Sławomir Topór, Bernard Wyględacz, Santina Topolska

The Effect of Welding Methods on Temperature Distribution in Steel Components with Composite Lining

Abstract: The paper presents the comparison of three welding processes, i.e. manual (i.e. hand-held) laser welding without the use of consumables (filler metals), manual laser welding involving the use of a solid wire as the filler metal and manual TIG welding with the solid wire used as the filler metal. Welding tests included measurements of temperature on the root side, i.e. 2 mm and 4 mm away from the weld axis, as well as the comparison of linear welding energy values. The measurement results enabled the identification of the most favourable solution applicable for the welding of steel materials with composite lining.

Keywords: manual laser welding, steel materials with composite liners, welding line energy, welding temperature distribution, welding temperature measurements

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Introduction

Presently, various industrial applications entail numerous structural solutions which require the joining of sheets or tubes using a minimum welding heat input. Some of such solutions include steels sheets and tubes coated with polymer-based composite layers, characterised by significantly different properties as those of materials subjected to welding. Standard arc welding differences are useless in the above-named joints as a high (welding) heat input destroys composite materials. The aforesaid situation necessitates the search for technologies enabling the welding of such materials.

The development of many industries of crucial importance, both for the national and global economy, such as aviation, chemical and food industries, marine and nuclear engineering as well as environmental protection require the development of new materials, new manufacturing technologies and new joining technologies. Products used in the above-named industries should be characterised by high mechanical properties, including abrasive wear resistance as well as resistance to highly aggressive corroding media both at ambient and high operating temperature. Welding is the basic process making it possible to join materials during the fabrication of elements making up various structures and machinery. The use of newly developed materials of various chemical compositions or provided with additional coatings or lining, characterised by required properties, necessitates the application of methods ensuring the smallest possible effect on the initial structure and cohesion. One of more important issues in relation to the above-named materials is the identification and obtainment of the appropriate quality and properties of welded joints. The obtainment of the required quality and repeatability of joints necessitates the development of appropriate welding technologies, the ensuring of repeatable conditions at each technological state and welding process control as well as the inspection of joint quality based on various tests [1−7].

Heat sources used when welding advanced structural materials include electric arc (TIG, MIG, MAG and MMA), plasma arc, laser beam and electron beam. Materials sensitive to high and long-lasting welding process temperature require

mgr inż. Sławomir Topór – Antea Polska S.A.; Wydział Mechaniczny Technologiczny, Katedra Spawalnictwa – Wspólna Szkoła Doktorska Politechniki Śląskiej /Faculty of Mechanical Engineering, Department of Welding, Joint Doctoral School of the Silesian University of Technology/

mgr inż. Bernard Wyględacz, dr hab. inż. Santina Topolska, prof. PŚ, – Politechnika Śląska, Wydział Mechaniczny Technologiczny, Katedra Spawalnictwa /Silesian University of Technology, Faculty of Mechanical Engineering, Department of Welding/

the application of appropriate welding methods and technologies. Classical arc welding methods can be used with some restrictions, where the choice of the method is primarily dictated by the width of the heat affected zone to be obtained and the post-weld cooling rate. The primary disadvantages of the above-named welding methods include a high heat input and the relatively large volume of the molten metal pool, which in turn, leads to the excessive heating of joints and adjacent base materials, the generation of internal stresses and strains as well as to the unfavourable grain growth in the HAZ. Because of the above-presented disadvantages, researchers' attention is focused on the search for joining methods ensuring the minimum thermal effect on the material and the possibility of precisely controlling the thermal cycle of the process [1, 2, 4, 6−10].

Among various arc welding methods, the TIG technique is used most commonly because of the precise control of the process and that of a heat input provided during welding. The TIG method is one of the most universal welding techniques used in most industrial sectors. The method is usually applied in manual welding performed by highly qualified personnel. In the TIG process, electric arc is generated between a non-consumable inert gas-shielded tungsten electrode and an element subjected to welding. One of the advantages of the method is the possibility of obtaining high-quality welded joints. Mechanical properties of the joint depend on the structure of the weld and that of the HAZ, which, in turn, depend on a given technology applied in the welding process [3, 11, 12].

