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The Effect of Heat Treatment on the Structure and Mechanical Properties of Laser-Welded Joints Made of Steel 17-4PH

Abstract: Steel 17-4PH belongs to the group of corrosion-resistant martensitic steels. Because of its favourable mechanical properties and corrosion resistance, the steel has found applications in the aviation, petrochemical, chemical and other industries. The article present results of the laser butt welding of steel 17-4PH without the use of the filler metal as well as the effect of selected types of heat treatment on the structure and mechanical properties of the weld. The test results revealed that the welding process alone enabled the obtainment of favourable mechanical properties, whereas the use of heat treatment led to the homogenisation of the welded joint area.

Keywords: laser beam welding, alloy steel, microstructure

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Introduction

The development of industry and the improvement of equipment efficiency necessitate the use of increasingly advanced engineering materials. In turn, improved efficiency entails an increase in operating parameters, which, in terms of mechanical properties, leads to situations, where previously applied materials either fail to satisfy related requirements or require significant wall thickening. However, changes of parameters may lead to changes of corrosion resistance, which, in turn, could require the disuse of previously applied materials [1–5]. Favourable operating conditions are obtainable, among other things, for corrosion-¬resistant steels (including martensitic steels), which, depending on previously applied heat treatment, may be characterised by very high mechanical strength (Rm of approximately 1200 MPa) without compromising favourable corrosion resistance [6–7].

An example of martensitic corrosion-resistant steel is steel grade 17-4PH (X5CrNiCuNb16-4). The obtainment of the martensitic structure and appropriate mechanical properties requires the performance of heat treatment. Necessary mechanical properties are obtained through precipitation hardening, including supersaturation performed at temperature restricted within the range of approximately 1020°C to1050°C (in relation to cooling in the air) and followed by ageing at temperature restricted within the range of 480°C to 620°C. Ageing leads to the precipitation of dispersive

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CU precipitates coherent with the matrix and constituting the reinforcing phase. Excessively long ageing time increases the precipitation of copper and, consequently, decreases hardness. A low carbon content in steel restricts the formation of chromium carbides and, at the same time, provides martensite with high plasticity (ductility). Supersaturation performed at temperature restricted within the range of 1020°C to 1050°C leads to the dissolution of precipitates in the solid solution, where copper precipitates (phase ε) are dissolved already at a temperature of 920°C, whereas phases rich ion chromium (σ, Z, M23C6) undergo dissolution at a temperature of more than 950°C. In such a situation, niobium carbides may remain undissolved [8–10]. The foregoing indicates that the welding of elements made of steel 17-4PH will be accompanied by the dissolution of the reinforcing phase in the high-temperature heat affected zone. Also, the use of the filler metal, the chemical composition of which will be consistent with the base material, will lead to situations, where the weld will not be hardened but characterised by lower mechanical properties than those of the base material after heat treatment. This, in turn, will necessitate the post-weld heat treatment of joints.

The article presents results of tests concerning the laser beam welding of steel 17-4PH without the use of the filler metal. The application of the laser beam significantly reduces a heat input to the material as well as decreased the size of the weld. The reduction of a heat input to the material is important as regards the evaporation of copper from the weld pool and the deposition of metal vapours on the surface of the area adjacent to the weld. Although the aforesaid phenomenon cannot be eliminated entirely, it is possible to decrease the negative effect of copper vapours by reducing welding stresses (tensile stresses), where the smaller volume of the weld triggers the smaller shrinkage of the metal during the cooling of the joint. The presence of metal vapours in the presence of tensile stresses and high temperature may trigger hot cracking (LME) and, consequently, fatigue cracks (particularly under fatigue operation conditions). In such a situation, initiated surface cracks play the role of stress concentrators (notch action) in areas where fatigue cracks are developed.

Test materials

Tests involved 3 mm thick sheets (250 mm x 100 mm) made of steel 17-4PH (X5CrNiCuNb16-4; 1.4548). The chemical composition of the steel (in accordance with the requirements of the EN 10088-1 standard), identified using the spark spectroscopy technique, is presented in Table 1. The welding process was performed in the flat position (PA), using a TruDisk 12002 disc laser. Welding was conducted along the longer edge of the sheet, without the use of the filler metal. The test joint was made using a laser beam power of 2 kW and a welding rate of 2 m/min.

