Characterization of Residual Stresses Distribution and Real Structure in Thick Welded Sheets by X-Ray Diffraction and Barkhausen Noise Analysis After Metal Active Gas and Laser Welding

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Abstract: Generally the manufacturing processes of machine component introduce residual stresses (RS) that have an essential influence on their behaviour during service life. The purpose of this study is to evaluate the residual stress distribution of specimens joined by using high power diode laser and metal active gas (MAG) welding. Non-destructive methods for detection and measurement of RS have been increasingly used in the last few years. The paper outlines the capability of Barkhausen noise analysis (BNA) for evaluation of real structure changes and residual stresses on cross-section of welds due to welding of ferromagnetic plates compared with X-ray diffraction (XRD), that can be used for quantitative analysis of macro and micro level RS separately. However, it is very difficult to use XRD in manufacturing. The principal advantages of BNA over XRD as a tool for RS analysis and real structure characterisation are that it is mobile, faster with more facile carrying out and hence BNA is frequently used for continuous monitoring of RS in industrial processes.

Keywords: Residual Stresses; Laser Welding; Metal Active Gas Welding; XRD; Barkhausen Noise.

1 Introduction

Recently, laser welding was used usually for joining of thin sheets. With the development of high power diode lasers (HPDL) that are distinguish by low heat loading of the material and high welding productivity, thick industrial components are joined more effectively in comparison with classical arc welding methods. Developed laser welding methods took over the capability to fill groove with cold or hot wire metal active gas (MAG) welding and thus to change mechanical properties of welds reducing their hardness [1]. These advanced laser welds are promising for use in transport engineering industry owing these profitable changes of real crystallographic structure in comparison with conventional laser welds [2]. Moreover, these changes improve the results during impact and tensile test and mainly enhance fatigue life as a result of a favourable distribution of RS in the weld zone and heat affected zone (HAZ). In order to accomplish and control required favourable fatigue behaviour of a laser joint welded with a filling wire it is indispensable to specify the real microstructure and the RS distribution and its relaxation during welding in weld zone and HAZ in comparison with the corresponding characteristics of a MAG weld [3].

Recently non-destructive methods for detection and measurement of RS have been used increasingly. X-ray diffraction is a well-established method for residual stress determination in polycrystalline materials. It is based on measurements of interplanar lattice spacing changes due to acted stress and their conversion to RS using theoretical elasticity equations. The measurement depth of this method is limited to a few microns. Subsurface stress determination by XRD requires electrochemical removal of material and repeated stress measurements.

Magnetic Barkhausen noise method for stress measurement exploits magneto-elastic interaction between magnetic domain wall movements and elastic stresses in the ferromagnetic materials. This domain wall movement is induced by applying a time varying magnetic field into the material which forces domain walls to find new equilibrium positions. During this movement, which could be pinned by various crystal lattice defects, a noise-like signal is detected. The amplitude of this signal, called Barkhausen noise, depends on the stress and microstructure of the material under investigation.

2 Welding Residual Stresses

High local residual stresses existing in components could have vital influence on properties of the component. When a welded part with high local RS is machined the equilibrium state of RS is disturbed, and thus significant distortion may occur. On the other hand it is supposed that high tensile RS due to welding have a strong negative effect on the strength properties, especially under fatigue loading. Therefore a great interest exists to receive an exact knowledge about the residual stresses in welded components.

Recent practical approaches distinguish between local and global welding RS [4]. The local RS are resulting from the local heating and cooling processes in the weld metal and adjacent HAZ. Then again, global RS exist in the entire component and are resulting from shrinkage processes which occur in the entire construction. These global RS are affected by the stiffness of the component and the local shrinkage processes (Fig. 1). Tensile RS around a single pass in a plane sample are expected due to the restraint which is generated by the cool adjacent zones in the base material of the plate. These cold zones are hindering strongly the longitudinal shrinkage of the weld zone where the transverse shrinkage principally is more or less free, i.e. not hindered [4].