One of the recently dynamically developing welding methods is laser beam welding, where the joint is formed as a result of a laser beam-based heat input provided to the interface of elements subjected to welding. The aforesaid heat is responsible for the melting of the edges of elements being welded and the formation of the welded joint. Unlike in the TIG method and classical arc welding processes, the laser beam constitutes a very highly concentrated heat source, which translates into the presence of enormous temperature gradients in the welding area. Such a phenomenon results in the very narrow heat affected zone of materials subjected to joining and their very small volume being melted during the process. Classical automated laser welding is characterised by many advantages, including high power density and the small diameter of the laser beam spot. The above-presented advantages enable the obtainment of significant penetration depth, high welding rates and a precise, low and controllable heat input (i.e. features of great importance when joining technologically advanced alloys and materials provided with coatings or lining). Because of their complexity, automated and stationary laser beam welding stations are multiply more expensive than TIG welding machines. Increasingly common are manual (or hand-held) laser beam welding methods, where welding machinery and devices are mobile, compact and cheaper than their stationary counterparts [2, 4−10, 13, 14].

The target task includes the welding of sheets/plates made of steel S235 or steel S355, the thickness of which will be restricted within the range of 2 mm to 10 mm. One of the surfaces will be provided with permanently deposited composite lining (opposite the welding side) having (depending on its application) a thickness restricted within the range of 2 mm to 8 mm. In terms of tubes, it is expected that the method will enable the joining of steel tubes having a diameter of 150 mm (and above) and thicknesses (depending on application) restricted within the range of 2 mm to 10 mm.

Individual study

The tests discussed in the article aimed to compare heating and cooling times concerning areas of welded joints in steel elements provided with composite lining. The tests involved the use of 3 mm thick sheets made of steel S355J2+N. The tests related to welding thermal cycles involved the use of specimens without composite lining (because of the necessity of welding thermocouples to the side where lining was to be present). The thermocouples (used in the tests and welded to the specimens on the weld root side) were located 2 mm and 4 mm (i.e. 3 in each case) away from the weld axes and were tasked with the recording of welding thermal cycles. The tests involved the use of K-type thermocouples (NiCr-Ni) of class 1 (in accordance with PN-EN 60584-1), having dimensions of 2 mm × 0.20 mm and provided with the GLGL-type insulation (glass fibre/glass fibre) [15]. Temperature values were recorded using a 39470A data acquisition unit (Agilent). The pre-welding activities involved the preparation of a LightWELD hand-held laser beam welding station (with and without the use of filler metals) as well as the preparation of a manual TIG welding

