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Assessment of Mechanical Properties of Laser Beam Welded Joints Made of Steel Strenx S700MC Subjected to High Impact Load

Abstract: The article assesses the strength and ductility of laser welded joints made of steel Strenx S700MC. The assessment was based on tests results concerning the material structure, hardness as well as quasi-static and dynamic tensile tests. The dynamic tests were performed using the tensile split Hopkinson pressure bar technique and strain rates of 10^3 s^{-1}. The obtained results revealed that the strength of joints under quasi-static and dynamic tensile test conditions were high and similar, yet their ductility significantly deteriorated under the impact load.

Keywords: laser welding, high-strength steel, impact energy absorber, split Hopkinson pressure bar technique

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Introduction

In Europe by the year 2020 the level of harmful substances emitted by cars will have been reduced to 147 g/km [1]. EU regulations will force car manufacturers to look for alternative drive methods (e.g. electric drives) and decrease car weights. The trend to reduce the weight is also visible in the production of lorries. The use of advanced materials in the production of lorry components has imposed a new approach to the design of vehicles and the use of advanced manufacturing technologies. The above-named approach is manifested, e.g. by using Advanced High-Strength Steels (AHSS), enabling the design of lighter vehicles characterised by lower fuel consumption and CO_2 emission [2]. However, activities connected with the reduction of vehicle weight entail the use of state-of-the-art innovative solutions ensuring the obtainment appropriately high vehicle safety. For this reason, car designs feature so-called crumple zones including impact (mechanical) energy absorbers, made primarily in AHSS. The ability to transmit required static and dynamic loads of a given structure is one of the key factors affecting the passive safety of vehicles [3].

Typically, steels used in the production of impact energy absorbers are low-alloy and dual-phase martensitic steels or manganese-boron steels intended for hardening during the stamping process. Absorbers are made of thin sheets or thin-walled closed shapes, the production of which involves the use of various manufacturing technologies based on the plastic working

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and joining of sheets. High requirements set for absorbers today make their production a significant technological and economic challenge. The foregoing issue can be exemplified by the joining of elements before or after the plastic working process.

Because of a limited heat input to a material during welding and the cost-effectiveness of the process, one of the most progressive and intensively developing joining technologies in the automotive industry is laser welding. This fact could be ascribed to the necessity of joining high-strength car body steels, increasingly popular in the production of cars.

The obtainment of high-quality welded joints of car body AHSS sheets poses numerous difficulties. The issue is particularly visible in the production of absorbers, where the welded joints should be capable of transmitting quasi-static, fatigue loads and impact loads occurring during collisions or crashes. In view of the foregoing, the issue related to the strength-related assessment of welds made when manufacturing impact energy absorbers is becoming crucially important. Joints are tested using a number of methods, which can roughly be divided into destructive and non-destructive methods. The research work discussed in this study involved primarily the destructive methods including the quasi-static and dynamic tensile test, hardness distribution measurements and metallographic tests.

The strength assessment of the laser weld based on the quasi-static tensile test is a frequently applied testing technique. The above-named test provides sufficient information concerning the strength of the joint and is relatively easy to perform. However, as regards the assessment of welded joints of absorbers, data obtained experimentally in the quasi-static tensile test may not reliably characterise the mechanical behaviour of the weld under impact load conditions.

As a result, it is necessary to apply other testing techniques, better reflecting the conditions of the weld plastic strain progressing at a significant rate.

The assessment of the weld strength was based on the split Hopkinson pressure bar technique (SHPB). Presently, the above-named testing technique is commonly used to determine mechanical characteristics under dynamic load conditions. This method makes it possible to subject a material specimen to an impact load under controlled experiment conditions. Plastic strain can progress at a strain rate exceeding 10^3 s^{-1}[4].

Strength tests under quasi-static and dynamic load conditions involved welded joints made of steel Strenx S700MC. Although the above-named steel is commonly used in the production of high-strength structures, little is written about it in scientific reference publications, with the exception for work [5] presenting test results concerning a 10 mm thick laser welded butt joint. The authors of the work demonstrated, among other things, the very low toughness of the joint at a temperature of -30°C, probably attributable to excessively high contents of alloying agents, i.e. titanium and niobium in the weld. Because of the fact that the effect of low temperature on mechanical properties of metals and their alloys, manifested by an increase in strength accompanied by the deterioration of material plasticity, was similar to the effect of a strain rate, this research work aimed to assess the strength of a laser welded joint made of steel Strenx S700MC under Hopkinson test conditions.

