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# Induction assisted laser beam welding of HSLA steel sheets

**A. Jahn, M. Krätzsch, B. Brenner**

## Abstract

The laser beam weldability of structural steels is limited by the hardness increase and the lost of toughness in the weld seam, depending on the metallurgical concepts of the steel grades. That's why, the laser welding behaviour of a Q + T HSLA steel (S690QL), two thermo mechanical treated HSLA steels (S500MC and S700MC) and a heat treatable steel (C45) were investigated in the thickness range of 3 up to 6.8 mm. In order to adjust the temperature time cycle during laser beam welding to the material requirements, an inductive heat source was integrated within the laser welding process. Several strategies of induction assisted laser beam welding processes have been tested and compared to each other regarding the applied temperature fields. The welding results were evaluated with respect to the metallurgical reaction and the resulting mechanical seam properties.

## Introduction

Nowadays Q+T HSLA steels as well as thermo mechanical treated HSLA steel are common used in industrial applications. These materials are more and more welded by laser because of the high welding process efficiency and consequently low base material damage. However, laser beam welding (LBW) leads to very high seam hardness and extreme property gradients within the welded seam, which usually affect the welded joint behaviour [1] – [4].

The temperature-time cycle during welding can be influenced by a process integrated inductive heat input. This procedure effects a clear enhancement of weld seam properties in case of welding of automotive power train components made of heat treatable steels as well as of advanced high strength multi phase steels for the BIW production [5] – [7].

Therefore, an enhancement of mechanical seam properties in case of joining HSLA steels can be expected too, when applying this combination of laser beam welding and inductive heat treatment. So various process strategies have been investigated regarding their metallurgical effects on the several material concepts and sheet thicknesses.

## 1. Materials

Several grades of structural steels, a Q+T steel, two thermo mechanical treated steels and a heat treatable steel, have been observed in the thickness range between 3 and 6.8 mm. Special focus was set on the comparative weldability investigations of the two different steel grades S690QL and S700MC, which exhibit similar mechanical properties but very different metallurgical concepts (see Tab.1).

Tab.1. Overview about investigated steel grades

| **Designation** | **S690QL** | **S500MC** | **S700MC** | **C45** |
|---|---|---|---|---|
| Thickness | 6,0 mm | 6,8 mm | 4,0 mm | 5,0 mm |
| Base Material Condition | water quenched | thermo mechan. treated | thermo mechan. treated | normalized |
| Chemical Composition | C = 0,156 %<br>CET = 0,33 % | C = 0,065 %<br>CET = 0,22 % | C = 0,048 %<br>CET = 0,24 % | C = 0,42 %<br>CET = 0,50 % |
| Mechanical Properties | $R_{p0,2}$= 690 MPa<br>$A_{80}$ = 14 % | $R_{p0,2}$= 500 MPa<br>$A_{80}$ = 14 % | $R_{p0,2}$= 700 MPa<br>$A_{80}$ =12 % | *Not available* |
| Microstructure | tempered martensite | mostly ferrite, partly perlite | mostly ferrite, partly perlite | ferrite + perlite |

## 2. Conceptions of induction assisted laser beam welding

The different material characteristics lead to special weldability properties. Especially in case of welding of materials with higher carbon content, pure laser beam welding effects a significant hardness increase in the weld seam and a loss of ductility and toughness. In order to prevent these seam property restrictions, a welding procedure using a $CO_2$-Laser in combination with an inductive assistance was developed. Main gaol of development was the creation of a material adapted temperature-time cycle of the welding procedure. With respect to the metallurgical effects different process strategies are possible (see Tab.2).

Tab.2. Process strategies of induction assisted laser beam welding

| **Process Strategy** | **Sources** | **Goal** |
|---|---|---|
| Reference | $CO_2$-Laser (defocused) | State of the art |
| Minimal heat input | Fiber Laser | Minimal base material affection |
| Increase of cooling time after welding | $CO_2$-Laser and:<br>- inductive preheating<br>- inductive post heating<br>- ind. preheating + post heating | Restriction or prevention of martensite formation |
| Increase of seam structure toughness | $CO_2$-Laser and inductive annealing | Annealing of post weld martensite structure |

Fig. 1 demonstrates the two fundamental opportunities of induction assisted laser beam welding procedure. The pure laser beam welding procedure is characterized by an extremely fast cooling after solidification (red, continuous curve). In contrast to this, an effective cooling time increase can be realized by inductive preheating, post heating or booth, in order to reduce or prevent martensite formation.

