

Article

Exploring the Efficiency of Post-Welding Vibratory Stress-Relief Treatment Applied on Multi-Pass Butt-Welded Thick Sheet of High-Strength Low-Alloy Steel

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Abstract

Post-welding vibratory stress relief (VSR) has been studied extensively for its capability of decreasing welding residual stresses (RS). This study examines the effectiveness of VSR applied on butt-welded thick sheets of high-strength low-alloy steel. The effect of thermal stress relief (TSR) was examined simultaneously. X-ray diffractometry (XRD), hole drilling method (HDM), and instrumented indentation technique (IIT) were employed for evaluating RS distribution. Global mechanical properties of the weld joint were assessed using tensile tests, bending tests, and Charpy impact tests. Hardness was employed to assess local variation in mechanical properties. The microstructure was observed through light optical microscopy (LOM) and electron back-scatter diffraction (EBSD). It was found that RS redistributed after VSR. The overall decrease in RS could be seen after VSR; however, the scatter in RS increased. TSR, on the other hand, resulted in the decrease in both magnitude and scatter of RS. Peak values of the post-welding RS were evaluated in the range of -200 to 200 MPa; meanwhile, the mean RS was within the range of -100 to 100 MPa. After TSR, RS was mostly within the range of -50 to 50 MPa. After VSR, RS was found to lie mostly within the range of -100 to 200 MPa with peak values being close to the yield strength. VSR had no adverse effect on the structural integrity of the weld joint. No significant differences in the microstructure were seen among as-welded, TSR, and VSR conditions.



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Keywords: structural steel; welding; residual stress; vibratory stress relief

1. Introduction

Welding is one of the most important fabrication processes joining materials together. Diffusion and phase transformations with complicated time history and spatial distribution govern the final weld quality. Higher demands on quality and new materials drive the advance in the weld research. New types of welding procedures are being proposed and the parameters of the current procedures are being refined (see [1]) in order to assure required structural integrity. As a consequence of the welding process, residual stresses were built in the weld joint. Meanwhile, compressive RS may be beneficial; tensile RS has adverse effects on the weld structural integrity. The conventional method for diminishing

post-welding residual stress (RS) is thermal stress relief (TSR). TSR is effective, although hardly applicable to large structures and some materials. Moreover, it leads to substantial microstructural changes, which consequently may weaken weld joints. To overcome these issues, vibratory stress relief (VSR) treatment has been proposed as an alternative. So far, there have been numerous published studies on the efficiency of VSR [2–20], although some of them show contradictory results.

VSR was studied either in the laboratory condition employing small-scale specimens or on bulky structures. Meanwhile, the laboratory tests on small scale specimens were carried out using high-stress amplitudes; the on-site tests on bulky structures used low-stress amplitudes generated by eccentric rotary vibrators. Several theories, which try to explain the VSR process, have been proposed. At first, RS relief occurs when the sum of induced stress and RS exceeds the local material yield stress (YS). This is the so-called standard plasticity model of VSR [21]. It is obvious that, for lower values of applied stresses (5–10% of YS), the standard plasticity model is hardly applicable. Consequently, the reduction of RS during VSR was explained by the cyclic creep in [22,23]. A micromechanical model of VSR based on dislocation motion was further proposed in [21]. A model has been postulated in which dislocation loops pinned by point defects are broken free by cyclic stresses. Afterwards, a revised theory of VSR has been proposed in [24] based upon the concept that the vibration activates mobile dislocations in such a manner that they move into configurations that promote the nucleation of martensite from retained austenite.

Although VSR was mostly reported as successful in RS reduction, some studies reported the opposite effect [25]. There are three main sources of the contradictions: firstly, the material, namely the chemical composition, the thermal history, welding parameters; secondly, VSR parameters, mainly the frequency and stress amplitudes [26–29]; and thirdly, the evaluation of RS. Generally, the measurement of RS is a complex task, especially in heterogeneous materials like weld joints. No single method is capable of measuring RS across all the scales (type I, II, and III stresses) [30]. Various experimental techniques have been applied to evaluate the effectiveness of VSR, frequently reaching different results [31]. Structures with higher RS usually have higher natural frequency, i.e., the decrease in the natural frequency can be used as a criterion of successful stress relief. However, it was found out in [32] that the decrease in the natural frequency did not necessarily mean a reduction in RS. An alternative to the experimental measurement of post-welding RS is the finite element modeling (FEM) [33], which, due to the process complexity, requires many simplifications.

Several studies investigated the effect of VSR on mechanical properties, namely fatigue life, hardness, impact toughness, and tensile properties [10,11,14,34–39]. The studies mostly reported either beneficial or no effect of VSR on the mechanical properties. In [40], the authors employed nanoindentation, measuring hardness and modulus of elasticity, for evaluating VSR efficiency. Correlations between VSR, RS, and fatigue life were studied in [41–44]. The results of the individual papers appear contradictory.

The effect of VSR on the microstructure has also been explored. VSR has been found to affect stored strain energy, dislocation movement, dislocation density, lattice orientation, grain size, and texture [11,13,21,36].

This study examines the effectiveness of post-welding VSR applied using the eccentric rotary vibrator on high-strength low-alloy steel multi-pass butt-weld joints. At the same time, the effect of TSR is also investigated. The residual stress is measured using three experimental techniques, namely the hole drilling method (HDM), X-ray diffraction (XRD), and instrumented indentation technique (IIT). Furthermore, the structural integrity of the weld joint is evaluated by employing bending tests, tensile tests, and Charpy impact tests. Hardness is exploited for the evaluation of the variation in local mechanical properties. The

microstructure is characterized using light optical microscopy and electron back-scatter diffraction (EBSD).

2. Materials and Methods

2.1. Material

The material under study is the high-strength low-alloy S355J2+N steel (Vitkovice Steel, Ostrava, Czech Republic). The chemical composition provided by the manufacturer is given in Table 1. Table 2 summarizes mechanical properties provided by the manufacturer. Sheets with dimensions of $200 \times 300 \times 30 \text{ mm}^3$ (approx. 14 kg) were butt-welded together by 19 passes using robotic MAG (Metal Active Gas—82% Ar + 18% CO₂) with a bevel angle of 25°. Sheets were constrained during welding (tack welded to the welding frame). A G3Si1 electrode with a diameter of 1.2 mm was used for welding. Table 3 shows typical chemical composition of the welding electrode. Inter-pass temperature did not exceed 300 °C. Figure 1 shows the picture of the welded sheet.

Table 1. Chemical composition of S355J2+N steel (in wt. %).

C	Mn	Si	P	S	Cu	Ni	Cr	Mo	V	Ti	Al	N	Nb
0.182	1.5	0.39	0.016	0.004	0.01	0.048	0.031	0.005	0.004	0.003	0.036	0.006	0.005

Table 2. Mechanical properties of S355J2+N steel.

