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Twin-spot laser welding of advanced high-strength multiphase microstructure steel

Adam Grajcar[a,*], Mateusz Morawiec[a], Maciej Różański[b], Sebastian Stano[b]

[a] *Silesian University of Technology, Institute of Engineering Materials and Biomaterials, 18a Konarskiego Street, 44-100 Gliwice, Poland*
[b] *Institute of Welding, 16-18 Bl. Czesława Street, 44-100 Gliwice, Poland*

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ABSTRACT

The study addresses the results concerning the laser welding of TRIP (TRansformation Induced Plasticity) steel using a beam focused at two spots (also referred to as twin-spot laser welding). The analysis involved the effect of variable welding thermal cycles on the properties and microstructure of welded joints. The tests were performed using a linear energy of 0.048 and 0.060 kJ/mm and the laser beam power distribution of 50%:50%, 60%:40% and 70%:30%. The tests also involved welding performed using a linear energy of 0.150 kJ/mm and the laser beam power distribution of 70%:30%. In addition, the research included observations of the microstructure of the fusion zone, heat affected zone and the transition zone using light microscopy and scanning electron microscopy. The fusion zone was composed of blocky-lath martensite whereas the HAZ (heat-affected zone) was characterised by the lath microstructure containing martensite, bainite and retained austenite. The distribution of twin-spot laser beam power significantly affected the microstructure and hardness profiles of welded joints. The highest hardness (480–505 HV), regardless of welding variants used, was observed in the HAZ.

1. Introduction

Presently, Advanced High Strength Steels (AHSS), including Dual Phase (DP), CP (Complex Phase) and TRIP steels are the most prospective sheet steels used in the automotive industry. Because of their high strength, the steels enable the use of thin-walled sections in modern car bodies, significantly reducing the weight of a vehicle. Particular attention should be paid to TRIP steels due to the strain-induced transformation of retained austenite into martensite taking place during their sheet forming [1–5]. As a result, it is possible to use AHSS when making sections of highly complicated shapes enabling the safety improvement by increasing the amount of absorbed collision energy [6–8].

One of the principal joining methods used in the automotive industry is laser welding. For this reason, it is important to know the phenomena and transformations taking place in the microstructure of steels subjected to laser welding. Research concerning the effect of various laser conditions on the weldability of high strength steels is currently very extensive [9–14]. Another important aspect is the presence of non-metallic inclusions formed during laser welding. The presence of the inclusions results from the chemical composition of steel and the welding atmosphere where the process is performed [15].

One of innovative welding methods is twin-spot laser welding. The twin-spot laser beam is obtained by the coupling of two welding stations or by using a special optical system in the laser head [16]. Presently, the twin-spot laser beam is used when welding galvanised steels, light metals (e.g. aluminium alloys) [17] and when joining steels with non-ferrous metals [18]. Milberg and Trautmann [19] showed that the dual beam laser welding of zinc-coated steels increased the quality of welds. The welds without underfilling, evaporation of material and spatters were obtained. Therefore, in case of twin-spot laser welding the decrease in the thermal cycle dynamics resulting from the use of the second beam may improve the quality of welded joints through the favourable effect on the microstructure and hardness of steels. However, because available publications do not refer to cases involving the use of this method when welding TRIP steels, the authors performed tests concerning the twin-spot laser beam welding of TRIP steels. The aim was to identify the effect of the method on the mechanical properties and microstructure of welded joints.

2. Experimental

The chemical composition of the investigated TRIP steel subjected to the tests is presented in Table 1. The sulphur and phosphorus

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* Corresponding author.
E-mail address: adam.grajcar@polsl.pl (A. Grajcar).

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Table 1
Chemical composition of the TRIP steel, wt%.

C	Mn	Si	Al	Nb	Ti	N	S	P
0.24	1.55	0.87	0.40	0.034	0.023	0.0028	0.004	0.010

contents are at low levels because the laboratory melts were produced using the induction vacuum furnace. The phosphorus is dissolved whereas sulphur is fixed as manganese sulphides [15]. Laser welding was performed on a 2 mm thick and 100 mm wide steel sheet. The steel was thermo-mechanically processed and controlled-cooled directly from the finishing rolling temperature. In order to stabilize retained austenite, the steel was held at a temperature of 350 °C for 600 s to obtain the incomplete bainite transformation phenomenon. The detailed results of microstructural tests after the thermomechanical rolling can be found elsewhere [5].