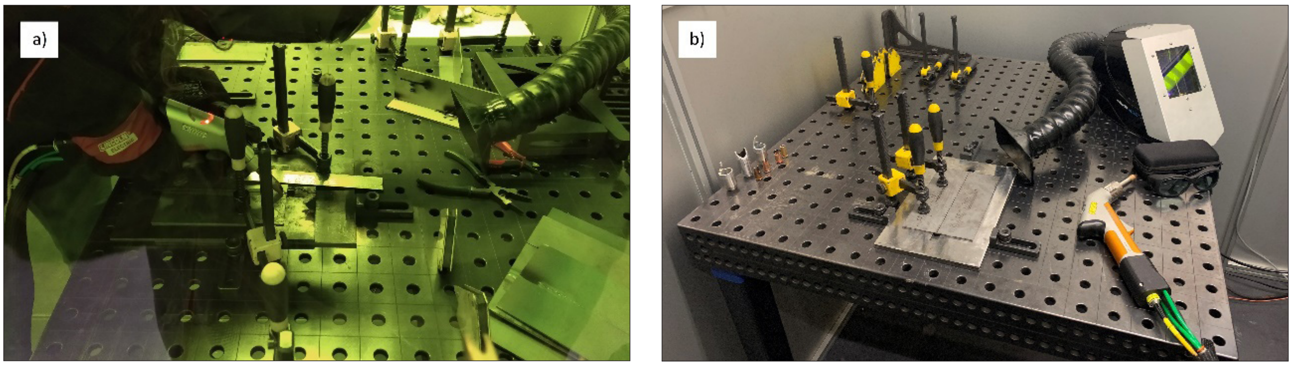

Fig. 1. Hand-held laser beam welding station along with necessary measurement equipment

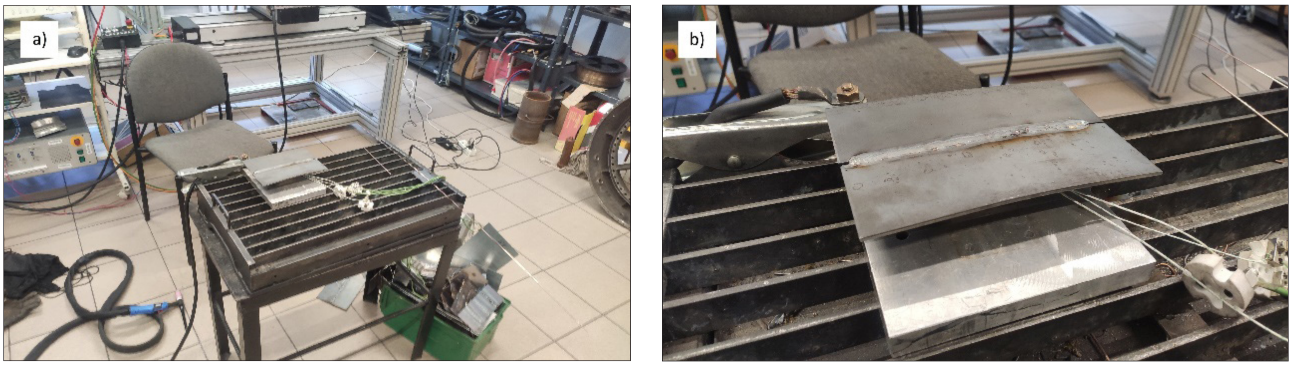

Fig. 2. Station for TIG welding along with necessary measurement equipment

station involving the use of filler metals. The station used for hand-held laser beam welding, temperature measurement equipment and specimens at various stages of preparation are presented in Figures 1a and 1b, whereas the TIG welding station and related specimens are presented in Figures 2a and 2b.

Pre-weld preparations

The edges of the sheets, both in terms of the laser beam and TIG welding processes, were subjected to milling-based square butt weld preparation. A gap between the edges of the test sheets during the hand-held laser beam welding process amounted to 0.5 mm, whereas that used during the TIG welding process amounted to 1.2 mm. The sheets were subjected to cleaning (aimed to obtain their metallic purity) and, afterwards, to degreasing. The specimens subjected to laser beam welding were pressed against the surface of the welding table using hand screws and tacked at the ends before welding. In turn, the specimens used in the TIG welding process were tacked at the end but not fixed as those used in the laser beam welding tests. In all cases, the welding process was performed in the flat position (PA) and at an ambient temperature of 20°C (which was also the temperature of the specimens subjected to welding).

