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Laser Beam Welding of 10 mm Thick T-joints Made of TMCP Steel

Abstract: The article presents research on the laser beam welding of 10 mm thick T-joints made of thermomechanically worked high-strength steel S700MC without using a filler metal. The research-related tests involved making single-sided and double-sided welded joints as well as performing non-destructive tests. The quality of joints satisfied the requirements of quality level B according to the PN-EN ISO 13919-1 standard. The single-sided welding performed using a beam power of 11 kW enabled the obtainment of 8 mm deep penetration without noticeable displacements in the web. The double-sided welded joints were characterized by correct geometry; the dimensions of pores present in the weld metal satisfied the maximum pore size criterion specified for quality level B. The weld microstructure was bainitic-ferritic; the hardness of the weld was by about 60 HV1 higher than that of the base material (280 HV1). The HAZ revealed a small decrease in hardness in comparison with that of the base material.

Keywords: laser beam welding, TMCP steel, T-joints

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Introduction

Laser welding has been relatively recently implemented in Polish industry, primarily because of high investment costs and technological difficulties. Presently, investments in this technology do not pose such a high financial risk as they did several years ago. Forecasts predict that the future will belong to companies applying laser technologies in an extensive range. This is because increasingly many welding companies are interested in employing technological lasers in production processes in order to modernise their production processes and take up the production of technologically advanced, new generation products. Increasingly, laser beam welding is often used to make T-joints of thick (over 4 mm) sheets. Presently, laser welding is applied not only in the automotive industry, but also in those of shipbuilding and power engineering, requiring joints of significant thicknesses. The use of laser beam welding enables the obtainment of high quality T-joints without using filler metals, which considerably decreases costs and reduces welding strains of such joints [1-6].

Individual Research

The purpose of the research-related tests was to determine the possibility of obtaining 10 mm thick T-joints made of steel S700MC using

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a laser beam without a filler metal. The chemical composition of the steel is presented in Table 1, whereas the structure of the steel is presented in Figure 1.

Table 1. Actual chemical composition of 10 mm thick steel S700MC

Contents of chemical elements, %										
C	Mn	Si	S	P	Al	Nb	Ti	V	N*	Ce**
0,056	1,68	0,16	0,005	0,01	0,027	0,044	0,12	0,006	72	0,33

* – N: content expressed in ppm, nitrogen identified through high-temperature extraction
** Ce – carbon equivalent

Welding Process

Processes of melting and welding were performed at Instytut Spawalnictwa using a TruLaser Robot 5120 robot laser processing station manufactured by Trumpf. The station was composed of a TruDisk 12002, disc laser having a maximum power of 12 kW with a working head installed on a KR30HA six-axial industrial robot produced by Kuka (Fig. 2). T-joints were welded using a D70 head manufactured by Trumpf, connected with the disc laser using an optical fibre having a diameter of 0.3 mm. The welding head was characterised by the following optical parameters:

– length of collimator focusing lens: f_{kol} = 200 mm,
– length of focal focusing lens: f_{og} = 400 mm.

Welding tests were performed for various values of laser beam power and various positions of the focus of the laser beam along its axis of propagation in relation to the T-joint web - parameter *f* (Fig. 3). The negative value of parameter *f* designates the penetration of the laser beam focus deep into the material being welded. In cases of double-sided welds, specimens were turned over after making the first run and the process of making another run was performed once the joint had reached a temperature of 40°C.

The adjustment of parameters enabling the obtainment of proper T-joints required the performance of tests involving the melting of the sheets using various process parameters. The adopted melting rate was constant and amounted to 2 m/min, changing the laser beam power and the position of the laser beam focus. The constant melting rate ensured the significantly higher efficiency of the laser welding of T-joints than the efficiency obtained using arc methods when welding similar types of joints.