YS (MPa)	UTS (MPa)	ϵ_f (%)	KV2 −20 °C (J)		
367	543	29.1	149	62	169
			158	116	144

Table 3. Typical chemical composition of the welding electrode.

	C	Si	Mn	Fe
G3Si1	0.1	0.9	1.5	bal.



Figure 1. A picture of the welded sheet.

2.2. Methods

2.2.1. Post-Welding Treatment

Vibratory Stress Relief (VSR)

VSR was carried out employing VIBMATIC 8000 (VSR Industrietechnik GmbH, Duisburg, Germany). A welded sheet was clamped to a steel table which was placed on vibration buffers. The rotor producing the vibrations was placed on the table in a distance of about 300 mm from the vibrated sheet so that the rotor axis was oriented in the perpendicular direction to the weld axis (see Figure 2). The eccentric mass was set to 10% imbalance, whereas the maximum force generated by the vibrator is 25 kN. The workpiece was subjected to the resonance frequency in five steps. Ten different working speeds, each for 60 s, were applied in each step. The change in the resonance frequency was evaluated after each step. The frequencies were in the range of 93–73.5 Hz. Overall, the change in the resonance frequency was rather low, characteristic to materials with a relatively small potential for a change, only 14% in the first step and gradually decreasing until becoming stabilized. The maximum value of the amplitude recorded by the accelerometer through the course of VSR was 19 ms^{-2} . The speed ranged between 5600 and 4400 rpm. Although stress amplitudes were not evaluated upon VSR, it is thought that they were minor compared to the material yield strength. VIBMATIC 8000 is intended for bulky structures with a weight over 100 kg. Hence, its efficiency for structures with lower weight needs to be clarified.



Figure 2. A picture of the VSR setting.

Thermal Stress Relief (TSR)

A welded sheet was heated up with a rate of $2 \text{ }^{\circ}\text{C}/\text{min}$ up to a target temperature of $620 \text{ }^{\circ}\text{C}$ followed by 90 min soaking interval and cooled down with a rate of $2 \text{ }^{\circ}\text{C}/\text{min}$.

2.2.2. Residual Stress Measurement

X-Ray Diffraction (XRD)

RS was measured by XRD employing XSTRESS Robot system (Stresstech Group, Rennerod, Germany) and $d\text{-sin}^2\chi$ method. An acceleration voltage of 30 kV and a current of 9 mA were applied during measurements. The distance of the collimator with a spot size of 2 mm from the sample surface was 17 mm. The tilting time was between 5 to 10 s. Eight measurements were conducted for each spot. The tilting angle varied from -45 to 45° , and 0.3 mm thick surface layer was removed with etching before the XRD measurement. The measurement was conducted on the weld face surface in three locations along the direction parallel to the weld longitudinal axis in the weld center, HAZ and BM (see Figure 3).

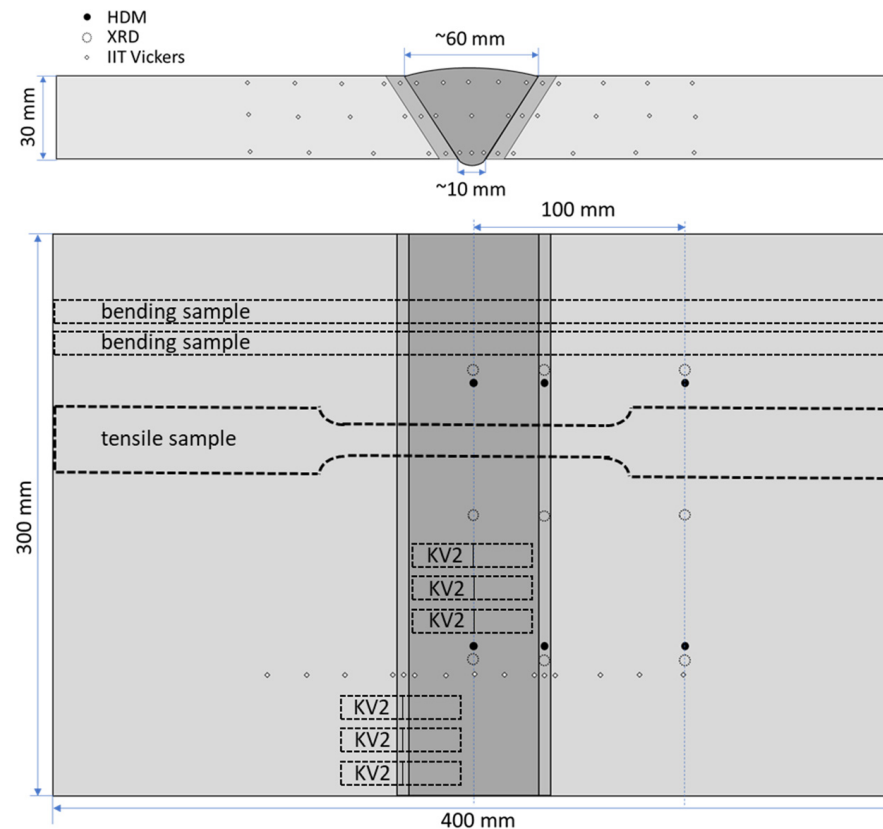


Figure 3. Schematic drawing of experimental measurements on a welded sheet.

Hole Drilling Method (HDM)

RS was measured using HDM on the weld face surface (see Figure 3). MTS3000-RESTAN (residual stress analyzer) system (SINT Technology, Calenzano, Italy) was employed. WC or diamond cutters with a diameter of 1.6 mm were applied. Type A strain rosettes with three grids (HBM) were applied in all measurements and placed in such a way that the rosette axes were oriented parallel with sheet edges. The strain gage diameter of the rosette was 5.10 mm. The drilling was carried out with a step of 0.05 mm until a depth of 2 mm was achieved. RS was evaluated until the depth of 1 mm using the integral method by applying calibration constants evaluated using FEM by SINT Technology. RS was measured in the weld center, HAZ and BM (100 mm far from the weld centerline), in two different positions along the weld axis, according to the illustration in Figure 3.

Instrumented Indentation Technique (IIT)

RS was measured with IIT employing AIS3000HD (Frontics, Seoul, Republic of Korea) using Vickers indenter. The applied methodology is described in detail in ISO-TS-19096 [45]. It is based on the comparison of load-displacement curves in the stressed and reference states of the same material. The following equation is exploited to yield σ_{res} :

$$\sigma_{res} = \frac{3}{2} \frac{L_{ref} - L_{stress}}{A_{stress}} \quad (1)$$

where L_{stress} and L_{ref} are the maximum loads (both in N) in the reference and stressed state, respectively, and A_{stress} is the contact surface in the stressed state at the maximum load (in mm^2) so that the positive σ_{res} means tensile stress and the negative σ_{res} means compressive stress. The factor 3/2 relates to the equi-biaxial stress state and stems from the fact that the shear deviatoric stress along the indentation direction is directly related to the indentation stress change (see [46]). IIT was performed on the weld face surface as well as on the

cross section (see Figure 3). Sheets were cut to a width of approximately 40 mm before IIT measurement. The measured surface was ground with abrasive papers up to a grit of at least 800. The indentations were carried out till the maximum load of 50 kgf, which corresponded to depths of approximately 100 μm .