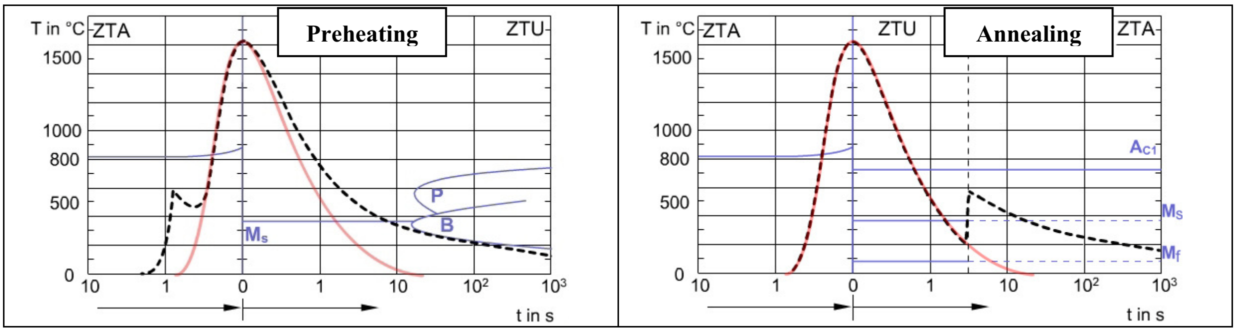

Fig.1. Schematic temperature-time curve: LBW + preheating (left), LBW + annealing (right)

During the process of laser beam welding and inductive annealing, the cooling down of the seam structure beneath martensite start temperature $M_S$ have to be realized. After that, the inductive short time annealing of the seam area starts. A crack free cooling of the seam structure after solidification is the necessary condition of that strategy.

To prevent an additional structure transformation during inductive heating and to minimize the global heat input, the maximum induction temperature is generally limited to values beneath austenite temperature $A_{C1}$.

## 3. Experimental set-up

The experimental set-up for the welding trails was arranged as shown in Fig.2. The applied induction coils were designed as linear inductors. The magnetic field was concentrated on the seam area by using a magnetic core. The various process strategies can be realized by the adjustment of the induction coil position in relation to the laser spot. During the welding trails, the processes were evaluated by the characteristic temperature-time curves measured on the upper side and on the root side of the sheet (Fig.2).

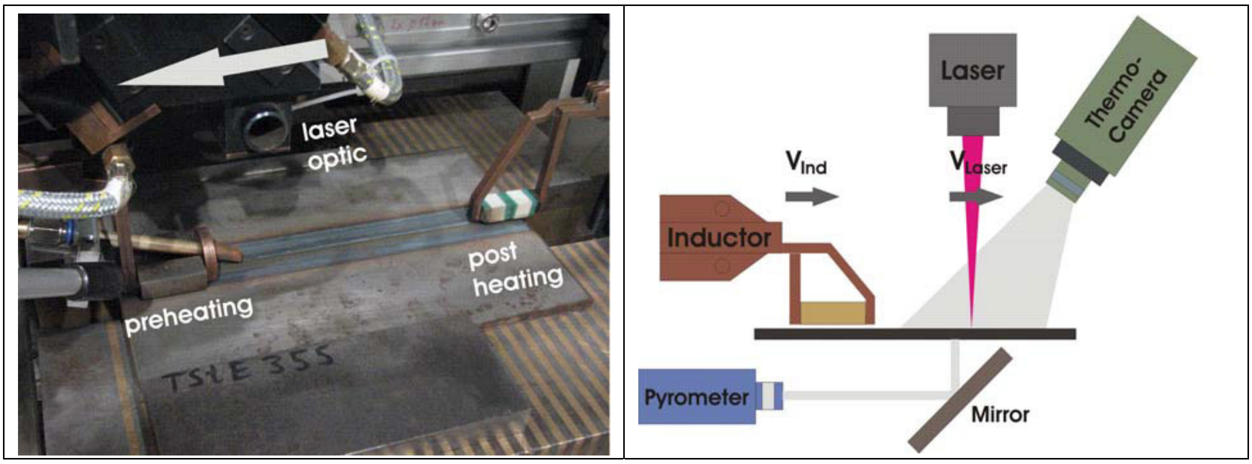

Fig. 2. Experimental set-up (left) and schematic overview (right)