Research work-related analyses involved non-destructive tests (visual tests and penetrant tests), destructive tests (light microscopy-based microstructural analysis) as well as tests of mechanical properties (hardness measurements and static tensile tests). The visual tests (VT) and penetrant tests (PT) were performed in accordance with the requirements of the EN ISO 17637 and EN ISO 3452-1 standards respectively. The assessment of quality was based on the requirements of quality level B in accordance with the EN ISO 13919-1 standard.

Table 1. Chemical composition of steel 17-4 PH

	C	Cr	Ni	Cu	Nb	Si	Mn	P	S
EN 10088-1	≤0.07	15÷17	3÷5	3÷5	5xC÷0.45	≤0.7	≤1.5	≤0.04	≤0.015
Analysis	0.06	15.4	5.38	3.52	0.26	0.46	0.89	0.008	0.004

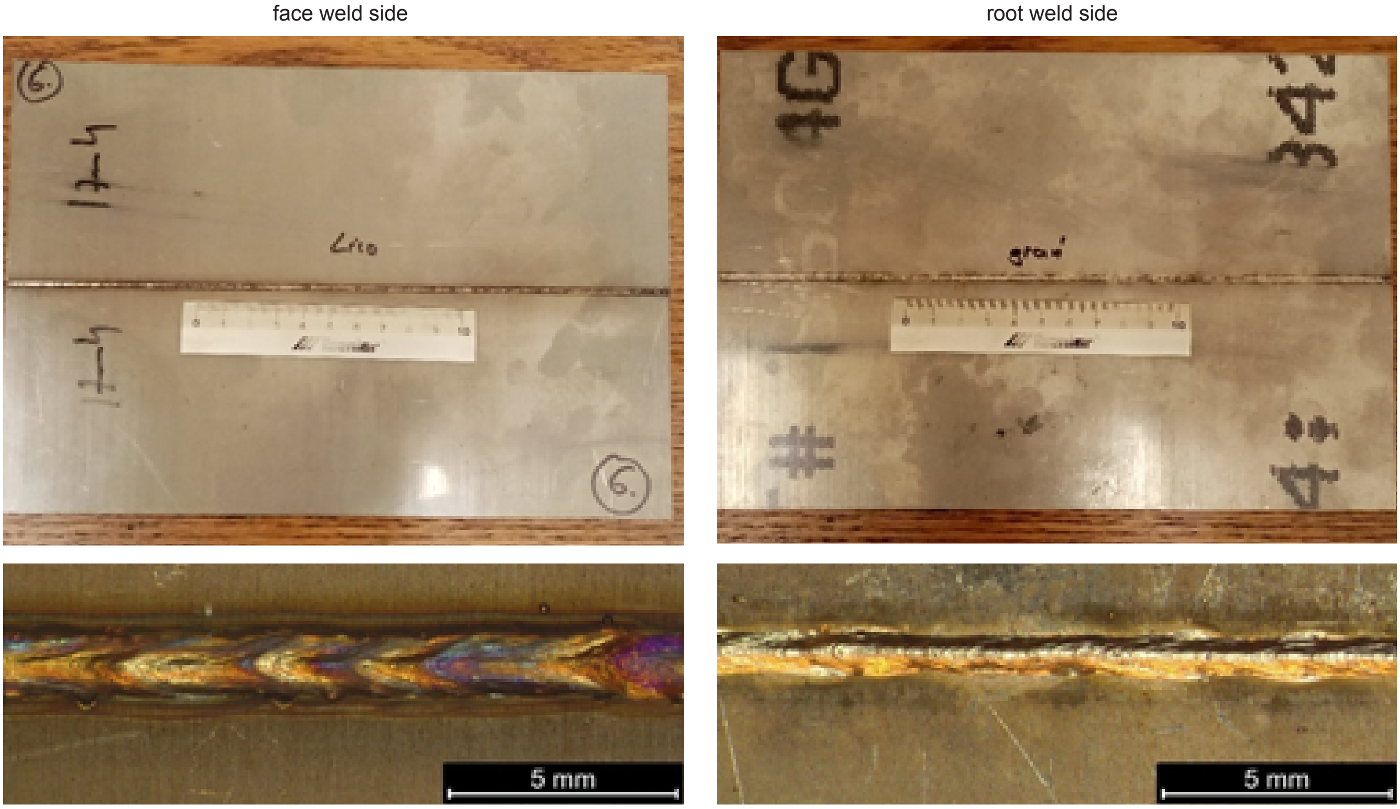

Fig.1. Test joint

The welded joint was cut through at the half of its length. One of the parts was subjected to heat treatment. The post-weld heat treatment procedure was performed using a chamber furnace. The heat treatment (H1150+1150) involved heating the specimen up to an austenitisation temperature of 1038°C, holding at the aforesaid temperature for 1 hour, cooling to temperature restricted within the range of 18°C to 20°C in time shorter than 1 hour and, next, two-time ageing at a temperature of 621°C for 4 h.

The specimens used in the metallographic tests were cut using a metallographic cutting machine (and intensive water cooling) and, next, subjected to grinding using water-resistant abrasive paper followed by polishing performed using polishing cloth and corundum slurry. The specimens prepared in the above-presented manner were subjected to electrochemical etching performed using Villela's reagent (for approximately 10 seconds). The structure was observed using magnification restricted within the range of 50 x to 1000 x.

The static tensile test was performed using flat specimens sampled transversely to the weld axis. The cross-section of the specimen had dimensions of 10 mm × 2.8 mm, whereas the measurement length amounted to 50 mm. The Vickers hardness test (performed using an indenter load of 98N (HV10)) involved the cross-section of the test joint.