2.2.3. Mechanical Properties

Tensile Tests

Tensile tests were performed according to ISO-4136 [47] at 20 °C. The specimen axis was oriented parallel to the weld transverse direction so that the weld centerline was positioned in the middle of the tensile specimen (see Figure 3). A rectangular sample with a width of 30 mm and a thickness of 25 mm was tested per a sheet.

Bending Tests

Bending tests were performed according to ISO-5173 [48] at 20 °C till 180° with a pin diameter of 40 mm. The specimen axis was oriented parallel to the weld transverse direction so that the weld centerline was positioned in the middle of the bending specimen (see Figure 3). Specimen dimensions were 400 × 30 × 10 mm³. Two samples per sheet were tested.

Impact Tests

Charpy impact tests were carried out at −20 °C, according to ISO-9016 [49], employing V-notched specimens with dimensions of 55 × 10 × 10 mm³. Specimen longitudinal direction was oriented parallel to the weld transverse direction so that the notch was placed either in the weld center or in HAZ (see Figure 3). Three specimens per each location were tested.

2.2.4. Microstructure

Metallography

The microstructure on the weld face surface was observed under light optical microscopy (LOM). Specimens were put into epoxy, ground, polished, and etched with 2% nitric acid before the observation.

EBSD

EBSD analysis was carried out on the weld face surface in a scanning electron microscope JEOL IT500HR (Jeol, Tokyo, Japan) equipped with EDAX Velocity camera and EDAX OIMTM Analysis (EDAX, New Jersey, USA) using spherical indexing. Before the analysis, the samples were electro-polished in 5% perchloric acid solution in ethanol at 40 V. Acceleration voltage of 30 kV was used, and samples were inspected at the angle of 70°. The step size was 0.5 μm in the case of 240 × 180 μm^2 overall scan and 0.1 μm in the case of 24 × 18 μm^2 detailed scan.

2.2.5. Hardness

Vickers hardness was measured on specimen cross sections in two parallel lines at the weld face and root, according to ISO-9015-1 [50]; altogether, there were 19 points per line. The applied load was 10 kgf.

3. Results

3.1. Microstructural Examination

Macroscopic examination of the etched cross sections showed no significant differences among the as-welded, heat-treated, and vibration-treated specimens. All joints were found

defect-free. Figure 4 illustrates the microstructure of the etched cross sections. The microstructure of the base metal (BM) consisted of layered ferrite (the light phase) and pearlite (the dark phase), which is characteristic for cold-rolled sheets. HAZ showed the coarse grain martensitic area at the fusion line, with the characteristic needle-like martensitic laths. The region of the weld metal (WM) consists preferentially of the bainite (the darker phase) lined by Widmannstätten ferrite (the lighter phase). No significant differences can be seen in the microstructure among as-welded, TSR, and VSR conditions.

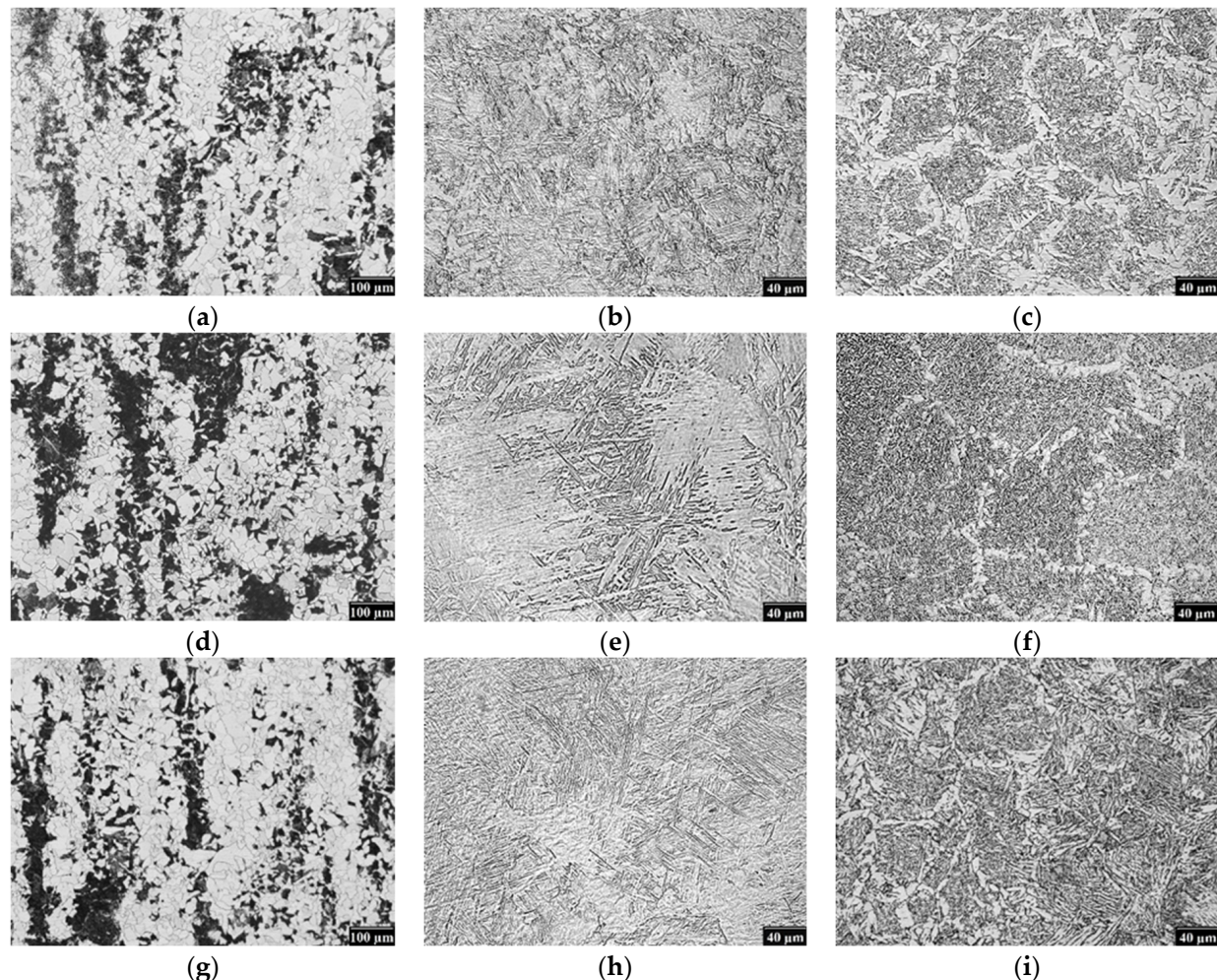


Figure 4. Light optical micrographs of tested specimens: (a) As-welded–BM. (b) As-welded–HAZ. (c) As-welded–WM. (d) Heat-treated–BM. (e) Heat-treated–HAZ. (f) Heat-treated–WM. (g) Vibrated–BM. (h) Vibrated–HAZ. (i) Vibrated–WM.

