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Residual Stress Surface Distribution in the Vicinity of Welds in Laser Welded Steel Sheets

PALA Zdenek[1, a], KOLAŘÍK Kamil[2, b], GANEV Nikolaj [3, c] and ČAPEK Jiří[4,d]

[1, 2, 3, 4]Department of Solid State Engineering, Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague; Trojanova 13, 120 00 Prague 2, Czech Republic

[a]zdenek.pala@fjfi.cvut.cz, [b]kamil.kolarik@email.cz, [c]nikolaj.ganev@fjfi.cvut,

[d]ge.capek@seznam.cz

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Abstract. Advent of high power diode laser has substantially contributed to the popularity of laser welding in industry where its virtues such as low heat input and good weld strength are highly appreciated. However, one of the drawbacks of the laser welding is distortion of the welded bodies that is closely linked with the generation and/or redistribution of residual stresses in the vicinity of the weld. In this contribution, mapping of surface macroscopic residual stresses in two directions, i.e. parallel and perpendicular to the welds, were performed for two bodies. The first contained a weld created with the high power diode laser beam speed of 2 m/min and the second with the speed of 15 m/min. Our aim was to compare not only resulting fields of residual stresses, but also to perform qualitative assessment of the possible presence of crystallographic texture and gain a qualitative apprehension about the grain sizes in the vicinity of a laser weld joining two steel sheets. Larger distortion of the body with a laser weld is exhibited by the sample manufactured with approximately 8 times bigger speed of laser beam. This sample is in the immediate vicinity characterized by substantial compressive residual stresses in the direction perpendicular to the weld.

1. Introduction

The cost effectiveness, non-contact character, high degree of automation and the resultant good reproducibility make laser welding ever more attractive for automotive and aeronautics. Industrial applications of laser welding using high-power diode laser (HPDL) are becoming more numerous since the usage of this type of laser was firstly published more than 20 years ago [1]. Multiple beam interaction of HPDL and its shorter wavelength in comparison with conventional CO_2 and Nd:YAG lasers is responsible for smaller heat-affected zone, better absorption of the beam energy, fewer cracks and lower porosity or in general more compact microstructure [2]. On the other hand, the HPDL beams are divergent and, hence, problematic to be focused into small beams which would be beneficial for welding of small components.

The fatigue life of an object with a laser weld or, more universally, its performance depends on several parameters of structure, most notably on the residual stresses which are considered as important criterion of the weld quality [3]. The aim of the laser welding process is not only to produce a joint, but also to avoid generation of tensile residual stresses that would significantly speed up crack propagation and to minimalize the distortion of the final object. It has been found that distortion and the macroscopic residual stresses after welding are two mutually affected phenomena and, therefore, upon controlling the residual stresses by the means of laser beam energy and speed of the weld creation, one can influence the undesirable distortion as well.

Determination of residual stress distribution in the vicinity of laser welds can be performed by employing by one of X-ray diffraction (XRD) methods, when the inter-planar lattice spacings are measured and then used for stresses calculation with the help of generalized Hooke's law [4] and appropriate elastic constants. However, there are some limitations to the applicability of XRD for establishing the state of residual stress in polycrystalline materials. Namely occurrence of crystallographic texture and too coarse material [5], the absolute extreme being the case when the irradiate volume lies in a single crystallite, belong to the state of the material when the standard methods fail to give reliable results.

In this contribution, mapping of surface macroscopic residual stresses in two directions, i.e. parallel and perpendicular to the welds, were performed for two bodies. The first contained a weld created with the HPDL beam speed of 2 m/min and the second with the speed of 15 m/min. Our aim was to compare not only resulting fields of residual stresses, but also to perform qualitative assessment of the possible presence of crystallographic texture and gain a qualitative apprehension about the grain sizes in the vicinity of a laser weld joining two steel sheets. Moreover, diffraction line broadening as a parameter of the degree of plastic deformation was computed from the measured profiles.

2. Experimental

The analysed bodies were manufactured by welding of two sheets made form *S355* steel. Power of the HPDL was set to 3.5kW; the speed of welding was 2 m/min and 15 m/min. The lengths of the welds were approximately 180 mm.

Distortions of both bodies were measured in six equidistant points in the direction perpendicular to the welds; the obtained values were, thus, 6 angles of deflection.