The article is divided into three parts. The first part is concerned with the mechanical characteristics of the above-named steel and the technological process of laser welding. The second part presents the methodology of metallographic tests involving the crystalline structure of welds, measurements of hardness distribution in the joint as well as strength tests under quasi-static and dynamic load conditions. The third part presents and discusses results obtained in the tests.

Characteristics of the material and laser welding process

Steel Strenx S700MC belongs to high-strength low-alloy steels (HSLA) characterised by higher mechanical parameters. Figure 1 presents the location of the above-named steel in an elongation–tensile strength diagram demonstrating that HSLA steels are characterised by high plasticity combined with high strength. The term of "Strenx" added to the steel name is only of commercial nature and is used by the steel manufacturer, i.e. SSAB of Sweden.

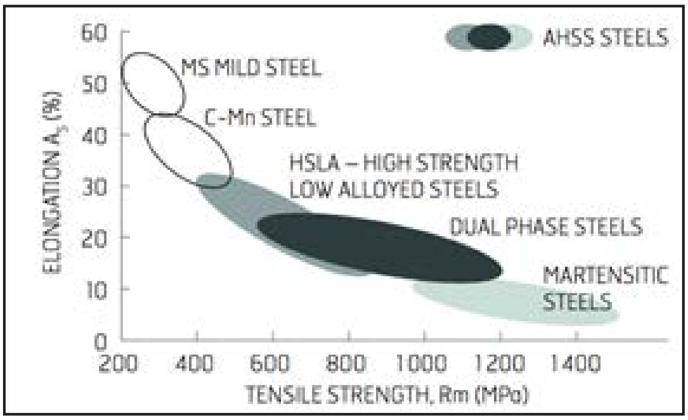

Fig. 1. Group of AHSS [6]

Steel Strenx S700MC is a TMCP type structural steel having a minimum yield point restricted within the range of 650 to 700 MPa (depending on the thickness of a sheet). Because of its favourable strength-elongation ratio, the steel can be subjected to cold plastic working enabling the making of lightweight structural elements characterised by high mechanical strength. The steel is supplied in coils, sheets or forms having thicknesses restricted within the range of 2 to 10 mm [7]. The research work involved welded joints made of 2 mm thick sheets. The mechanical properties of sheets made of steel Strenx S700MC, guaranteed by the manufacturer, are presented in Table 1.

The chemical composition of steel Strenx S700MC is presented in Table 2. The steel contains little carbon, yet is precisely supplemented by other alloying agents including niobium, titanium and vanadium. According to data provided by the manufacturer in the material certificate the carbon equivalent was CET(CEV) = = 0.25(0.39) %.

Butt laser welding of steel Strenx S700MC

One of the challenges related to the laser welding of steel Strenx S700MC is to avoid the loss of mechanical properties (obtained through the thermomechanical control process) triggered by the welding thermal cycle [8]. Because of the foregoing, the adjustment of laser welding technological parameters ensuring the obtainment of the optimum welding linear energy is of great importance.

The analysis concerning the effect of the parameters of the laser welding of 2.0 mm thick sheets made of steel Strenx S700MC on the quality of butt joints was performed using a production welding station of the BOZAMET company. The welding station is provided with a fibre laser (IPG) having a maximum power of 6 kW and a wavelength of 1068 nm. The station is also equipped with a 6-axis industrial robot (ABB) provided with an IPG laser head and positioners with tables enabling the fixing of welding equipment. The production station and the welding head are presented in Figure 2.

Table 1. Selected mechanical parameters of steel Strenx S700 MC [7]

	R_e [MPa]	R_m [MPa]	A80 [%]
Minimum values of mechanical parameters declared by SSAB	≥ 700	750-950	≥ 10
Values of parameters contained in the material certificate in relation to the specimen having crystalline texture parallel to the tensile direction	766	816	16

Table. 2. Chemical composition of steel Strenx S700MC (ladle analysis) [7]

C (max %)	Si (max %)	Mn (max %)	P (max %)	S (max %)	Al_{tot} (min %)	Nb (max %)	V (max %)	Ti (max %)
0.12	0.21	2.10	0.020	0.010	0.015	0.09	0.20	0.15

Fig. 2. Production welding station and the IPG laser head

To provide the appropriate quality of welded surfaces, semi-finished sheets were cut out using a welding station provided with a CO_2 laser. The laser cutting process was not followed by the additional treatment of the surfaces of sheets to be joined.

