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The Preliminary Analysis of the Effect of Low-Energy Plasma Treatment on Internal Stresses in a Welded Plate of Steel S355

Abstract: The article presents a pilot study aimed to provide preliminary assessment concerning the effect of the low-energy plasma treatment on the level of internal stresses in welded plates. In addition, the article discusses the similarity of a stress relief mechanism based on annealing and that based on low-energy plasma treatment. The extensometric measurements of internal stresses involving steel S355 after welding and after treatment in the plasma chamber revealed the low-energy plasma treatment-induced reduction of internal stresses.

Keywords: welding stresses, low-energy plasma, elimination of stresses

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Introduction

Welding, as the most popular method used in the joining of metallic components, finds applications in many sectors of industry. Welded joints constituting indispensable elements of bridges, ships, containers and many other crucial structures and products are usually recognised as the most vulnerable structural elements. In simple terms, joining processes consist in the local heating of elements to be joined and filler metals (if any). Because of the energy of a given welding power source and the adjustment of other welding parameters, the local heating of materials leads to various stresses and deformations. This fact is of particular importance in welding processes, involving the melting of materials and the formation of welds. As their presence worsens the operational properties, e.g. strength, toughness or creep resistance, of materials, and could significantly

shorten the service life of structures, welding stresses should be eliminated.

Stresses generated during welding processes can be partly or entirely eliminated through heat treatment (stress relief annealing) or mechanical stress relief treatment (e.g. vibratory stress relief). Stress relief annealing in furnaces is the most effective stress relieving method as it enables the relatively precise performance of the process including the adjustment of temperature and its changes in time. Heat treatment activates the displacement of vacancies and dislocations as well as is responsible for the formation of subgrains. The above-named phenomena constitute the primary mechanisms responsible for the relaxation of internal stresses [1]. The effectiveness of heat treatment in the elimination of welding stresses has been demonstrated in many works, the results of which indicate, for instance, the possibility or

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reducing internal stresses in steel pipelines by approximately 60% [2], a decrease in internal stresses of joints made in high-strength low-alloy steels (HSLA) by more than 20% [1] and many other favourable results.

In spite of its high efficiency in eliminating welding stresses, the heat treatment of welded elements, also referred to as post-weld heat treatment (PWHT), is characterised by certain disadvantages. For instance, because of the limited dimensions of the furnace, joints of large structures, e.g. tanks or pipelines, can only be subjected to local stress relief annealing. In addition to dimensional limitations of elements, post-weld heat treatment is an energy-consuming and, thus, cost-generating, process. Also, the post-weld heat treatment leaves scale on surfaces of steel elements. The removal of the aforesaid scale adds to the aforementioned PWHT-related costs. Stress relief annealing triggers microstructural changes, some of which may be desirable, e.g. grain size homogenisation. However, stress relief annealing, the temperature of which in relation to unalloyed and low-alloy steels may be restricted within the range of approximately 550°C to 650°C, could trigger the precipitation of detrimental phases, usually increasing the brittleness of joints or decreasing their corrosion resistance.

Another popular method enabling the elimination of internal stresses is vibratory stress relief (VSR). VSR methods involve the application of cyclic loads. Usually, VSR treatment involves putting an element into resonant vibration aimed to achieve the significant amplitude of stresses, which can be achieved using relatively inexpensive portable equipment [3, 4]. The primary advantages of the process include high efficiency, low energy consumption and the short time of treatment. The effectiveness of vibratory stress relief has been demonstrated in numerous works, informing about e.g. the reduction of internal stresses made in welded tubes

made of HSLA steels by 50% [5].

