EAN 2014
52nd conference on experimental stress analysis

Residual Stress Mapping by X-ray Diffraction in Thick Laser Welded Sheets of DOMEX S355 Steel

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Keywords: Laser welding, thick steel sheets, residual stresses, hardness.

Introduction

Since the breaking of SS Shenectady, WWII T2 type Liberty ship, in 1943 [1], analysis of residual stresses (RS) in welds represent a traditional partnership between an ever evolving, and vital, technological process and a quantity vitally characterizing the result of this process. As the modern way of joining materials is shifting gradually from conventional welding into friction stir or laser welding, RS remain a crucial parameter which gives clues about the welds' behaviour under dynamic loads. Yet especially in the case of welds and the surrounding material it holds true that RS in thin surface layer cannot provide complete information and ideally 3D maps of the whole area affected by welding should be ascertained. This can be done by for example by technique called neutron strain scanning [2]. However, when neutrons are not easily accessible, X-ray diffraction (XRD) methods can offer 2D maps of RS from cross-sections of the welds comparable to those obtained by contour method [3].

Employing laser beams for welding is gaining popularity in the last decade especially because of the introduction of high power diode lasers (HPDL) that are distinguished by low heat input and high efficiency [4]. However, the ability of this process has been often put into question when steel sheets with larger thickness of 10 mm or even more are to be joined by a laser weld with proper structure, parameters and durability.

This contribution will demonstrate that laser welding is capable of jointing thicker steel sheets of 10 and 20 mm and, moreover, virtues of the RS mapping by XRD will be shown as well. The thick sheets were made from high strength, cold forming steel DOMEX S355. It has already been shown [6] that this material is suitable for laser welding and that the hardness in the heat affected zone increases to 450-500 HV as compared with around 200 HV in the base material, but residual stresses have not been investigated.

Experimental

Altogether, three welds 300 mm in length were prepared. *Firstly*, two 10 mm thick sheets were laser welded without filler wire and 5.5 kW laser with 0.75 m/min beam speed. *Secondly*, the 10 mm thick sheets were joined by using filler wire and 0.5 m/min beam speed.

And since this second weld showed satisfactory parameters, *eventually*, two 20 mm thick sheets were joined together by double-sided laser welding of two sheets, each with dimensions 150×300×20 mm^3. The material of filler wire was EN ISO 14341-A-G3Si1, power of the HPDL was set to 5.5kW; the speed of welding was 0.5 m/min and 18 l/min of Ar was used as shielding gas.

The welded sample was then cut in the middle and the emergent cross-section electro-chemically polished in order to eliminate the effect of cutting. A layer with thickness of 0.2 mm was removed by polishing. 2D map of RS on cross-section were obtained by XRD analysis in two mutually perpendicular directions, one being the direction of the weld in cross-section, in 960 points. The XRD measurements were performed on PROTO iXRD COMBO diffractometer in ω-goniometer, or iso-inclination mode, and {211} diffraction line of bcc iron was measured by CrKα radiation. Aside from stresses in two directions, denoted as σ_L and σ_T, the width of {211} bcc Fe diffraction profiles were characterized by a parameter which can be related to real structure [6]. Moreover, surface stresses and hardness were analysed as well. We obtained HV10 map by measuring in over 700 positions on the cross-section using Vickers Limited HTM indentation tester, constant load of 98.07 N applied for 13 s; the average distance between indents was 0.8 mm. All three welds were also subjected to impact test, according to ČSN ISO 148-1 norm, and to tensile test following the rules of ČSN ISO 4136.

Results

The results of tensile and impact test of all three welds can be seen in Table 1. Surface RS obtained on all three samples are depicted in Fig. 1 and 2D map of RS on the cross-section is in Fig. 2.

Table 1. Results of impact and tensile tests.