3.2. EBSD Results

EBSD measurements were performed in the area encompassing the fusion line, where the most significant differences in structure or dislocation density could be expected. The results, in the form of correlation index (CI), a measure of how well an acquired Kikuchi diffraction pattern matches a simulated pattern for a given crystal orientation, useful for reliable grain boundary detection; inverse pole figure (IPF), showing crystallographic directions aligned with normal sample direction; and kernel average misorientation (KAM), the average misorientation angle between a measurement point and its neighboring points, which can be converted to the density of geometrically necessary dislocations using Nye's dislocation theory, are presented in Figure 5.

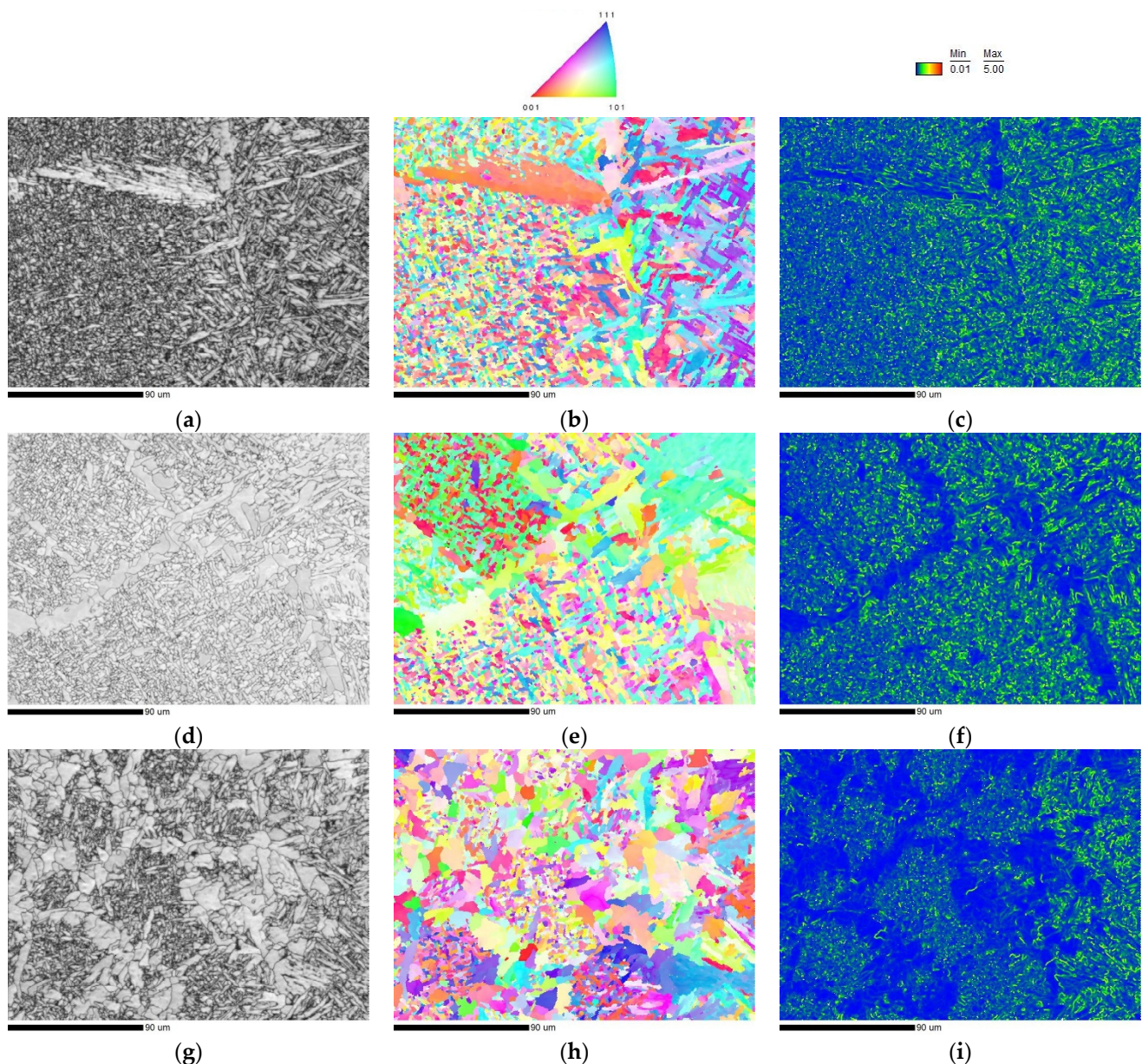


Figure 5. EBSD results in the fusion line region: (a) As-welded–CI. (b) As-welded–IPF. (c) As-welded–KAM. (d) Heat-treated–CI. (e) Heat-treated–IPF. (f) Heat-treated–KAM. (g) Vibrated–CI. (h) Vibrated–IPF. (i) Vibrated–KAM. CI—correlation index of acquired and matching patterns, IPF—inverse pole figure, KAM—kernel average misorientation.

The results were in agreement with light microscopy observation confirming the ferritic-bainitic microstructure in the WM and coarse-grained martensite in the HAZ. Highest geometrically necessary dislocation density was observed in martensite, followed by bainite; ferritic grains were relatively “clean” of geometrically necessary dislocations. No substantial differences in structure or geometrically necessary dislocations density were observed comparing the as-welded, heat treated, and vibrated state. To note that the detection limit of the EBSD setup for geometrically necessary dislocation density can be estimated to be greater than 10^{-12} m^{-2} , the measured geometrically necessary dislocation density within the grains did not exceed 10^{-14} m^{-2} .

3.3. Results of RS

RS was preferentially evaluated on the sheet-face weld surface. With increasing number of passes in multi-pass welding, the peak tensile RS gradually reduced at the root side and gradually increased at the face-weld side [51]. That is why higher values of RS as well as more significant changes in RS after TSR and VSR can be expected there.

3.3.1. XRD Results

Table 4 summarizes RS values averaged over the individual regions along with the standard deviations. The results are plotted in Figure 6 as a function of the distance from the weld axis. The datapoints show the individual mean values (averaged over a measured location) coming from different locations on the sheet surface. The plotted lines correspond to standard deviations reflecting the variation at the measured location and along the weld centerline. Longitudinal RS has a similar trend in the transverse direction like the transverse RS after welding. The highest RS is in HAZ, followed by the region of WM. The lowest RS was evaluated in BM. The transverse RS is mostly compressive. The longitudinal RS, on the other hand, is mostly tensile. The compressive RS was measured only in BM. A sheet after TSR shows more even RS distribution with slightly tensile RS, 0–50 MPa. A sheet after VSR shows different distribution of RS compared to the as-welded sheet. The longitudinal RS is lower in HAZ but higher in WM. The transverse RS is substantially higher in all regions of the weld joint.