Welding processes

Tables 1 and 2 present parameters used during the welding of 3 joints made of 3.0 mm thick sheets. The formula used to calculate linear energy used in the laser beam welding process was *E* =

Table 1. Laser beam welding parameters used in relation to joints nos. I and II

Joint no.	Welding power [W]	Filler metal wire feed rate [cm/min]	Welding rate [cm/min]	Linear energy [kJ/mm]
I	1200	–	25	0.29
II	1200	40	30	0.24

Table 2. Parameters used in the TIG welding of joint no. III

Joint no.	Welding current [A]	Arc voltage [V]	Current type/ polarity	Welding rate [cm/min]	Linear energy [kJ/mm]
III	110	10.9	= (–)	15	0.48

P/*V*, whereas that used to identify linear energy in the TIG welding process was $E = (U\ I)/V$. In order to compare direct values of linear energy, the calculations did not include thermal efficiency coefficients of the welding processes performed within the tests. Joint no. I was welded using the LightWELD hand-held laser beam welding unit (without the filler metal), joint no. II was welded using the LightWELD hand-held laser and the filler metal in the form of a solid wire (grade G3Si1) having a diameter of 1.2 mm. Joint no. III was welded using the TIG welding machine and the filler metal in the form of a bar (grade G4Si1) having a diameter of 2.4 mm.

Figure 3 contains a diagram presenting the correlation between temperature and welding time in relation to joint no. I and thermocouples located 2 mm away from the weld axis. In turn, Figure 4 contains a diagram presenting the correlation between temperature and welding time in relation to joint no. I and thermocouples located 4 mm away from the weld axis. Similarly, Figures 5 and 6 contain diagrams presenting the correlation between temperature and welding time in relation to joint no. II, whereas Figures 7 and 8 contain diagrams presenting the correlation between temperature and welding time in relation to joint no. III.

Table 3 presents heating times from a temperature of 120ºC to the maximum temperature, cooling times from the maximum temperature to a temperature 120ºC, the sum of heating and cooling times as well as cooling times $t_{8/5}$ for the welded joints.

All the joints were subjected to visual tests and qualified as representing quality level B, i.e. joints no. I and II in accordance with the PN-EN ISO 13919-1 standard, whereas joint no. III in accordance with the PN-EN ISO 5817 standard [16, 17].

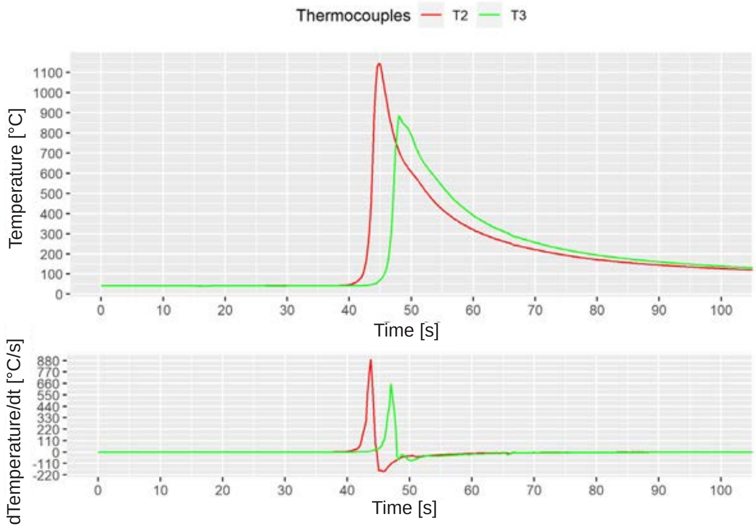

Fig. 3. Joint no. I – welding thermal cycle during hand-held laser welding (distance between the thermocouples and the weld axis: 2 mm, thermocouples T2 and T3) and the rate of temperature changes