The welding process was performed in production conditions without the use of shielding gas. The process parameters were adjusted on the basis of previous technological tests performed using various sets of parameters including welding power restricted within the range of 1500 W to 4100 W and a welding rate restricted within the range of 10 mm/s to 70 mm/s. The welded joints were evaluated on the basis of visual tests performed in accordance with the PN-EN ISO 13919-1 standard. The joints represented the requirements of quality level B. Selected joints were subjected to hardness measurements based on the Vickers hardness tests and performed under a load of 10 N. The assessment criterion was uniform microhardness distribution in the weld and in the HAZ similar to that of the base material. The foregoing enabled the adjustment of the welding parameters presented in Table 3.

Table 3. Laser welding process parameters

Parameter	Value/Description
Beam trajectory	linear
Welding power [W]	3100
Welding rate [mm/s]	70
Process spot diameter [mm]	0,6
Linear energy [J/mm]	44
Sheet thickness [mm]	2
Type of joint	butt joint

Testing methodology

Metallographic tests

Optical microscopic tests were performed using metallographic specimens prepared by means of an automatic Rotopol 21 grinder-polisher (Struers). The specimens were subjected to grinding followed by polishing performed using diamond slurries of decreasing granulation, i.e. 9, 6, 3 and 1 μm. The final polishing was performed using the slurry of silicon oxide (OPS). The microscopic tests were performed using an PMG 3 metallographic microscope (Olympus). The steel microstructure was revealed by etching performed using Nital (2% solution of nitric acid in ethanol).

Quasi-static tensile test

Tensile tests performed at a strain rate of 0.001 s^{-1} and following the requirements of PN-EN ISO 6892-1:2010 were conducted using an MTS Criterion C45 testing machine. Comparative tests involved flat welded and unwelded specimens characterised by geometry presented in Figure 3.

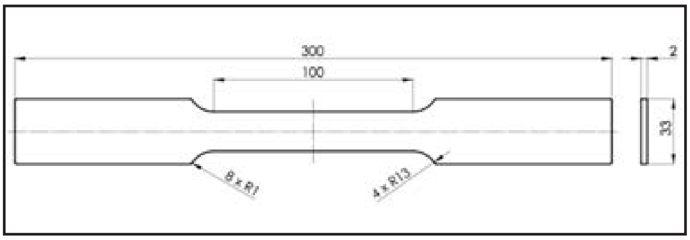

Fig. 3. Test specimen geometry

The specimens were cut out using laser. The laser cutting parameters were adjusted to minimise a heat input to the material without compromising the quality of a surface subjected to cutting. The specimens were made in two orientations, i.e. perpendicularly and in parallel to the sheet rolling direction. The welded specimens after laser cutting are presented in Figure 4.

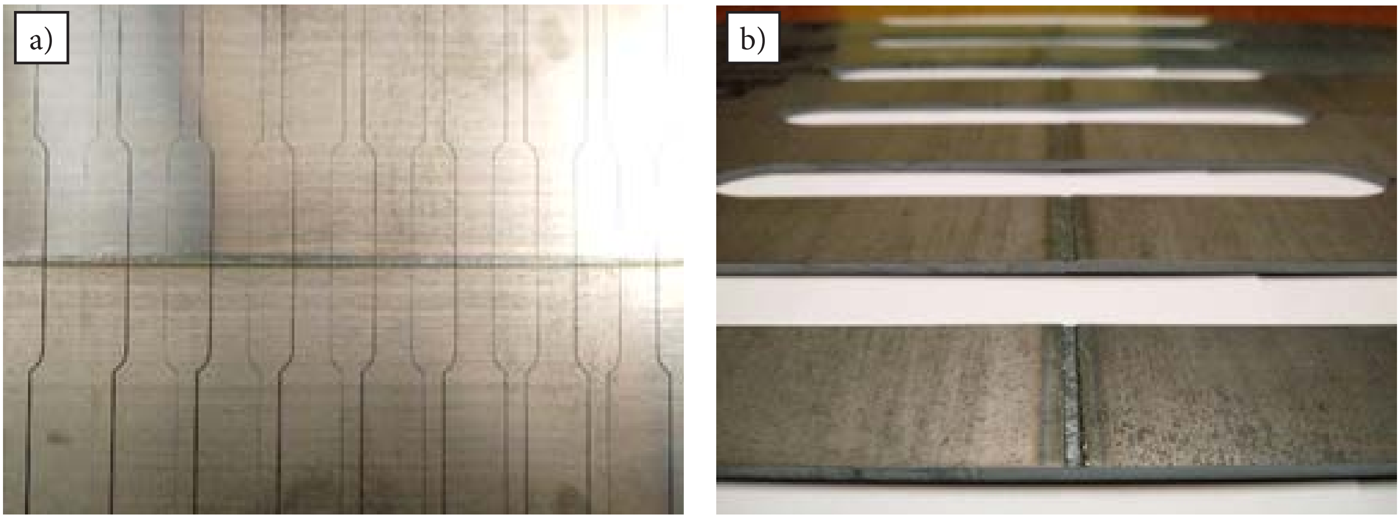

Fig. 4. Welded specimens after laser cutting

Split Hopkinson Pressure Bar Test (SHPB)

