Mateusz Przybyła, Jacek Górka

The Effect of High-Frequency Peening on Properties of MAG-Welded Joints Made of Steel S960QL

Abstract: The study discussed in the article aimed to analyse the effect of the peening of each bead on properties of butt joints made of steel S960QL and welded using the robotic MAG welding method (135) and a ceramic backing strip. In addition, the objective of the study was to identify the effect of the peening treatment on the level of stresses. The analysis involved the comparison of three butt joints in the post-weld state (i.e. only after welding), subjected to peening (preceded by welding) and to post-weld heat treatment (stress relief annealing). The purpose of the high-frequency peening (90 Hz) of each bead was to reduce stresses in the welded joint by introducing tensile stresses into the latter. The study-related tests involved the use of a Weld Line 10 air hammer (PITEC GmBH). The tests required by the EN ISO 15614-1 standard were supplemented with measurements of stresses involving the use of the Barkhausen effect (based on a testing procedure proposed by the technology provider, i.e. the NNT company). The tests revealed that the performance of high-frequency peening following the making of each bead did not lead to the obtainment of negative results of all the tests required during welding procedure qualification concerning the plate made of steel S960QL (in comparison with test plates after welding and stress relief annealing). The interpass peening of the weld face and that of the HAZ reduced post-weld residual stresses at a distance of 15 mm away from the joint axis (in comparison with stresses measured in the specimens after welding). The test results justified the positive assessment of peening in respect of tensile stress reduction in the fusion line area and in the HAZ.

Keywords: Peening, Butt joints, Steel S960QL, Welding method, MAG-welded joints

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Introduction

Welding techniques have dominated methods used for the fabrication of metal structures. However, welding processes entail numerous technological challenges for welding engineers. Some of many issues connected with welding include the formation of stresses and strains generated during the process. The above-named problems, strictly connected and typical of welding processes, include phase transformations related to changes of volume, non-uniform as well as fast heating and cooling, changes of such properties as Young's modulus *E*, yield point R_e or the coefficient of thermal expansion during heating and cooling. The most common method applied to reduce post-weld stresses and strains is stress relief annealing (heat treatment). The performance of the aforesaid treatment requires the use of an electric or gas furnace. In cases of local treatment it is possible to apply induction or resistance equipment. One of the alternatives to classical post-weld heat treatment methods is peening. The above-named technique involves interpass peening or the treatment of the weld face only (of either butt or fillet welds), aimed to introduce compressive stresses through plastic strains. One of the advantages of the method is the possibility of performing both the local (e.g. in case of repairs|) or global (e.g. when 100% of welded joints are subjected to peening) effective post-weld

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treatment [1–5]. Peening can be performed using several different systems including conventional methods, such as peening, involving the use of electric or pneumatic machines for the impact treatment of welds. Relatively new methods enabling the reduction of stresses through peening include ultrasonic peening treatment (UPT), high frequency impact treatment (HiFIT), ultrasonic peening (UP), pneumatic impact treatment (PIT) and ultrasonic needle peening (UNP). Each of the above-named methods was developed primarily to increase the efficiency of impact effect and treatment precision. In addition, the above-named methods increase work comfort by reducing vibration affecting the operator and enabling them to work longer than in cases of classical equipment used for the impact treatment of welds [6–10]. Because of the fact that European standards do not contain information whether the application of high-frequency mechanical impact treatment (HFMI) is a significant variable in terms of the welding process, it is not necessary (in accordance with the aforesaid standards) to perform such tests. However, in relation to the HFMI treatment as additional treatment accompanying and following the welding process (for the purpose of this work), the authors performed tests concerning key issues during arc welding procedure qualification in relation to metallic materials and the satisfaction of requirements specified in the PN-EN ISO 15614-1 standard (including the effect of peening on test results) [11].

Individual study

The study aimed to analyse the effect of peening of each bead on properties of a MAG welded joint (135) made using a robotic welding station and a ceramic backing strip. Another purpose of the study included the identification of the effect of the peening process on the level of stresses. The comparison with a specimen subjected to interpass peening involved the use of stress relief annealing (heat treatment). The analysis involved three welded joints made of steel S960QL (Table 1) in the post-weld state, after the peening of each bead and after stress relief annealing. The filler metal used in the tests was filler metal wire ED-FK 1000 having a diameter Ø1.2 mm (Fliess) (Table 2).

Welded joints

The tests involved the use of three test plates made of steel S960QL (10 mm × 150 mm × 600 mm). The weld groove (bevelled) between two test plates was V-shaped. The plates along with the backing strip were mounted on the robotic station table (CLOOS); the backing strip being placed on the axis of the target welded joint (Fig. 1, 2).