Another interesting method enabling the elimination of internal stresses is a process involving the use of the glow discharge low-energy plasma beam. Previous tests revealed that interaction between charged particles of the plasma beam and the radiated surface of a crystalline material rearranges the crystal lattice of a material subjected to treatment [6]. The bombarding of the solid surface with the low-energy ion beam excites the oscillation of the atoms of the crystal lattice and makes it move deep inside the material [7]. The induced displacement of vacancies and dislocations is similar to the mechanism connected with the relaxation of stresses during heat treatment. Therefore, it is possible that treatment involving the use of the glow discharge low-energy plasma beam could produce a result similar to that provided by heat treatment, yet simultaneously excluding high temperature-related risks such as microstructure degradation or other above-presented unfavourable changes. It has been observed that the processing of metallic materials using cold plasma improves their resistance to tribological wear [8, 9] as well as increases their strength and hardness.

Test materials

The material used in the tests was structural steel grade S355. The chemical composition of the test steel is presented in Table 1. The ferritic-pearlitic microstructure of a plate made in the test steel, characterised by banding transverse in relation to the joint axis, is presented in Figure 1. Before welding, the plates, having dimensions of 350 mm × 150 mm × 12 mm, were subjected to Y bevelling (joint preparation); the angle amounted to 60°, the height of the threshold being 5 mm. The distance between butt-welded joints amounted to 2 mm.

Table 1. Chemical composition of the test steel plate [% by weight]

C	Mn	Si	P	S	Cr	Cu	Al	Fe
0.17	1.39	0.16	0.016	0.004	0.02	0.02	0.04	rest

The plates were subjected to arc welding (121) performed in one run and involving the use of filler metal wire grade S2 having a diameter of 4 mm (in accordance with PN-EN ISO 14171) and flux grade AR (in accordance with the above-named standard). The welding process was performed using voltage $U=30$ V, current $I=600$ A and welding rate $v=8.5$ mm/s.

Testing methodology

Treatment based on the glow discharge low-energy plasma beam

The test plate, between the first and the second measurement of stresses, was subjected to

treatment performed using the glow discharge low-energy plasma beam. The treatment was carried out in a special vacuum plasma generator. The schematic diagram of the generator is presented in Figure 2. The treatment was performed under a pressure of 2.5×10^{-2} Tr in the atmosphere of tail gases. Ion energy was restricted within the range of 2 keV to 5 keV. The temperature of the plate during treatment was controlled and amounted to 50 ± 5 °C. The plate surface radiation time amounted to 30 minutes.

Measurements of internal stresses

The welded plates were subjected to measurements of internal stresses two times, i.e. after the completion of the welding process and after the performance of plasma treatment. Internal stresses were measured using the extensometric (pinhole) method involving the plate surface subjected to grinding (Fig. 3). Because of the fact that the below-presented experiment was a pilot study, aimed to initially confirm the hypothesis about the possibility of eliminating welding stresses using the low-energy plasma beam, in each case, stresses were measured at two points, i.e. 4.5 mm and 60 mm away from the edge of the joint face. Both the plate subjected to welding and the plate subjected to plasma treatment were next subjected to measurements

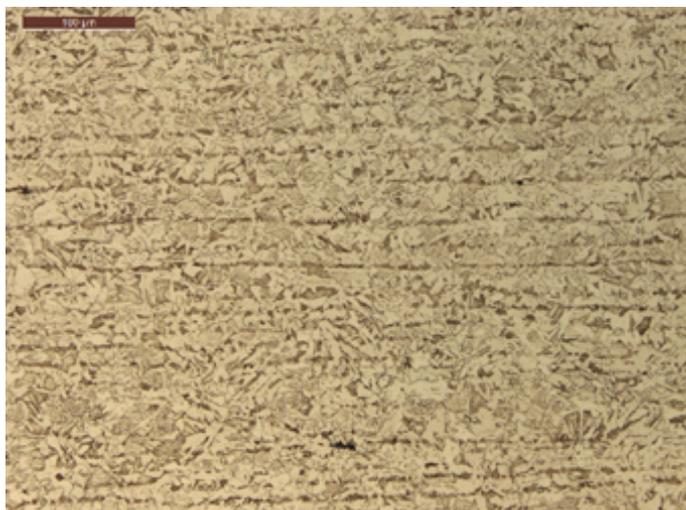


Fig. 1. Banded ferritic-pearlitic microstructure; mag. 200x, etchant: Nital (2%)