Tests under dynamic plastic strain conditions occurring at a strain rate of 1000 s^{-1} were performed on a test rig using the tensile split Hopkinson pressure bar technique. The test SHPB test rig is presented schematically in Figure 5.

The test rig was composed of a pneumatic striker, two bars, i.e. the incident bar and the transmitter bar as well as of a system of strain gauges. The test rig design was based on a classical solution proposed by Kolsky [9], who initially developed a system enabling the performance of dynamic compressive tests. The improvement of the above-named solution, following the idea suggested by the author of work [10], led to the development of a testing system enabling the tension of a specimen by a so-called transmission sleeve, i.e. an element compressed between the faces of the incident and the transmitter bar, the ends of which were connected to the tip of the mechanical test specimen. The impact by the striker bar against the incident bar generated an elastic compressive wave (in the incident bar), propagating in the direction of the specimen. After reaching the specimen, because of the use of the steel sleeve, the above-named wave only triggered elastic strains in the specimen. Afterwards, the elastic wave, via the sleeve and, partly, the specimen, moved towards the transmitter bar, i.e. its free end. After reflecting against the free end of the transmitter bar the wave changed its sense (into backward) and transformed into an elastic tensile wave. After reaching the specimen, the elastic tensile wave extended the specimen both in the elastic and the plastic manner (as, at that stage of the loading process, the sleeve was not mechanically connected to the faces of the bars).

The waveforms recorded using the extensometric measurement system, i.e. striking $\varepsilon_I(t)$, reflected $\varepsilon_R(t)$ and transmitting $\varepsilon_T(t)$, enabled the determination of the dynamic curve related to the tension of the test specimen. The above-named determination required the application

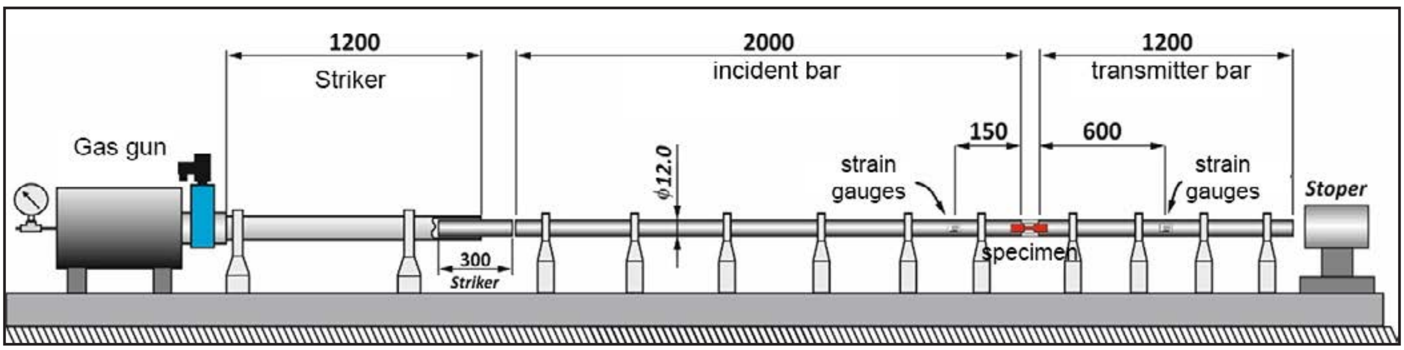

Fig. 5. Schematic diagram of the tensile SHPB test rig

of the following equations:

$$\sigma_p(t) = E\frac{A_o}{A_{op}}\varepsilon_T \tag{1}$$

$$\dot{\varepsilon}_p(t) = -\frac{2C_o}{l_o}\varepsilon_R \tag{2}$$

$$\varepsilon_p(t) = -\frac{C_o}{l_o}\int_0^t \dot{\varepsilon}_p(t)dt = -\frac{2C_o}{l_o}\int_0^t \varepsilon_R(t)dt \tag{3}$$

The detailed description of the test rig design along with data concerning the metrological properties of the measurement system are presented in work [11]. The tests required the development of grips (Fig. 6b) enabling the fixing of the miniature flat specimens (Fig. 6a) between the bars used in the SHPB test. The reduction of wave disturbances resulting from specimen fixing backlashes required the particular geometrical correctness and workmanship precision when making the specimens and the grips. Similar to quasi-static tests, the specimens used in the dynamic tests were made in two variants, i.e. welded and unwelded (10 pieces each). To minimise the HAZ, the specimens were cut out of sheets using the spark erosion wire cutting technique.