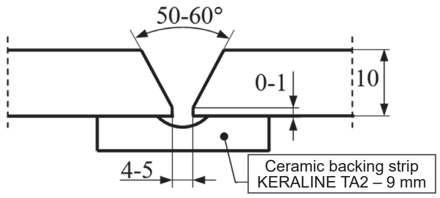


Fig. 1. Pre-weld joint preparation

Fig. 2. Test plate with the ceramic backing strip on the welding robot table

Table 1. Chemical composition of the base material subjected to welding (plate) according to the material certificate (3.1)

	Chemical composition [% by weight]						
S960QL	C	Mn	Si	P	S	Cr	Mo
	0.12	1.42	0.47	0.008	0.003	0.59	0.56
	Ni	V	Cu	Al	Ti	Nb	As
	0.79	0.05	0.11	0.007	0.005	0.02	0.002

Table 2. Chemical composition of filler metal wire ED-FK 1000 according to the material certificate (3.1)

	Chemical composition [%]					
ED-FK 1000 Ø1.2 mm	C	Mn	Si	P	S	Cr
	0.11	1.75	0.81	0.007	0.009	0.36
	Ni	V	Cu	Al	Mo	Ti+Zr
	2.24	0.002	0.009	0.005	0.57	0.08

Table 3. Welding parameters (L = 600 mm)

Specimen designation	Bead no.	Temperature after the making of each bead [°C]	Average welding current [A]	Average arc voltage [V]	Welding time [min]	Linear energy [kJ/mm]
S960QL not subjected to treatment (welded only)	1	28.6	201	23.9	2:46	1.07
	2	82.5	203	27.0	1:36	0.70
	3	104.5	255	26.3	2:31	1.35
S960QL subjected to peening	1	47.5	200	23.8	2:44	1.04
	2	89.6	202	27.1	1:37	0.71
	3	114.5	255	26.3	2:29	1.34
S960QL subjected to PWHT	1	36.0	202	24.0	2:44	1.06
	2	92.4	202	27.0	1:38	0.71
	3	119.7	254	26.4	2:33	1.37

The ceramic backing strip was used to ensure the proper penetration and formation of the weld root (on one side). The welding process was performed using a robotic station (CLOOS) so that each test plate could be welded using the comparable welding parameters such as arc voltage, welding current, number of beads, welding rate, shielding gas (92% Ar + 8% CO_2) or the distance between the workpiece and the contact tube (referred to as electrode extension). Welding parameters were recorded by the welding station operator; each test plate was welded using three beads (Table 3).

Table 3 presents welding parameters in relation to each bead and test plate. Temperature was measured using a contact thermostat (after making each bead). The specimen subjected to peening was made as the last one in a given series; the welding table and fixtures were already heated hence the lack of differences in temperature resulting from pauses (lasting 3 minutes each) for peening after each bead. Average results of linear energy revealed that the robotic welding process enabled the obtainment of similar welding conditions in respect of the linear energy in relation to each bead.

Interpass peening

The high-frequency (90 Hz) peening mechanical treatment of each joint aimed to reduce stresses in the welded joint by introducing compressive stresses to the former. The treatment was performed using a Weld Line 10 air hammer (PITEC GmBH). The peening process was recognised as proper when 100% of the area of each bead along with the weld face was subjected to mechanical treatment (Fig. 3). A manufacturer's guideline concerning the frequency of the peening process affecting structural steel was 90 Hz, whereas proper treatment was defined as the peening of the entire area of the weld. The treatment was performed manually (Fig. 4).

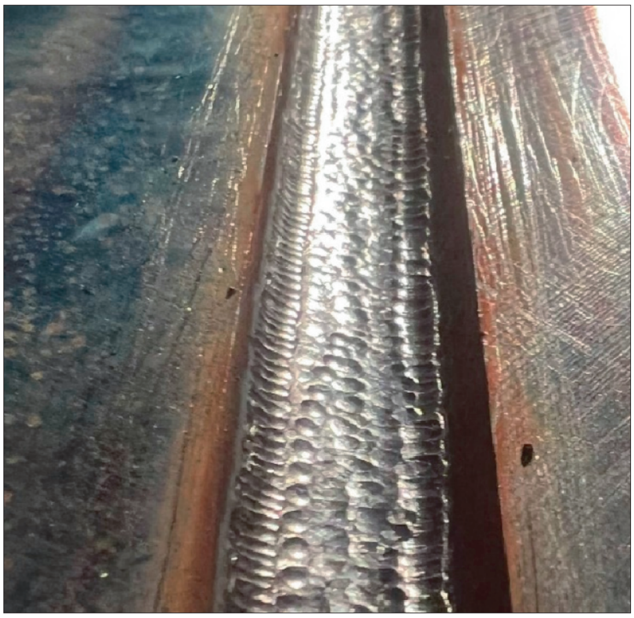


Fig. 3. Bead after the peening of the entire area using a pin having a radius of 4 mm

