UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

HIGH ENERGY BEAM WELDING OF ADVANCED HIGH STRENGTH STEELS

Booklet of PhD Theses

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1. INTRODUCTION

1.1 PRELUDE

The development of high strength weldable steels (HSWS) has diversified the field of application, range of design alternatives subjected to more severe operation conditions than previous time. Several steel manufacturers have increased their interest in high strength steels (HSSs) or advanced high strength steels (AHSS)/ ultra-high strength steels (UHSS) [1]. Todays, categorisation of HSSs based on the tensile strength level whether it is HSSs or UHSS is cumbersome. So, using tensile strength as threshold for whether a steel qualifies as HSSs or UHSS is quite difficult. However, in general, above 600 MPa yield strength steels can considered as HSSs and probably above 960 MPa they can be considered as UHSS. Due to global environment, climate change and fuel crisis, the demand for lightweight structures from HSSs with the combination of higher tensile strength and toughness has increased over the last few decades [2, 3, 4]. As a result of it, there were several categories of HSSs developed according to their intended applications area (e.g. frames, cranes, bridges [5], automotive industry [6] etc). HSSs provide high strength to weight ratios, improved toughness and sufficient deformation capacity, acceptable weldability especially with undermatching (UM) and matching (M) filler materials (FM), while the overmatched welds can result increased cold cracking sensitivity (CCS) due to the higher carbon equivalent. Financial benefits can also be realized through reduced transportation and lifting costs (reduced weight), material savings (smaller/lighter cross-sections) and reduced weld volumes (thinner plates). Nowadays, HSSs application, in particular thicker plates for heavy steel structures getting more and more attention. HSSs with good structural safety in particular against the brittle fracture and acceptable fabrication properties (welding) are already in widespread application and in huge demands. However, main points to be considered while designing structure with HSSs should be fatigue analysis. Considering application areas, fatigue properties improvement, more strength and thicknesses etc., several production processes for HSSs were evolved which influences the final intended application and properties of the steels. So, it is important to understand how the microstructural and mechanical behaviour of these HSSs produced by the different methods influenced by the application of power beam process [5, 7].

With the development of various new HSSs and their difficulty in weldabilities arises, leads to the requirements of the applicability's of new technologies of other promising innovative welding technological processes like Electron Beam Welding (EBW), Laser Beam Welding (LBW) etc. that can be applied for HSSs [8]. The application of these high energy density welding processes not only provides the quality joints to fulfil its intended function, but it also reduces the area influenced by the heat i.e., heat-affected zone (HAZ) to achieve mechanical properties similar to the base material (BM). The use of innovative welding technologies like EBW, LBW etc. growing importance in the field of HSSs because of its excellence in providing quality of the welds, high welding speed, high power density, low heat input, ability to make exceedingly narrow HAZ, deep penetrated weld, low heat distortions etc. This stands in remarkable contrast to the fusion pattern in arc welds and is attributable to the unique penetration mechanism of the beam welding processes [9]. Regarding the economic advantages, the high productivity and the less FM costs should be emphasised. Due to the narrow and deep penetrated weld structure (keyhole technique) lower amount of FM is needed in EBW and in high power density (5×10^4 to 10^7 W/cm^2) [10] LBW processes. It can be also beneficial to the mechanical properties of the whole welded joints since in HSSs the weld can be similarly critical as the HAZ.

In real welded joints, HAZ properties can be limitedly analysed by conventional material tests. The thermal cycles experienced by the workpiece during the welding can be easily reproduced and enlarged the volume of HAZ in small size specimen by using thermomechanical physical simulator called Gleeble. Therefore, physical simulator was used for the examination of microstructure and different properties in the HAZ areas of different grades of DP steels for different cooling time ($t_{8/5}$) and heat inputs (Q). The equipment provides the opportunity for very short time cycles e.g., beam welding processes since the specimen can be heated rapidly by resistance heating system with the maximum rate as high as 10,000 °C/s and cooled intensively due to the water-cooled grips and external cooling if necessary. Another motivation for the application of physical simulators is the time- and material-saving, as compared to real welding experiments.

DP steel within the group of HSSs has become an important material of choice for automotive industry as it helps to improve energy absorption during impact, provides higher strength, and ensures a lightweight design and cost-efficient methods to produce automotive parts [11]. The laser welding of DP steels may result in a large amount of martensitic (M) structure in the FZ due to the rapid cooling during welding, leading to a considerable increase in the hardness. In presented dissertation the effect of autogenous DLBW and the influence of post weld heat treatment (PWHT) on microstructural changes and mechanical properties of different grades of DP HSS butt welded joint (BWJ) are investigated. The high-power diode laser (HPDL) technology ensures high quality welded joints in HSSs, facilitate the welding and PWHT by same process and equipment. An advanced characteristic of HPDL, vital in the welding process and PWHT, is the rectangular or square shape of their laser beams [12]. PWHT reduces residual stress (RS) levels and tempers the hard regions, particularly in the HAZ. It is performed to temper the weld metal and HAZ with the aim of decreasing hardness and improving toughness, and decreasing the RS associated with welding. Furthermore, besides autogenous LBW, DP1000 HSS with a matching filler wire (MFW) is also welded with the aim to improve the mechanical properties of the weld.

The temperature-time cycles during welding have a significant effect on the mechanical properties of a welded joint. The behaviour of the cooling curve in the temperature interval (A_3 to 500 °C, simplified to 800- 500 °C) is decisive for the final microstructure and mechanical properties in the steels. So, the EBW and the LBW are the opportunity for the minimization of HAZ and fusion zone (FZ) where the material is brittle. Therefore, in the dissertation I tried to explore the details of $t_{8/5}$ related to the investigated beam technologies. The comparative evaluation of various methods for determination of cooling times from 800-500 °C ($t_{8/5}$) in diode laser beam welding (DLBW) process of dual phase (DP) steel is presented. The thermal cycles and therefore cooling time were measured and compared using different measurement techniques (thermocouple measurement method and analytical method).

Also, a deeper understanding of phenomena occurring during welding that influence the microstructure, and thus mechanical properties of welded joints, becomes an important issue in the broader application of these steels [13]. So far, the studies on EBW on high strength Q+T and TMCP with different yield strength (YS) have not been carried out extensively.