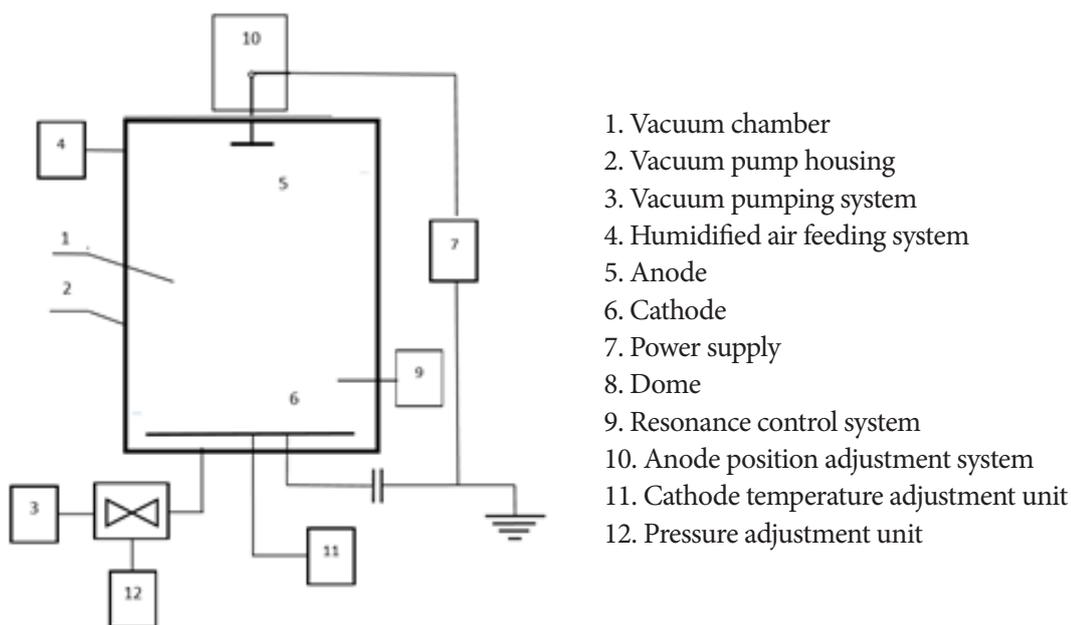


Fig. 2. Schematic diagram of the plasma chamber along with process control equipment



Fig. 3. Fragment of the joint face: a) prepared for measurements of stresses, b) with extensometers; 1 – joint face, 2 – plate surface after grinding, 3 – rosette extensometers on the surface

of primary stresses σ_{max} and σ_{min} as well as angle α , i.e. the angle constituting the measure indicating the deflection of the direction of primary stresses in relation to the axis perpendicular to the joint axis.

Test results

The results of the measurements of internal stresses are presented in Figure 4. After welding, maximum internal stresses σ_{max} measured 4.5 mm away from the edge of the joint face amounted to 573 MPa. In turn, after plasma treatment the aforesaid stresses amounted to 326 MPa. The value of σ_{max} at the point

located 60 mm away from the joint did not change significantly and amounted to 275 MPa after welding and to 260 MPa after plasma treatment. After welding, 4.5 mm away from the edge of the face, the minimum internal stresses σ_{min} amounted to 291 MPa. In turn, after plasma processing, the aforesaid stresses amounted to 101 MPa. The value of σ_{min} at the point located 60 mm away from the joint did not change significantly and amounted to 201 MPa after welding and to 214 MPa after plasma treatment. The angle of deflection of primary stresses (angle α) changed from -15° to 30° at the measurement point located 4.5 mm