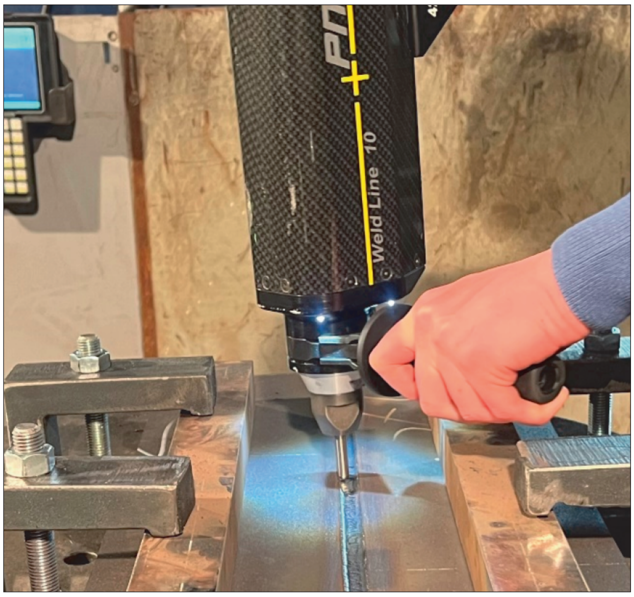


Fig. 4. Test plate during peening

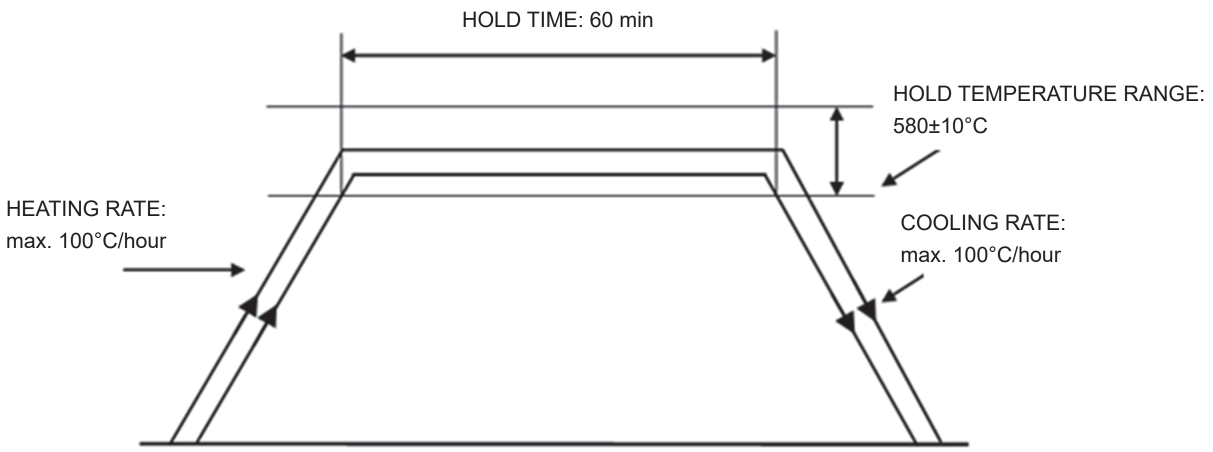


Fig. 5. Post-weld heat treatment (stress relief annealing) of the test plate

Post-weld heat treatment of the welded joint – stress relief annealing

The third test plate (after welding) was subjected to heat treatment, commonly used to reduce stresses and strains generated during welding processes. The stress relief annealing process in the electric furnace is divided into three stages, i.e. controlled heating, holding (at target temperature) and controlled cooling (Fig. 5).

Tests performed in accordance with the requirements of the PN-EN ISO 15614-1:2017 standard

In accordance with the requirements of *Specification and qualification of welding procedures for metallic materials – Welding procedure test – Part 1*, each of the test plates was subjected to non-destructive tests, including:

- visual tests (VT), performed in accordance with PN-EN ISO 17637,
- penetrant tests (PT), performed in accordance with PN-EN ISO 3452-1,
- radiographic tests (RT), performed in accordance with PN-EN ISO 17636-1.

All the non-destructive test results were positive.

The subsequent step involved the making of specimens used in destructive tests, in accordance with the PN-EN ISO 15614-1:2017 standard:

- transverse tensile tests – 2 specimens, in accordance with PN-EN ISO 4136,
- bend tests – 4 specimens, in accordance with PN-EN ISO 5173,
- impact strength tests – 2 specimens, in accordance with PN-EN ISO 9016,
- hardness tests – 2 measurement lines, in accordance with PN-EN ISO 9015-1,
- macroscopic tests – 1 specimen, in accordance with PN-EN ISO 17639.

