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Residual stresses of laser-welded pressure vessel steel determined by X-ray and neutron diffraction

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Abstract. To gain insight into the quality of the laser weld, information about the residual stress state across the weld is very useful. In this contribution, the residual stress profiles for low-alloy carbon steel plates of P355NL1 grade, which were laser welded from both sides, are presented. To separate the effects of the production of plates from the welding process, the samples were annealed for stress relieving. Using X-ray and neutron diffraction, the surface and bulk RS profiles were obtained. From the obtained data, first, the difference in the character of the longitudinal (parallel to the weld axis) and the transversal component of the RS tensor can be seen. The longitudinal component has a tensile character with a maximum value approximately 500 MPa. Values and character of the transversal component vary strongly with depth and distance from the weld axis.

Introduction

Welding is a widely used method in fabrication industries producing ships, trains, steel bridges, pressure vessels, and more. Therefore, high demands are laid on mechanical properties and durability of welds used to connect two or more components together. For the superior properties, such as high welding speeds, low thermal load of the surrounding material, precision and strength of the weld, or possibility of joining components of a wide range of thickness (0.01 to 50 mm), the laser welding has become one of the suitable welding techniques [1,2].

However, despite the advantages of the laser welding, due to a heterogeneous application of energy and localized fusion which occur during the welding process, great residual stresses (RSs) can be present in a region near and in the weld itself. These RSs are a superposition of thermal and transformation processes and can reach high values and subsequently cause fatigue or in combination with cracklike defects promoting of brittle fractures [3]. Therefore, it is necessary to reduce the values of the RSs and size of the area affected by the welding process. These properties of the weld can be influenced by the used method, parameters used in the process and by the treatment of the material before and after welding.

Using X-ray and neutron diffraction, the residual stress state across the laser weld were examined. Specifically, double-side square butt welds performed on P355NL1 steel plates for high-pressure vessels were analysed. This fine-grained low-alloy carbon steel is widely used for fabrication of high-pressure vessels, steam boiler parts, pressure piping, compressors, etc.

Experiment

The P355NL1 hot-rolled steel plates of dimensions of 150×300×10 mm^3 and 150×300×8 mm^3 were studied. The composition of this steel determined by glow-discharge optical emission spectroscopy (GDOES) is given in Table 1. The error at low concentrations is up to 10%. The determined composition is in agreement with the European Standard EN 10028-3:2017 [4] with one exception, manganese, whose weight fraction is below the minimum value 1.10 wt% stated in the norm.

In order to separate the effect of the production of the plates and the laser welding, the samples were separated into two groups, where the first group was laser welded with no extra treatment. The second group was firstly annealed for stress relieving in inert gas atmosphere. Samples were held on the temperature of 560 °C for one hour and subsequently cooled down to 350 °C in the inert gas atmosphere. Cooling to room temperature was performed in air. The double-sided square butt weld (the "Up" side was welded first and "Down" as second) was performed under the same conditions for the first and second group. The most important welding parameters, such as laser power P, welding speed v, welding mode and laser wavelength λ are given in Table 2.

Table 1: Chemical composition of the P355NL1 steel determined for 10 and 8 mm thicknesses using glow-discharge optical emission spectroscopy

Element	Fe	C	Mn	Si	Ni	Cr	Cu	V	Al
Weight fraction [wt%], 10 mm	98.92	0.067	0.80	0.004	0.005	0.021	0.018	0.002	0.037
Weight fraction [wt%], 8 mm	99.10	0.071	0.65	0.002	0.004	0.022	0.021	0.000	0.038

Table 2: Welding parameters

P [W]	v [$mm \cdot s^{-1}$]	mode	λ [nm]
3000	5.5	Continuous	900–1080

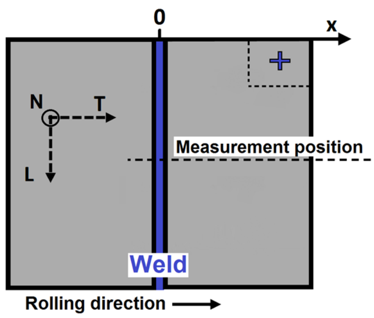

Fig. 1: Scheme of the sample. The cross in the right upper corner denotes the place where the depth profile was measured

RS measurements were performed on PANalytical X'Pert PRO MPD diffractometer with Cr$K\alpha$ radiation (λ = 0.229 nm). The surface residual stress state across the weld and the depth dependence up to approximately 300 μm was determined by X-ray diffraction on {211} α-Fe lattice planes. The position of the measurements is depicted in Fig. 1. The data from different depths under the surface were obtained using electrolytic polishing to remove the material. In order to prevent redistribution of the RSs due to the polishing, the size of the electrolytically polished area was chosen to be 150 mm^2, which was approximately 1/40 of the total area of the sample.