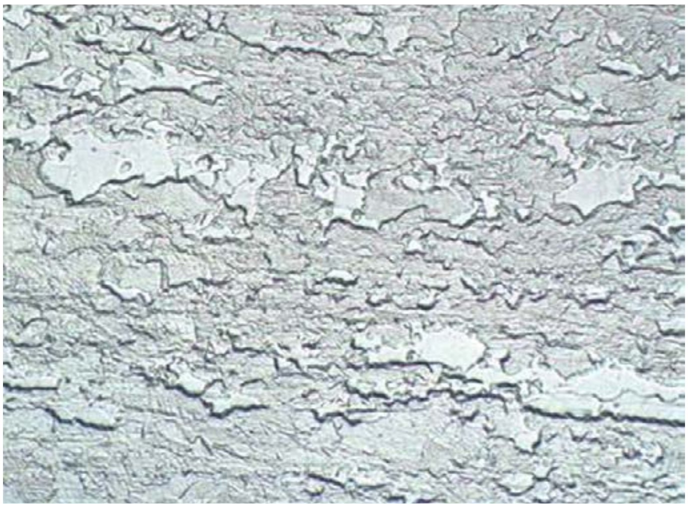


Fig. 1. Bainitic-ferritic structure of steel S700MC

Fig. 2. Station for the laser welding of T-joints

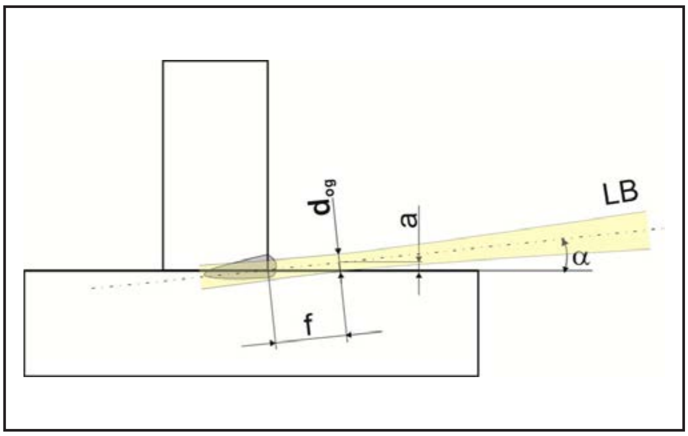


Fig. 3. Scheme of primary geometric dependences between the position of the laser beam focus having diameter d_{og} and the interface line of the sheets making up the joint

More stable melting (fewer spatters) was obtained when the laser beam focus penetrated the material being welded (negative values of parameter *f*). The analysis of metallographic specimens enabled determining the geometric dimensions of a penetration run for a given group of parameters. Afterwards, a graphic software programme was used to outline the penetration lines of a sheet melting run; the shape of a weld obtained in such a manner was plotted on the scheme of a T-joint (Fig. 4). Next, the foregoing as well as the theoretical calculations of the divergence angle of the focused laser beam were used to adjust the energy parameters of the double-sided laser welding of T-joins, the appropriate laser beam insertion angle and the position of the focus in relation to the interface of sheets being joined:

- laser beam insertion angle: $\alpha = 6°$,
- lifting of the laser beam in relation to the T-joint base: a = 0.5 mm.

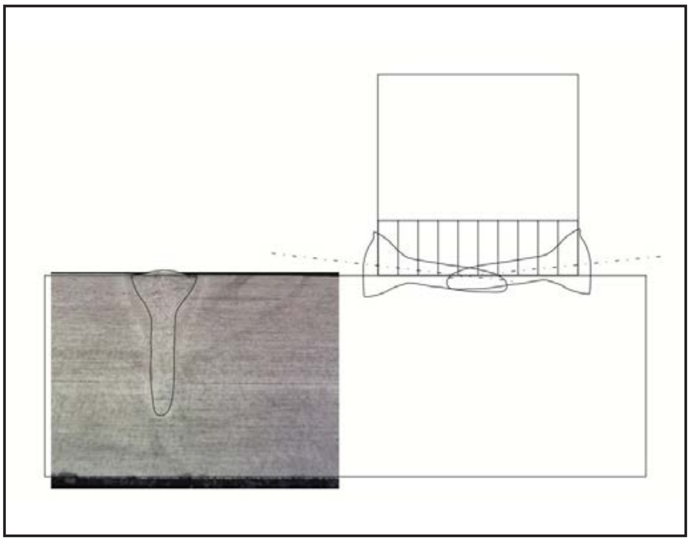


Fig. 4. Macrostructure of the sheet melting run for a laser beam power of 7 kW along with the outlined penetration line and the melting run outline plotted on the T-joint scheme