The stresses developed by the thermal contraction of the cooling weld which must be compensated by the strain in the weld metal. In rigid structures the natural contraction stresses are intensified because of the restraint imposed on the weld by the different parts of the joint. These RS can be more troublesome because it generates the stress concentration (SC) at joints, weld toe, root of the weld and the possible chances of deleterious microstructures in the HAZ [14, 15]. The calculation and evaluation of the RS is highly difficult task in the welded specimen specially in the high energy beam welded samples due to its narrow weld and HAZ. The RS develop in the welded specimen is a complex combination of various factors like geometrical features of the weld, welding parameters, stiffness of the structure, manufacturing process, environment and volumetric changes due to phase transformations in the weld zone etc. [16, 17]. The effects of the tensile residual stress (TRS) may lead to the structural failure, so the proper analysis of these stresses is important.

One of the important issues that limits the applications of HSSs is fatigue. The fatigue resistance of the welded structures limits the use of higher strength steels in dynamically loaded structures. The fatigue of the welded material affects a wide range of application areas, e.g., cars, cranes, bridges, trucks, crankshafts. However, the rapid development of several fracture mechanical approaches for assessing the fatigue damage of welded joints have been developed. Since the structures often have fatigue loading and these HSSs material have high crack sensitivity, therefore it is very important to know the resistance level to the fatigue crack propagation. FCG tests on EB-welded HSSs (S960QL and S960M) joints are limitedly found in the literature. Therefore, it is aimed in this dissertation to compare the fatigue crack growth (FCG) characteristics of EBW HSSs joints with conventional gas metal arc welding (GMAW) since the EBW welds are prepared with narrow FZ and HAZ, without the application of filler material. The question arises whether the fatigue crack resistance of an autogenous low heat input EB-weld can be equal or higher compared to a GMA weld of the same grade.

1.2 THE PURPOSE OF DISSERTATION

The work presented in this dissertation focuses on the comprehensive and systematic study of the application of innovative welding processes (LBW and EBW) on the different grades of HSS and to analyse the microstructural changes and mechanical properties of the welded joints. The motivation that the different grades within the group of DP steels are presented in this dissertation have limited information for its behaviours (HAZ characterization, residual stresses, welding with matching filler metal) during LBW (especially diode laser beam welding) and PWHT. Diode lasers are rarely used for the welding of high strength steels however its application growing nowadays, and it provide unique solution for the PWHT and welding by the same device. Before real experimental work it is recommended to investigate the HAZ characteristics of DP steels, since physical simulation based HAZ characterization of these grades is rarely available in the literature.

With the application of EBW, the joints can be prepared without the limitedly available filler materials, so it is a question whether an autogenous EB weld can be competitive with a matching alloyed weld of the conventional GMAW.

The specific aims of the research work are as follows.

- Determination and comparison of thermal cycle and $t_{8/5}$ cooling time during diode laser beam welding of dual phase steels using analytical method and thermocouple measurement.
- Analysis of hardening and softening behaviour in the relevant $t_{8/5}$ cooling time interval of the different HAZ subzones (CGHAZ, FGHAZ, ICHAZ, SCHAZ) of DP steels (4 different grades DP800, DP1000 DP1200 & DP1400) by thermophysical simulation using Gleeble 3500 simulator.
- Analysis of microstructural changes and mechanical properties of autogenous diode laser beam welded joints and the effect of post weld heat treatment on the different grades (DP800, DP1000, DP1200 & DP1400) of DP steels.
- To study the combined effect of diode laser beam welding process with matching filler material and PWHT on the microstructural characteristics, mechanical properties and residual stresses of DP1000 high strength steel welded joint.
- Comparative study of the microstructural and mechanical properties (especially toughness) of the electron beam and gas metal arc welded S960QL steel joint.
- Evaluation of microstructural and mechanical properties (especially toughness) of the electron beam welded S960M steels joint and comparison with the characteristics of the S960QL joint.
- Investigation of the residual stresses of EBW high strength steel welded joints (S960QL and S960M) with non-destructive X-ray diffraction technique.
- Determination and analysis of the FCG characteristics of autogenous electron beam welded joints from S960QL and S960M, and comparison of the results with effect of the conventional GMAW technology.

2. METHODOLOGY

In the first part of my dissertation, a comprehensive literature review on the high strength steels and their weldability including classification and trends of development, production processes and their influences on welding, physical simulation, residual stress and as well as fatigue behaviour of HSSs and their welded joints are summarised. In recent years, more stringent quality requirements and cost effectiveness have not only led to the various rationalization measures being adopted in European steel industry in the past but also to the significant technological advances. This is particularly apparent in the significant improvements in the HSSs with the combination of good strength and toughness properties but also in energy and materials efficiency that have been achieved [18]. Among the available HSS sheets, several types of HSSs were developed which primarily focused on the automotive industry based on the principle of light-weight design, innovative forming processes and new tooling concepts, as well. However, the most common HSS is in growing demand for wide application in the automotive industry is the group of DP steels owing to their good combination of high strength, ductility and formability. This approach enhanced the development of high strength DP steels, which contain a ferrite matrix and martensite island. Nowadays, there are several grades of DP steels available with different tensile strengths like DP600, DP800, DP1000, DP1200 and DP1400.

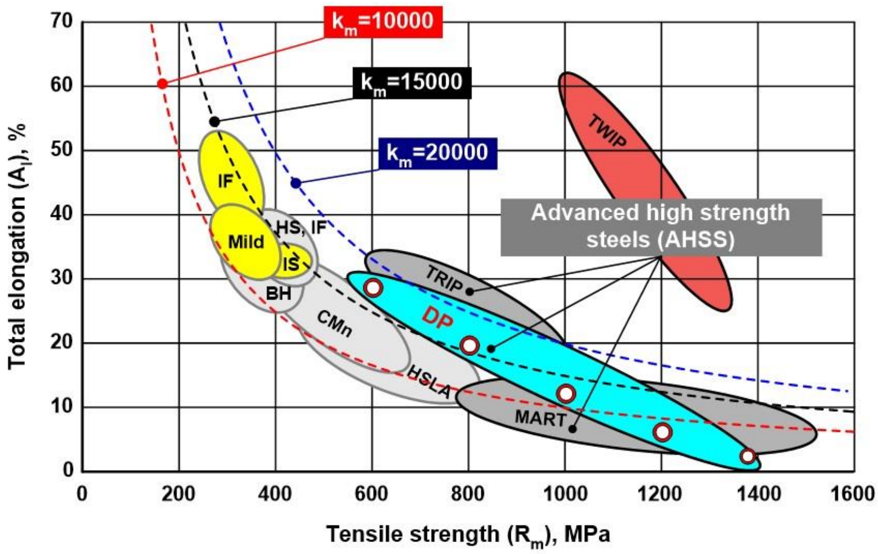

Fig.2.1. Chronology of Automotive AHSS developments [19, 20]

Fig.2.1. shows the grouping of traditional and advanced high strength steels which typically falls into the category of thin plates.