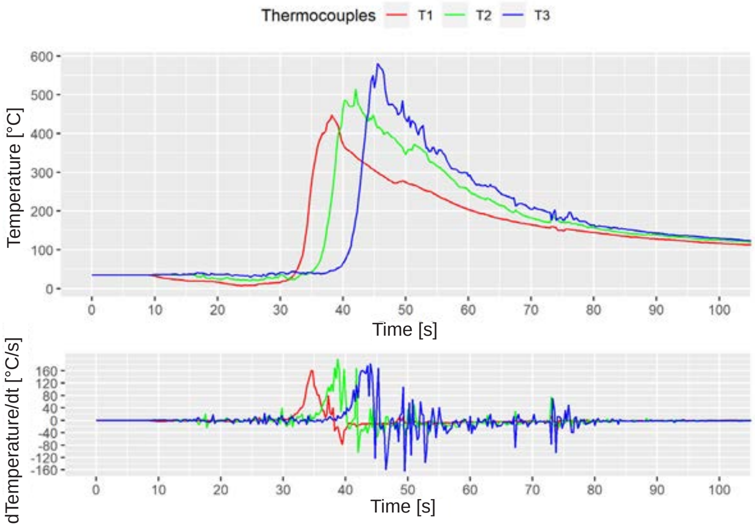

Fig. 4. Joint no. I – welding thermal cycle during hand-held laser welding (distance between the thermocouples and the weld axis: 4 mm, thermocouples T1, T2 and T3) and the rate of temperature changes

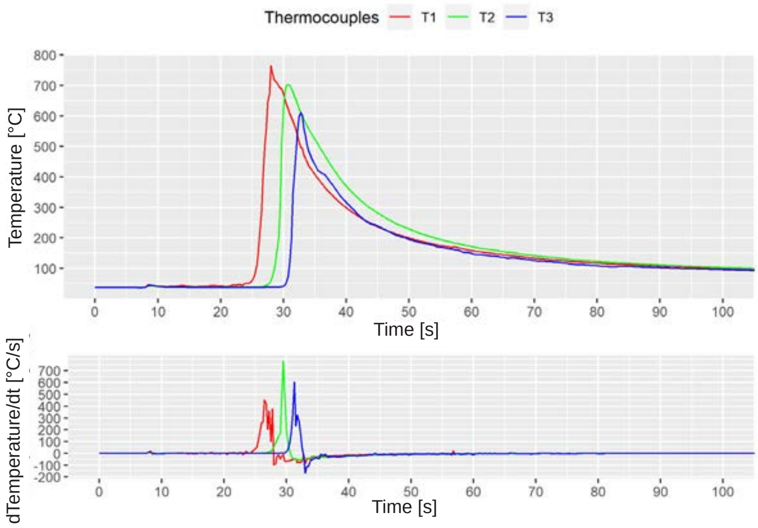

Fig. 5. Joint no. II – welding thermal cycle during hand-held laser welding (distance between the thermocouples and the weld axis: 2 mm, thermocouples T1, T2 and T3) and the rate of temperature changes

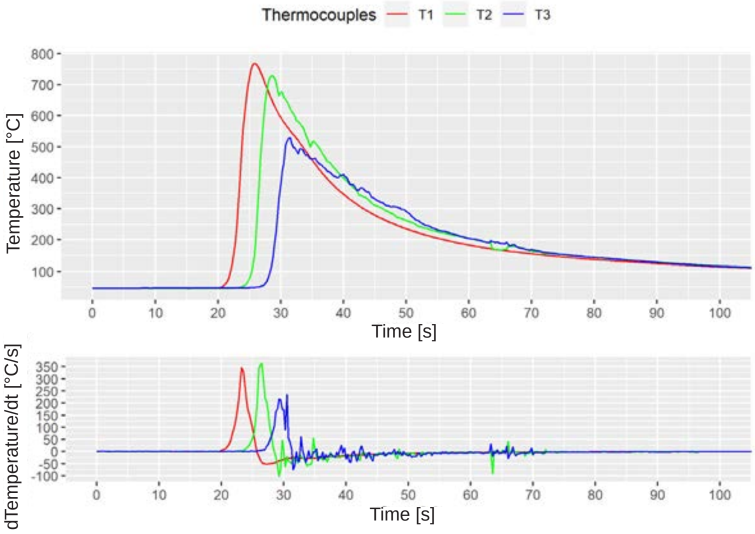

Fig. 6. Joint no. II – welding thermal cycle during hand-held laser welding (distance between the thermocouples and the weld axis: 4 mm, thermocouples T1, T2 and T3) and the rate of temperature changes