Table 4. Mean values of RS evaluated by XRD.

		RS Longitudinal (MPa)	RS Transverse (MPa)
BM	as-welded	-30 ± 31	-74 ± 28
	TSR	4 ± 24	13 ± 16
	VSR	-23 ± 15	-9 ± 17
HAZ	as-welded	70 ± 8	-3 ± 12
	TSR	6 ± 17	49 ± 12
	VSR	1 ± 5	152 ± 14
WM	as-welded	42 ± 24	-51 ± 31
	TSR	27 ± 11	35 ± 10
	VSR	93 ± 22	184 ± 13

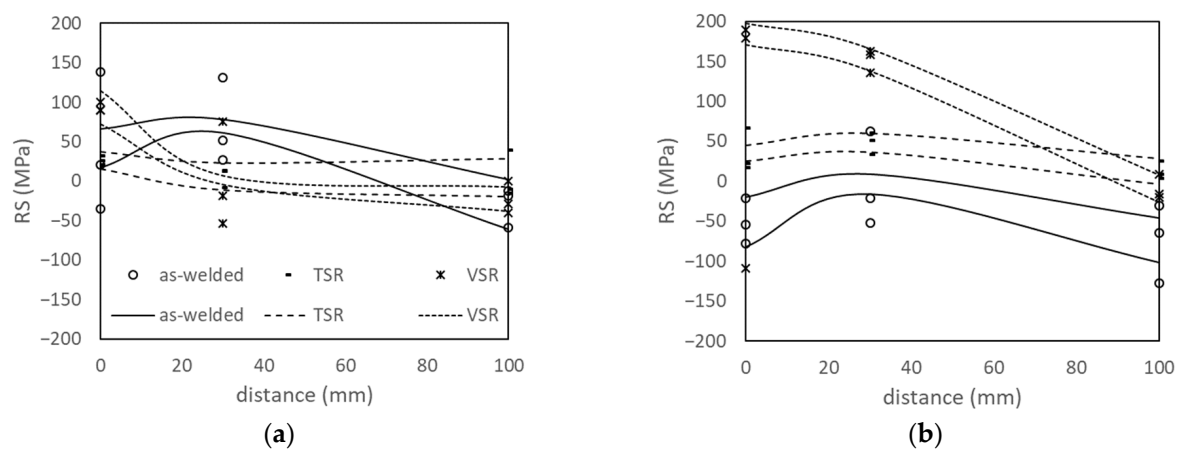


Figure 6. Results of XRD as functions on the distance from the weld axis: (a) Longitudinal RS. (b) Transverse RS.

3.3.2. HDM Results

Figure 7 depicts the depth profiles of RS evaluated by HDM. The stress components oriented in the weld longitudinal and transverse directions are plotted in the graphs as well as the shear RS. The results of the shear RS oscillate around the zero value. This suggests that the weld longitudinal and transverse directions correspond to the directions of principal stresses. The shear stress appears slightly higher on a sheet after VSR, mainly in HAZ, compared to as-welded and TSR conditions. Some values, especially close to the surface layer, are much larger compared to the rest depth profiles. These outliers are believed to be an error of the measurement or a consequence of the surface preparation before HDM measurements and are not considered in the following analysis. The increased variation in RS in the regions of WM and HAZ after VSR along the depth is clearly seen. Meanwhile, TSR resulted in more equalized RS profiles in WM and HAZ.

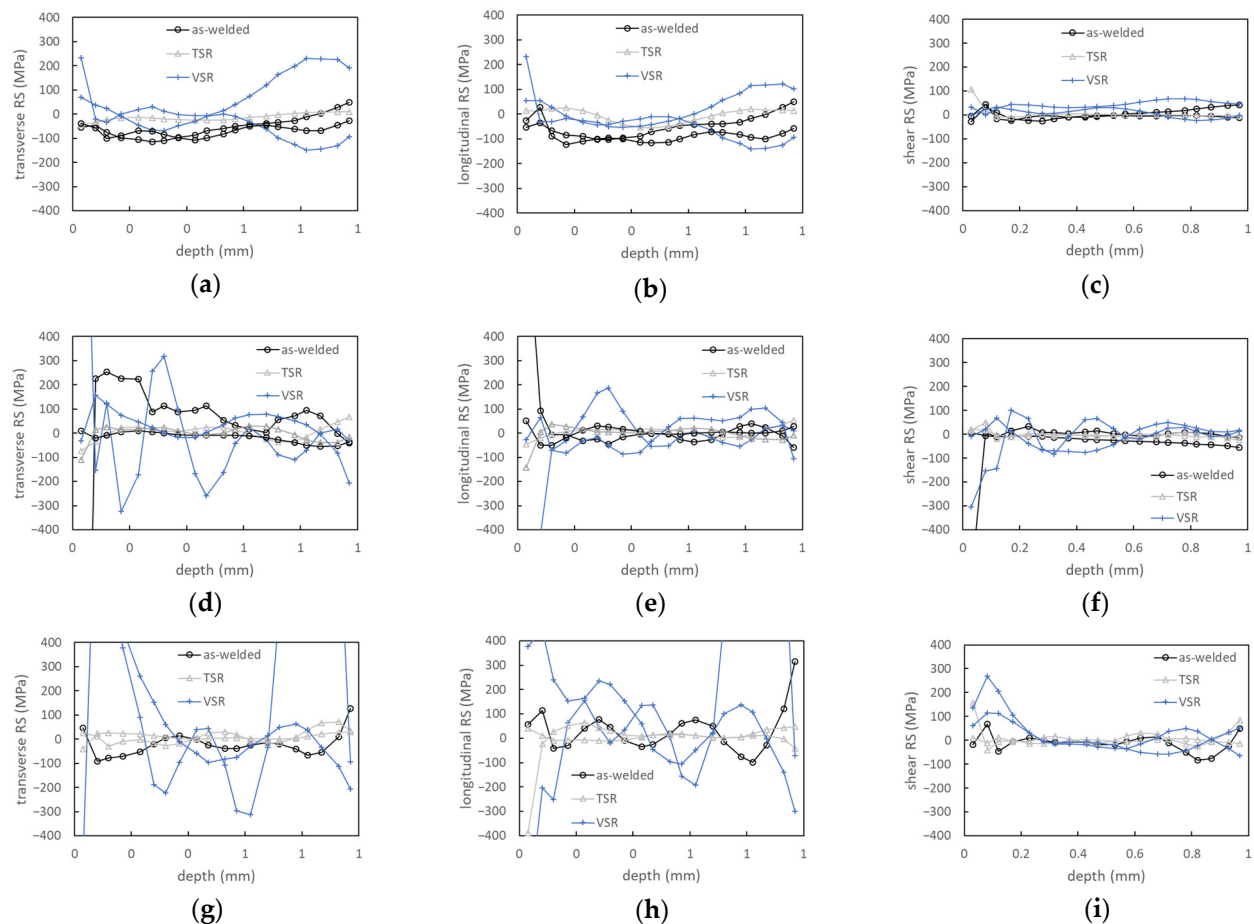


Figure 7. Depth profiles of RS evaluated by HDM: (a) Transverse RS in BM. (b) Longitudinal RS in BM. (c) Shear RS in BM. (d) Transverse RS in HAZ. (e) Longitudinal RS in HAZ. (f) Shear RS in HAZ. (g) Transverse RS in WM. (h) Longitudinal RS in WM. (i) Shear RS in WM.