Because of the base material thickness, specimens used in the impact strength tests had dimensions of 7.5 mm ×10 mm ×55 mm (the so-called specimens of reduced cross-section). The bend tests involved two specimens used in face bend tests of butt welds (weld face width amounting to 40 mm) and two specimens used in root bend tests of butt welds (weld root width amounting to 40 mm). The tests required by the PN-EN ISO 15614-1 standard were supplemented with stress

Table 4. Acceptance criteria for the destructive tests

Test	Acceptance criteria
Transverse tensile test	Value R_m should not be lower that the appropriate minimum value for the base material, i.e. a minimum of 980 MPa
Transverse bend test	During/after the test, test specimens should not contain any imperfections in excess of 3 mm, in any direction; bending pin radius: 90 mm
Impact strength test	Impact energy should be consistent with a related standard concerning the base material, i.e. KV_2 of minimum 40 J at -20°C
Hardness test	Hardness (HV10) of the specimens not subjected to heat treatment should amount to max. 450 HV10; hardness of the specimens subjected to heat treatment (PWHT) should amount to max. 380 HV10
Macroscopic test	Lack of imperfections at quality levels lower than those specified in Table 4 of the PN-EN ISO 15614-1 standard

measurements involving the Barkhausen effect, based on a testing procedure proposed by the provider of the technology, i.e. the NNT company.

Analysis of test results

The tests discussed in the article were performed in the destructive test laboratory of the FAMET Group S.A. in Kędzierzyn-Koźle. The laboratory was approved by the Office of Technical Inspection to perform destructive tests. The tests finished positively in relation to all the test specimens sampled from the three test plates. The acceptance criteria for individual tests are presented in Table 4.

Table 5. Test results obtained for the test plate not subjected to treatment

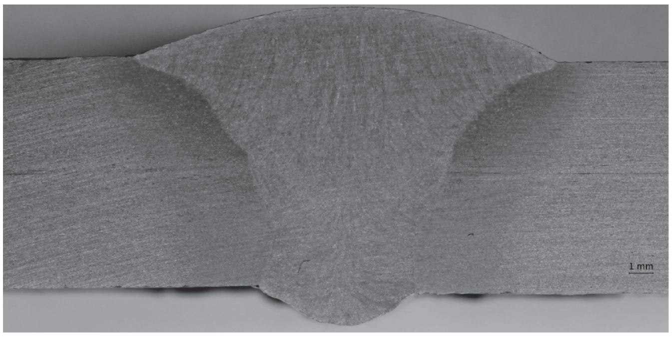
<table>
<tr><th>Test</th><th>Specimen</th><th colspan="5">Result</th><th colspan="5">Specimen</th><th colspan="6">Result</th></tr>
<tr><td>Transverse tensile test</td><td>TT-1</td><td colspan="5">1007 MPa</td><td colspan="5">TT-2</td><td colspan="6">1011 MPa</td></tr>
<tr><td rowspan="2">Transverse bend test</td><td>TFBB1</td><td colspan="5">positive</td><td colspan="5">TRBB1</td><td colspan="6">positive</td></tr>
<tr><td>TFBB2</td><td colspan="5">positive</td><td colspan="5">TRBB2</td><td colspan="6">positive</td></tr>
<tr><td rowspan="3">Impact strength test</td><td>VWT 0/2</td><td colspan="5">58.9 J</td><td colspan="5">VHT 0/2</td><td colspan="6">82.4 J</td></tr>
<tr><td>VWT 0/2</td><td colspan="5">54.9 J</td><td colspan="5">VHT 0/2</td><td colspan="6">79.5 J</td></tr>
<tr><td>VWT 0/2</td><td colspan="5">59.8 J</td><td colspan="5">VHT 0/2</td><td colspan="6">74.6 J</td></tr>
<tr><td rowspan="2">Hardness test</td><td rowspan="2">Ma-1
HV10</td><td>L1</td><td>367</td><td>370</td><td>356</td><td>313</td><td>301</td><td>335</td><td>341</td><td>331</td><td>330</td><td>352</td><td>285</td><td>334</td><td>365</td><td>353</td><td>357</td></tr>
<tr><td>L2</td><td>350</td><td>351</td><td>345</td><td>279</td><td>290</td><td>334</td><td>366</td><td>349</td><td>356</td><td>349</td><td>316</td><td>279</td><td>340</td><td>359</td><td>356</td></tr>
<tr><td>Macroscopic test</td><td>Ma-1</td><td colspan="16"> </td></tr>
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Table 6. Test results obtained for the test plate not subjected to peening