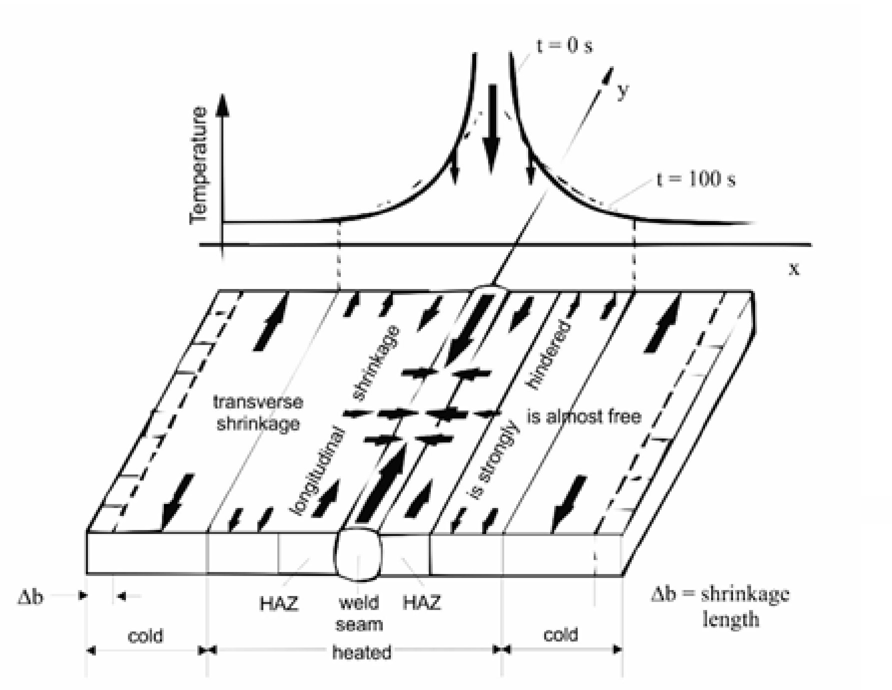


Fig. 1: Shrinkage tendency and constraint conditions in a single pass weld (schematically) [4].

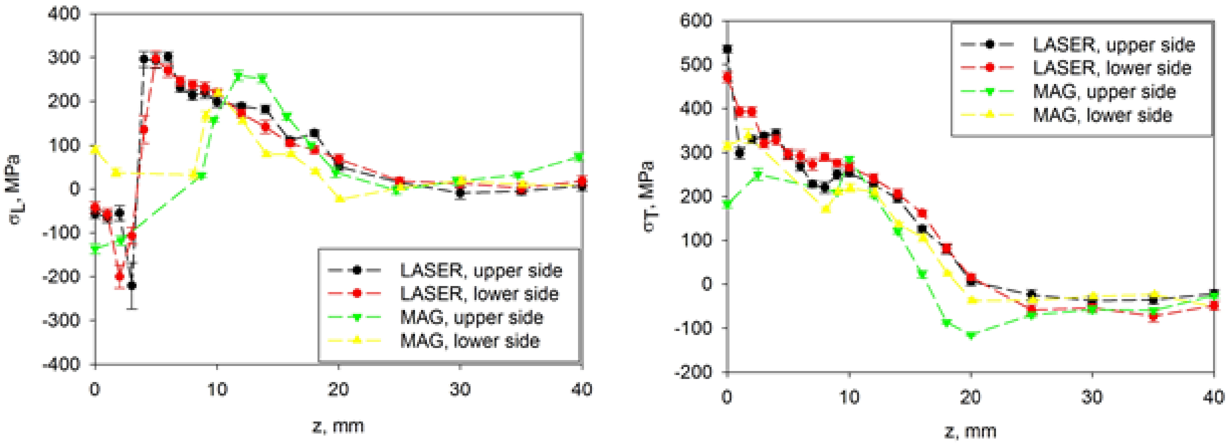
For complete describing the austenite phase transformation associated with a change in volume must be taken into consideration as a significant source of residual stresses especially in high strength steels. The local compressive residual stresses, which arise in the weld zone as a consequence of the restrained volume expansion during the transformation of austenite in martensite, bainite or ferrite, are superimposed to the global tensile residual stresses explained according to the model described above (Fig. 1). The resulting distribution of residual stresses is a combined effect of hindered shrinkage and phase transformations.