Test results

Figure 1 presents the joint after the completion of the welding process. The shape of the weld was proper and regular along the entire length of the joint. Neither the visual nor the penetrant tests revealed the presence of discontinuities. Both VT and PT revealed that the joint represented quality level B (strict requirements) in accordance with the EN ISO 13919 standard.

On the face and the root side, the weld was characterised by slight convexity (excessively large reinforcement on the face and root) without visible undercuts (Fig. 2). The shape of the weld resembled X or Y, which resulted from welding conditions. The width of the face amounted to approximately 3 mm, whereas that of the root amounted to approximately 1 mm (in various joints). The shape of the heat affected zone (HAZ) was regular and symmetric. The width of the HAZ amounted to approximately 1 mm.

The analysis of the microstructure was performed using a light microscope and metallographic specimens cut out perpendicularly to the weld axis. Figures 3 and 4 presents the microstructures of the joints made of steel 17-4PH after welding (Fig. 3) as well as after supersaturation and ageing at a temperature of 621°C (Fig. 4). The base material is characterised by the fine-grained martensitic structure. The heat treatment did not trigger the grain growth. The slight grain growth could only be observed in the heat affected zone (HAZ). The HAZ, particularly near the fusion line, contained (in addition to martensite) small amounts of ferrite δ along the grain boundaries (see Fig. 3b). The presence of ferrite δ resulted from the heating of the HAZ to temperature above or within the austenite+-ferrite δ range. Fast cooling did not trigger the complete transformation of ferrite into austenite, and, below temperature Ms, into martensite. The areas heated up to the austenite formation temperature would have the structure of martensite.