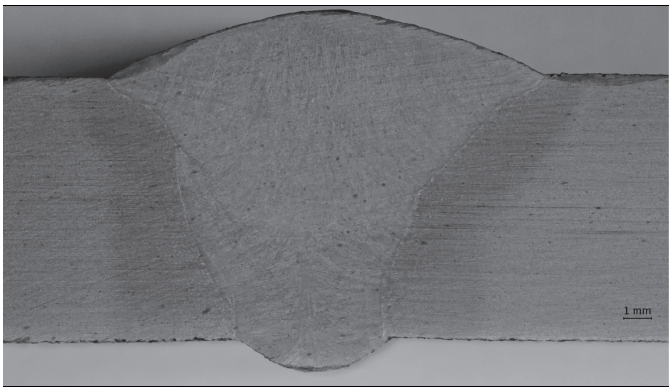
<table>
<tr><th>Test</th><th>Specimen</th><th colspan="5">Result</th><th colspan="5">Specimen</th><th colspan="6">Result</th></tr>
<tr><td>Transverse tensile test</td><td>TT-1</td><td colspan="5">1011 MPa</td><td colspan="5">TT-2</td><td colspan="6">989 MPa</td></tr>
<tr><td rowspan="2">Transverse bend test</td><td>TFBB1</td><td colspan="5">positive</td><td colspan="5">TRBB1</td><td colspan="6">positive</td></tr>
<tr><td>TFBB2</td><td colspan="5">positive</td><td colspan="5">TRBB2</td><td colspan="6">positive</td></tr>
<tr><td rowspan="3">Impact strength test</td><td>VWT 0/2</td><td colspan="5">58.9 J</td><td colspan="5">VHT 0/2</td><td colspan="6">66.7 J</td></tr>
<tr><td>VWT 0/2</td><td colspan="5">58.9 J</td><td colspan="5">VHT 0/2</td><td colspan="6">70.6 J</td></tr>
<tr><td>VWT 0/2</td><td colspan="5">58.9 J</td><td colspan="5">VHT 0/2</td><td colspan="6">68.7 J</td></tr>
<tr><td rowspan="2">Hardness test</td><td rowspan="2">Ma-1
HV10</td><td>L1</td><td>355</td><td>366</td><td>362</td><td>303</td><td>360</td><td>326</td><td>326</td><td>370</td><td>361</td><td>365</td><td>385</td><td>327</td><td>315</td><td>355</td><td>360</td></tr>
<tr><td>L2</td><td>356</td><td>341</td><td>334</td><td>282</td><td>278</td><td>356</td><td>336</td><td>320</td><td>309</td><td>326</td><td>334</td><td>295</td><td>316</td><td>353</td><td>356</td></tr>
<tr><td>Macroscopic test</td><td>Ma-1</td><td colspan="16"> </td></tr>
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Table 7. Test results obtained for the test plate subjected to PWHT

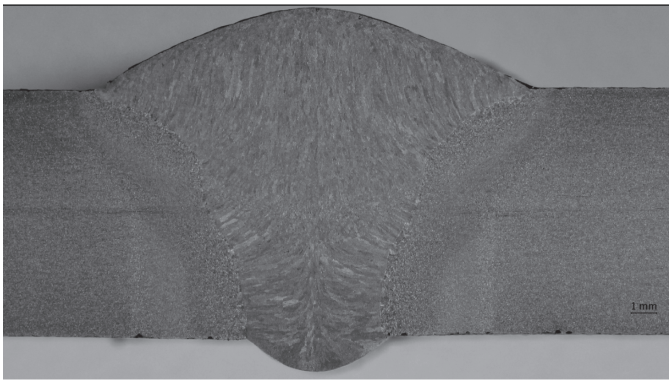
<table>
<tr><th>Test</th><th>Specimen</th><th colspan="5">Result</th><th colspan="5">Specimen</th><th colspan="6">Result</th></tr>
<tr><td>Transverse tensile test</td><td>TT-1</td><td colspan="5">998 MPa</td><td colspan="5">TT-2</td><td colspan="6">992 MPa</td></tr>
<tr><td rowspan="2">Transverse bend test</td><td>TFBB1</td><td colspan="5">positive</td><td colspan="5">TRBB1</td><td colspan="6">positive</td></tr>
<tr><td>TFBB2</td><td colspan="5">positive</td><td colspan="5">TRBB2</td><td colspan="6">positive</td></tr>
<tr><td rowspan="3">Impact strength test</td><td>VWT 0/2</td><td colspan="5">82.0 J</td><td colspan="5">VHT 0/2</td><td colspan="6">117.7 J</td></tr>
<tr><td>VWT 0/2</td><td colspan="5">96.1 J</td><td colspan="5">VHT 0/2</td><td colspan="6">116.7 J</td></tr>
<tr><td>VWT 0/2</td><td colspan="5">101.0 J</td><td colspan="5">VHT 0/2</td><td colspan="6">100.0 J</td></tr>
<tr><td rowspan="2">Hardness test</td><td rowspan="2">Ma-1
HV10</td><td>L1</td><td>360</td><td>361</td><td>370</td><td>300</td><td>319</td><td>328</td><td>334</td><td>355</td><td>349</td><td>307</td><td>290</td><td>310</td><td>338</td><td>344</td><td>347</td></tr>
<tr><td>L2</td><td>356</td><td>354</td><td>344</td><td>292</td><td>288</td><td>345</td><td>371</td><td>387</td><td>398</td><td>330</td><td>300</td><td>294</td><td>327</td><td>329</td><td>344</td></tr>
<tr><td>Macroscopic test</td><td>Ma-1</td><td colspan="16"> </td></tr>
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Figure 6 presents the arrangement of hardness measurement points.