Besides the sheet category high strength steels are also available in the form of plates (structural steels) produced by several production methods. Due to the technological advancement and growing demand of HSSs since the seventies, when Q+T group appeared, combination of varying alloying components along with the Q+T heat treatment process, now the maximum yield strength has been reached to the 1300 MPa. However, it should not be ignored that FM are currently available in the market are up to 1100 MPa of yield strength so for this extreme strength HSSs only undermatching (UM) (approximately 15-20%) is available if it is allowed. However, the application of UM during the selection of the FM may have some additional positive effects (lower residual stress, higher fatigue resistance etc.). Due to the above-mentioned reasons, instead of S1100Q and S1300Q, the S960Q is more widespread, which can be welded by MFW as well [21]. Generally, the ultra-high strength categories of structural steels are produced by Q+T process with a final microstructure of martensite [22]. Since martensite can only offer a high strength, improving its impact toughness has become a major concern [23]. It is well known that toughness can be improved by grain refinement without loss in strength [24]. The improvement of the thermomechanical treatment (TM), combined with several heat treatment technologies (e.g. precipitation hardening), the yield strength of thermomechanically treated HSSs can approach the level of Q+T steels [25]. TM rolled steels require significantly fewer alloying elements, especially less carbon than normalised steels (NS) or Q+T steels. Due to the good weldability of TM steels, preheating during welding can be significantly reduced or avoided. The chronology of structural steel development trends with increasing strength of steels are summarised in Fig.2.2.

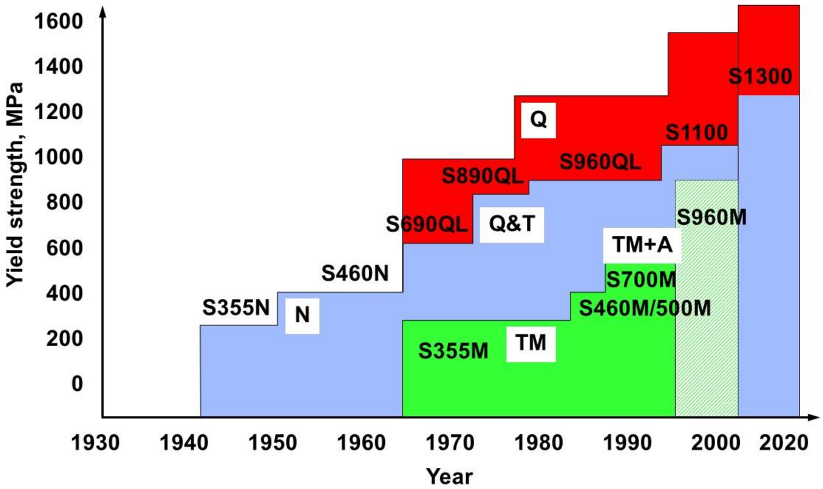

Fig.2.2. Development trend of structural steels [8, 13, 26]

There are several possible ways to increase the strength of steels (e. g. grain size reduction; formation of a complex phases, like DP, TP and TWIP; precipitation hardening of the maraging steels). In case of the examined heavy plate thickness range, the higher strength can be effectively reached by grain refinement and the change of the second phase quality, size and distribution [14, 17].

The difficulties arise in the welding of HSS due to its non-equilibrium microstructure resulting from the alloys added to the steel and refining method used in the production of the steels. As a result of welding heat input, the HAZ of the welded joint has an extremely inhomogeneous microstructure and different mechanical properties compared to the BM. In case of HSSs, the reduction of toughness properties usually occurred due to the effect of the welding heat input resulting grain growth and the formation of M-A constituents. That's why, the weldability study is of primary importance and being a very important technological features of structural steels which depends on the processing, carbon concentration and alloying element composition [1, 27]. The major problems that encountered during welding of HSSs are HAZ phenomena, cold cracking phenomena and mismatch phenomena.

The second part of my dissertation is related to the application of beam welding technology processes (Laser beam Welding and Electron beam welding) on HSS. HPDL welding is considered as boon and state-of-the-art technology in modern automotive industrial application. The advanced feature of HPDL, crucial in the welding process is the inherent beam stability, adjustable square or rectangular shape of the laser beam spot with a top hat profile in one direction and a Gaussian like in the other leads to uniform heating of the surface over a relatively large area [28], high energy conversion efficiency of 30-50% and relatively high radiation absorption rate on the surface of most metals due to its shorter wavelength lies near infrared range from 0.808 to 0.960 μm [12, 29]. The spectral ranges of light and different lasers are shown in Fig. 2.3. The HPDL with its application does not only provide an ideal beam geometry and intensity distribution but is also an efficient way for heat treatment processes, including PWHT [30]. So, it is very crucial to evaluate the laser weldability of HSS, including microstructural changes in weld and HAZ and to analyse the applicability of laser PWHT [5, 31].

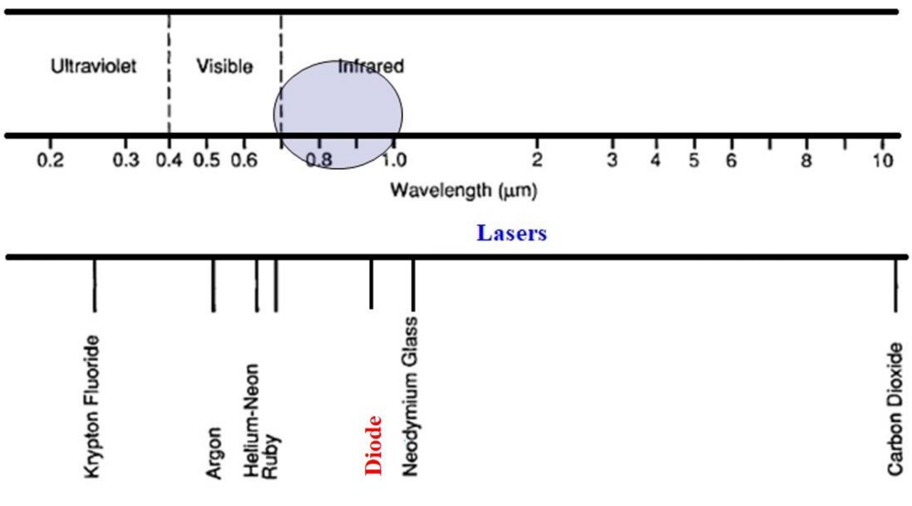

Fig.2.3. The spectral ranges of light and different lasers [32]

EBW was invented as innovative welding technological process with significant breakthrough in the development of electron beam is a unique as a processing heat source by virtue of it focusing ability, intensity and high vacuum operation which in turn provides the greater penetration depth and narrow FZ is of particular importance [33]. These combined characteristics of the EBW processes completely distinguishes it from other conventional arc and resistance welding processes [34]. It is fusion welding process in which high energy density beam (10^7 W/cm^2) [8, 35] is impinging on materials surface to be welded and vaporises metals (kinetic energy of high velocity of electron used to produce heat energy) [36, 37]. Firstly, it was intended to use in nuclear and aerospace industries but with the subsequent development in the technology (process and equipment) broaden the dimension of application area of EBW [35, 38]. Nowadays, it is widely used in welding and material processing like in construction area, ship building, petrochemistry, medical equipment etc. [39]. The outstanding combination of EBW process and HSS Q+T and TMCP with a ground-breaking result pioneering in the field of different industrial sectors like automotive and vehicle industry (crane, truck etc.) [40].