To non-destructively determine the RS profile across the weld in the different depths in the material, the neutron diffraction was used. Measurements were performed in the Institute of Nuclear Physics of Czech Academy of Sciences using the HK4-Strain scanner. For this purpose, the wavelength of the radiation used for the diffraction on {110} α-Fe lattice planes was $\lambda = 0.213$ nm and $2\Theta = 65°$.

Results and discussion

First of all, to analyse the effect of annealing, the depth profiles of RSs up to 300 μm were analysed. From this comparison depicted in Fig. 2, a significant difference between annealed and non-annealed plate can be seen. With respect to the results for the annealed plate, where the values of RSs insignificant, the next presented RS profiles for annealed plates can be related only to the welding process and not to the preparation (hot-rolling) of the plates.

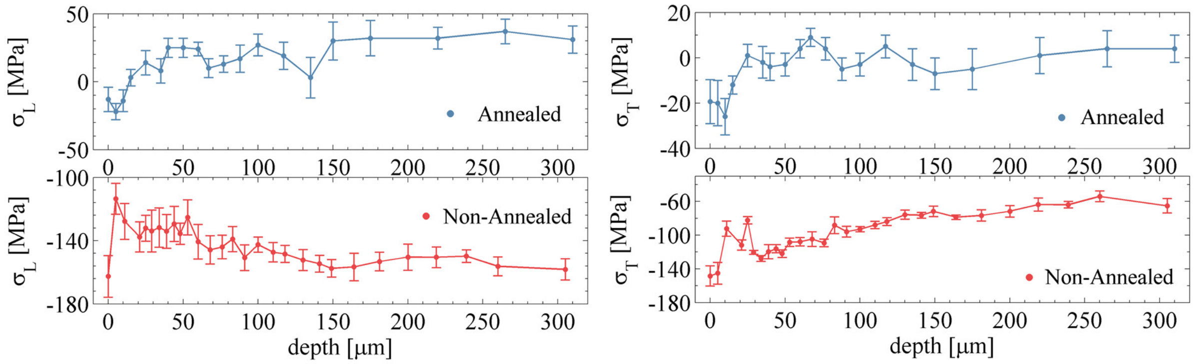

Fig. 2: Longitudinal L (parallel to the weld axis) and transversal T (perpendicular to the weld axis) RSs with respect to depth under the surface

A comparison of longitudinal RSs across the weld for annealed and non-annealed plates of both thicknesses is presented in Fig. 3. From this comparison, the differences between annealed and non-annealed plates are small. The main difference is the smaller stress affected zone (SAZ) of annealed plates. The approximate beginning of this zone is depicted by the lines of a relevant colour. For non-annealed plates, the SAZ extends approximately 3–15 mm further from the weld axis than for annealed plates.

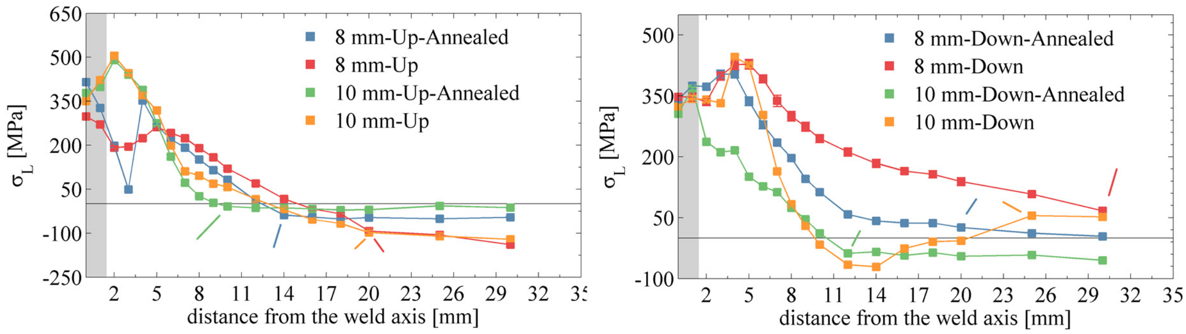

Fig. 3: Longitudinal RSs on “Up” and “Down” side determined for annealed and non-annealed plates

From the obtained depth profiles, it can be seen, that the RSs in longitudinal direction have mainly tensile character, on the other hand, the character of the RSs in the transversal direction is compressive, see Fig. 4 and 5. A value of 0 mm corresponds to the “Down” side. This is in agreement with the mechanisms giving rise the RSs during the welding process, wherein the longitudinal component of stress tensor is mainly given by thermal stresses caused by shrinkage of the material along the weld. In the case of the transversal component, the contribution of stresses given by phase transformation, which material undergoes during cooling, is more significant and causes smaller tensile RSs or even high compressive RSs. For the detailed description of the origin of the RSs see reference [5].