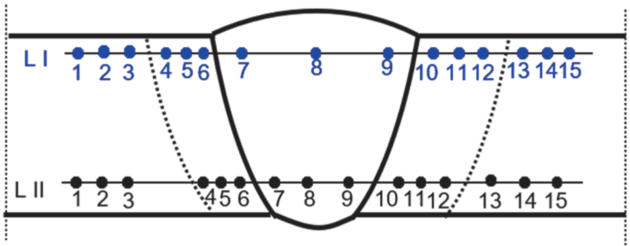

Fig. 6. Arrangement of hardness measurement points

Measurements of stresses involving the Barkhausen effect

Stresses were measured using a Barkhausen effect meter and a standard single-core probe. The direction of magnetisation determined the EB intensity test direction. The recorded EB signal was converted in the meter (parameter INT), being the measure of the root-mean-square voltage of the EB signal. The stress measurements involved 3 specimens, i.e. the one which was subjected to welding, the one which was subjected to heat treatment (stress relief annealing) and the one which was subjected to the peening process. The aim of the measurements was to refer values measured in relation to individual plates. Figure 7 presents the arrangement of the measurement points.

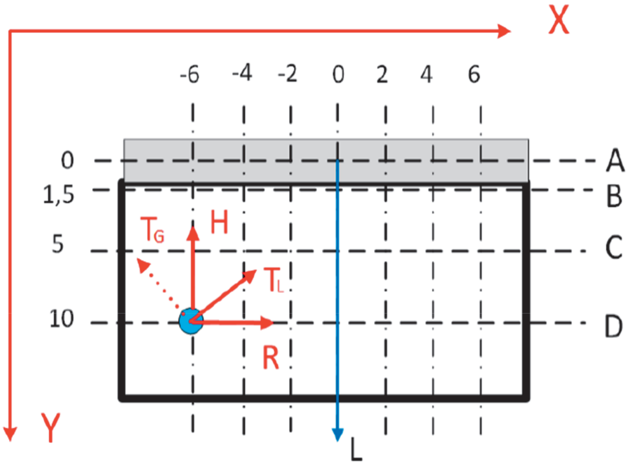

Fig. 7. Arrangement of measurement points (cm) and directions of tests in relation to the welded joint

All the three specimens were subjected to measurements involving the same number of measurement points. The results are presented in the form of a curve – distance of measurement point Y in the function of stress expressed in MPa (Fig. 8–10). The measurement points on the weld face side are designated as L, whereas those on the root side are designated as G. Each side was subjected to three series of measurements, where the distance from the weld face axis amounted to 0 mm, 7.5 mm, 15 mm, 22 mm, 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, 85 mm and100 mm respectively.

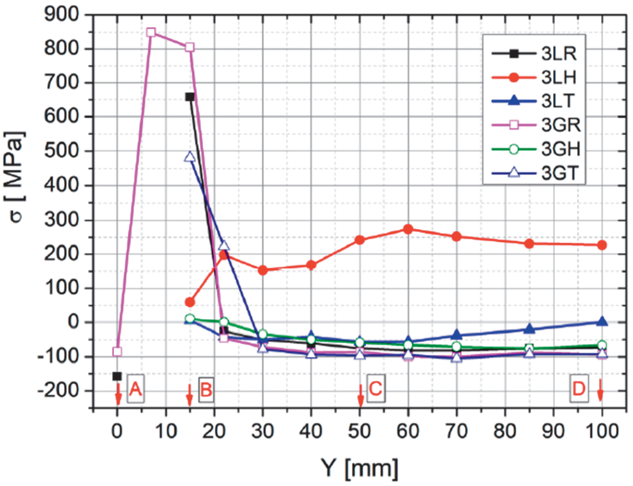

Fig. 8. Distribution of stresses along line L (blue line in Fig. 6) in relation to the specimen subjected to welding