While the third part of my dissertation is related to the detailed information of the investigated materials, processes, different tests involved, advanced characterisation methods and the result analysis. The different grades of dual phase (DP) steels (DP800, DP1000, DP1200 and DP1400), a product of SSAB (for Physical simulation and LBW), WELDOX 960E (S960QL in EN 10025-6) and ALFORM 960M, a product of SSAB and VOESTALPINE respectively (for EBW) base materials, Union X96 (G895M21Mn4Ni2.5CrMo according to EN ISO 16834-A standard), diameter Ø1 & Ø1.2 mm, filler metal used in diode LBW & EBW respectively. A series of physical simulation experiments together with the related material tests were performed to explore in the details the HAZ properties of welded joints from DP steels, which information is limitedly available in the literature (mostly structural steels are investigated by Gleeble). The characteristics of the inhomogeneous HAZ was investigated in order to identify the critical subzones in terms of hardness and microstructure and to see the tendencies based on the examined $t_{8/5}$ = 5-30 s cooling time interval (shorter cooling is not possible with acceptable reliability with sheet metal specimen configuration and air cooling). However, based on this range it can be estimated what happens during shorter cooling time of LBW in the different subzones. Samples are simulated with different peak temperatures (CGHAZ-1350 °C, FGHAZ- 950 °C, ICHAZ- 775 °C and SCHAZ- 650 °C), characteristic for the different subzones, and Rykalin 2D model were selected due to the 1 mm sheet thickness. The energy input for $t_{8/5}$ = 5 s and $t_{8/5}$ = 30 s cooling time were given as 88 J/mm and 216 J/mm respectively.

Besides the investigated lower strength categories of DP steels (DP800, DP1000) in the literature, in present dissertation higher grades (DP1200 & DP1400) are also studied which are rarely available in the literature. The laser welding was done using a diode laser at the industrial partner. A Laserline LDL 160-3000 diode laser head was mounted on a Reis SRV 40 robotic arm. A Laserline LDF 5000-40 diode laser was characterised by a rectangular 15 mm laser beam spot size emitted in continuous wave at 940 nm-1060 nm, with maximum output power of 5 kW was used for post weld heat treatment. The applied LBW parameters without filler material, determined by preliminary experiments, used in the present study are shown in Table 2.1. The diode laser was characterised by a rectangular laser beam spot size 2×2 mm and emitted in continuous wave at 940 nm-980 nm, with maximum output power of 3 kW. The linear heat input was calculated [41] with parameters provided in Table 2.1 as 0.125 kJ/mm.

Table 2.1. LBW and PWHT parameters without filler material

Steel grades	Process	d (mm)	P (W)	s (mm/s)	G (l/min)	Shielding gas purity
DP800/DP1000/ DP1200/DP1400	LBW	2×2	1000	8	7	Ar 4.6
	PWHT	15×6	275	4	7	Ar 4.6

The base material used to analyse the LBW with a matching filler material and the effect of PWHT on the welded joint was an uncoated cold rolled DP1000. This grade has 1000 MPa guaranteed tensile strength, which is the maximal strength level, that can be welded by matching filler material. The filler wire used in this study was matching Union X96 (ER120S-G) with diameter of 1 mm. The optimum LBW parameters with filler material are shown in Table 2.2. The linear heat input was calculated with parameters provided in Table 2.2 as 0.125 kJ/mm which is similar to the LBW without filler material.

Table 2.2. LBW and PWHT parameters with filler material

Steel grade	Process	d (mm)	P (W)	s (mm/s)	f (mm/s)	G (l/min)	Shielding gas purity
DP1000	LBW	2×2	2500	20	13	12	Ar 4.6
	PWHT	15×6	275	4	-	7	Ar 4.6

Finally, different tests were performed for both LBW with and without filler materials welded joints like microstructure of the welded joints were observed using an optical microscope (OM) and a scanning electron microscope (SEM) analysis.