Impact test no.	10 mm thick sheets, no filler wire	10 mm thick sheets, with filler wire	20 mm thick sheets, with filler wire
1	26 J	223 J	56 J
2	41 J	157 J	81 J
3	35 J	197 J	79 J
Result	**34 ± 8 J**	**192 ± 33 J**	**72 ± 14 J**
Tensile test no.			
1	536 MPa	493 MPa	524 MPa
2	476 MPa	502 MPa	527 MPa
Result	**506 ± 42 MPa**	**498 ± 6 MPa**	**526 ± 2 MPa**
Remark	fracture in the weld	fracture in base material	fracture in base material

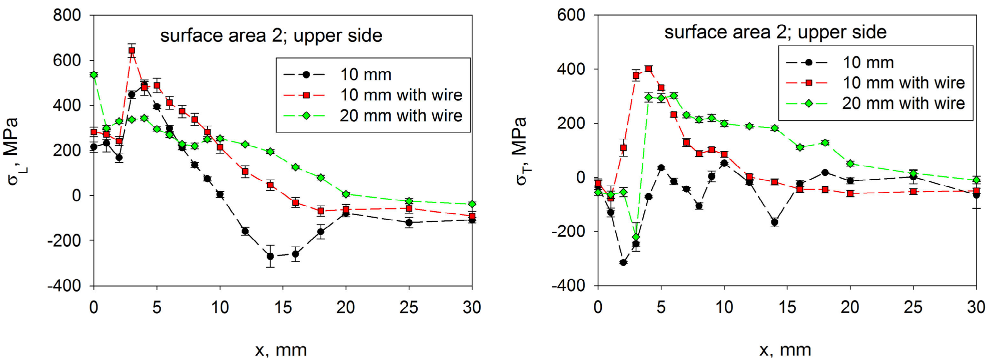

Fig. 1. Surface residual stresses (thickness of the irradiated area approx. 4 μm) in both analysed directions for all three welds; x stands for distance from the weld’s centre.

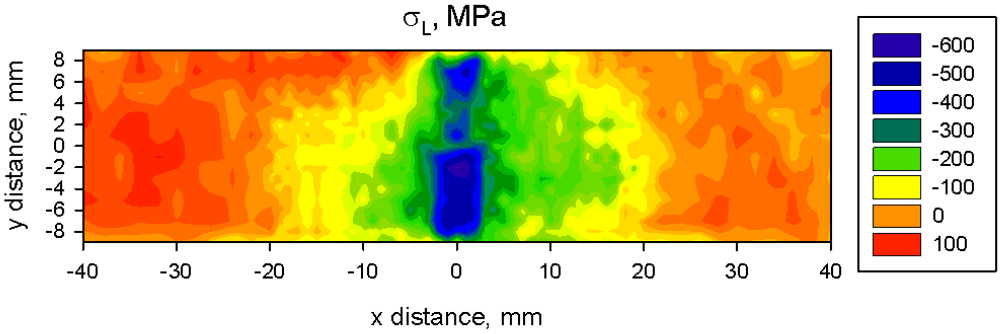

Fig. 2. Map of macroscopic residual stresses in direction perpendicular to the weld.

It is a generally accepted view that values of microhardness correlate with microstrains [7] which can be evaluated from diffraction profiles. Hence, a parameter of {211} bcc Fe diffraction profile, namely Full Width at Half Maximum (FWHM), is juxtaposed with HV10 values in Fig. 3. Furthermore, metallographic cross-section of the weld which joined 20 mm thick steel sheets is shown as well.