The structure of the welds and the adjacent areas of the steel sheets were qualitatively characterized by 2D diffraction patterns, or more precisely by Debye rings of *{211}* planes of α-Fe obtained in the backscattering layout of Debye-Scherrer method. For this purpose, *ISO DEBYEFLEX 3003* apparatus, non-filtered radiation from X-ray tube with chromium anode, cylindrical primary slit with 1 mm in diameter and image plate detector were employed.

Surface distributions of macroscopic residual stresses were established perpendicularly to the welds in eleven areas mutually shifted by 0.5 mm. Each analysed area had a rectangular shape with dimensions 10 × 0.5 mm2; the longer sides being parallel with the welds. Stresses were determined in the directions parallel with the welds, longitudinal stresses σ_L, and perpendicular as well, transverse stresses σ_T.

We assumed biaxial state of stress and used the „$\sin^2\psi$"[6] method coupled with Winholtz-Cohen least squares fitting procedure [7] to compute both longitudinal and transverse stresses. The measured diffraction profile of α-Fe *{211}* planes has for the used filtered CrKα radiation it maximum at $2\theta \approx 156°$. Detected doublets were separated by Rachinger method [8] to the contributions from CrKα1 and CrKα2. Diffraction profile corresponding to CrKα1 radiation was fitted by Pearson VII function. Maxima of this function for all measured profiles served as input data for inter-planar lattice spacing's calculations. In the generalised Hooke's law, we used X-ray elastic constants $s_1 = -1.25\ \mathrm{TPa}^{-1}$ and $\frac{1}{2}s_2 = 5.76\ \mathrm{TPa}^{-1}$ obtained with the help of Eschelby-Kröner model [9]. Eventually, the diffraction profile corresponding to α-Fe *{211}* planes parallel with the surface was characterized by FWHM (Full Width at Half Maximum) profile parameter which represents another parameter, often described as „degree of plastic deformation", because the diffraction profile broadening can be related to such phenomena as grain size, microscopic residual stresses or dislocation density whose evolution is closely connected with plastic deformation.

Diffraction measurements were carried out on vertical *θ/θ X'Pert PRO MPD* diffractometer equipped with monocapilary optics in the primary beam, i.e. the beam impinging on the analysed sample was pseudo-parallel. Positioning of the measured objects to the coveted locations was done by combining versatile positioning system seen in Fig. 1 which with six degrees of freedom and laser triangulation for precise surface position determination with accuracy of approx. 5 µm.

Fig. 1. In-house designed versatile positioning system for XRD analyses of real objects.

3. Results

Prior to the XRD analyses of residual stresses by „sin²ψ“ method, diffraction patterns capturing *{211}* α-Fe Debye rings were obtained. Table 1 shows the selection of three patterns: one form the initial state of the steel sheets prior to laser welding and one from each object 2 mm far from the welds' boundaries. The six angles of deflection for each object are summarized in Tab. 2. Surface distributions of macroscopic residual stresses can be seen in Figs. 2 and 3 as well as corresponding FWHM parameters in Fig. 4 and 5.

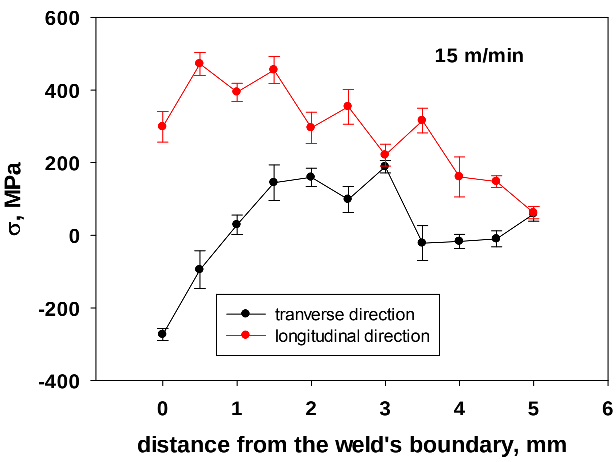


Fig. 2. Surface distribution of residual stresses in the vicinity of the laser weld created with the HPDL beam speed of 15 m/min.