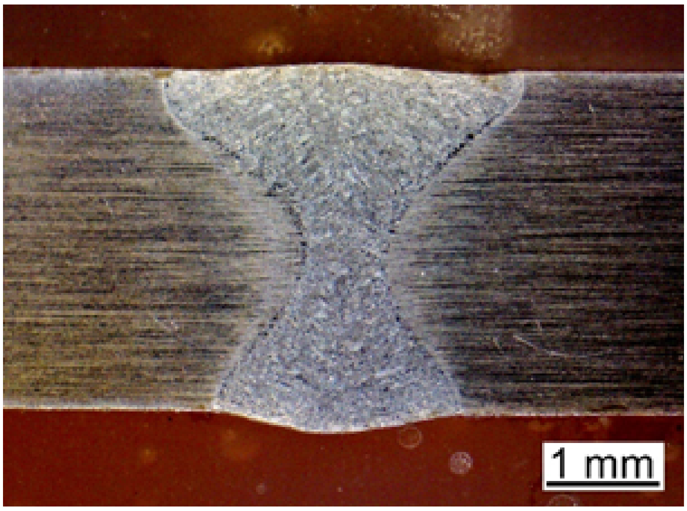

Fig. 2. Test joint macrostructure

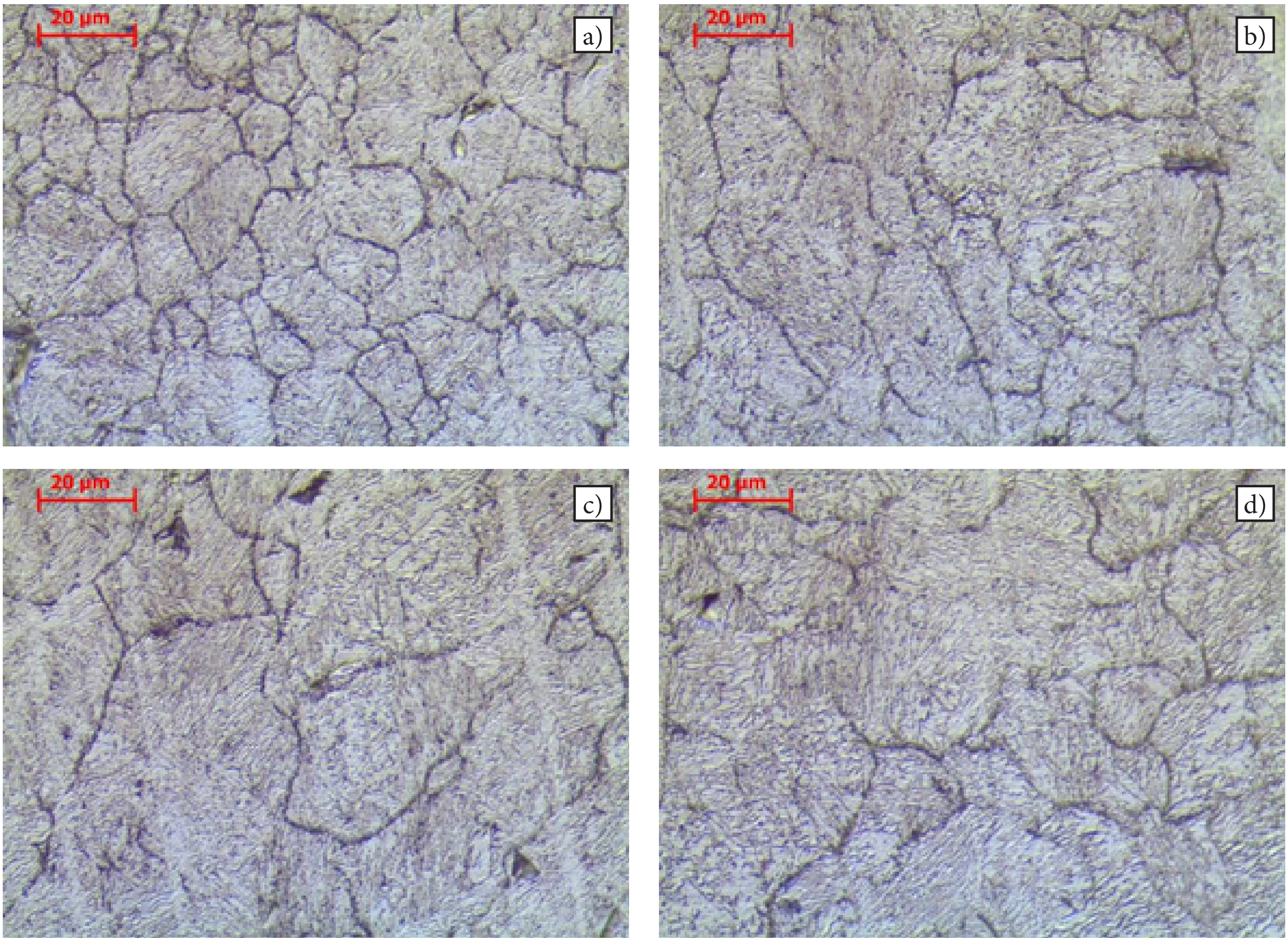

Fig. 3. Microstructure of steel 17-4PH after welding: a) BM – fine-grained martensitic structure, b) HAZ – martensitic structure with slight amounts of ferrite along the grain boundaries (indicated with the arrows), visible slight grain growth and c–d) weld – martensitic structure