The results of HDM, averaged over the depth profile and along the weld axis, are summarized along with standard deviations in Table 5. The averaged values of RS appear lower than the values evaluated by XRD, but the scatter is much higher. It is a consequence of the strong variation of RS along the sheet thickness direction. Figure 8 plots RS averaged over the depth profile as a function of the distance from the weld centerline. The datapoints show individual mean values coming from different locations on the sheet surface. The plotted lines correspond to standard deviations reflecting the variation across the depth as well as along the weld axis. Compressive RS was assessed in the region of BM. RS appears

less compressive on sheets after TSR as well as after VSR. Transverse RS appears slightly tensile after VSR. Mean values of RS in HAZ are very close to zero, irrespective of the post-welding treatment. Longitudinal RS in WM is tensile for all sheets, though TSR shows much lower RS. In the contrast, transverse RS in WM is compressive after the welding and becomes slightly tensile after TSR. The sheet after VSR, on the other hand, has the transverse RS in WM more compressive. RS is much more scattered after VSR, especially in the regions of HAZ and WM. The scatter is lowest for the TSR sheet. The scatter is higher in the regions of HAZ and WM compared to BM in the as-welded state and after VSR. The tendency in RS after welding is similar to the tendency evaluated by XRD, although higher longitudinal RS was measured in WM compared to HAZ. TSR shows even distribution of RS. No tendency in RS is clearly seen after VSR due to the substantial scatter.

Table 5. Mean values of RS evaluated by HDM.

		RS Longitudinal (MPa)	RS Transverse (MPa)
BM	as-welded	-72 ± 33	-62 ± 37
	TSR	-8 ± 29	-11 ± 13
	VSR	-20 ± 59	11 ± 78
HAZ	as-welded	-4 ± 22	34 ± 58
	TSR	7 ± 17	6 ± 25
	VSR	6 ± 72	-8 ± 127
WM	as-welded	60 ± 87	-13 ± 50
	TSR	13 ± 17	10 ± 23
	VSR	37 ± 116	-55 ± 114

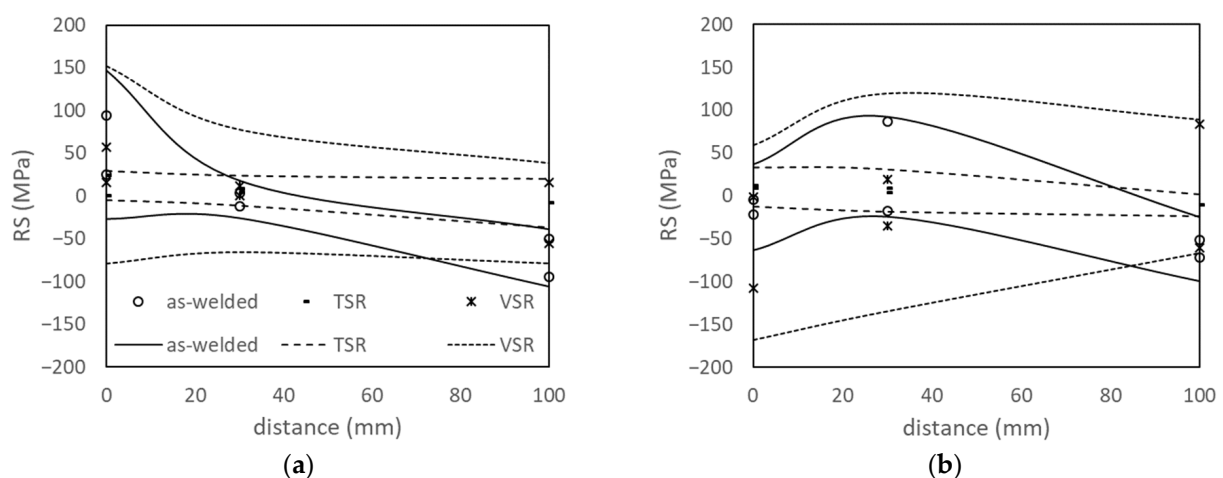


Figure 8. Results of HDM: (a) Longitudinal RS. (b) Transverse RS.

3.3.3. IIT Results

IIT was carried out after cutting the welded sheet in the weld transverse direction into a slice with a width of 40 mm. RS is expected to partially relax after the cutting, especially in the longitudinal direction, as was reported in [52]. The relaxation of transverse RS was, on the other hand, negligible after cutting in the direction perpendicular to the weld axis in [53]. IIT setting employed in this study requires stress-free reference material to assess RS. Since only the change in RS is necessary for evaluating VSR effectiveness, the as-welded state was chosen as a reference and the difference between VSR and as-welded states was evaluated as a function of the distance from the weld axis on the sheet weld face surface, on the cross-section at the weld face, in the mid-thickness, and at the weld root (see the schematic drawing in Figure 3). The microstructural examination as well as the results of

mechanical testing (see below) showed no significant differences between the as-welded and VSR states, which justifies the employed IIT procedure. The results of IIT are plotted in Figure 9 as a function of the distance from the weld centerline.

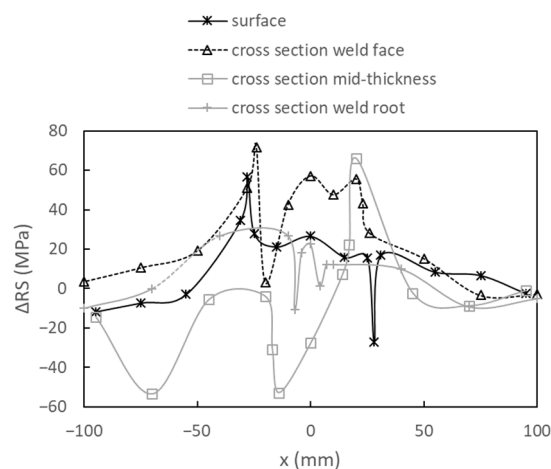


Figure 9. Change in RS after VSR evaluated by IIT in dependence on the distance from the weld axis.