Initial welding tests revealed that the stable single-sided welding of 10 mm thick T-joints proved very difficult and was demonstrated, among other things, by the problematic formation of the weld root. After full penetration had been reached, the liquid metal tended to regularly leak locally on the weld root side (Fig. 5). At the same time, the weld face side revealed an incompletely filled groove along the entire length of the joint (Fig. 6). Because of the very narrow window of stable single-sided welding parameters, double-sided welding was considered as a favourable alternative as it could ensure the proper formation of a weld face without compromising the possibility of adjusting welding process parameters within a wide range (Fig. 7). Welding process parameters for selected joints are presented in Table 2.

Table 2. Parameters of the laser beam welding of 10 mm thick T-joints made of steel S700MC

Joint designation	Laser beam power *P*, kW	Welding rate *v*, m/min	Focus location *f*, mm	Beam lift *a*, mm
Joint 1	6	2	-4	0.5
Joint 2	6	2	-6	0.5
Joint 3	7	2	-4	0.5
Joint 4	7	2	-6	0.5
Joint 5	7	2	-8	0.5
Joint 6	8	2	-6	0.5
Joint 7	11	2	-8	0.5

Fig. 5. Single-sided T-joint with excessive penetration on the root side

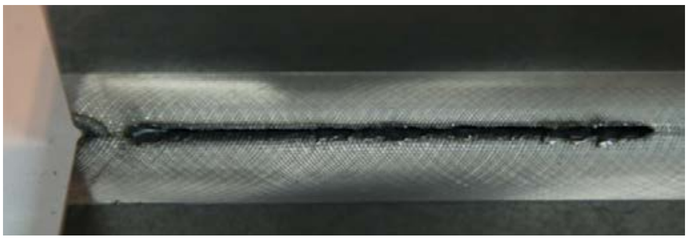


Fig. 6. Single-sided T-joint with an incompletely filled groove

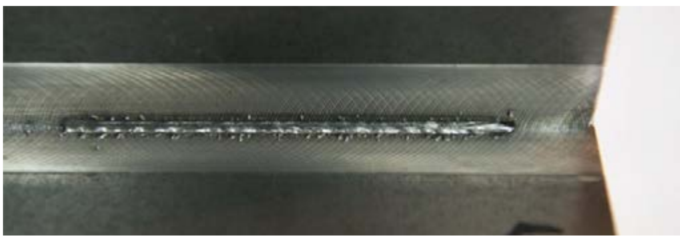
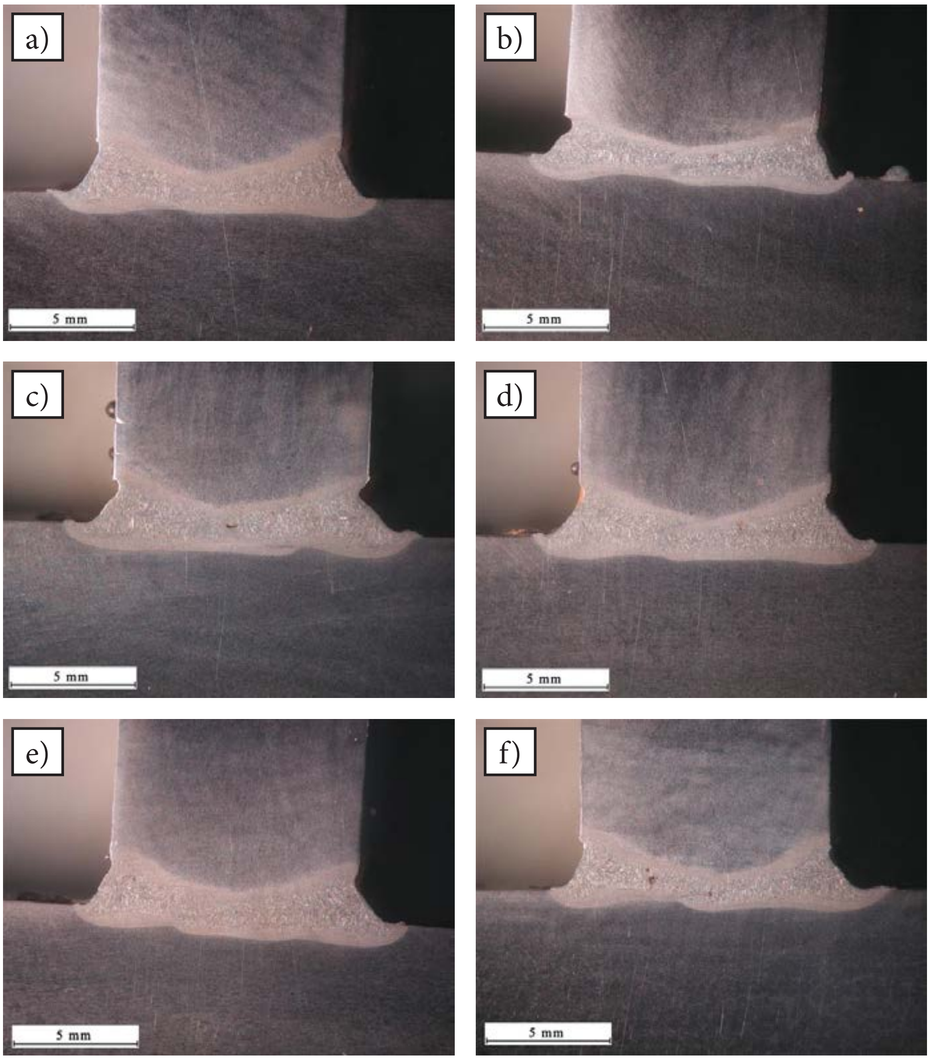


Fig. 7. Double-sided T-joint with a proper weld face

Tests of Welded Joints

The welded joints were subjected to visual tests according to PN-EN ISO 17637:2011 followed by the following destructive tests:

- macroscopic metallographic tests performed using an Olympus SZX9 stereoscopic light microscope; specimens were etched using Adler's reagent,
- microscopic metallographic tests performed using a NIKON ECLIPSE MA100 light microscope; specimen were etched using Nital,
- Vickers hardness tests performed using a WILSON WOLPERT 430 testing machine in accordance with PN-EN ISO 9015-1.



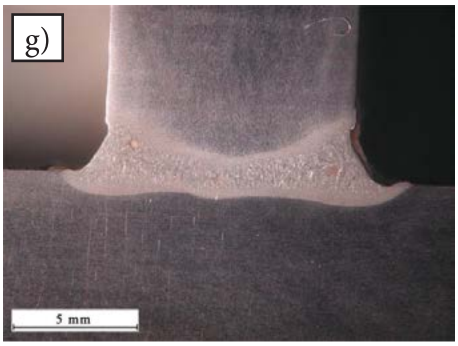


Fig. 8. Macrostructure of the test joints: a) joint 1; b) joint 2; c) joint 3; d) joint 4; e) joint 5; f) joint 6; g) joint 7 (Table 2)

Analysis of Test Results

Visual tests enabled the elimination of joints characterised by the lack of penetration or excessive penetration on the root side. In the remaining cases, the double-sided T-joints were characterised by the proper geometry of welds (Fig. 8).

