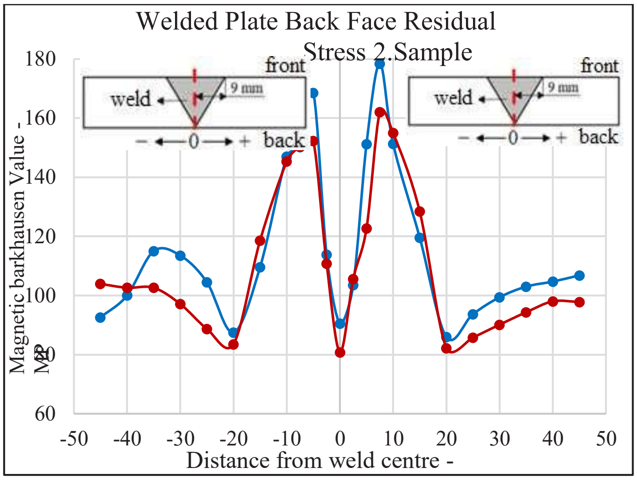

Fig. 16. Welded plate back face residual stress – 2. Sample

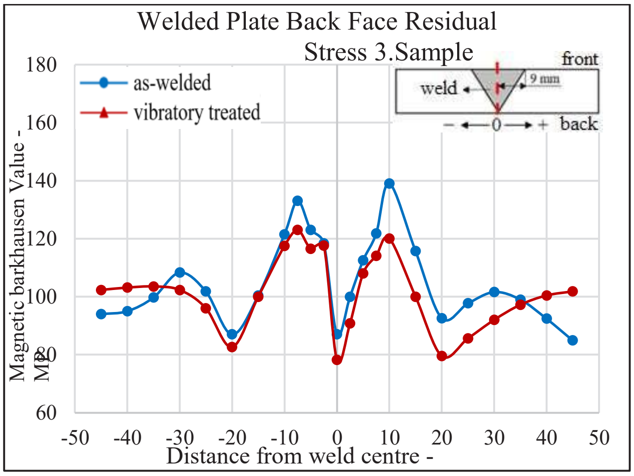

Fig. 17. Welded plate back face residual stress – 3. Sample

3.3 Fatigue Result

After static bending test, yield point was determined and selected four different loads (2.3, 2, 1.6 and 1.25 kN) were applied to the samples for testing the fatigue life. The tests were carried out at 6 Hz and R=0.9 ratio. Before general fatigue test results, the displacement behavior difference was examined under the same load and cycle between vibratory treated after welding and as-welded test samples as can be seen in Figure 17. Under 1.6 kN dynamic load, as-welded part goes from 0.66 mm to 0.7 mm, while vibration treated part only goes from 0.66 mm to 0.67 mm. This result also overlaps with the increase elastic modulus previously obtained from the tensile tests.

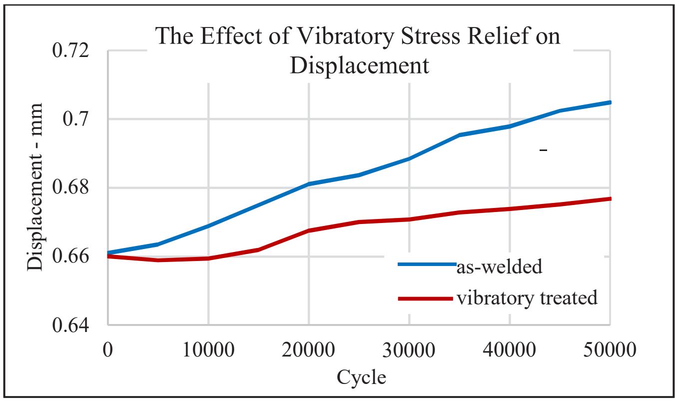

Fig. 17. The effect of vibratory stress relief on displacement

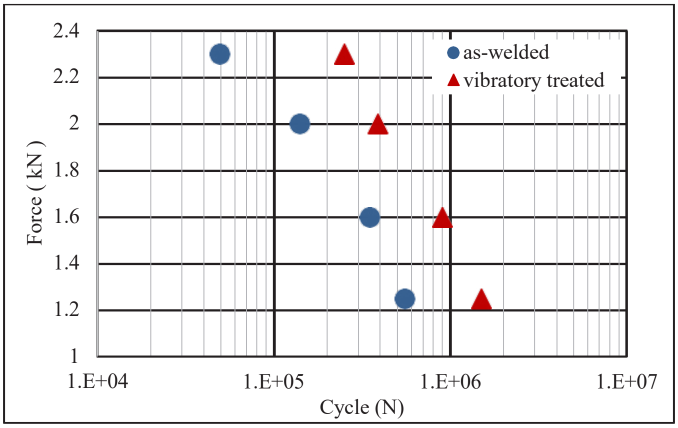

Fig. 18. Fatigue tests results

As-welded and vibratory treated samples' fatigue tests results are shown in Figure 18 and Table 6. Applied loads were 2.3, 2, 1.6, and 1.25 kN respectively. It was observed that the fatigue life increased about three times after vibration stress relieving process. The main reason for the increase in fatigue life of vibratory treated specimens is the tendency to deform less under the same load. The increase in fatigue tests overlaps with the results of previous work with different materials, different thicknesses and different welding types [1, 13].

Table 6 Fatigue test numeric results

Sample No	Force (kN)	Stress weld center (MPa)	As welded (Cycle)	Vibratory treated (Cycle)
1	2.3	330	49 500	250 000
2	2	280	140 000	390 000
3	1.6	225	350 000	900 000
4	1.25	175	550 000	1 500 000

4. CONCLUSIONS

Tensile test results show that yield strength, tensile strength and elasticity modulus of the vibratory stress relieved samples have higher values than the as welded samples. Vibratory treatment after welding enhanced the material's toughness because of the increase in elasticity modulus. Also it was observed that the two parameters have different displacement behavior under the same load. Hardness was found to be higher in the front and the back of the plates, that caused the increase in the strength of welded. Residual stress values were observed less on the front and the back surfaces of plate according to Magnetic Barkhausen noise measurement. After vibratory treatment, the fatigue lives of the test samples increased due to the increasing the elastic modulus and decreasing the residual stress in the weld zone. Thus, the VSR method could be used to increase the fatigue life of the large welded structures which are working under heavy cycling loads to some extent.

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