The change in RS is mostly positive in the regions of WM and HAZ. It suggests that RS increased after VSR in WM and HAZ regions. On the other hand, the change in RS in BM is almost zero, although it appears as increasing slightly when approaching the weld. The highest number of negative changes in RS, which are also highest in magnitude, is seen in the mid-thickness on the cross section. Their distribution is quite uneven. This procedure could not be applied on the sheet after TSR because TSR changed mechanical properties, as will be shown below. The assumption of the same mechanical properties between the reference and stressed state is essential for the evaluation of RS by IIT.

3.4. Results of Mechanical Properties

3.4.1. Global Mechanical Properties

Bending, tensile, and Charpy impact tests were conducted in order to assess VSR effect on the weld structural integrity. All bending tests were evaluated as defect-free. The results of tensile and impact tests are presented in Table 6. The tensile strength as well as the impact energy in WM appear lower in the sheet after TSR. Contrary, the impact energy in HAZ is higher after TSR. However, the results of tensile tests need to be treated with caution since they were acquired by only one specimen per sheet. The sample after TSR fractured within the weld region after the tensile test. The absorbed energy during the impact test, KV2, is much higher in WM than in HAZ for all conditions.

Table 6. Results of mechanical testing.

Tensile Tests			Charpy Impact Tests			
Sample	Fracture Location	UTS (MPa)	WM		HAZ	
			KV2 (J)	stdv	KV2 (J)	stdv
as-welded	BM	585	164	5	70	28
TSR	weld	553	152	16	101	7
VSR	BM	588	164	14	60	16

3.4.2. Local Mechanical Properties

Table 7 summarizes mean values and standard deviations of the hardness values measured in the individual regions of weld joints. Results of hardness measurements are plotted in Figure 10 as a function of the distance from the weld centerline. It is clearly seen that hardness is substantially lower after TSR compared to the as-welded and VSR conditions. The highest difference between as-welded and TSR sheets is in HAZ, approximately 20%, followed by WM and BM, approximately 15%. VSR sheet shows only slightly lower hardness compared to the as-welded condition. The difference is approximately 3–4% in all regions, which is well within the experimental scatter.

Table 7. Mean values of HV10.

	As-Welded	TSR	VSR
BM	186 ± 10	159 ± 4	181 ± 10
HAZ	237 ± 33	188 ± 14	228 ± 32
WM	200 ± 6	170 ± 8	191 ± 13

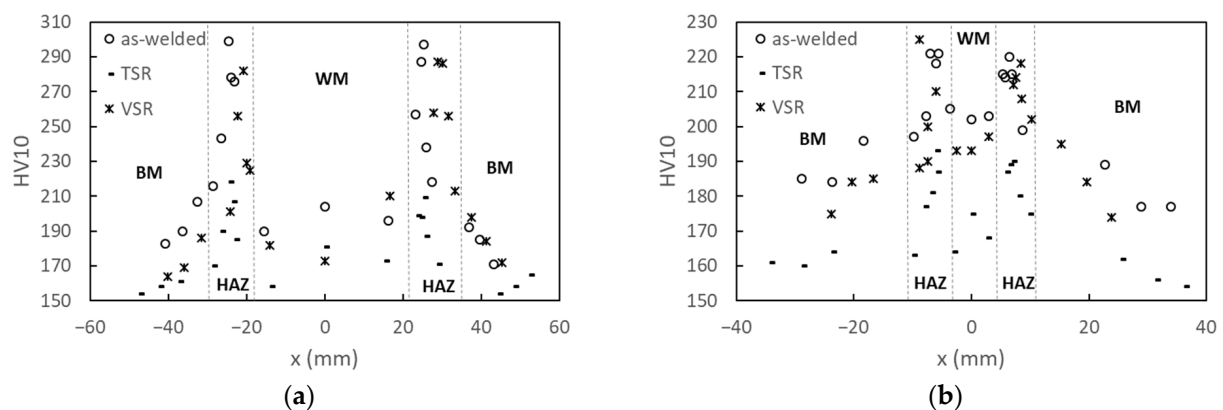


Figure 10. Results of HV10 on the cross section: (a) At the weld face. (b) At the weld root.

4. Discussion

4.1. Comparison of RS Results

The substantial scatter in the results of RS appears as a consequence of the strong spatial variation in RS, especially along the thickness direction. Figure 11 compares RS measured by HDM and XRD. The results of both methods are in satisfactory agreement. Only RS in the transverse direction in WM and HAZ after VSR shows substantial deviation. This is attributed to the increased scatter of HDM results seen after VSR in the transverse direction (see Figure 8). Figure 7 shows that VSR treatment led to increased variation along the depth in transverse RS. The variation has a period of an order of tens or hundreds of microns. XRD analysis comes from thin surface layer, several tens of microns thick. Also, the scatter of XRD results is minor compared to HDM results. That is why the transverse RS after VSR evaluated by XRD and HDM vary from each other substantially. Additionally, HDM is not sensitive to RS types II and III. That is why the variation in RS along the plate thickness corresponds to the macroscopic RS resulting from the welding. XRD, on the other hand, is capable of recording a nonzero volume averaged phase micro-stress or grain stress [54].

HDM equations used for the calculation of RS were derived for homogeneous stress distribution across the measured spot. Steep gradients in RS could deteriorate the accuracy of HDM. Furthermore, if RS approaches YS, then the results of HDM are rather qualitative

and usually overestimate real values of RS. This explains the values of RS exceeding material YS measured by HDM (see Figure 7). Those values were not considered in the analysis.

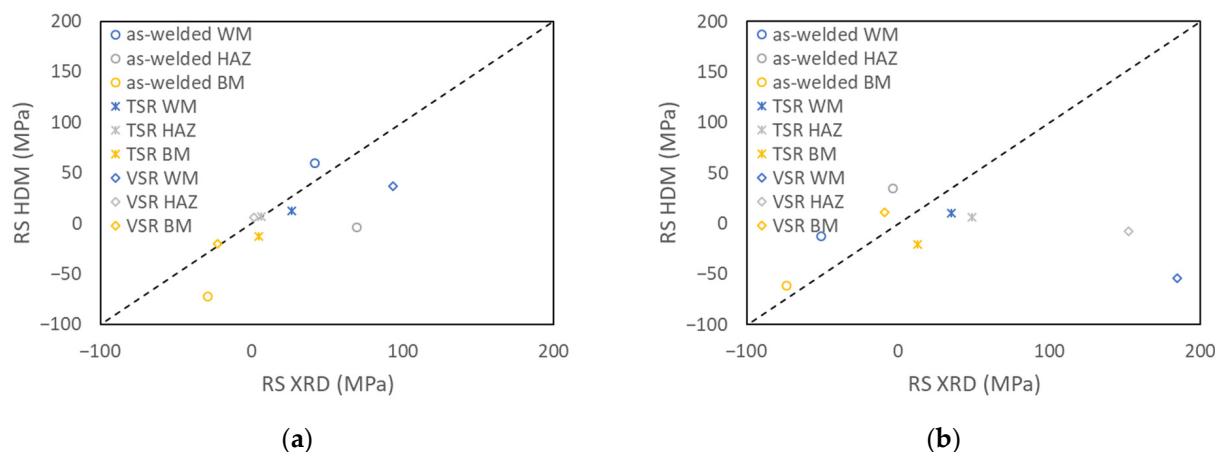


Figure 11. The comparison of RS evaluated by XRD and HDM: (a) In the longitudinal direction. (b) In the transverse direction.

