1. Introduction

Technical and economic aspects resulting from the possibility of manufacturing metallurgical products made of TMCP steels characterised by high yield points and suitable when making various structures, including those exposed to extreme weather conditions, are responsible for the significant interest in this group of materials, their development and joining, also by means of HLAW techniques [1-15]. The hybrid laser arc welding (HLAW) technology combines two conventional welding methods. This process involves the simultaneous use of a heat source in the form of a laser radiation beam and electric arc. According to the ISO 15614-14 standard, a welding process can be referred to as hybrid where two coupled heat sources are used to form one common weld pool. The combination of two independent welding methods into one hybrid process results in the synergetic effect of two heat sources. Consequently, the hybrid welding process is characterised by advantages typical of both methods. In addition, the above-presented combination reduces or eliminates limitations and disadvantages related to the use of only one heat source. Arc methods usually used in the HLAW method are those where the electrode is the filler metal fed to the welding area in a continuous manner (MIG, MAG) [16-22]. The filler metal makes it possible to adjust the chemical composition of the weld through supplying appropriate alloying elements to the weld pool and ensures the proper course of the welding process when joining sheets with a gap (in terms of laser welding, there should be no gap between elements to be joined).

The laser beam enables the obtainment of deep penetration using low linear energy, stabilises arc and improves the thermal efficiency of the process. The electrode wire ensures the complete filling of the weld groove gap and the formation of excess weld metal. The process of hybrid welding can be particularly useful in large-size industrial-scale production, primarily because of higher tolerance when preparing elements to be welded, the possibility of joining sheets in one run and lower accuracy when positioning sheets to be joined [23-29].

2. The range of studies

The research-related tests aimed to identify the properties of the hybrid welded (laser beam – MAG) T-joints made of 10 mm thick steel S700MC using a solid wire GMn4Ni1.5CrMo having a diameter of 1.2 mm. The chemical composition and the properties of the steel and weld deposit are presented in Tables 1 and 2, whereas the steel structure is presented in Fig. 1.

2.1. Welding process

The welded joints were made at using a robotic station (Fig. 2). The tests were performed using a TruLaser Robot 5120 chamber equipped with a TruDisk 12002 disc laser (TRUMPF) having a power of 12000 W (wavelength \( \lambda = 1030 \text{ nm} \)) and an EWM Phoenix 452 RC PULS synergic power source. The hybrid
A series of welding tests involving T-joints was performed changing the primary process parameters (Table 3) and obtaining one-sided welded joints with complete and incomplete penetration as well as two-sided welded joints. The position of a MAG torch was similar to that used when making a fillet weld in the horizontal position. The laser beam was inclined at an angle of 10° in relation to a vertically positioned web of a T-joint (Fig. 3). All of the welding tests except for the last one involved the use of a welding direction where the leading heat source was a laser beam, i.e. LA (Laser Leading) welding direction. The LA technique allows to obtain a significant penetration depth, which is very important in such joints. The parameters used when making the joint (adjusted on the basis of preliminary tests) are presented in Table 3.

Exemplary one-sided and two-sided welded joints are presented in Figs. 4 and 5.
2.2. Tests of Welded Joints

The test welded T-joint was subjected to the following non-destructive tests:
- visual tests performed on the basis of the requirements specified in the ISO 17637:2011 standard;
- magnetic particle tests performed following the guidelines referred to in the ISO 3059:2005, ISO 9934-2:2003 and ISO 9934-3:2003 standards. The necessary contrast was

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<tr>
<td>1</td>
<td>8.5</td>
<td>280</td>
<td>LA, two-sided</td>
<td>High quality; slight angular displacement of plates</td>
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<td>2</td>
<td>7</td>
<td>295</td>
<td>LA, two-sided</td>
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<tr>
<td>5</td>
<td>8.5</td>
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<td>LA</td>
<td>Low quality; excessive melt-through with excess penetration bead along the entire length of the joint</td>
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<td>6</td>
<td>7.6</td>
<td>290</td>
<td>LA</td>
<td>Low quality; excessive melt-through with excess penetration bead in the initial and final part of the joint; significant amount of spatters</td>
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<tr>
<td>7</td>
<td>7.6</td>
<td>290</td>
<td>AL</td>
<td>Low quality; excessive melt-through with excess penetration bead in the middle and final part of the joint; significant amount of spatters</td>
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Welding speed $v = 1.1$ m/min

![Fig. 3. View of the welding process](image1)

![Fig. 4. T-joint one-sided welding technique LA](image2)

![Fig. 5. T-joint welded double-sided welding technique LA](image3)
obtained using white contrast paint MR 72. The tests were performed using magnetic powder suspension MR 76S and a yoke electromagnet.