The microscopic tests revealed the bainitic-ferritic structure in the weld area. The HAZ area did not reveal any significant grain size changes in relation to the base material, which was connected with a very low heat input to the welded joint area (Fig. 9).

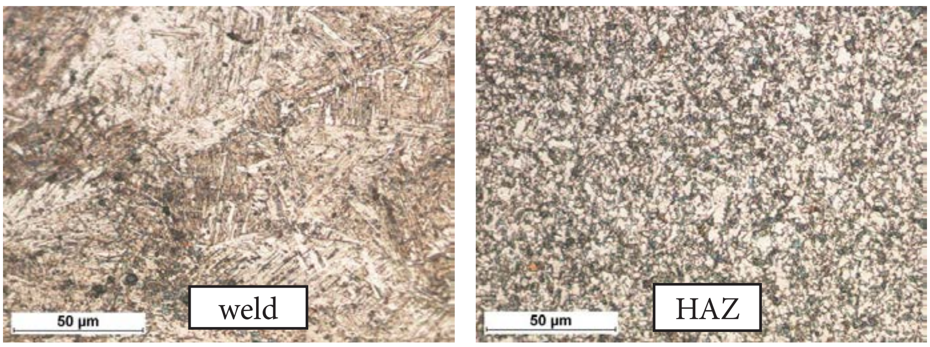


Fig. 9. Microstructure of the laser beam welded T-joint made of steel S700MC

The microscopic tests revealed the presence of gas pores in the joints. Such pores can be formed as a result of the very fast solidification of the liquid metal pool, related to a very high welding rate which impeded the release of gases from the weld zone. The pores are formed because of the confinement of gases dissolved in the metal or due to the evaporation of alloying elements or of impurities, if any, located on the interface of sheets being joined. In order to identify the effect of this welding imperfection on the joint quality, the imperfection was subjected to verification in accordance with standard PN-EN ISO 13919-1:2002 (Table 3). The quality assessment involved joint no. 3, characterised by the greatest gas pore size (Fig. 10).

Calculations:

h = 500 µm = 0.5 mm,
t = 10 mm.

$$0.5 \text{ mm} \leq 0.3 \cdot 10 \text{ mm}$$
$$0.5 \text{ mm} \leq 3 \text{ mm}$$
$$0.5 \text{ mm} \leq 2 \text{ mm}$$

Satisfied requirements of quality level B

As the greatest T-joint imperfection satisfied the criteria of quality level B, the remaining joints would also meet the requirements of quality level B.

The analysis of hardness test results revealed that when the welding rate was constant, a change in the laser beam power did not significantly affect the hardness in the weld area, restricted within the range of 340 HV1 to 350 HV1, where the base material hardness amounted to 280 HV1 (Fig. 11). The HAZ area revealed the distinct effect of welding linear energy and the beam power location on the hardness of this area. As regards the HAZ, the greatest hardness was measured in the joints made using a beam power of 7 kW (280 HV1). When the beam power increased to 11 kW, the HAZ decreased

Table. 3. Maximum dimensions of welding imperfections – gas pores according to PN-EN ISO 13919-1:2002

Maximum dimensions of welding imperfections for quality levels		
Mild requirements D	Medium requirements C	Restrictive requirements B
l or $h \leq 0.5\,t$ or 5 mm; lower value prevails, $f \leq 6$ %	l or $h \leq 0.4\,t$ or 3 mm; lower value prevails, $f \leq 2$ %	l or $h \leq 0.3\,t$ or 2 mm; lower value prevails, $f \leq 0.7$ %

Key:
l – length of a welding imperfection (measured in any direction),
h – dimension of a welding imperfection (height, width),
t – thickness of an element being welded,
f –projective areas of gas pores or cavities.