RSs for both the thicknesses have similar pattern. In the longitudinal direction, RSs reach the maximum values. Only for 8 mm thick sample, there is a certain asymmetry for the 6.5 mm line. On the contrary, in the transversal direction, the compressive RS reach about 100 MPa higher values for 8 mm thick sample. Conversely, for 10 mm thick sample on the "Up" side, tensile RSs are approximately 200 MPa higher.

The comparison of both the methods (X-ray and neutron diffraction) showed that longitudinal components of the surface RS obtained by X-ray diffraction are comparable with the longitudinal components of the residual stresses in the bulk material determined by neutron diffraction. On the other hand, in the case of transversal components, great differences across the thickness were observed. These differences could be explained due to the fact that length of heated material and subsequent shrinkage is many times shorter than along the weld and residual stresses due to transformation could have occurred. This volume change has different impact in the surface layers and inside the weld. Another significant influence is the double-side welding and the associated warping in the direction perpendicular to the weld.

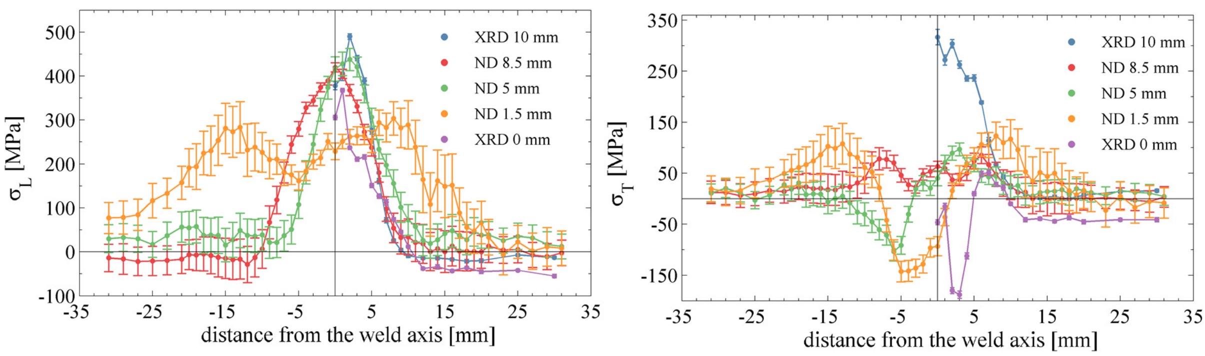

Fig. 4: Longitudinal and transversal RSs for 10 mm thick sample with respect to distance determined across the weld for different depths

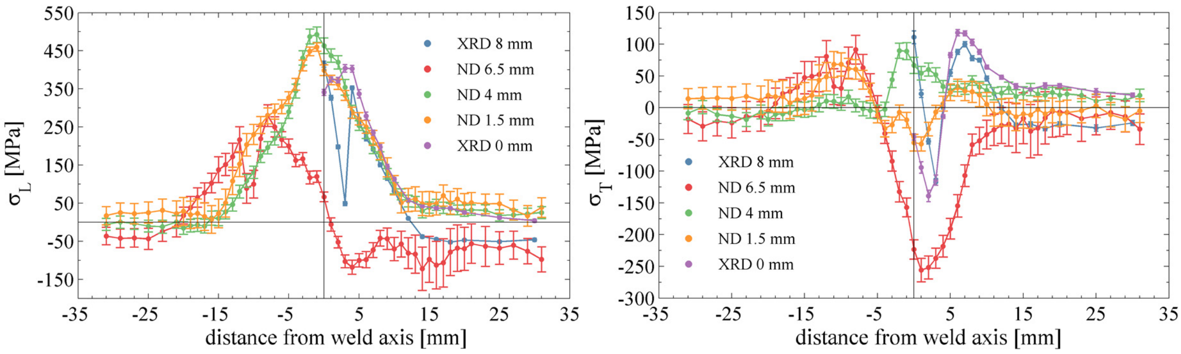

Fig. 5: Longitudinal and transversal RSs for 8 mm thick sample with respect to distance determined across the weld for different depths

Conclusions

From this observation, it can be said that the longitudinal surface RSs obtained by X-ray diffraction are, with respect to measurement errors and differences between samples, representative for the longitudinal state of residual stresses across the weld. On the other hand, the measurements show that the transversal RSs change significantly with depth and the nature of the residual stresses below the surface cannot be assessed on the basis of the surface state of stresses. Other non-destructive methods, e.g. neutron diffraction or ultrasonic velocity measurement [6], should be used to describe subsurface gradient of residual stresses. Alternatively, destructive approach using X-ray diffraction together with electrochemical polishing (removal) of surface layers can be applied.

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