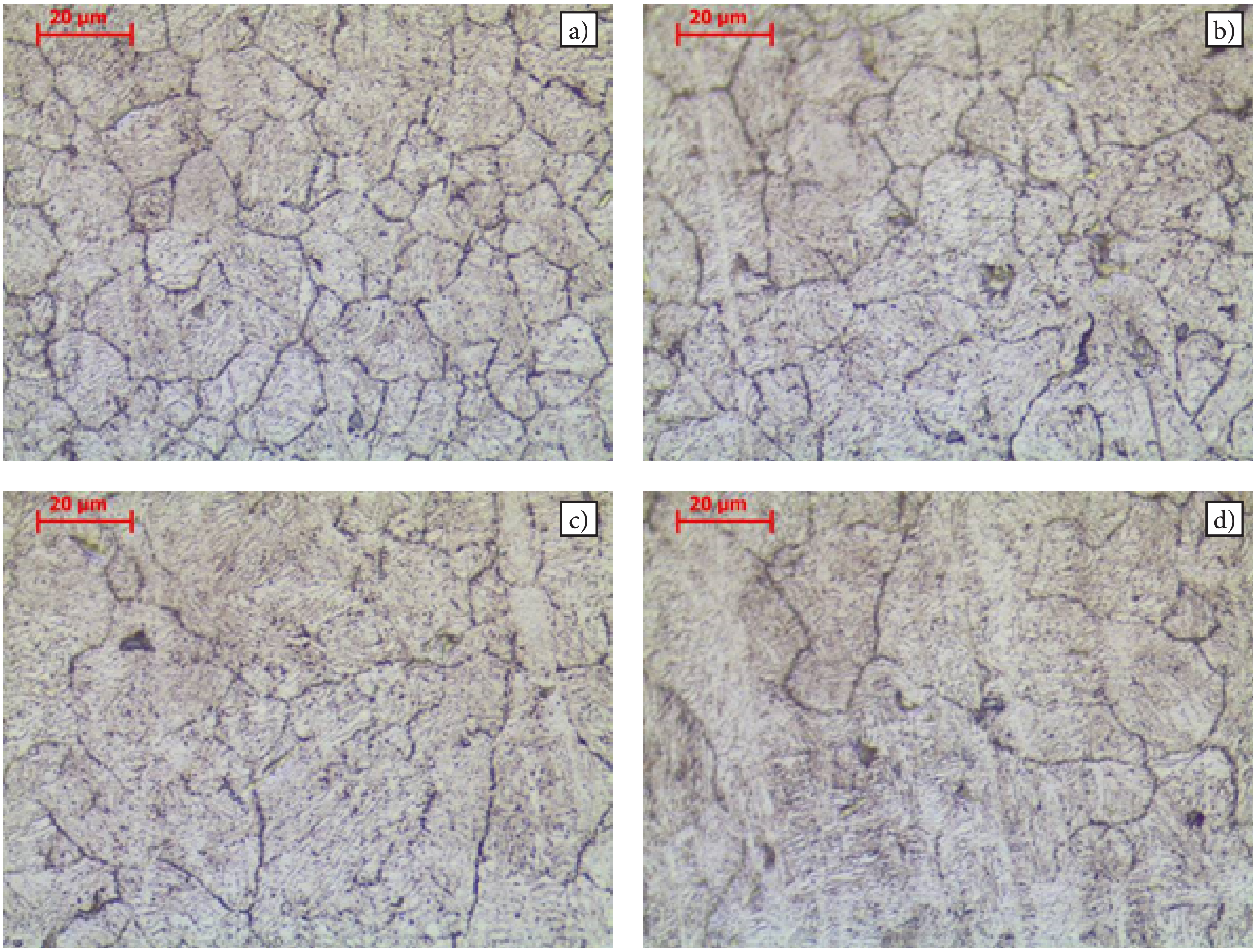

Fig. 4. Microstructure of steel 17-4PH after ageing at a temperature of 621°C: a) BM – fine-grained martensitic structure, b) martensitic structure, visible slight grain growth and c–d) weld – martensitic structure