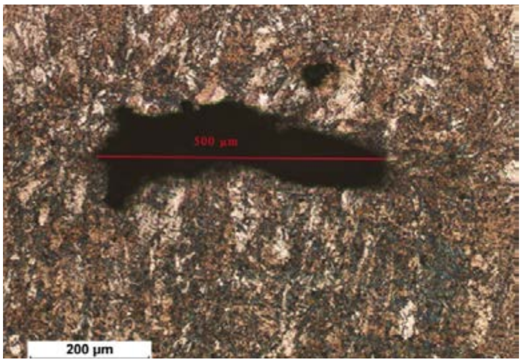


Fig. 10. Size of the gas pore in joint no. 3

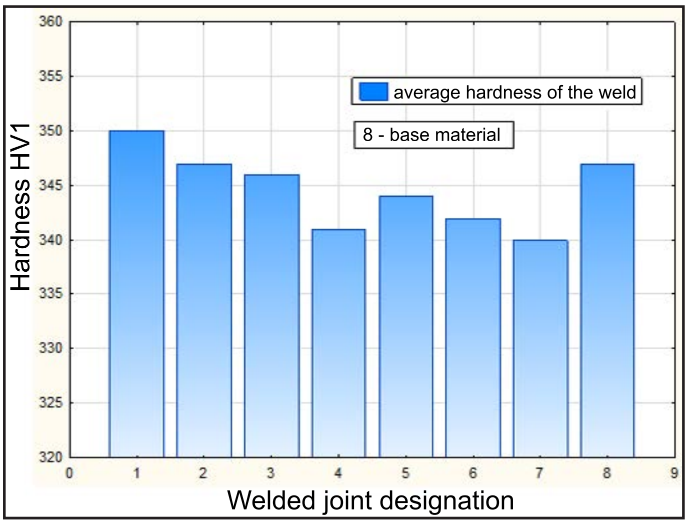


Fig. 11. Averaged hardness in the weld area of the T-joints

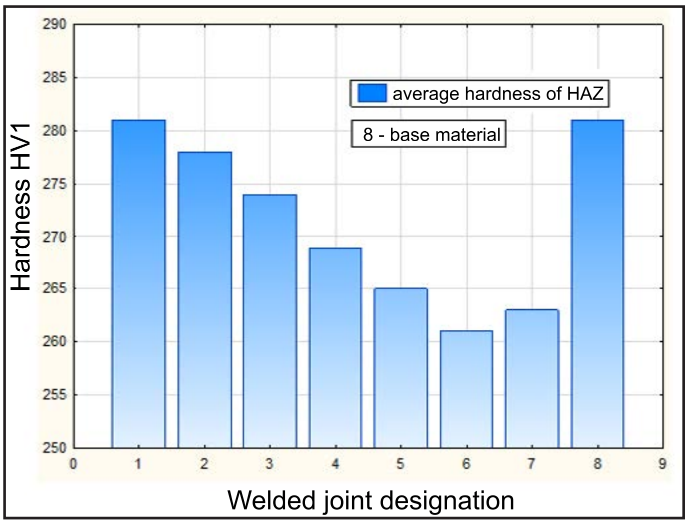


Fig. 12. Averaged hardness in the HAZ area of the T-joints

to 260 HV1 (Fig. 12). Such softening of the HAZ area did not affect the mechanical properties of the welded joint [7, 8].

Summary

The tests involving the laser welding of 10 mm thick T-joints made of steel S700MC performed using a TruDisk 12002, disc laser having a maximum beam power of 12 kW revealed that it is possible to obtain two-side welded T-joints characterised by high quality, satisfying the requirements of quality level B according to PN-EN ISO 13919-1, and by very well-shaped geometric penetration. The double-sided welding enabled the obtainment of 10 mm thick high quality butt T-joints (full penetration). The welds contained single gas pores, yet their size did not affect the operational properties of the welded joints. The weld structure was bainitic-ferritic (having a hardness of approximately 350 HV1). The HAZ area was characterised by slight grain growth and the partial loss of properties obtained during the Thermo-Mechanical Control Process. This resulted in the formation of a zone softer than the base material (260 HV1), yet this slight softening did not reduce the mechanical properties of the joints made during the tests [7, 8].

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