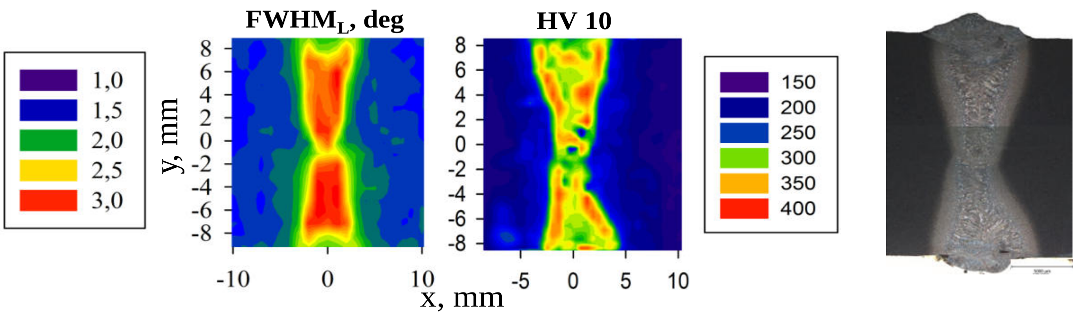

Fig. 3. Juxtaposition of FWHM parameter (left) with HV10 (centre). The FWHM can be related to cold work, i.e. microstrains, crystallite sizes and dislocations, and origination of martensite. Microstructure of the weld, seen on metallographic cross-section, is on the right.

Discussion

For the chosen welded material, the norm ČSN EN ISO15614-1 permits maximal HV10 value of 380 HV which is fully complied by all three welds as seen in Fig. 4. However, the welding without filler wire is not suitable, because the cracking occurred in the weld during tensile testing. When the filler wire was used, the cracking was observed in the base material for both 10 and 20 mm thick welds which gives evidence about sufficient strength of the weld.

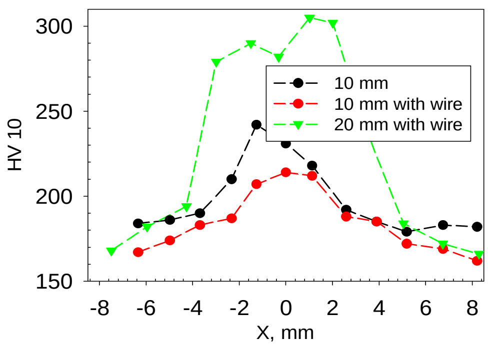

Fig. 4. Comparison of measured hardness on all three welded structures. Hardness of the weld and HAZ area of 20 mm thick welded sheets is by approximately 100 HV higher.

The cracking took place in all three welded structures at the level of approximately 500 MPa, however there are significant differences in impact test results. The best behaviour during impact is exhibited by 10 mm thick weld with filler wire, characterized by approximately 200 J. On the other hand, the sample without wire is completely unsatisfactory. Suitably chosen parameters of laser welding are, thus, capable to manufacture weld with good quality.

Results of RS, indeed, prove that surface values cannot fully describe the stresses originated after welding and, if time and fund permits, at least 2D RS map should be obtained. In our case, RS map clearly shows that there are compressive RS in the welds amounting to over -500 MPa while the HAZ is characterized by values of ranging from -300 to -150 MPa. Moreover, RS are not symmetrical and the slight asymmetry can be probably attributed to anisotropy of HPDL beam movement during welding. These values support the dominance of phase transformational mechanism of RS creation during cooling of the welded area when fcc austenite is transformed into tetragonal martensite. We have also found a correlation between FWHM parameter and hardness values; more detailed analysis of microstrains, crystallite sizes from the diffraction profile and weight fraction of hard martensite from Rietveld refinement of diffraction pattern is topic for further works.

Conclusions

Thick sheets from cold forming steel were joined by double-sided laser welding with filler wire and the originated RS analysed on cross-section by XRD. The obtained 2D maps show that high compressive stresses even exceeding -500 MPa occur in the direction perpendicular to weld and also compressive stresses around -200 MPa in the HAZ. This beneficially influences the behaviour of the weld under dynamic loads and supports the observation that cracks are more likely to originate in the base material rather than in weld or HAZ.

Acknowledgements

This research was carried out in the frame of research projects TA02011004 of Technology Agency of the Czech Republic and LO1201 of the Ministry of Education, Youth and Sports in the framework of the targeted support of the "National Programme for Sustainability I".

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