Test Results

Joint microstructure

The macrostructure of the welded joint and the microstructure of its selected areas are presented in Figure 7. The macro and microstructural test results revealed that the joint was characterised by high quality and the lack of welding imperfections such as porosity or metallic inclusions. The lack of porosity and the parallelism of the fusion line in the weld indicated full material penetration (penetration width amounted to approximately 0.8 mm)[12], resulting from the appropriate adjustment of welding parameters. The heat affected zone (Fig. 7c) was characterised by the structure similar to that of the base material, having the uniform ferritic-bainitic structure (Fig. 7b). However, the HAZ structure was significantly more fine-grained and did not reveal any directivity (because of crystallisation). The fusion line area (Fig. 7d) contained primarily bainite (B) with a slight amount of ferrite α (F_α). Photographs in Figure 7e-f present the diversified weld microstructure, including bainite (B) and allotriomorphic ferrite α_{af} as well as acicular ferrite α_{ac} surrounded by the phase of allotriomorphic ferrite α_{af}. Locally, the microstructure contained Widmanstatten ferrite α_{wf} (Fig. 7f) and single precipitates of polygonal ferrite α_{pf} (Fig. 7e).

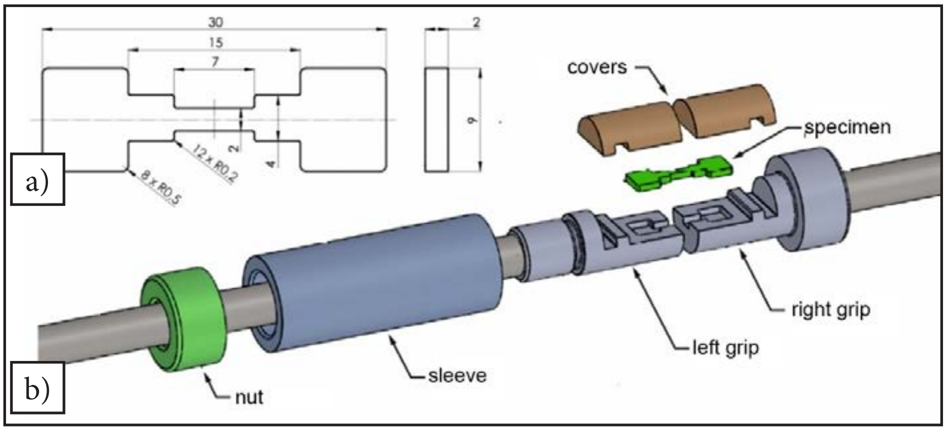

Fig. 6. Geometry of the mechanical test specimen (a); solution enabling the fixing of the specimen between the bars used in the SHPB test (b)

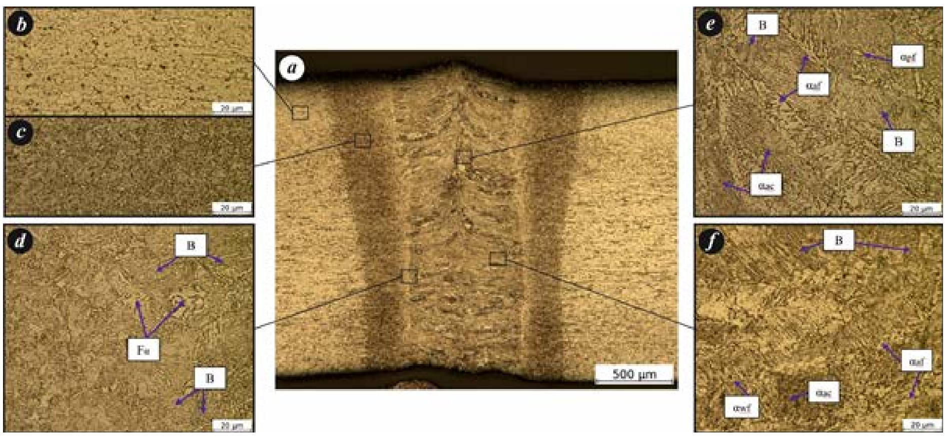

Fig. 7. Macro and microstructure of the laser welded joint made in steel Strenx S700MC: a) joint macrostructure, b) base material microstructure, c) HAZ microstructure, d) fusion line microstructure, e) and f) weld microstructure