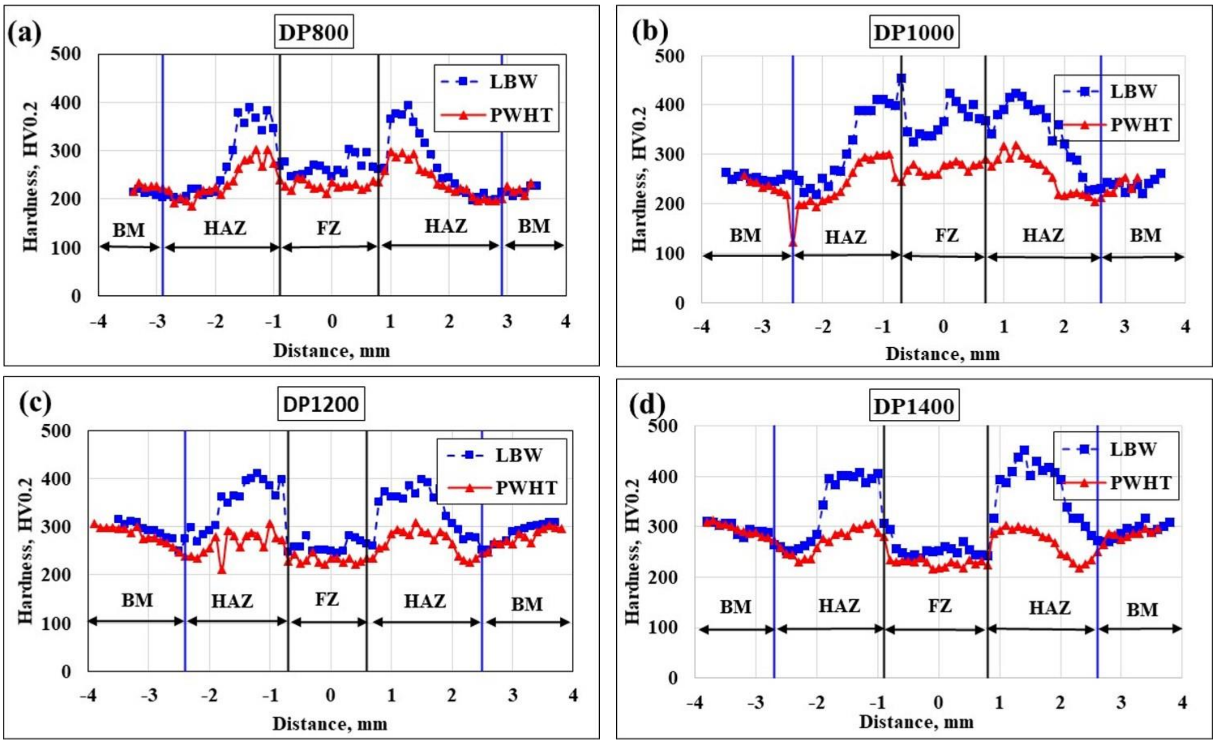

Fig.2.4. Microhardness distribution graphs: LBW and PWHT (a) DP800 (b) DP1000 (c) DP1200 (d) DP1400

The microhardness graphs for DP800, DP1000, DP1200 & DP1400 steels for LBW without filler materials & PWHT were presented in Fig. 2.4.

The tensile properties (ISO 4136: 2012) perpendicular to the weld directions were evaluated at room temperature on two samples and fractography. A three-point bending test (EN 5173: 2010) was carried out at room temperature on four samples.

The residual stress measurement was performed by using X-ray diffraction method (XRD) for DP1000 steel, LBW with filler material. Results of the residual stress measurements in longitudinal and transverse direction were presented in the Fig.2.5a & Fig.2.5b respectively for both LBW and PWHT.

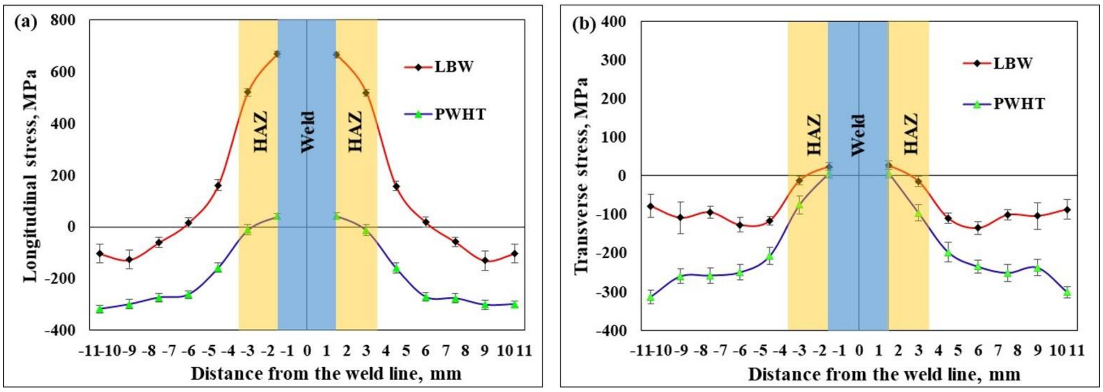

Fig.2.5. Residual stress graphs on DP1000: (a) longitudinal stress, (b) Transverse stress

The cooling time determination was performed using experimental method (thermocouple measurement method) while DLBW processes on 1 mm thickness DP800. Also, cooling time was calculated using analytical method for LBW process.

Further, EBW experiments were performed on the BM S960QL and S960M and the steel plate of thickness 15 mm were cut into pieces of 300 mm × 150 mm each for a butt welded joint (according to EN 15614-11:2002 by means of a plasma cutting machine). The backing plate material was same as of BM and cut into the dimension of 300 mm × 50 mm. The welding was done in a single pass without a filler metal addition and no preheating. The EBW was performed using EBOCAM EK74C – EG150-30BJ EBW machine in completely vacuum condition, 2×10^{-4} mbar (1.97×10^{-7} atm) and the same level was maintained in the electron gun and work chamber. The linear heat input was calculated with the optimal parameters provided in Table 2.3 and efficiency ($\eta = 0.9$) [42] as 661.5 J/mm.

Table 2.3. EBW optimal parameters

Steel grades	**V_a (kV)**	**I_b (mA)**	**s (mm/s)**	**d_b (mm)**	**Focus lens for welding (mA)**
S960QL/S960M	150	49	10	0.4	2067

After welding, microstructural and mechanical properties of the EBW joints were investigated. The samples for optical microscope (OM) and scanning electron microscope (SEM) observations were sectioned through the weld in transverse direction. The specimen for metallography study comprised of BM, HAZ and FZ. The microstructural examination was carried out using an OM (Axio Observer D1m (Zeiss) inverted microscope) and SEM (Zeiss Evo MA10) analysis. Fig.2.6a & Fig.2.6b shows a comparison of experimentally observed (stereo microscope) cross sections of an EB and a GMA welded S960QL butt welded joints.

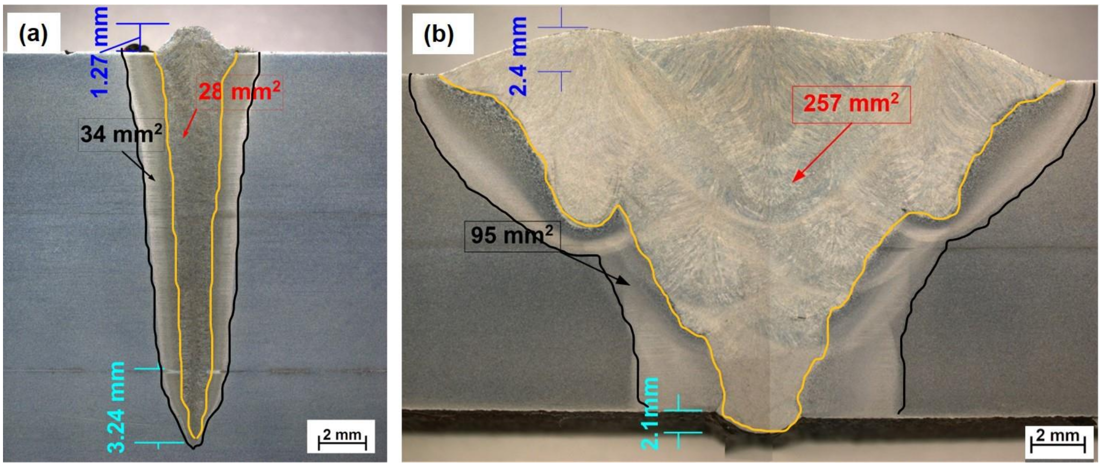

Fig. 2.6. Calculated cross sections area of FZ and HAZ in case of S960QL: (a) EBW (b) GMAW, M=6.5× [43]

The Vicker's macro hardness (ISO 22826: 2005) of the BM, HAZ and FZ are tested by Reicherter UH 250 Universal hardness tester. The macro indentations were taken in three horizontal directions of different regions (BM, HAZ & FZ) of a specimen for S960QL are shown in Fig.2.7a and the GMAW hardness graph for face and root side is shown in Fig.2.7b.