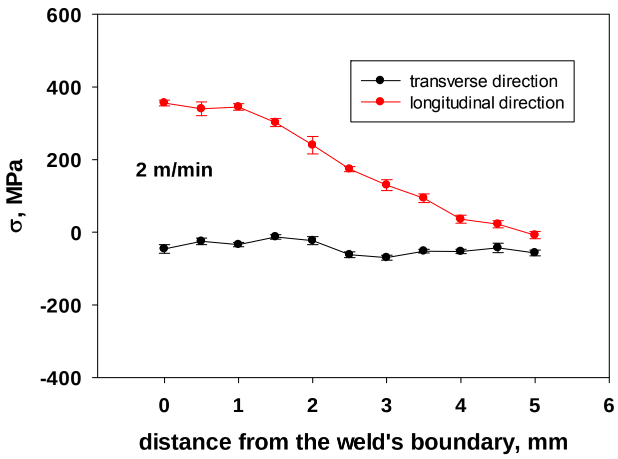


Fig. 3. Surface distribution of residual stresses in the vicinity of the laser weld created with the HPDL beam speed of 2 m/min.

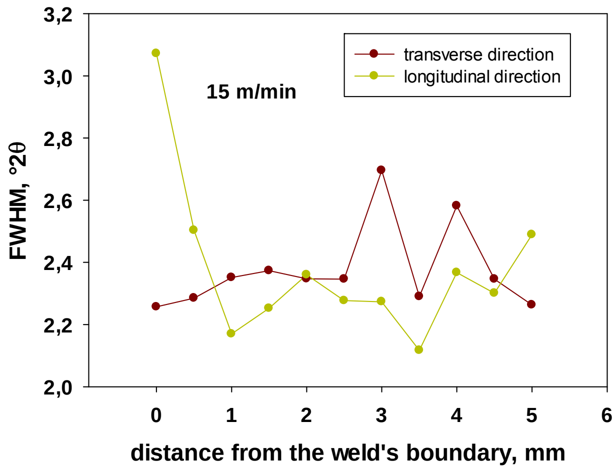


Fig. 4. Surface distribution of FWHM of α-Fe *{211}* diffraction profile of planes parallel with the sample surface; measured in the vicinity of the laser weld created with the HPDL beam speed of 15 m/min.

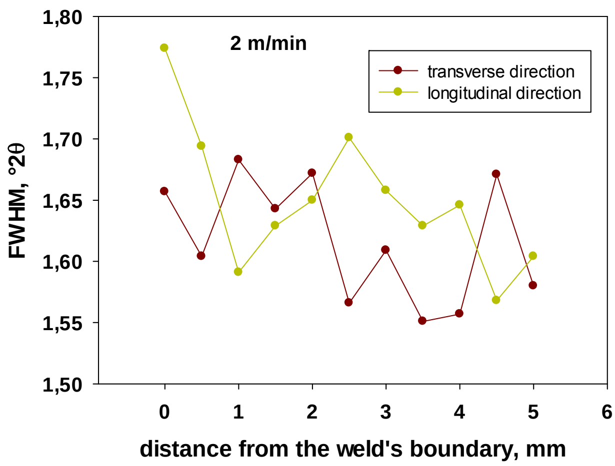


Fig. 5. Surface distribution of FWHM of α-Fe *{211}* diffraction profile of planes parallel with the sample surface; measured in the vicinity of the laser weld created with the HPDL beam speed of 2 m/min.

Table 1 Backscatter diffraction patterns with Debye rings of α-Fe *{211}* planes.

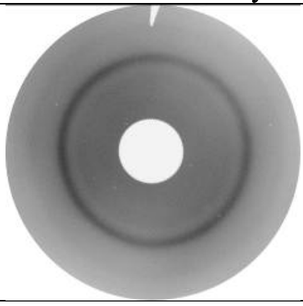
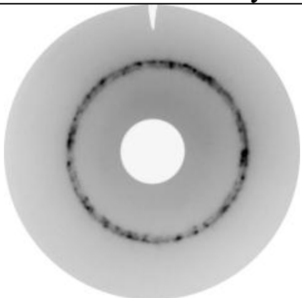
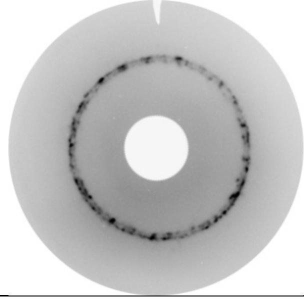
Sample, area	**2 m/min**, 2 mm from the weld's boundary	**15 m/min**, 2 mm from the weld's boundary	state prior to laser welding
Diffraction pattern			

Table 2 Deflection of both analysed bodies in seven equidistant points in the direction perpendicular to the welds.