The maximum temperature during heating can be adjusted by the inductive power. Treatment time and cooling rate is mainly defined by the induction coil length. Therefore, various coil geometries, with lengths of 25 mm, 60 mm and 120 mm, have been observed. The process parameters are shown in Tab.3. With respect to the considerable sheet thicknesses, the lowest available induction frequency was chosen.

## 4. Process investigations

The process characteristic has been evaluated with the help of the temperature-time curves, measured on the upper side and on the root side of the sheet sample (see Fig. 3). Pure laser beam welding is characterized by a rapid cooling after solidification ($t_{8/5}$ < 1 s). In comparison to this, preheating or post heating lead to a significant increase of cooling time, up to more than $t_{8/5} = 6$ s.

Tab. 3 Experimental parameters

| **Des.** | **Parameters** | |
|---|---|---|
| Laser Source | DC060<br>($CO_2$- slab laser) | YLR4000<br>(fiber laser) |
| $P_L$ | 2,5 kW (S700MC)<br>3,5 kW (S690QL) | 4,0 kW |
| $V_W$ | 1,0 m/min | 2,5 m/min (S690QL)<br>4,5 m/min (S700MC) |
| $d_{Spot}$ | 600 µm (defocus.) | 125 µm |
| Gas | He (20 l/min) | He (20 l/min) |
| Induction | EFD Minac 80 | |
| $f_{Ind}$ | 6 – 8 kHz | |
| Induction Coils | Linear coils (b x l)<br>(8 x 25, 8 x 60, 8 x 120) | |

The determined curves on the upper side and the root side exhibit remarkable differences in maximum temperature during inductive heating, which depends on the sheet thickness. For the example of a 6 mm sheet, the root temperature amounts nearly 200 K lower than the upper side value.

Due to the covering of the measure field by the inductor itself during inductive heating, the maximum temperature on the upper seam side can not detected by the thermo camera measurement. The numerical simulation of the temperature field proved that the actual maximum temperature beneath the induction coil exceeds the measured maximum by app. 100 K.

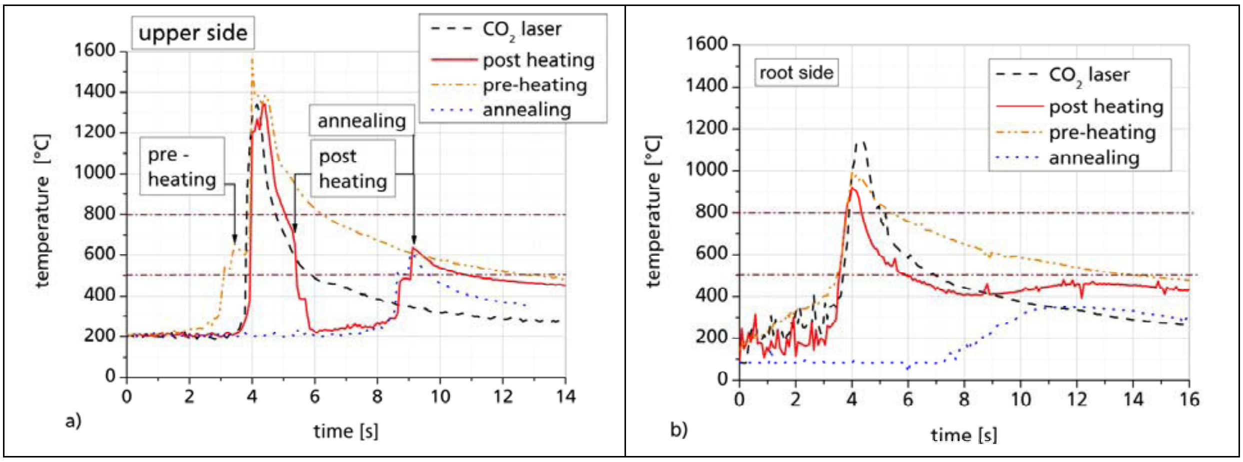

Fig. 3. Measured temperature-time curves, S690QL (6 mm)