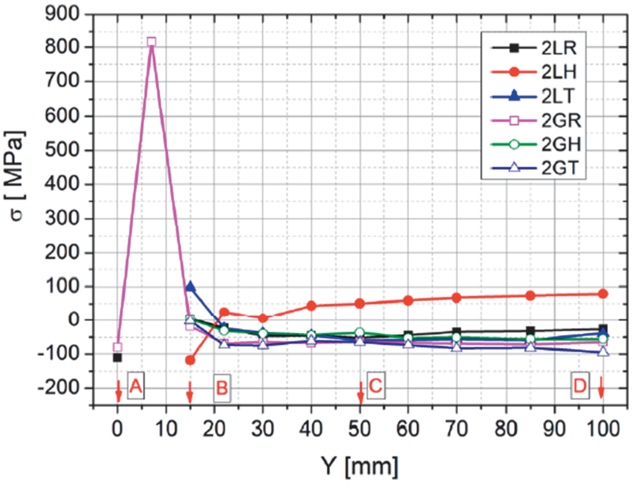

Fig. 9. Distribution of stresses along line L (blue line in Fig. 6) in relation to the specimen subjected to peening

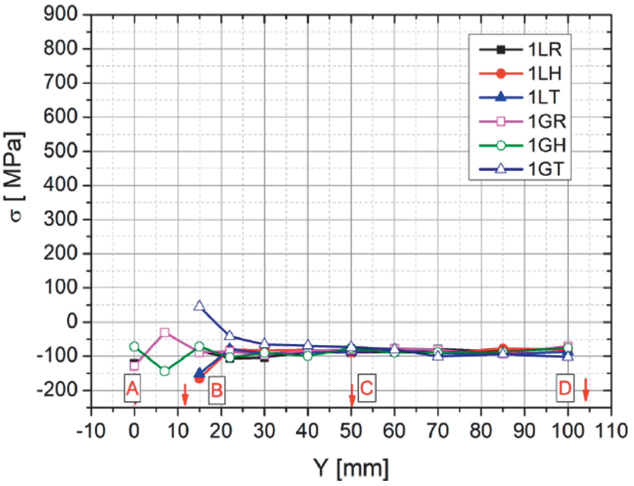

Fig. 10. Distribution of stresses along line L (blue line in Fig. 6) in relation to the specimen subjected to heat treatment (stress relief annealing)

The diagram presented in Figure 8 reveals that the post-weld level of tensile stresses in the fusion line and in the HAZ was high and restricted within the range of 800 MPa to 850 MPa. Along with the growing distance between the measurement points and the welded joint axis, the level of stresses stabilised within the range of -100 MPa to 0 MPa. The diagram presented in Figure 9 reveals that the post-weld level of tensile stresses in the fusion line and in the HAZ amounted to 0 MPa and was reduced in comparison with the specimen not subjected to treatment. In the weld axis (point A), compressive stress amounted to approximately -100 MPa. In order to explain the above-presented phenomenon it was necessary to perform measurements using a larger number of measurement points. In order to avoid additional stresses (disturbing results), the measurement involving the probe was performed without grinding the weld face. At a distance of 10 mm away from the weld axis, the EB measurement result was high and amounted to 800 MPa, revealing the lacking effect of peening on the weld area neighbouring the HAZ. Along with the growing distance between the measurement points and the welded joint axis, the level of stresses stabilised within the range of -100 MPa to 0 MPa. The depth of EB-based measurements was restricted within the range of 0.01 mm to 1.0 mm.

Figure 9 reveals that the welding and stress relief annealing processes resulted in the level of stresses in the fusion line and in the HAZ below 0 MPa. The above-named level of compressive stresses was expected as characteristic of the material with the reduced level of post-weld residual stresses. Along with the growing distance between the measurement points and the welded joint axis, the level of stresses (compressive in nature) stabilised and amounted to -100 MPa.

Summary

The above-presented tests revealed that, during welding procedure qualification for steel S960QL, the high-frequency peening of each bead did not lead to the obtainment of negative results in all required tests in comparison with the test plates subjected to welding and post-weld heat treatment (stress relief annealing). The test results (obtained after the robotic MAG welding of the 10 mm thick plates made of steel S960QL) justified the formulation of the following conclusions:

- in relation to all the test plates, the tensile test results (R_m) were restricted within the ranges of acceptance criteria specified in related standards,
- neither the face bend tests nor the root bend tests of the butt welds revealed any imperfections; the

results obtained in the above-named tests satisfied criteria specified in related standards,