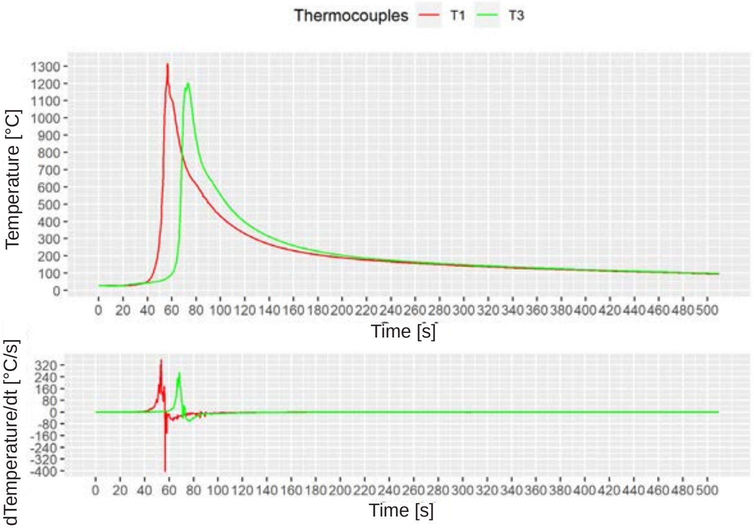

Fig. 7. Joint no. III – welding thermal cycle during hand-held laser welding (distance between the thermocouples and the weld axis: 2 mm thermocouples T1 and T3) and the rate of temperature changes

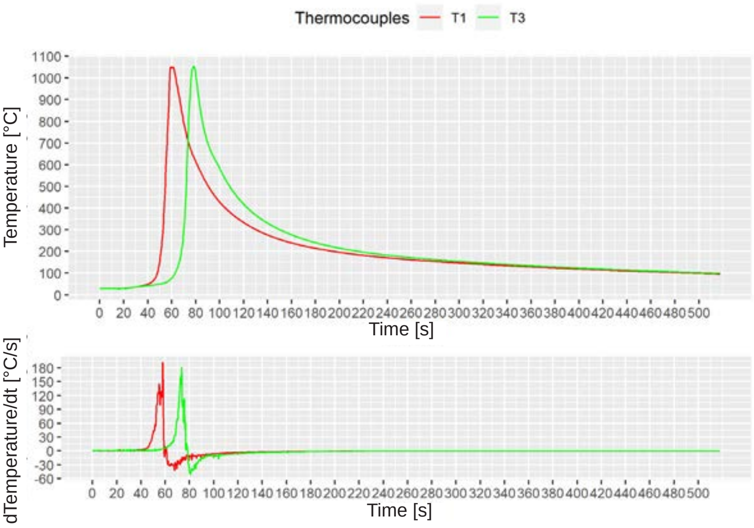

Fig. 8. Joint no. III – welding thermal cycle during hand-held laser welding (distance between the thermocouples and the weld axis: 4 mm, thermocouples T1 and T3) and the rate of temperature changes

Analysis of test results

The highest linear energy was observed when welding joint no. III, whereas the lowest linear energy was recorded during the welding of joint no. II. As regards the LBW and TIG methods, the difference between related values of linear energy was relatively large. In terms of the welding process involving joint no. I, linear energy was higher than that observed in joint no. II. The aforesaid fact was connected with the lower welding rate necessary for the obtainment of high-quality joints during the hand-held laser welding process without the use of the filler metal.