With the help of an inductive preheating, a significant increase of welding speed can be achieved. For example in case of welding a 6 mm but joint, a increase of 30 % in comparison to the pure laser beam welding process was determined (Fig. 4). In case of post heating, the length of the induction coil influences the cooling time. The over all cooling time from 800 °C to 500 °C ($t_{8/5}$) in dependence on the inductor length is shown in Fig. 4. For the example of a 4 mm thick sheet, the cooling time on the upper sheet side directly depends on the coil length. However, the influence of the inductive heat on the T-t cycle on the root side is much lower and depends on the sheet thickness. Consequently, the inductive heating should be applied on the higher loaded side of the seam.

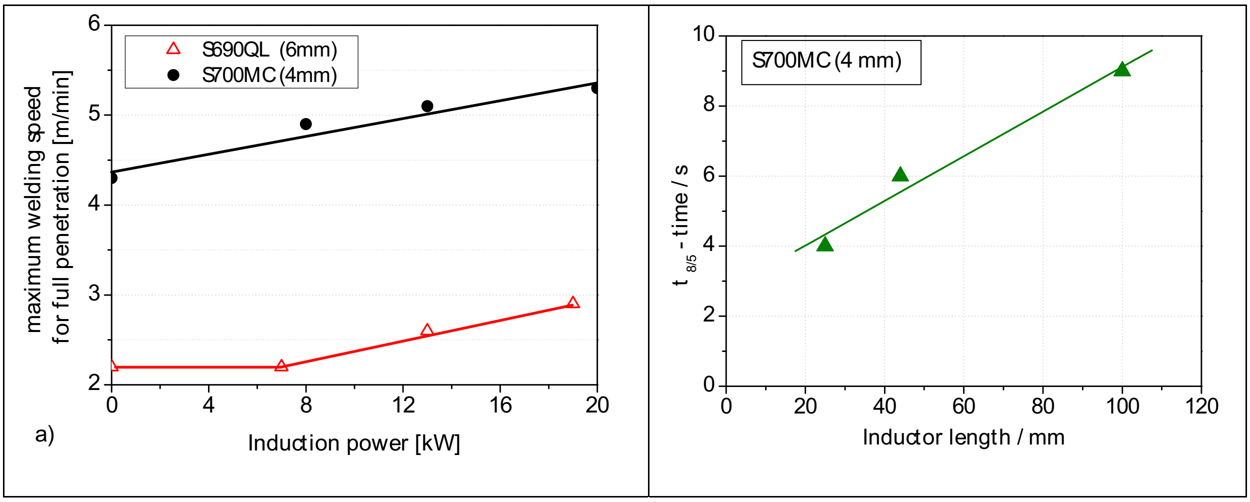

Fig. 4. Maximum welding speed for full penetration (left) and cooling time $t_{8/5}$ (right)

## 5. Joint properties

The mechanical seam properties strength, ductility, toughness and fatigue strength were observed. Additionally, residual stress measurement was performed on welded but joints. The results of these investigations are monitored in the papers below. The typical seam geometry depending from the used welding technology is shown in the cross sections in Fig. 5. Further, Fig. 6 shows the measured hardness distributions and the determined maximum seam hardness values of S690QL and S700MC.