Hardness distribution in the joint

Hardness measurements were performed along the line located at the half of the sheet thickness, at intervals amounting to 0.25 mm (Fig. 8). The hardness in the base material was restricted within the range of 281 HV1 to 296 HV1. The hardness in the HAZ (approximately 0.3 mm in width) was slightly lower and restricted within the range of approximately 272 HV1 to 280 HV1. The material hardness near the weld axis was slightly higher and amounted to 304 HV.

Small differences in the material hardness across the cross-section of the joint indicated its high strength, corresponding to that of the base material. The high mechanical properties resulted primarily from the presence of three phases in the weld. The above-named phases were bainite, being the mixture of supersaturated ferrite and precipitated carbides (B), acicular (fine-grained) ferrite α_{ac}, being the form of bainite, yet nucleating in a different manner and allotriomorphic ferrite α_{af} surrounding islands of bainite or acicular ferrite, depending on the weld area. The most favourable phase enabling the obtainment of optimum mechanical properties was acicular ferrite, nucleating inside former austenite grains, usually on intermetallic inclusions in steel [13]. The effect of the above-named phase on material properties resulted from the directivity and size of its lamellas. By contrast with bainite, fine-grained (acicular) ferrite lamellas grow freely in various directions, as their growth is not restricted by the boundary of finite austenite grains (ferrite lamellas do not nucleate on the boundary as is the case with bainite) and are usually 10 µm in length and 1 µm in width [14]. The content of acicular ferrite in the weld microstructure was significantly lower than that of bainite. This resulted primarily from the technological process parameters, the low content of non-metallic inclusions in the weld and the fact that a shielding gas was not used during the welding process [15]. The lack of cracks in the weld generated through mechanical tests could be ascribed to the presence of allotriomorphic ferrite around islands of bainite. Because of their significantly lower contents in the weld, the remaining phases had considerably lower influence, yet they were typical phases present in welded joins made of high-strength steels.

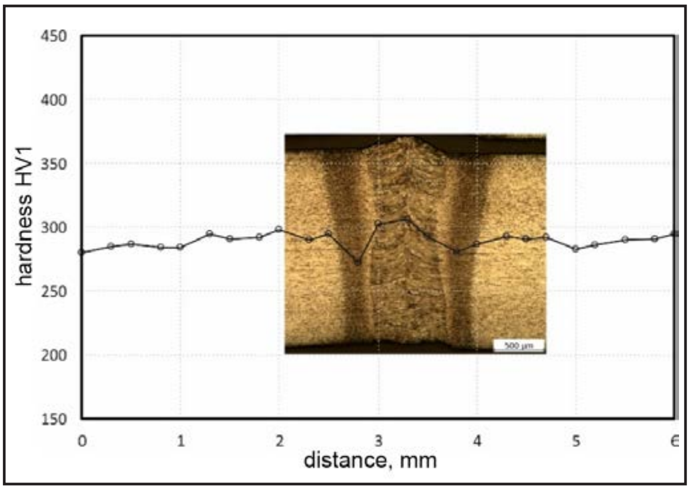

Fig. 8. Hardness distribution in the welded joint made of steel Strenx S700MC

Quasi-static and dynamic strength of the weld

The quasi-static test results presented in Figure 9 revealed that the high strength of the welded joints subjected to laser welding performed using the beam parameters presented in Table 3. The specimens ruptured in the base material, near the HAZ. The above-named observation was confirmed by hardness measurement results indicating the most significant decrease in material hardness at the interface of the aforesaid areas. The strength of the welded specimen was nearly the same as that of the unwelded one, regardless of the orientation in relation to the direction of rolling, i.e. (⊥) perpendicular or (=) parallel. The ductility of the welded joint also proved high, with only a slight decrease in elongation detected in relation to the welded joint. The specimens of the perpendicular orientation (to the direction of rolling) were characterised by slightly higher yield point R_e = 810 MPa, yet accompanied by slightly lower ductility A_{10} = 15% in comparison with the specimens of the parallel orientation (R_e = 790 MPa and A_{10} = 17% respectively).