The structure of the weld made of steel 17-4PH was martensitic. The crystallite boundaries were clearly visible (see Fig. 4d). The heat treatment did not trigger any microstructural transformations (specimen being observed using light microscopy). The martensitic structure of the weld resulted from the fact that temperature Ms was above room temperature. As a result, during the cooling of the weld, austenite could transform into martensite.

The tensile strength assessment of the specimens involved the welded joints subjected to mechanical working before heat treatment. The thickness of the specimens amounted to 2.8 mm; the cross-section in the part subjected to measurement having dimensions of 10 mm × 2.8 mm. The measurement length amounted to 50 mm and contained the weld symmetrically (25 mm on the side of the HAZ and 25 mm the side of the base material). The weld was perpendicular to the direction of tensile strength action. The assessment involved the area of rupture and the value of tensile strength R_m. Figure 5 presents the specimen after rupture and fractures. The specimens ruptured in the weld area. Tensile strength R_m amounted to 1020 MPa and 1039 MPa, in relation to the total unit elongation – 14.3% and 15.4% respectively. The cross-sectional hardness measurements revealed the non-uniform hardness distribution after welding and the uniform distribution of hardness after heat treatment. After heat treatment, hardness was reduced and restricted within the range of approximately 330HV10 to 340 HV10 (in comparison with an initial value of approximately 440 HV in the base material area). After welding, the HAZ hardness decreased and was restricted within the range