3 Experimental

The analysed samples were prepared by a HPDL laser with cold wire and MAG welding from two sheets made of S355J2 steel, each of dimensions $150\times300\times20$ mm^3. The material of filler wire was EN ISO 14341-A-G3Si1. Then the welded samples were cut in halves and the emerged cross-section was electro-chemically polished. This way a layer of 0.2 mm in thickness affected by cutting was removed. 2D map of RS on cross-section were obtained by XRD analysis, in 960 points. The XRD measurements were performed by PROTO iXRD COMBO diffractometer with ω-goniometer and $\{211\}$ diffraction line of α-Fe was measured by CrKα radiation. Breadths of diffraction line were characterized by Full Width at Half Maximum (*FWHM*) parameter. Distributions of RS and microstructure changes were also studied by the use of the BNA. The measurements of magnetoelastic parameter (*mp*) were performed before polishing using a commercial magneto-elastic analyser Stresstech with a standard sensor. Moreover, weld surface stresses and 2D map of hardness were studied as well.

4 Results

Surface RS obtained on both the samples are depicted in Fig. 2. The 2D map of RS on the cross-section for laser and MAG weld is in Fig. 3 and4. Fig. 5 and 6 describe dependence of *FWHM* parameter in direction perpendicular to the laser and MAG weld. An illustration of 2D map of RS and *mp* in direction perpendicular to welds can be seen in Fig. 7 and 8.



(a) direction perpendicular to welds (b) direction parallel to welds

Fig. 2: Surface residual stresses (thickness of the irradiated area is approx. 4 µm) in both the analysed directions for laser and MAG weld; z stands for distance from the weld's centre.

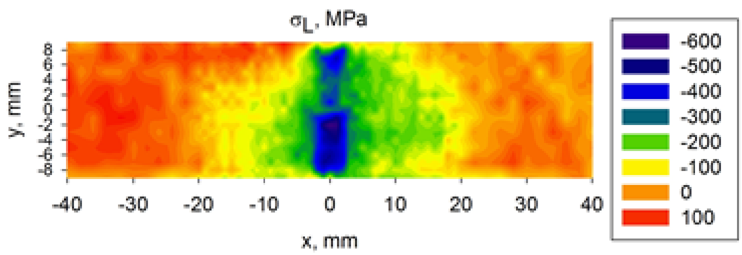


Fig. 3: Map of macroscopic RS in direction perpendicular to the laser weld.

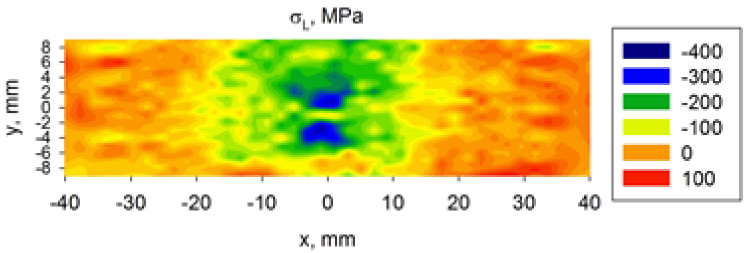


Fig. 4: Map of macroscopic RS in direction perpendicular to the MAG weld.