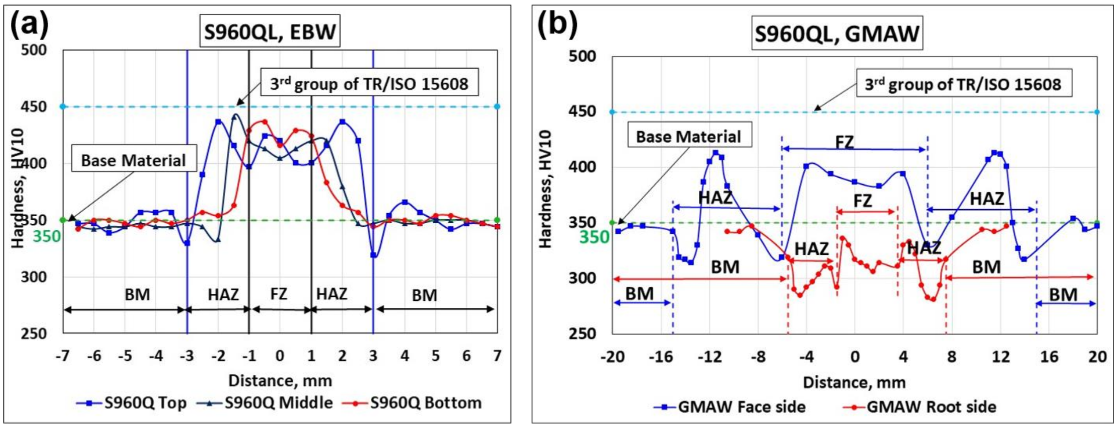

Fig. 2.7. The macro hardness distribution. (a) EBW (b) GMAW [43]

The hardness profiles across the middle of welded joint of S960QL and S960M EB-welded joints are shown in Fig.2.8. Instrumented Charpy V-notch impact tests (according to EN ISO 14556) were done by Heckert instrumented impact testing equipment and fractured surface was observed by SEM. Tensile test was executed with a ZD 100 (1000 kN) hydraulic materials testing equipment at room temperature and the specimens used for mechanical tests were designed according to ISO 4136:2012 standard.

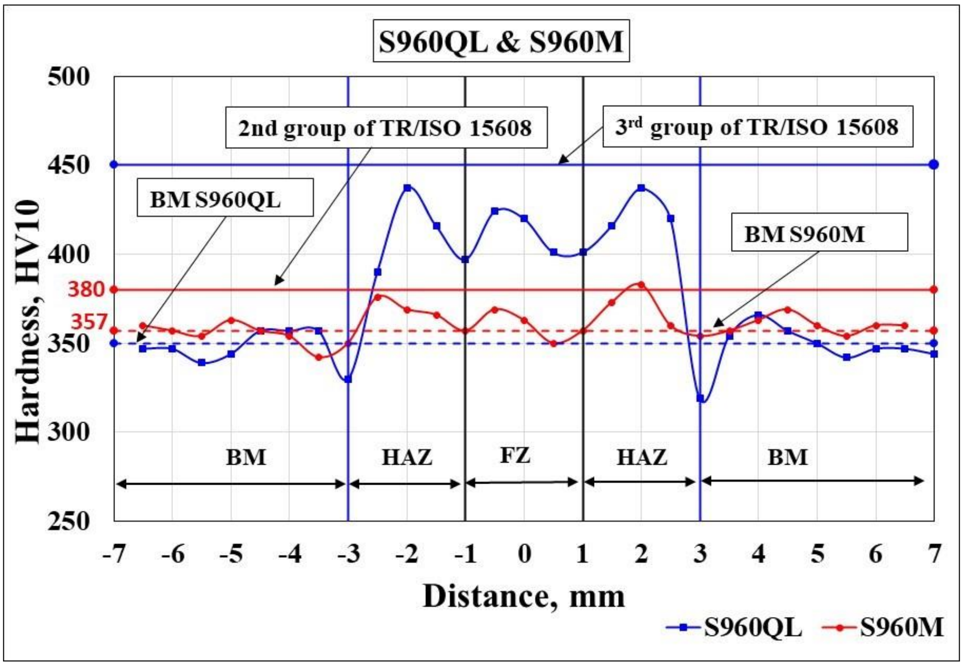

Fig.2.8. Macrohardness, S960QL & S960M

The as-welded surface residual stress distribution in the 15 mm thick EB welded sample was measured with the X-ray diffraction (XRD) method. The measured RS distribution i.e., longitudinal and tensile (parallel and perpendicular to the weld direction at each point of measurement respectively) in as welded samples at three different location top, middle and bottom marked by green, blue and red colour respectively as shown in Fig.2.9.