The obtained mechanical characteristics were consistent with the information contained in the certificate provided by the manufacturer (SSAB).

The results of the dynamic SHPB tests performed at a strain rate of 1000 s^{-1} (Fig. 10) provided the basis for a different assessment related to the strength of the joint made in steel Strenx S700MC. In the above-named case the specimens cracked not only in the base material area but also in the heat affected zone. In addition, the ductility of the welded specimens deteriorated as well. The ductility of the unwelded specimens continued to be high (approximately A = 18%), yet the elongation value related to the welded specimens dropped to approximately 10%. The above-presented feature is undesired in terms of requirements related to impact energy absorbers. In addition, the plastic strain of the steel flow was slightly higher in comparison with the results of statistical tests (by approximately 40 MPa). The foregoing demonstrated that the steel subjected to the tests belongs to the group of materials characterised by low sensitivity to the strain rate within the range obtained within the research work. The above-named property of steel Strenx S700MC is favourable in terms of the requirements concerning impact energy absorbers. It should also be noted that the plastic strain values related to the flow within the range of low strain values (up to approximately 4%) were higher in relation to the welded specimens than those concerning the unwelded ones. The above-named phenomenon was also visible when comparing the quasi-static stress-strain curves (Fig. 9), yet to a lesser degree than in terms of the dynamic stress-strain curves.

In comparison with the quasi-static stress-strain curves, the dynamic stress-strain curves are irregular and characterised by significant oscillations impeding the interpretation of the mechanical strength test results related to the specimen. Disorders of the dynamic stress-strain curve profiles could be ascribed to the occurrence of undesired wave effects, triggered primarily by backlashes generated in various joints and contact surfaces. As a result, the interpretation of dynamic test results should take into consideration the specific nature of test conditions and the fact that curves obtained in tests could be encumbered with errors.

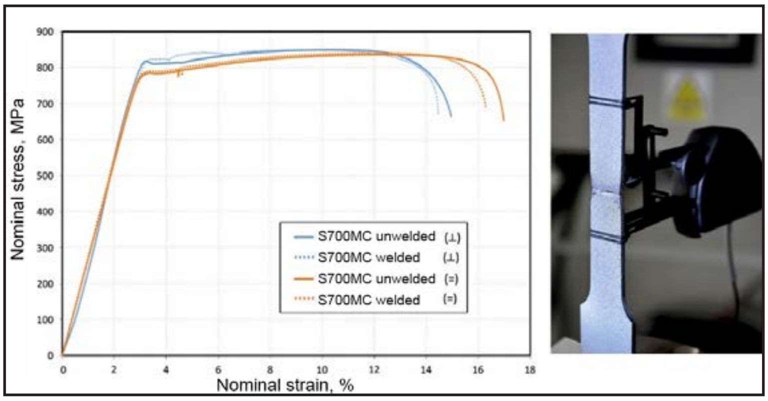

Fig. 9. Stress-strain curves of the welded and unwelded specimens in steel Strenx S700MC and the specimen after the rupture with the fixed strain gauge (specimen orientation in relation to the direction of rolling: (⊥) perpendicular; (=) parallel

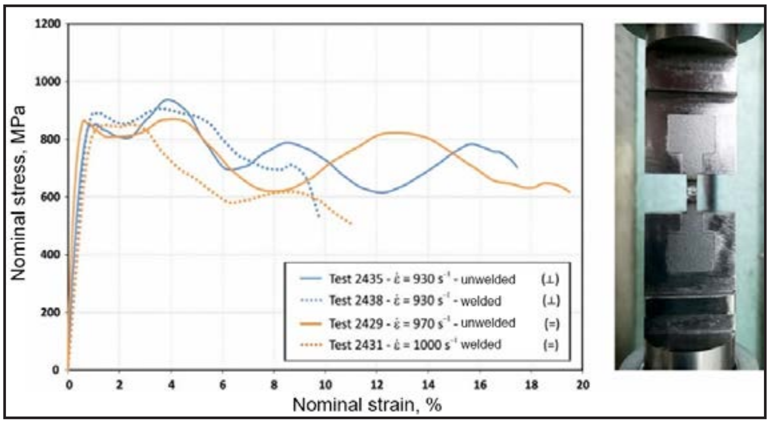

Fig. 10. Dynamic stress-strain curves of welded and unwelded specimens in steel Strenx S700MC and the specimen after the rupture (specimen orientation in relation to the direction of rolling: (⊥) perpendicular; (=) parallel

Conclusions

The tests concerning the mechanical properties of the 2 mm thick butt joints made of steel Strenx S700MC revealed that it was possible to obtain the high strength and ductility of the joint, even higher than those of the base material. The obtainment of the high strength and ductility required the precise adjustment of laser process parameters as well as the appropriate preparation and performance of the entire technological process (quality of edges to be joined, gap width etc.).