Following the non-destructive tests, the welded joint was subjected to the following destructive tests:

- macroscopic metallographic tests performed using an Olympus SZX9 light stereoscopic microscope; the test specimens were etched using Adler’s reagent;
- macroscopic metallographic tests performed using a NIKON ECLIPSE MA100 light microscope; the test specimen were etched using Nital;
- hardness measurements performed using a Vickers 401MVD hardness testing machine (Wilson Wolpert) and a load of 1 kg. Three measurements were taken in each joint area in accordance with the requirements of ISO 9015: 2011E.

3. Results and discussion

Related visual tests enabled the elimination of the joints characterised by the lack of penetration or excessive penetration on the root side and failed to satisfy quality-related requirements (joints nos. 5-7, Table 3). Related macroscopic tests revealed that joints nos. 1-4 were free from welding imperfections and were characterised by proper geometry (Fig. 6).

Microscopic tests of the joints revealed changes in the microstructure of the weld and HAZ areas in comparison with that of the base material. Both in the weld and HAZ of each test joint the plastic strain effect in the form of grains elongated in the direction of rolling, obtained during the production of the plates, was eliminated. The weld area structure was dendritic and composed of bainite and ferrite lamellas formed out of retained austenite grains. The HAZ in each of the test joints contained a fine-grained microstructure visibly dominated by ferrite (Figs. 7 and 8). Both the weld and HAZ areas of each test joint revealed the presence of hard nitride precipitates (Fig. 9).

Hardness tests revealed that an HLAW (hybrid welding) thermal cycle translated into higher hardness in the weld area and lower hardness in the HAZ area in comparison with that of the base material. The base material hardness amounted to approximately 280 HV1, the hardness in the weld area was restricted within the range of 295 HV1 to 315 HV1, whereas the hardness in the HAZ area was restricted within the range of 235 HV1 to 260 HV1. The increased hardness in the weld area resulted from the effect of filler metal alloying agents, increasing hardenability. In turn, the decrease in the HAZ hardness resulted from the loss of properties obtained during the thermomechanical control process, (Fig. 10 and 11) and lost through the effect of a welding thermal cycle.

![Fig. 6. Macrostructure of T-joints in the order of 1-4 (Table 3)](image-url)
Fig. 7. Microstructure T-joint welded one sided

Fig. 8. Microstructure T-joint welded double-sided
4. Summary

The tests justified the formulation of the following conclusions:

- The obtainment of a butt weld with full penetration in a T-joint made of 10 mm thick plates in one run during welding performed using the HLAW method is difficult because of the high volume of the liquid metal pool formed during welding and excessive penetration tending to occur on the weld root side.

- One-sided hybrid welding (with incomplete penetration) of T-joints made of 10 mm thick plates in steel S700MC enables the obtainment of high quality welds characterised by a penetration depth of 8mm. Parameters decisive for the penetration depth of welds in hybrid-welded T-joints include the power of the laser beam and the angle at which the laser beam is inclined in relation to the horizontal plane of the plate subjected to welding.

- The two-sided hybrid-welded (HLAW) T-joint was characterised by the highest quality in comparison with that of the remaining test joints. Two-sided welding enables the obtainment of full penetration using lower laser beam power, which, in turn, facilitates the stabilisation of the welding process. In addition, the above-named welding method eliminates slight angular deformations which might occur during one-sided welding.

- The LA (Laser Leading) technique allows to obtain a significant penetration depth, which is very important in such joints.

- The base material structure was bainitic-ferritic and contained irregular-sized gains elongated in the direction of thermomechanical rolling. The weld area structure was dendritic and contained ferrite and bainite lamellas. The HAZ area contained the homogenous structure as regards the size of grains.
The weld area hardness was higher (up to 320 HV1) than that of the base material (280 HV1). As a result of the welding thermal cycle effect, the HAZ area lost its properties obtained during the thermomechanical rolling process. Consequently, the hardness of the HAZ area dropped to 250 HV1.

REFERENCES