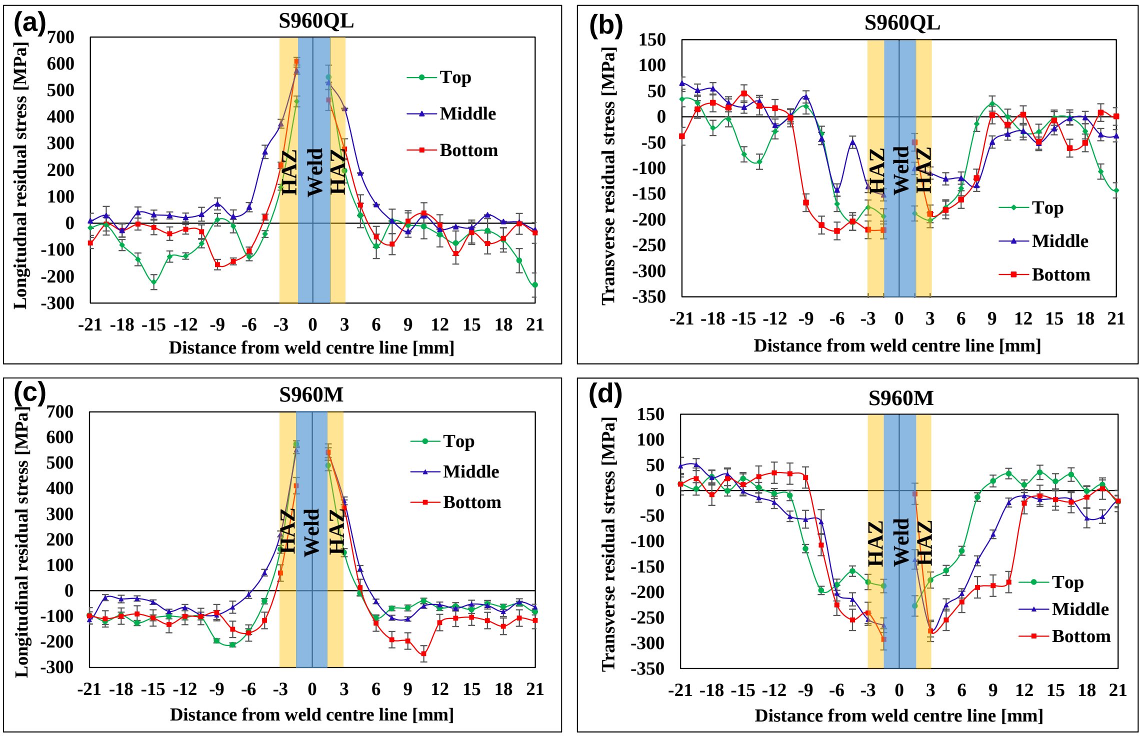

Fig. 2.9.Residual stress graphs: (a) Longitudinal stress, S960QL (b) Transverse stress, S960QL (c) Longitudinal stress, S960M (d) Transverse stress, S960M

Finally, The FCG tests were executed on three-point bending (TPB) specimens, nominal W values were W = 26 mm and W = 13 mm for the base materials (S960QL & S960M) welded joints (t = 15 mm), in the 21W and 23W directions, respectively. The position of the notches correlated with the rolling direction (T-S and T-L). Straight notches were applied with 0.2W nominal length, 2 mm wide, 90° tip angle and 0.25 mm tip radius. The positions of the cut specimens from the welded joints are shown in Fig.2.10 [44, 45].

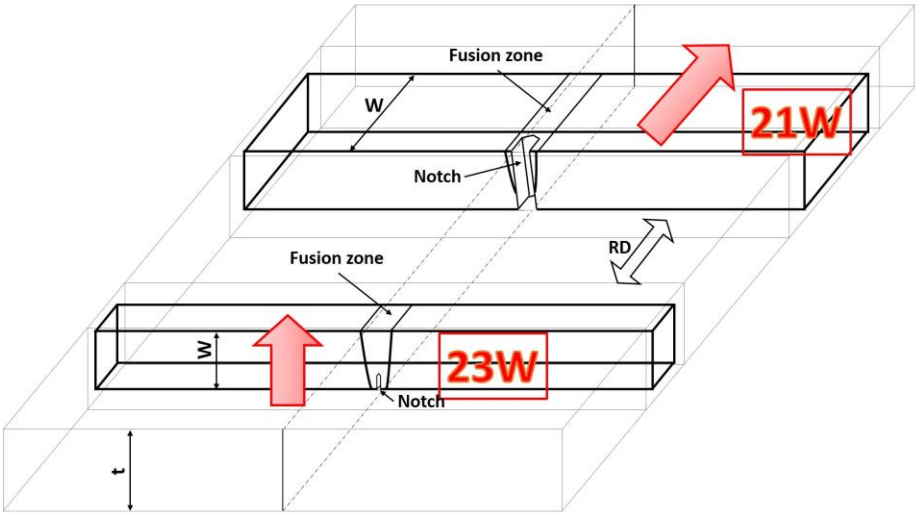

Fig.2.10. TPB specimen locations in welded joint with notch directions (RD = rolling direction) [40, 45].

The FCG examinations were performed with tensile stress, R = 0.1 stress ratio, sinusoidal loading wave form, at room temperature and using MTS type electro-hydraulic testing equipment. The loading frequency was f = 20 Hz for two-thirds of the growing crack's length, approximately, and it was f = 5 Hz for the last third. Secant method [46] was used to evaluate the fatigue crack growth data. The calculated stress intensity factor range vs. fatigue crack growth rate values, the kinetic diagrams of FCG, are shown in Fig.2.11.

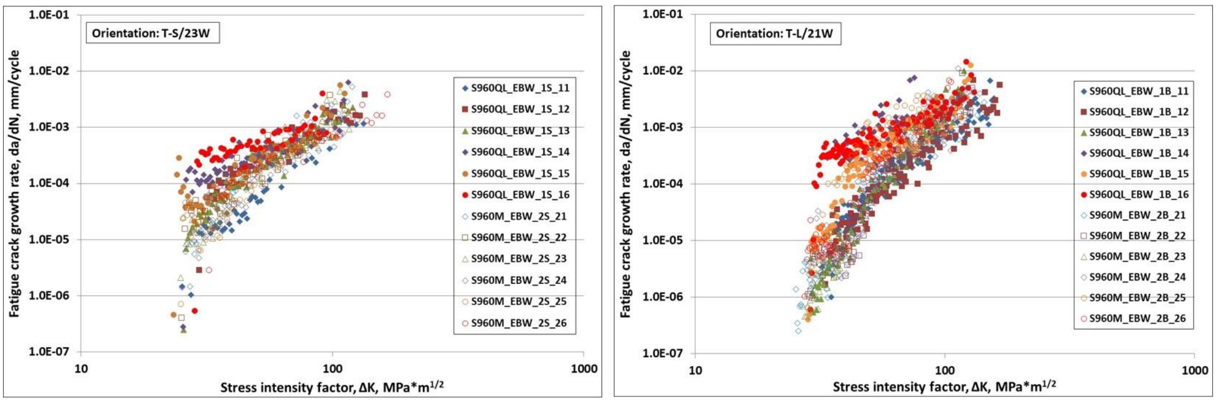

Fig. 2.11.Kinetic diagrams of FCG tests on S960QL / S960M welded joints (altogether 12 specimens).