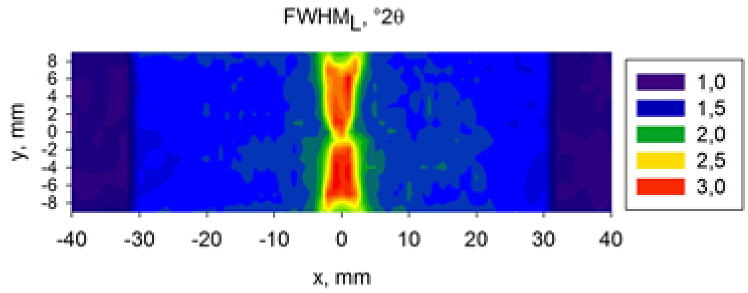


Fig. 5: Map of *FWHM* parameter in direction perpendicular to the laser weld.

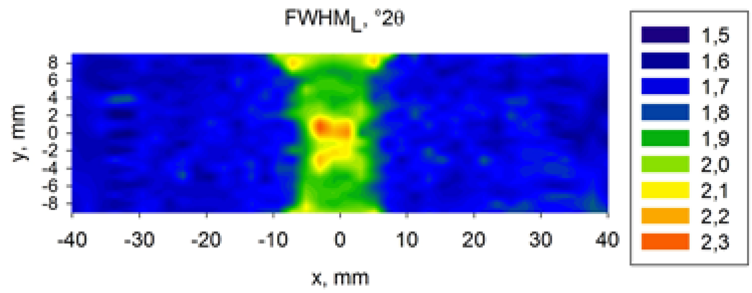


Fig. 6: Map of *FWHM* parameter in direction perpendicular to the MAG weld.

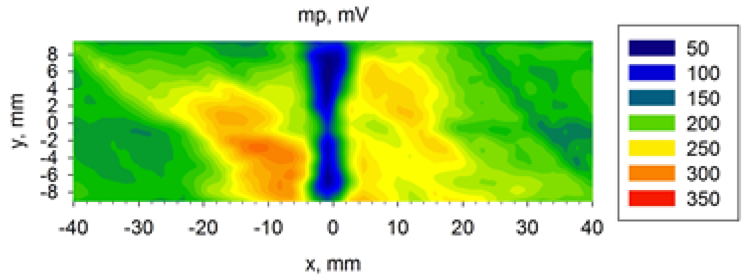


Fig. 7: Map of *mp* in direction perpendicular to the laser weld.

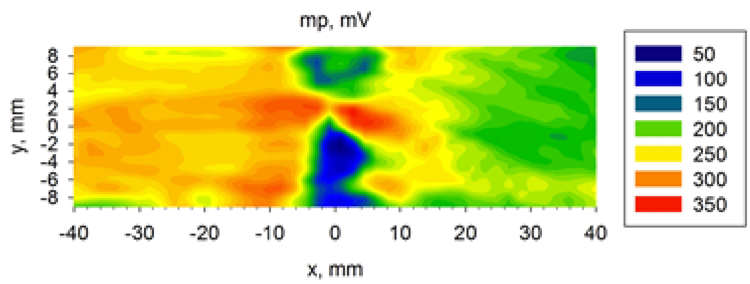


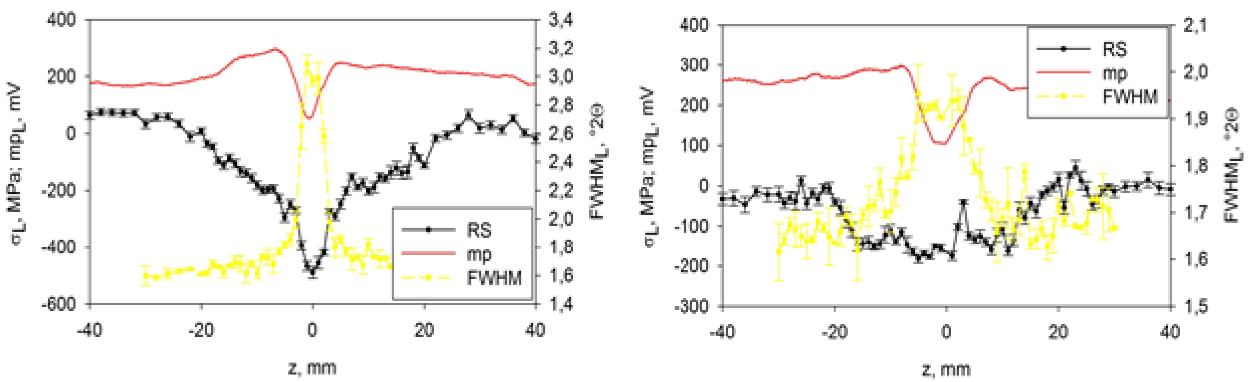
Fig. 8: Map of *mp* in direction perpendicular to the MAG weld.