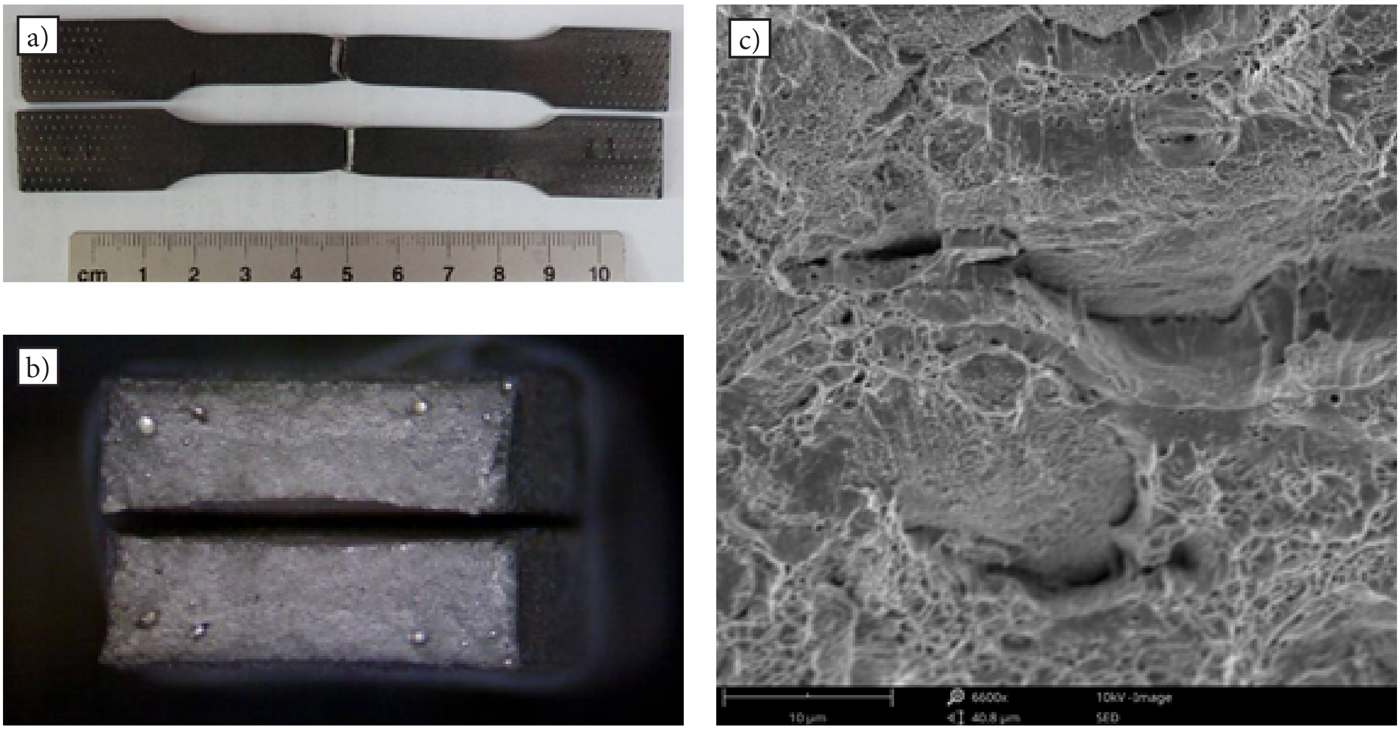

Fig. 5. Results of the tensile strength test of the joint made of steel 17-4 PH, after heat treatment (1038/621): a) specimens after rupture with the visible area of rupture in the weld; visible area reduction, b) specimen fracture (LM) and c) specimen fracture (SEM) – plastic fracture

of approximately 330HV10 to 340 HV10. The above-presented situation indicates that the heat input to the material (during the welding process) led to the dissolution of the hardening phases (mechanism similar to supersaturation). In spite of the high welding rate, the HAZ was characterised by reduced hardness, necessitating post-weld heat treatment.

Concluding remarks

The above-presented technological welding tests justified the formulation of the following conclusions:

– it is possible to make high-quality laser welded joints of 3 mm thick steel 17-4PH without using the filler metal. The test joint (weld) did not contain deformations or cracks (microcracks);
– after the completion of the welding process, the structure of weld and that of the HAZ were martensitic,
– welding process led to a decrease in hardness if compared with that of the base material. The foregoing resulted from the dissolution and/or coagulation of the precipitates of the hardening phase,
– heat treatment led to favourable unit elongation restricted within the range of approximately 13% to 14% (with visible area reduction). However, rupture took place in the weld area (Rm = approximately 1020 MPa), which could result from the presence of the coarse crystalline structure in the aforesaid area. The base material contained fine-grained structure. Heat treatment did not trigger significant changes in the size of the grain.

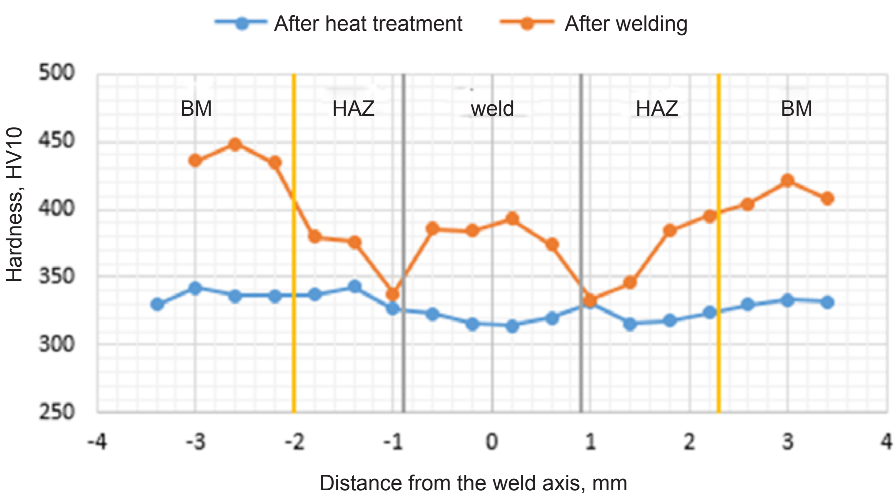

Fig. 6. Distribution of hardness (HV10) in the cross-section of the welded joint

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