The comparison of the welding thermal cycles as well as of heating and cooling times (presented in Table 3) revealed that the highest temperatures of the cycle recorded both 2 mm and 4 mm away from the weld axis were obtained during the TIG welding process. The maximum temperatures of the cycle indicated by the thermocouples (located 2 mm and 4 mm away from the weld axis) differed only slightly as regards this welding method. The lowest temperatures of the cycle were recorded when welding joint no. II. The largest temperature-related differences between the thermocouples located 2 mm and 4 mm away from the weld axis were observed when making joint no. I. The foregoing indicated that during the welding process performed without the filler metal, the field of higher temperatures was significantly narrower. The highest heating and cooling rates were recorded in the joint no. II by the thermocouple located 2 mm away from the weld. The very high cooling rate visible in diagram 7 in relation to thermocouple T1 resulted from the contact between the thermocouple and the liquid metal. The aforesaid cooling rate was only momentary and was not representative of the cooling rates observed in relation to the welded joint.

The thermal degradation of polymer composite lining started after the exceeding of a temperature of 120°C. For

Table 3. Heating and cooling times in relation to joints I–III

Joint no.	Distance between the thermocouple and the weld axis [mm]	Thermocouple no.	Heating time from 120°C to the maximum temperature [s]	Cooling time from the maximum temperature to 120°C [s]	Sum of heating and cooling times above 120°C [s]	Cooling time from 800°C to 500°C $t_{8/5}$ [s]
I	2	T1	-	-	-	-
		T2	2.75	60.75	63.5	5.5
		T3	2.25	66.5	68.75	6
	4	T1	4.5	58.25	62.75	-
		T2	3.25	60.75	64	-
		T3	4	62.75	66.75	-
II	2	T1	2.25	49.25	51.5	-
		T2	2	50.75	52.75	-
		T3	1.75	40.75	42.5	-
	4	T1	3.5	67.75	71.25	-
		T2	4.5	66.25	70.75	-
		T3	3	58	61	-
III	2	T1	10.75	328	338.75	23
		T2	-	-	-	-
		T3	11.25	323.25	334.5	23.25
	4	T1	11.25	334.75	346	21
		T2	-	-	-	-
		T3	14.25	323.25	337.5	22.75

this reason, it was necessary to maximally reduce the heating temperature affecting the root of the welded joint in elements containing composite lining as well as to reduce the time during which higher temperature was maintained in the aforesaid area. The fastest heating from a temperature of 120°C to the maximum temperature recorded by the thermocouple located 2 mm away from the weld axis was observed in joint no. II, whereas the slowest cooling was observed in relation to joint no. III. The fastest heating from a temperature of 120°C to the maximum temperature recorded by the thermocouple located 4 mm away from the weld axis was observed in joint no. I, whereas the slowest cooling was observed in relation to joint no. III.

When summarising the above-presented test results it was possible to observe that, because of the hold time at a temperature exceeding 120°C, the maximum temperatures of thermal cycles recorded 2 mm and 4 mm away from the weld axis as well as the proportion of the maximum temperature recorded 2 mm away from the weld axis and of the maximum temperature recorded 4 mm away from the weld axis, the laser beam welding process performed with and without the filler metal generated a thermal cycle which was significantly more suitable for the welding of steel materials with composite lining than that accompanying the use of the TIG welding method.

The tests were performed using the specimens without composite lining as the latter could affect both heating and cooling rates during the welding process.

Because of its key importance in relation to unalloyed and low-alloy steels, the value of cooling time $t_{8/5}$ (welding thermal cycle parameter) in the test joints was subjected to analysis. The values of cooling time $t_{8/5}$ concerning the thermal cycles of the laser beam welding process with the filler metal were significantly shorter than those observed in relation to the TIG welding thermal cycle. The thermal cycle recorded by the thermocouple located closer to the weld axis precluded the calculation of cooling time $t_{8/5}$, which indicated the narrowness of the high temperature field in the weld root (triggered by the use of the method).

Another stage of the research should include the identification of the quality and structure of the welded joints by performing macro and microscopic tests. It is also necessary to verify the hardness of the welded joints through the performance of hardness measurements.

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