Point	**Deflection of sample 2 m/min**	**Deflection of sample 15 m/min**
1	-1° 4′	2° 20′
2	-1° 3′	2° 25′
3	-1° 3′	2° 25′
4	-0° 8′	2° 25′
5	-0° 7′	2° 20′
6	-0° 8′	2° 20′

4. Conclusions

Considering all the results from the analysis of two objects with laser welds prepared with HPDL laser and two distinctive beam speeds entitles us to make the following conclusions.

- The structure of the material in the vicinity of welds was suitable for residual stress determination by means of XRD.
- From the comparison of the Debye rings from both samples (Table 1) emerges the fact that the structure in the vicinity of the weld created with lower speed is distinguished by larger grains of b.c.c. iron. It is, thus, coarser-grained than the areas adjacent to the weld done with much higher speed of 15 m/min. Taking the effect of temperature-related phenomena, the performed measurements affirm that laser welding with lower beam speed leads to more pronounced heat impact of the structure.
- On the surface of both the objects, anisotropic biaxial state of stress was established, i.e. $\sigma_T \neq \sigma_L$. Residual stresses σ_L in the direction parallel with the welds are tensile in all measured areas and decrease in value with larger distance from the welds' boundaries. The decline has monotonous character for the sample 2 m/min, but oscillations between neighbouring areas occur in the case of the body with 15 m/min weld.
- Whereas character of σ_L surface distributions is similar, the stresses in perpendicular direction to the welds are qualitatively different for both bodies.
- The stresses σ_T are within comparatively narrow interval from -70 to -13 MPa for the sample 2 m/min which is in stark contrast to the other sample where the stresses rise from approx. -300 MPa to approx. 150 MPa within the 1.5 mm wide area fast beside the weld's boundary.

- From the comparison of all four surface distributions of {211} α-Fe FWHM parameter, it is visible that higher values are seen for faster beam speed, see Fig. 4 versus Fig. 5. Both areas closest to the welds show apparent increase in this parameter, but only for diffraction profiles measured in longitudinal directions, i.e. parallel with the welds.

Larger distortion of the body with a laser weld is exhibited by the sample manufactured with approximately 8 times bigger speed of HPDL beam. This sample is in the immediate vicinity characterized by substantial compressive residual stresses in the direction perpendicular to the welds.

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References

[1] L. Li, The advances and characteristics of high-power diode laser materials processing, Optics and Lasers in Engineering 34 (2000) 231-253.

[2] J. Lawrence, L. Li, Wettability characteristics of an Al2O3/SiO2-based ceramic modified with CO2, Nd:YAG, excimer and high-power diode lasers, J Phys D 32 (1999) 1075-1082.

[3] A.G. Olabi, K.Y. Benyounis, M.S.J. Hashmi, Application of Response Surface Methodology in Describing the Residual Stress Distribution in CO2 Laser Welding of AISI304, Strain 43 (2007) 37-46.

[4] I. Kraus, N. Ganev, Residual Stress and Stress Gradients, Industrial Applications of X-Ray Diffraction, Marcel Dekker, New York, 2000, pp. 793-811.

[5] J. M. Leoni, P. Scardi, S. Rossi, L. Fedrizzi, Y. Massiani, (Ti, Cr) N and Ti/TiN PVD coatings on 304 stainless steel substrates: Texture and residual stress, Thin Solid Films 345 (2), 263-269.

[6] Macherauch E., Müller P.: Das $\sin^2\psi$ -Verfahren der röntgenographischen Spannungsmessung, Zeitschrift für angewandte Physik 13 (1961) 33 – 38.

[7] R.A. Winholtz, J.B. Cohen, Generalised Least-squares Determination of Triaxial Stress States by X-ray Diffraction and the Associated Erors, Aust. J. Phys. 41 (1988) 189-199.

[8] W.A. Rachinger, A Correction for the α_1 α_2 Doublet in the Measurement of Widths of X-ray Diffraction Lines, J. Sci. Instrum. 25 (1948) 254 - 259.

[9] J.D. Eshelby, The Determination of the Elastic Field of an Ellipsoidal Inclusion, and Related Problems, Proc. Roy. Soc. A 241 (1957) 376 – 396.