- impact strength tests of the test plates only subjected to welding and those additionally subjected to interpass peening led to the obtainment of comparable results; in terms of the specimens sampled from the test plate subjected to heat treatment, the impact energy of the specimens sampled from the heat affected zone amounted on average to approximately 30 J, i.e. more than in the analogous specimens sampled from the two other test plates,
- average post-weld hardness of the test plate in the base material area amounted to 356 HV; the average hardness of the weld amounted to 345 HV, whereas that of the heat affected zone (HAZ) amounted to 315 HV. In terms of the test plate subjected to stress relief annealing, the hardness of the base material amounted to 357 HV, that of the weld amounted to 385 HV, whereas the hardness of the HAZ amounted to 307 HV. As regards the test plate subjected to peening, the hardness of the base material amounted to 352 HV, that of the weld amounted to 337 HV, whereas the hardness of the HAZ amounted to 328 HV. It was possible to notice an increase in the hardness of the HAZ (subjected to the peening treatment),
- as regards hardness measurements concerning the measurement line on the weld face side (related to the weld and HAZ), hardness in the weld of the test plate subjected to peening increased by 18 HV, whereas that of the HAZ increased by 24 HV in comparison with the plate only subjected to welding,
- as regards hardness measurements concerning the surface layer of the test plate subjected to peening, it was possible to observe an increase in the hardness of the weld by 6 HV and that of the HAZ by 35 HV in relation to the test plate subjected to stress relief annealing (post-weld heat treatment),
- decrease in hardness in relation to the specimen subjected to PWHT in the area subjected to peening was caused by local intensive plastic strain,
- macroscopic tests did not reveal any imperfections in the cross-section of any of the three test plates,
- EB-based stress measurements made it possible to analyse how individual specimens were affected by welding, peening and PWHT. The post-weld heat treatment (stress relief annealing) of the welded joints nearly entirely reduced residual stresses generated during the welding process,
- interpass peening of the welded joints reduced post-weld residual stresses at a distance of 15 mm away from the welded joint in comparison with stress measurement results concerning the specimen subjected to welding. The foregoing justified the positive assessment of the peening process as regards the reduction of tensile stresses in the fusion line and in the HAZ,
- high level of stresses observed in the specimen subjected to peening and located approximately 8 mm away from the axis of the surface layer (800 MPa) revealed the lack of effective mechanical treatment (peening) and was similar to that measured in the specimen subjected to welding.

References

[1] Lefebvre F., Peyrac C., Elbel G., Revilla-Gomez C., Verdu C., Buffière J-Y.: Understanding of fatigue strength improvement of steel structures by hammer peening treatment 6th Fatigue Design conference, Fatigue Design, 2015.

[2] Marquis G. B., Barsoum Z.: A guideline for fatigue strength improvement of high strength steel welded structures using high frequency mechanical impact treatment 5th Fatigue Design Conference, Fatigue Design, 2013.

[3] Hobbacher A.: IIW Recommendations for Fatigue Design of Welded Joints and Components, WRC Bulletin 520, The Welding Research Council, New York 2009.

[4] Kanga H., Leeb Y., Sunb X.: Effects of residual stress and heat treatment on fatigue strength of weldments, Materials Science and Engineering A, 2008, vol. 497, pp. 37–43.

[5] Przybyła M.: Obróbka cieplna i mechaniczne metody redukcji naprężeń i odkształceń powstałych w wyniku procesu spawania. Sympozjum Katedr i Zakładów Spawalnictwa, Brenna 2019.

[6] Fuštar B., Lukačević I., Dujmović D.: High-Frequency mechanical impact treatment of welded joints, Građevinar, 2020, vol. 72, no. 5, pp. 421–436, doi: https://doi.org/10.14256/JCE.2822.2019.

[7] Haagensen P.J., Maddox S.J.: IIW Recommendations On Methods for Improving the Fatigue Strength of Welded Joints: IIW-2142-10, 2013.

[8] Gerster P., Schäfers F., Leitner M.: IIW Pneumatic Impact Treatment (PIT) – Application and Quality Assurance: IIW Document XIII-WG2-138-13.

[9] Statnikov E.S., Shevtsov U.M., Kulikov V.F.: Ultrasonic impact tool for welds strengthening and reduction of residual stresses, Publications Scientific Works: Metallurgy, SEVMASH, USSR, 1977, vol. 92, pp. 27–29.

[10] Harati E., Svensson L., Karlsson L., Hurtig K.: Effect of HFMI treatment procedure on weld toe geometry and fatigue properties of high strength steel welds,

Procedia Struct Integr, 2016, 2, pp. 3483–3490, https://doi.org/10.1016/j.prostr.2016.06.434.

[11] PN-EN ISO 15614-1:2017-08 Specyfikacja i kwalifikowanie technologii spawania metali – Badanie technologii spawania – Część 1: Spawanie łukowe i gazowe stali oraz spawanie łukowe niklu i stopów niklu.

[12] PN-EN ISO 17637:2017-02 Badania nieniszczące złączy spawanych – Badania wizualne.

[13] PN- EN ISO 3452-1 Badania nieniszczące – Badania penetracyjne – Część 1: Zasady ogólne.

[14] PN- EN ISO 17636-1:2013-06 Badania nieniszczące spoin – Badanie radiograficzne – Część 1: Techniki promieniowania X i gamma z błoną.