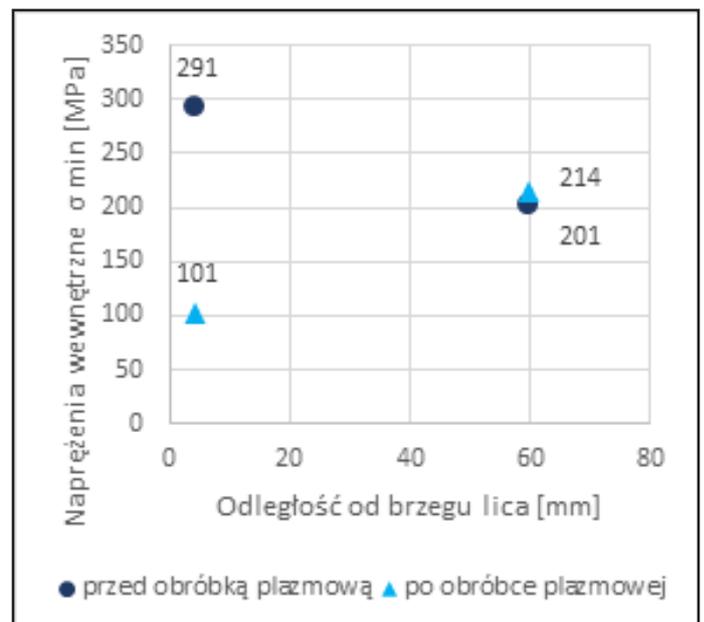
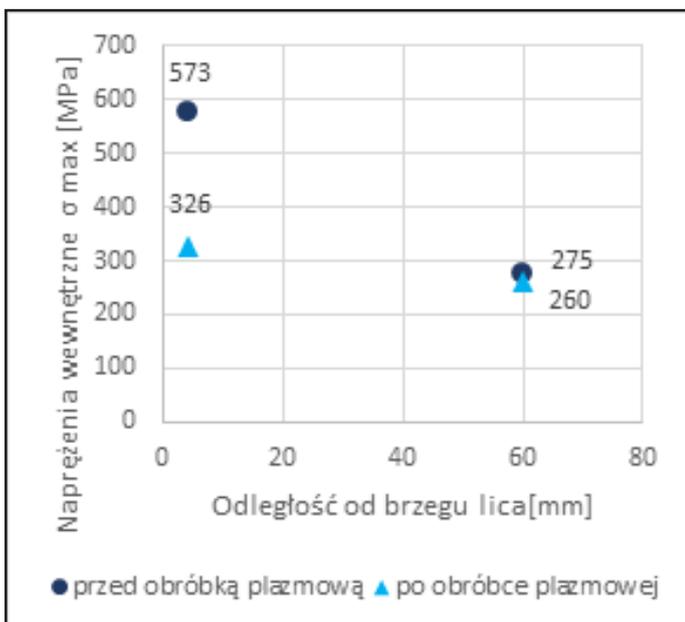


Fig. 4. Results of extensometric measurements of internal stresses σ_{max} (a) and σ_{min} (b) obtained in relation to the plate after welding and after treatment in the plasma chamber

away from the joint and from 44° to 38° at the measurement point located 60 mm away from the joint.

The test results revealed that 4.5 mm away from the edge of the joint face, the plasma processing of the welded plate reduced primary stresses, i.e. σ_{\max} and σ_{\min} , by 43% and 65% respectively. The internal stresses measured at the point located 60 mm away from the edge of the joint changed insignificantly.

Concluding remarks

The above-presented tests and their results revealed that the glow discharge low-energy plasma beam-based treatment reduces internal welding stresses in welded structures. In addition, the test results, referred to information contained in reference publications, revealed that the efficiency of the stress relaxation process involving the use of the above-presented technology and commonly used heat treatment could be comparable in relation to selected elements, yet after taking into consideration the course of the process in a dimensionally limited vacuum chamber. The experiment justifies the necessity of performing further tests concerned with the elimination of welding stresses using the method involving the application of the glow discharge low energy plasma beam.

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