The steel subjected to analysis was characterised by the reduced content of silicon, if compared to traditional TRIP steels containing approximately 1.5% Si. The reduced content of silicon results from its negative effect on the hot-dip galvanising process. In order to compensate the shortage of silicon, the steel was provided with approximately 0.4% aluminium, which, similar to silicon, prevents the precipitation of carbides during the bainitic transformation (the carbides adversely reduce the fraction of retained austenite). Microadditions of Ti and Nb were added in order to improve the mechanical properties of the steel using the refinement effect through the dispersive carbonitrides and precipitation hardening. The metallurgical weldability of the steel was preliminary assessed using the Eq. (1) enabling the identification of the carbon equivalent of the steel (C_{eq}=0.54%).

$$C_{eq} = C + \frac{Mn}{6} + \frac{Si}{24} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4}[\%] \tag{1}$$

The twin-spot laser welding tests were performed at the Welding Institute, Gliwice, using a solid state laser integrated with a robotic system for laser processing. This laboratory test rig satisfies the requirements of most advanced industrial rigs and is equipped with a TruDisk 12002 laser, i.e. a Yb: YAG solid-state laser (Trumpf) having a maximum power of 12 kW and laser beam quality designated by the parameter of BPP ≤8 mm mrad. The power stability on nominal power is ± 1%. The laser is provided with the system enabling the control of 4 optical outputs, making it possible to lead four independent optical fibres via four independent optical paths out of the resonator and to programme the selection of an optical fibre to be used for the transmission of a laser beam. The principal part of the laser is a CFO head (Trumpf) used for single-spot laser welding. The head was connected to the laser source using an optical fibre having a diameter of 200 µm and focusing lens having a focal length of fog =300 mm. The diameter of the laser beam focus amounted to 300 µm.

The twin-spot laser welding tests were performed using a rig equipped with a D70 head (Trumpf) provided with a system enabling the twin-spot focusing of a laser beam. The distribution of power density between two focuses was monitored using a UFF100 laser beam analyser (Prometec). The tests also involved the selection of an optical fibre and a laser beam focusing lens with a laser beam focus of 0.6 mm in diameter.

In order to ensure the precise positioning of the laser beam during welding, the sheet was fixed to the table (constituting an integral part of the rig) using eccentric clamps. The tests were performed using argon as the shielding gas. The determination of the effect of laser beam power distribution on the microstructure and hardness involved the selection of 7 welding protocols. All of the welding variants are presented in Table 2.

Table 2
Welding protocols in relation to individual process variants.

No.	Beam power, kW	Power distribution, %	Welding speed, m/min	Linear energy, kJ/mm
11	6	50:50	7.5	0.048
12	4	50:50	4	0.060
13	6	60:40	7.5	0.048
14	4	60:40	4	0.060
15	6	70:30	7.5	0.048
16	4	70:30	4	0.060
17	2	70:30	0.8	0.150

Obtaining two focuses of the laser beam in solid-state lasers (with the fibre optic transmission of the laser beam to the working head) varies depending on manufacturers of laser heads and expected adjustment of parameters related to the obtainment of two laser beam focusing points. The most popular solution involves the splitting of a laser beam from one optical fibre using a special optical module. The schematic beam power distribution and expected thermal cycles are presented in Fig. 1. The laser beam distribution was obtained by placing a special optical module across the laser beam, thus splitting it and changing its trajectory. Afterwards, the beam is focused on two spots by standard focusing lenses. The distance between the focuses of the laser beam is affected by the inclination of the optical module plane. The laser beam power distribution is influenced by the position of the optical module in relation to the laser beam (Fig. 1). The maximum distance between the beam focuses adopted when making the test joints amounted to 4 mm.

The tests have been performed with the beam power distribution of 50:50; 60:40 and 70:30 (the first value defines the percentage fraction of beam power in the first focusing point of the tandem system). The adjustment of laser beam power distribution consisted in the manual change in the position of the optical module in relation to the laser beam. Each change entails a change in the density distribution between two focuses and requires verification. In the tests, the verification of the actual power density distribution was performed using a UFF100 laser beam analyser.

The geometry of the welded joint and the microstructure of its individual zones were identified in macro- and microscopic tests performed using a MeF4 light microscope manufactured by Leica. Morphological details were identified using a SUPRA 25 scanning electron microscope in the BSE observation mode using an accelerating voltage of 20 kV. Cross-sectional hardness measurements of the welded joints were performed by means of a KB50BVZ-FA testing machine manufactured by KB Prüftechnik, using an indenter load of 9.81 N (HV1).

Specimens used in the metallographic tests were prepared in the plane perpendicular to the weld axis. The specimens were included in epoxy resin, subjected to grinding by means of abrasive paper having a granularity of 80, 320, 1000 and 2500 and next to polishing by means of diamond and corundum slurry. The microstructure of the specimen was revealed by etching in 3% Nital and then in aqueous solution of sodium pyrosulphate to identify better retained austenite in the microstructure.

The hardness measurements were carried out in a middle part of the welds. The force was set to 9.81 N and the step used for this measurement was 0.15 mm for all the welds.

3. Results and discussion

3.1. Microstructure of base material

The microstructure of the base material consists of the fine-grained mixture of ferrite, bainitic-austenitic islands, martensite and a certain fraction of retained austenite (Fig. 2). It can be seen that the retained austenite is present within the bainitic areas (in the form of layers of various thicknesses) as well as on the edges of bainitic and martensitic