The quasi-static and dynamic tensile strength of the test joints was slightly higher, i.e. by approximately 4% than that of the base material. The hardness in the HAZ was lower than that of the base material. In addition, the ductility of the welded joints identified on the basis of experimental data obtained in the quasi-static tensile strength was high and only little lower than that of the base material (by approximately 2-3%). However, a significant decrease in the ductility of the joints (by approximately 40%) was observed under the Hopkinson test conditions at a strain rate of 10^3 s^{-1}. The reason for the above-named decrease could be ascribed to the unfavourable weld geometry, in terms of the joint impact energy absorbability, (excessively steep toe angle), increasing the susceptibility of the weld to structural notch-induced cracking. The above-presented reason justified the conclusion that in terms of welded joints of elements intended for transmitting impact loads (impact energy absorbers), standard, i.e. "static", methods of joint quality assessment were insufficient to design a welding process in an optimum manner.

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References

[1] Yang Z., Bandivadekar A.: *2017 Global update. Light-duty vehicle. Greenhouse gas and fuel economy standards.* International Council on Clean Transportation, 2017.

[2] Trailer Design Guideline. Strenx: The fastest route to efficient transport. SSAB, 2014.

[3] Keller S., Kimchi M., Mooney P.: *Advanced High Strength Steels.* Application Guidelines Version 6.0, 2016.

[4] Janiszewski J.: *Badania materiałów inżynierskich w warunkach obciążenia dynamicznego.* Wydawnictwo Wojskowej Akademii Technicznej, Warszawa, 2012.

[5] Górka J., Stano S.: *Properties and Structure of Laser Beam Welded Joints of S700MC Thermomechanically Treated Steel.* Biuletyn Instytutu Spawalnictwa, 2014, no. 5, pp. 35-40. http://bulletin.is.gliwice.pl/article/properties-and-structure-laser-beam-welded-joints-s700mc-thermomechanically-treated-steel

[6] SSAB: Advanced High Strength Steels For The Automotive Industry. Because green and safe cars will never go out of style. 2014, p. 5.

[7] SSAB: Data sheet Strenx S700MC, 2017, p. 1.

[8] Górka J.: *Study of structural changes in S700MC steel thermomechanically treated under the influence of simulated welding thermal cycles.* Indian Journal of Engineering & Materials Sciences, 2015, vol. 22, p. 497.

[9] Kolsky H.: *An investigation of the mechanical properties of materials at very high rates of loading.* Proceedings of the Physical Society. Section B, Volume 62, Number 11 pp. 676-700. http://dx.doi.org/10.1088/0370-1301/62/11/302

[10] Nicholas T.: *Tensile testing of materials at high rates of strain.* Experimental Mechanics, 1981, no. 21, pp. 177–185. http://dx.doi.org/10.1007/bf02326644

[11] Janiszewski J., Panowicz R.: *Tensile Split Hopkinson Bar Technique: Numerical Analysis of the Problem of Wave Disturbance and Specimen Geometry Selection.* Metrology and Measurement Systems, 2016, vol. 23, no. 3, pp. 425-436. https://doi.org/10.1515/mms-2016-0027

[12] Norris J.T., Robino C.V., Hirschfeld D.A., Perricone M.J.: *Effects of laser parameters on porosity formation: investigating millimeter scale continuous wave Nd:YAG*

laser welds. Welding Journal, 2011, no. 90, pp. 198-203.
[13] Illescas S., Fernandez J., Asensio J., Sanches-Soto M., Guilemany J.M.: *Study of the mechanical properties of low carbon content HSLA steels.* Revista de Metalurgia, 2009, 45(6), pp. 424-431. *http://dx.doi.org/10.3989/revmetalm.0902*
[14] Bhadeshia H.K.D.H.: *Bainite in steels.* Institute of Materials, 2nd ed., London, England, 2001.
[15] Hydraś D., Węgrzyn T., Piwnik J.: *Plastic propreties of fine-grained WMD after micro-jet cooling.* Archives of Metalurgy and Materials, 2014, vol. 59, no. 3, pp. 1-5. *http://dx.doi.org/10.2478/amm-2014-0155*