Comparison of laser and electron beam weldability of high-strength steels

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Abstract. Pressure vessels made of high-strength steels are usually welded by arc methods. The paper deals with the development of laser and electron thick-walled beam welding technology for the mentioned applications. The mechanical and structural properties of laser and electron beam welds of plates with a thickness of 5–20 mm are compared both with and without additional filling material. The study is completed with a detailed analysis of residual stresses and their relation not only to the used welding technology but also to the results in the weld area. Laser and electron beam welds achieve high mechanical values and sufficient fatigue life. Therefore, the technology has been verified and applied for welding the test pressure vessel.

1 Introduction

Welding is a widely used method for joining materials in many branches of industry. Therefore, high demands are laid on mechanical properties and durability of welds used to connect two or more components. Up to now, laser, electron and conventional arc welding are some of the most widely used welding methods. Due to lower heat input, laser and electron beam welding give better mechanical properties and the favourable surface state of residual stresses [1] compared with conventional MAG (metal active gas) technique. Nevertheless, due to the heterogeneous application of energy and localized fusion, which occur during the welding process, high undesirable residual stresses (RS) can be present in the region near weld and in the weld itself. These RS occur because of the superposition of thermal and transformation processes [2] and could reach high values and subsequently could cause fatigue life reduction or promote crack growth [1, 3].

In terms of service life, the microstructural changes of plastically deformed crystalline materials are necessary to study. Fusion welding causes to decrease toughness, ductility and corrosion resistance of ferritic steel due to the grain coarsening, carbides precipitation and martensite formation occurred in their microstructure [4]. These so-called microstructural notches are the potential critical areas for the potential crack initialization, e.g. in the fusion zone.

The purpose of this investigation is to analyse strengthening behaviour and reveal relationship between microstructure of weld metal, mechanical properties and surface residual stresses.

2 Experimental techniques

The investigated specimens were prepared by welding of plates 300×150 mm² in size and 5–20 mm in thickness made of P355NL1 and P460NL1 (marked as "N" and "H") fine-grained ferritic-perlitic steel
used for pressure vessels, heat exchangers and reactors. The laser and electron beam welded specimens (marked as “L” and “E”) were prepared using a high-power diode laser by the company RAPTECH s.r.o. and at Faculty of Materials Science and Technology in Trnava, respectively. The welding parameters were as follows: power 3 kW, welding speed 5.5 mm·s⁻¹, continuous mode, laser wavelength 900–1080 nm for laser beam welding and welding speed 30 mm·s⁻¹, voltage 55 kV, current 220 mA for electron beam welding. 20 mm plates were laser beam welded according Fig. 1a. The butt part was double-side welded, where top sides “U” were welded as the first and bottom sides “D” as the second one. Further, the V-shape groove was filled using G3Si1 filling wire. All plates welded by the electron beam and plates with thickness of 5 mm welded by laser beam were single-side welded from the top sides “U”, see Fig. 1b. The others plates were double-side welded. Using these marks, “N8LD” sample denotes laser welded 8mm plate made of P355NL1 analysed on the bottom side.

![Figure 1. a) The double V-groove shape of laser beam welded 20 mm plates geometry b) the others](image)

Specimens for metallographic analysis were hot embedded into conductive bakelite resin with the carbon filler. After the embedding, the specimens were prepared by machine grinding and polishing. Microstructure was revealed by etching in 2 % Nital (98 ml ethanol + 2 ml HNO₃). Microstructure was investigated by optical microscope Zeiss Axio Observer Z1M.

The tensile test was carried out at room temperature according to ČSN EN ISO 6892-1 on the EUS 40 testing machine. Charpy V-notch impact test was performed in accordance with ČSN EN ISO 148-1 standard on PSWO 30 impact testing machine at 0 °C.

The PROTO iXRD COMBO diffractometer in θ–goniometer set-up with chromium anode was used for determination of lattice deformations of α-phase (ferrite, bainite, and martensite). Diffraction angles 2θ were determined using Gaussian function and Absolute peak method from the peaks of the diffraction lines Ka of the {211} planes. To describe the state of residual stresses (RS), the Winholtz & Cohen method [5] and X-ray elastic constants ½S₁ = 5.75 TPa⁻¹, S₂ = −1.25 TPa⁻¹ were used. The specimens were analysed in the direction perpendicular “T” and parallel “L” to the welds (welding direction) on both sides of the specimens. Welded plates were analysed in the middle part in 18 points (x = 0–30 mm from the axis of the weld). The irradiated area was approx. 11×1 mm² with the average effective penetration depth of the X-ray radiation approx. 4 µm [6].

3 Results and discussion

3.1 Microstructure

Comparison of laser and electron beam weld macrostructure is shown in Figs. 2 a) and b), respectively. The laser beam weld is almost three times wider than the electron beam weld, which is a consequence of the different power input and welding speed of the technologies.

Scanning electron microscope (SEM) micrographs of the base material of P355NL1 and P460NL1 steels are shown in Figs. 3. The microstructure of both steels consists of polygonal ferrite (PF) and pearlite (P). PF is fine-grained, but the case of P460NL1 volume fraction of P is occurred in the case of P355NL1. P is in typical lamellar morphology.