5 Discussion

From the results of surface XRD measurements, it was found that the laser weld has narrower HAZ and exhibits unfavourable tensile “thermal” stresses of absolute value greater in both the analysed directions in comparison with conventional MAG welding, see Fig. 2. Results of RS, indeed, prove that surface values from welded sheets cannot fully describe the stresses originated after welding and, if time and fund permits, at least 2D RS map should be obtained [2]. Residual stress map obtained by XRD measurements from cross-section laser weld (Fig. 3) indicates that there are compressive RS in the welds amounting to over –500 MPa while the HAZ is characterized by values 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 transformation mechanism of RS creation during cooling the welded area when fcc austenite is transformed into martensite. We have also observed a correlation between FWHM parameter and hardness values [5, 6].

The results from cross-sectional MAG weld (Fig. 4) testimony to considerably wider stress affected zone compared to laser weld (Fig. 3). Compressive residual stresses inside the weld achieve only maximum value of about –350 MPa. Decline in RS is due to the fact that during MAG welding, which has a slower speed i) cooling is very slow and thus a structure close to equilibrium form and ii) multiple passages while creating a weld lead to sequential annealing of previous beads and thus the hardness of the weld gets lower. This statement correlates with a decrease of the *FWHM* parameter (Fig. 6). *FWHM* parameter depends on dislocations’ density, microstrains, crystallite sizes and weight fraction of martensite phase.

The applicability of Barkhausen noise analysis for complex online monitoring of welding process in manufacturing has been also verified. Acquired 2D maps of parameter *mp* shown on Fig. 7 and 8 demonstrate a better correlation with the results of RS (Fig. 5 and 6) for the laser weld in comparison with the MAG one. This could be consequence of hard phases (martensite and bainite) formation [7] as a result of the significantly higher welding speed and reduced heat input of the surrounding area in the case of a laser weld in comparison with a MAG technology. The non-equilibrium new phases mentioned above notably contribute to the increase of *FWHM*, as shown in Fig. 5. Based on Fig. 9, on which *mp*, RS, and *FWHM* from the 2D maps and other partial analysis are compared, we can clearly say that *mp* is more sensitive to changes in real structure (dislocations’ density, microstrains, crystallite sizes) than to the state of residual stresses. Furthermore, on the basis of obtained *FWHM* and *mp* could be state that BNA is more sensitive to possible defects in the welded joints, e.g. in the case of imperfect penetration. Our surmise that the MAG weld had unfused root (see Fig. 6 and 8) proved correct by carried out metallography investigation. The BNA is thus a very suitable tool for a preliminary study of major structure gradients which are associated with the occurrence of stress peaks on real complex objects applicable without special surface preparation. By using BNA as a preliminary searching technique of whole the investigated surface the critical parts/areas could be designated for costly and time-consuming XRD measurements.



(a) laser weld (b) mAG weld

Fig. 9: Comparison of RS and *FWHM* parameters obtained by XRD analysis with *mp* parameter which describes change of real structure for laser and MAG weld.

6 Conclusion

The obtained 2D maps of welding residual stresses by X-ray diffraction technique show that high compressive residual stresses exceeding –500 MPa occur in the direction perpendicular to the laser weld and over –350 MPa in the MAG weld zone. The results describing HAZ width are very similar for both analytical methods applied and laser weld has the narrower HAZ than MAG one. Another advantage of laser welding with filler wire is higher welding speed and better quality of the weld.

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