3. NEW SCIENTIFIC RESULTS – THESES

T1. Based on the detailed HAZ characterization of dual-phase steels (DP800, DP1000, DP1200 & DP1400) by GLEEBLE 3500 thermomechanical simulator for the 5-30 s cooling time interval the HAZ is susceptible to hardening and softening in the function of subzones and $t_{8/5}$ cooling time (6):

a) At short, $t_{8/5}$ = 5 s cooling time, up to DP1000, the CGHAZ of the investigated DP steels tends to hardening, whilst above its grade, in DP1200 and DP1400, CGHAZ is softening compared to BM. In case of long ($t_{8/5}$ = 30 s) cooling time CGHAZ softens in all grades, and the level (ratio) of softening is increasing with the higher grades.

b) Among the investigated subzones not only ICHAZ and SCHAZ, but FGHAZ also tends to soften in the $t_{8/5}$ = 5-30 s cooling time range, although at the shorter ($t_{8/5}$ = 5 s) cooling time ICHAZ is the most critical part of the HAZ in terms of softening.

T2. Based on the performed diode laser beam welding and post weld heat treating experiments on the investigated DP steels (DP800, DP1000, DP1200, DP1400), I verified the beneficial effect of the technology on the joint properties (3) (4) (8):

a) Due to the flexible adjustment of spot diameter in autogenous diode laser beam welding and post-weld heat treatment the hardness peaks in CGHAZ and FGHAZ of the investigated DP steels can be reduced to the level of base materials, resulting lower cold cracking sensitivity, without losing significantly the load bearing capacity of the welded joints.

b) Nearly equal-matching welded joint can be prepared with significantly lower longitudinal and transversal residual stresses from 1 mm thick DP1000 steel sheets by diode laser welding with G895M21Mn4Ni2.5CrMo (according to EN ISO 16834-A standard) filler metal and post-weld heat treatment.

T3. Based on the performed high vacuum electron beam welding experiments on the investigated 15 mm thick S960QL and S960M steels (1) (25):

a) Approximately same strength and toughness welded joint could be prepared from S960QL with electron beam welding as with gas metal arc welding without the application of alloyed filler material. Electron beam welding is an effective way to compensate the HAZ brittleness, characteristic in the whole 2.5-30 s $t_{8/5}$ range of S960QL, by the significantly narrower heat affected zone.

b) A nearly equal matching weld with low cold cracking sensitivity can be achieved by the autogenous EBW with S960M.

T4. Based on the performed residual stress measurements with XRD on the electron beam welded joints (2):

a) The maximum longitudinal tensile stress near the weld toe of the EB welded S960QL joint is higher than the S960M.

b) The transverse residual stresses in the S960QL and S960M welded samples shown the characteristic W-shape of residual stress distribution.

T5. The autogenous electron beam welded joints of the investigated S960QL steel are significantly more sensitive to the location (FZ, FL, HAZ) of the fatigue cracks than the welded joints of the examined S960M EB welded joint. I proved this statement by fatigue crack growth tests performed and analyzed with cracks propagating in different zones of the welded joint. (26)

T6. The fatigue crack growth resistance of the investigated S960M EB welded joint in the examined directions (21 and 23) is significantly different, there is no such difference for the investigated S960QL grade. I proved this statement by fatigue crack growth tests performed and analyzed in different directions. (26)

4. INDUSTRIAL UTILIZATION AND FURTHER DEVELOPMENT

There is an increasing demand, especially in the vehicle industry for the application of high strength steels. HSSs are achieved by a varying microalloying elements and special manufacturing technology that results in a special, complex microstructure. As a result, the main challenges for development engineers and researchers to understand the weldability of these HSSs with application of various welding technological processes, including conventional and high energy beam welding processes to take up technological advancement and benefits of it. The extensive experimental work and the gained achievement of present dissertation from material, technology and design perspectives, can contribute to the wider spread of high strength steels in the industry.

Related to DP steels, the gained experiences during the physical simulation of HAZ and real welding experiments provide opportunity to study the weldability of newly developed high-strength steels. The results presented in the dissertation provide important information not only for welding professionals but also for material engineers involved in steel development.

The application of diode LBW process for various grades of DP steels and the effect of PWHT provide the detailed information about the mechanical properties and the microstructural changes, which may provide a basis for the development of new types of steels. The comparison of $t_{8/5}$ cooling time by analytical and experimental methods can contribute to the more accurate predictions of the properties of the weld. The application of diode lasers in fusion welding can be considered as a relatively new area, however the welding and PWHT can be performed by the same equipment due to the widely adjustable spot diameter. This property could be effectively utilized in the examined DP steels however this methodology can be also beneficial for other types of high strength steels having even higher hardenability. PWHT had clearly a beneficial effect in terms of the cold cracking sensitivity and residual stresses, therefore its application should be in focus related to high strength steel welds.

The application of power beam processes for the HSSs (S960QL & S960M) has clearly an industrial significance. Practical guides and tips for welding these steels with conventional arc welding process are already available in many cases, however, sufficient information is not yet available on the effects of lower welding heat input (EBW process), dynamic and fatigue behaviour of welded joints made of these steels. Therefore, the basic aim of the present dissertation is to summarize knowledge that will also provide useful information to industry professionals. These results will help the engineers/technologists and users of HSS for the application of research data and can be implemented in the production of cranes and vehicles (trucks, trailers etc.). In this dissertation, applicability of the electron beam welding for two types of HSSs were presented which will have significant contribution in reducing the HAZ, weld zone, full penetration in thicker plate without filler materials, good strength, reduced brittle zones, higher speed, better quality, higher production time, reduced material wastage etc. as compared to the conventional arc welding processes. Electron beam welding is considered to be the most promising welding method for the structural fabrication, thick material welding etc. as the microstructural properties of the produced weld are outstanding and the faster processing times are favourable to conventional arc welding techniques. By EBW process, the tensile strength of the EB-welded joints can reach the level of BM without the application of filler metal and similar toughness can be achieved as by GMAW. Although in the near future primarily the application of LBW is predictable in this sector, the EBW experimental results can be partially transmissible to the application of LBW on the same grades with keyhole technique due to the similar weld and HAZ structure. It is worth noting that during performed instrumented impact tests, the specimens, which far exceeded the 27 J & 40 J impact work required at -40 ºC for S960QL & S960M respectively, also behaved basically a brittle fracture with low amount of ductile parts, in accordance with literature. The absorbed energy during the fracture mostly included the energy for crack initiation, which is generally high, even during brittle behaviour, due to the high tensile strength of the investigated HSSs. Consequently, it is worth critically considering to increase the present 27 J requirement in these high strength steels.

The FCG analysis results of the two different grades of HSSs welded joint using EBW process and its comparison with previously performed work by the different researchers on GMAW welded joint for the same grade of HSSs provided the deep insight into critical investigation and characteristic influence on the FCG resistance. The obtained results provide useful information to the researcher and as well as engineers designing the welded structures and can be applied for future applications and research.

5. LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

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