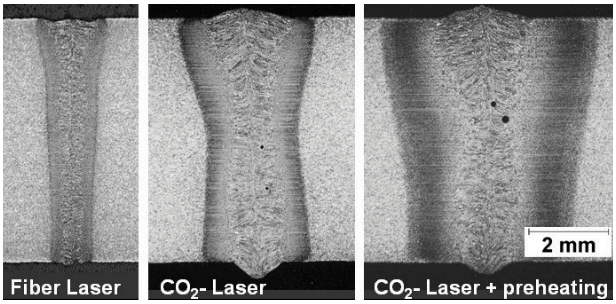

Fig. 5. Cross sections

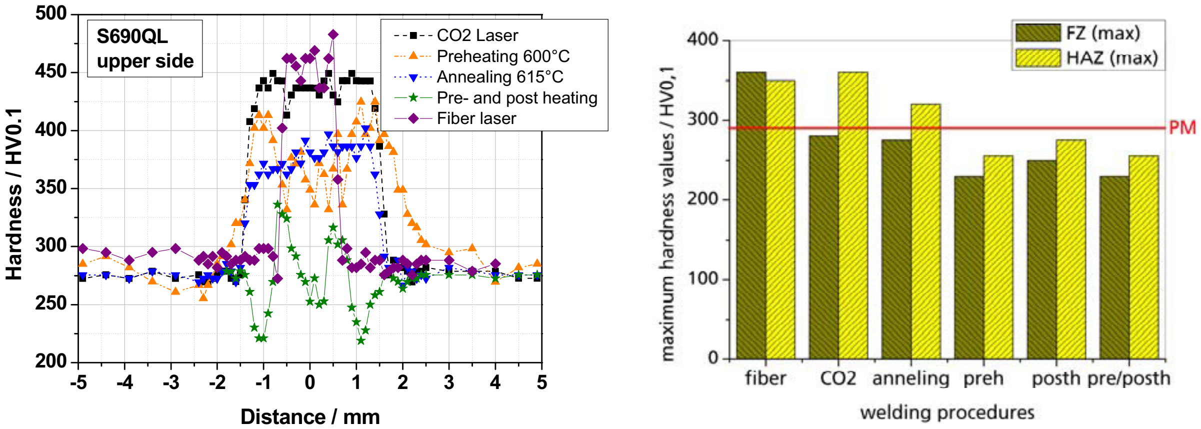

Fig. 6. Hardness distribution across the seam of S690QL (left) and maximum seam hardness values of S700MC (right)

For all investigated materials, a significant hardness reduction without a loss of seam strength can be achieved by all kinds of induction assistance. In case of welding and annealing the Q+T material S690QL, a strong increase of toughness especially in the HAZ was proven.

## 6. Laser induction welding head

Finally, an integrated welding head, consisting of a laser optic and an induction coil was developed. This head, mounted on a conventional industrial welding robot, enables 2D applications and simple 3D welding. The various process strategies of induction assisted laser beam welding can be realized by adjusting the induction coil in different positions in relation to the laser spot and by choosing the travel direction. The functional capability was proven by welding of 2D seam contours with inductive preheating, using a 25 mm inductor (Fig. 7).

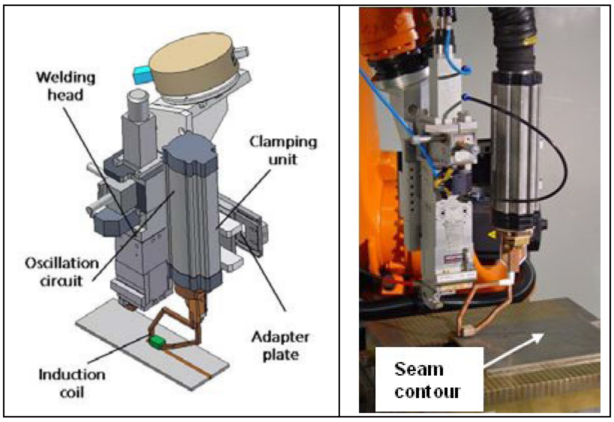

Fig. 7. Integrated laser-induction head

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## Authors

Dipl.-Ing. Jahn, Axel
Fraunhofer IWS
Winterbergstraße 28
D-01277 Dresden, Germany
E-mail: axel.jahn@iws.fhg.de

Dipl.-Ing. Krätzsch, Mathias
Fraunhofer IWS
Winterbergstraße 28
D-01277 Dresden, Germany
E-mail: mathias.kraetzsch@iws.fhg.de

Prof. Dr. Brenner, Bernd
Fraunhofer IWS
Winterberstraße 28
D-01277 Dresden
E-mail:
berndt.brenner@iws.fhg.de