Only the change in RS after VSR was evaluated with IIT. IIT results suggest that RS rather increased after VSR. Hence, IIT results better agree with XRD results. The values of RS evaluated using XRD are comparable to the change in RS after VSR evaluated by IIT, although XRD showed larger differences in the transverse RS between the as-welded and VSR states in HAZ and WM. The depth analyzed with IIT extends as far as 100 microns (corresponding to a maximum load of 50 kgf). Thus, more averaged data across the thickness direction and a higher variation in RS can be expected in the case of IIT compared to XRD. IIT, like HDM, is not sensitive to RS types II and III.

Although IIT employed in the present study was derived based on the equi-biaxial stress state, it was shown that this setting works well also for the non-equi-biaxial stress state (see [46]). However, it was reported in [46] that this setting is incapable of detecting pure shear stress because RS evaluated by Vickers IIT corresponds to the average of normal stresses in the plane perpendicular to the indentation axis. HDM analysis showed that the weld longitudinal and transverse directions corresponded to the directions of principal stresses with zero shear stress. However, the shear stress increased after VSR, mainly in HAZ. Additionally, Vickers indents were oriented randomly in this study so that the Vickers tip diagonals were not perfectly aligned with the weld longitudinal and transverse directions. This could deteriorate the accuracy of IIT.

4.2. Effect of VSR

XRD and IIT results suggest that RS rather increased after VSR. HDM results, on the other hand, suggest that RS decreased after VSR, but the scatter in RS increased. The increased variation in RS across the thickness direction after VSR has, undoubtedly, a substantial effect on XRD results since XRD extends only over several tens of micrometers in depth. IIT, when carried out on the sheet weld face surface, is supposed to measure an average of the longitudinal and transverse RS. When carried out on the weld joint cross section, IIT results are supposed to be related to the mean RS of the transverse and sheet thickness directions. The longitudinal RS is not supposed to influence IIT results on the cross section. Hence, the results of IIT acquired on the cross section indicate that RS in the sheet thickness direction increased after VSR. However, the volume examined by IIT is also much lower compared to HDM, and it needs to be emphasized that IIT was carried out

after the sheet segmentation in the weld transverse direction so that it is anticipated that longitudinal RS is partially redistributed after the cutting.

A slightly lower hardness, by up to 5%, which is still comparable with the experimental scatter, was evaluated on the sheet after VSR in all regions of the weld joint. It could be a consequence of material variability rather than the effect of VSR. Hardness has been used as a measure of RS change in several studies. Generally, tensile RS leads to lower values of hardness. Compressive RS, on the other hand, increases the hardness. Studies [55,56] showed that RS changed hardness by up to 10%. On the other hand, Tsui et al. [55] showed that the hardness is rather invariant of RS and that the observed change in the hardness with varying RS is a consequence of the variation of material pile-up and sink-in around the indentation imprint with varying RS.

It was reported in [34] that VSR successfully suppressed RS of S355J2 steel sheet of a thickness of 10 mm. Meanwhile, mechanical properties, such as UTS and Brinell hardness, slightly increased after VSR. Hot rolled S355J2 30 mm thick steel sheets welded by MAG using ESAB OK Autrod 12.51 welding wire (similar to the one used in the present study) and CO₂ shielding gas were subjected to VSR and RS were successfully reduced by about 40% in [14]. No effect of VSR on mechanical properties was seen in that study. Similar experimental setting of VSR was applied in both studies as well as in this study, although the parameters of VSR differed. All studies exploited an auxiliary table to which the welded sheets and the force inducers were firmly attached. The resonant frequency (90 Hz) was applied in the study [34] for the total operating time of 30 min. The resonant frequency (79.6–84.3 Hz) was applied in the study [13] for the total operating time of 25 min employing 35% of imbalance (of 350 kg). Peak RS decreased from more than 300 MPa to less than 200 MPa in the weld center after VSR. An imbalance of 10% (of 25 kN) was applied in the present study. No significant change in RS was observed further from the weld centerline, where RS ranged between −150 and 0 MPa. Generally, VSR efficiency is related to the magnitude of initial RS. Higher initial RS results in more efficient VSR [11,35]. The magnitude of initial RS is much lower in this study, less than 150 MPa, compared to the welding RS reported in [14], i.e., 335 MPa in the weld center. It is even lower than the RS reported in [14] after VSR. This can explain the lower efficiency of VSR reported in this study.

Several studies [11,37,45] reported significant microstructural changes after VSR applied on small laboratory base metal specimens. This study attempted to examine the VSR effect on the microstructure at the fusion line of welded thick plates. However, the microstructural analysis realized by LOM and EBSD did not reveal significant differences between the as-welded and post-welding VSR conditions in terms of increased geometrically necessary dislocation density or sub-grain formation. The reason is that the changes in RS are only moderate, and the examined microstructure is fairly heterogeneous.

5. Conclusions

The efficiency of VSR on multi-pass butt-welded high-strength low-alloy steel sheets was examined. Three experimental techniques, namely HDM, XRD and IIT, were applied for RS measurements. The structural integrity of welded joints was also investigated. The changes in the microstructure were monitored employing LOM and EBSD. The following conclusions have been drawn based on the obtained results:

- The welding resulted in highly heterogeneous distribution of RS across the weld joint, especially in the regions of WM and HAZ, although the magnitude of RS was rather low, less than 150 MPa.
- In most cases, satisfactory agreement was achieved among RS evaluated by IIT, XRD and HDM.

- As the magnitude of the post-welding RS was relatively low, VSR had only moderate effect on RS, while TSR resulted in non-negligible decrease in RS.
- VSR had no adverse effect on the structural integrity of the weld joint assessed by tensile, bend, and Charpy impact tests. However, the redistribution in RS might affect other mechanical properties that are more prone to local RS variation such as fracture toughness and fatigue endurance. This needs to be further clarified.

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Abbreviations

The following abbreviations are used in this manuscript:

VSR	Vibratory stress relief
RS	Residual stress
TSR	Thermal stress relief
XRD	X-ray diffractometry
HDM	Hole drilling method
IIT	Instrumented indentation technique
LOM	Light optical microscopy
EBSD	Electron back-scatter diffraction
BM	Base metal
HAZ	Heat affected zone
WM	Weld metal
CI	Correlation index
IPF	Inverse pole figure
KAM	Kernel average misorientation

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