Microstructure in the heat-affected zone (HAZ) and weld metal (WM) is mostly affected by temperature input and cooling rate. The highest cooling rate is in WM, which led to the formation of non-diffusion ferrite morphologies. Allotriomorph ferrite (ALF) is occurred along the primary austenitic grains and the rest of primary austenite transformed to the acicular ferrite (AF) and bainite ferrite (BF), see Fig. 4 c). The boundary between WM and HAZ, well-known as a fusion zone (FZ), is
formed by coarse bainite. As can be seen from Fig. 4 d), the mixture of BF, PF and P was found in the HAZ. In areas where the base material was heated to a temperature higher than A1, lamellar perlite transformed to globular, see Fig. 4 b).
The results of the tensile strength of welded steels are shown in Figs. 5. During the tensile tests, a minimum scatter was observed and almost all specimens reached the minimum strength of the base material, which is 490 MPa and 570 MPa for P355NL1 and P460NL1 steels, respectively. The final fracture was almost always observed far from the WM and the HAZ. Unsatisfactory results were found in specimen H5E, where a significant lack of fusion was found on the fracture surface, which led to a reduction of tensile strength and localization of the final fracture to the weld area.

![Figure 5. Tensile strength of laser beam welded, electron beam welded P355NL1 and P460NL1 steel](image)

The results of the Charpy V-notch impact test ($K_V$) are shown in Figs. 6. A significant scatter was observed between individual specimens, which is caused by a different amount of porosity in the welds and mainly by the deviation of the main crack from WM to HAZ and base material. Deviation of crack from WM causes that the values of absorbed energy are artificially increased, this issue is also widely discussed in all technologies that create narrow weld beads such as laser and electron beam welding. Many articles [e.g. 7, 8] discuss this problem in detail and it is generally called fracture path deviation (FPD). FPD arises not only in $K_V$ but also in static three-point bend tests and fracture toughness tests. Different fracture micromorphology was also observed depending on FPD - dimple morphology occurred on specimens with higher $K_V$ energy and cleavage facets on specimens with lower $K_V$ energy, see Fig. 7.

![Figure 6. $K_V$ energy of laser and electron beam welded P355NL1 and P460NL1 steel](image)
3.2 X-ray diffraction

A selected residual stresses (RS) dependences for both unconventional technologies are presented in Figs. 8, where N, H, 8, L, E, U, and D indicate P355NL1 steel, P460NL1 steel, the thickness of the plate in millimetres, laser beam welded specimen, electron beam welded specimen, the side which was welded first, and the other side, respectively. Since the main stress component of the longitudinal weld of the pressure vessel is in the direction perpendicular to the weld, i.e. the T direction.

![Figure 7. Effect of FPD on fracture propagation of N8L sample](image)

![Figure 8. Surface residual stresses in relation to the analysed area of the welded specimen, where x denotes the distance from the axis of the weld](image)
Comparison of surface RS of specimens after different welding techniques shows, that the type of welding has a significant influence on the state of RS, compared to [2]. Presented trends follow a combination of anisotropy shrinkage during cooling and volume-limited phase transformation from austenite to ferrite and/or martensite and/or bainite. In direction T, higher tensile RS were found for the laser beam weld on the top side, while lower compressive stresses are on the bottom side. These stresses are probably generated due to the filling the groove during laser beam welding and the associated deformation during cooling, or generally due to accumulation of heat of double-side weld. In this case, the effect of shrinkage did not prevail along the weld, which resulted in a high tensile RS. Another effect could be lateral warping of the plate when welding the bottom side. These RS near the weld could be higher than the yield strength, see Fig. 8 N10LU specimen in the L direction. This effect could be caused by the higher hardness of weld, which indicates the occurrence of hard phases with a higher yield strength.

For electron beam welding, the favourable compressive RS were analysed in the HAZ in the distance of 1–3 mm from the weld axis in the T direction. Stress affected zone is approx. 15–20 mm in the distance from the axis of the weld. Because of the amount of heat, the laser and electron beam welds exhibit comparably narrower HAZ in the comparison with e.g. MAG welding.

4 Conclusion
The most critical areas for the potential initialization of surface fatigue crack is FZ because of higher hardness, microstructural and surface notches. The microstructural notch of FZ is formed by coarse bainite. From surface RS point of view, the area with high tensile RS is the most critical. The positive finding was that the final fracture was localized in the base material during the tensile tests. The combination of welds properties (microstructural, RS, hardness, imperfections etc.) exceeds the properties of base materials.

Despite the scatter of KV₂ energy between individual specimens, there are no significant differences between laser and electron beam welded specimens. Moreover, higher KV₂ energy was observed for thinner specimens. This trend could be caused by a different amount of porosity in the WM and high tensile RS. The main reason for tensile RS generation in the WM and HAZ is a higher amount of thermal energy, i.e. using the filling wire and double-side welding.

Therefore, the laser and electron are a suitable tool for welding of pressure vessels steels, nevertheless, the biggest advantage of laser compared with electron beam welding is that there is no need to have a vacuum chamber. Contrarily, the electron beam welds have narrower WZ which could improve the mechanical properties of the weld.

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References
[1] Čapek J, Ganev N, Trojan K, Němeček S and Kolařík K 2019 Adv. X-Ray Anal: Proc. Denver X-Ray Conf. vol 63 (USA: ICDD)
[2] Nitschke-Pagel T and Digler K 2014 Mater. Sci. Forum 783–786 2777
[3] Radaj D 2012 Heat effects of welding: temperature field, residual stress, distortion (Berlin: Springer Science & Business Media)
[4] Khorrami MS, Mostafaei MA, Pouraliakbar H and Kokabi AH 2014 Mater. Sci. Eng. A 608 35
[5] Welzel U, Ligot J, Lamparter P, Vermeulen AC and Mittemeijer EJ 2005 J. Appl. Crystallogr. 38 1
[6] Čapek J and Pala Z 2015 Mater. Struct. 22 78
[7] Ohata M, Morimoto G, Fukuda Y, Minami F, Inose K and Handa T 2015 Weld. World 59 667
[8] Üstündağ Ö, Gook S, Gumenyuk A and Rethmeier M 2020 J. Mater. Process. Tech. 275 116358