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Residual stress analysis after laser welding

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Abstract. The paper deals with experimental measurement of residual stress in high strength steel sample by x-ray method before and after laser welding. All the data was collected and then processed in program Matlab to create surfaces of stress distribution in the sample. Polynomial functions were fit to the data to smooth them and achieve better understanding of results. Finally, results of residual stress in welded sample were compared to those in non-welded sample for determining the effect of welding on residual stress.

Introduction

Nowadays, the use of high strength steels is being developed, yet their usage is sometimes limited by their fatigue critical welds [1]. One common problem associated with welding is formation of residual stress, which is defined as any stress that would exist in a continuum body if all external loads were removed [2]. Heating, melting and cooling of the weld and nonuniform temperature distribution are causing plastic thermal strain formation, which results in permanent deformation and residual stress near the weld and its heat-affected zone and can be high enough to cause cracking without any applied loads. The welding-induced tensile residual stresses have harmful effect on fatigue lifetime of structures, corrosion resistance and other mechanical properties. On the other hand, compressive residual stress can improve fatigue resistance of material [7]. This issue has been studying for many years by researchers and is still underway. According to fatigue resistance it is of utmost importance to investigate detailed distribution of welding-induced residual stresses [8,9].

Residual stress determination

Calculation of residual stress requires the introduction of many simplifications due to vast number of variables included. These assumptions enable a mathematical description of processes, but also simplify their physical nature; calculation of the stress is complicated nevertheless. Therefore, the residual stresses, despite huge progress in computer science and good results in the simulation of the process, are still largely determined by application of experimental measurements.

Traditionally, residual stresses can be measured by destructive or non-destructive methods [10]. The former contain for instance cutting and hole-drilling techniques, the latter neutron and x-ray diffraction techniques. X-ray diffraction method obtains strains through change of micro-structural crystal lattice spacing in material; and from this quantity, the total stress can be acquired [3]. When x-ray beam is cast over a solid material, it is sprinkled by the atoms forming the material. The diffracted (sprinkled) waves lead to interferences and the beam can be collected to reach the diffraction intensity peak according to the Bragg's Law (Eq. 1).

$$2D_0 sin\theta_0 = n\boldsymbol{\lambda}\ (n = 1, 2, 3 \dots) \quad (1)$$

Where, D_0 is original distance between lattice planes of adjacent crystal surfaces at the non-stress state,

θ_0 is original diffraction angle between the x-ray beam and crystal surface at the non-stress state,

$\boldsymbol{\lambda}$ is the wavelength of the x-ray beam,

n is order of diffraction.

However, the x-ray beam can penetrate into the material usually not deeper than 40μm, hence this method assumes plane-stress condition i.e. stress perpendicular to the surface is assumed to be zero. For many applications, particularly where fatigue failure is involved, this is not a serious disadvantage [4].

Welding induced residual stress

A number of factors influence residual stress in a welded structure. Shrinkage of the weld metal, thermal expansion and contraction of the base metal, quenching effects, phase transformation and fixtures of structure being welded are the most important.

The diagram in Fig. 1 shows the influence of increasing heat input on the distribution of transverse residual stresses along a line perpendicular to the weld seam. In the case of low heat input (Curve 3), one can see a reduction of tensile residual stress or even compressive residual stresses. In the case of high heat input (Curve 1), one can expect a buildup of high tensile stresses across the weld seam [6]. On account of this fact, welding the sample by means of laser technology was selected.

Laser welding has become popular recently owing to high power density, which has the possibility of focusing the beam power to a very small spot diameter resulting in small heat affected zone. This is a huge perquisite in contrast to the conventional welding processes, e.g. arc welding as it means also lower distortions, residual stresses and strains [5, 2].

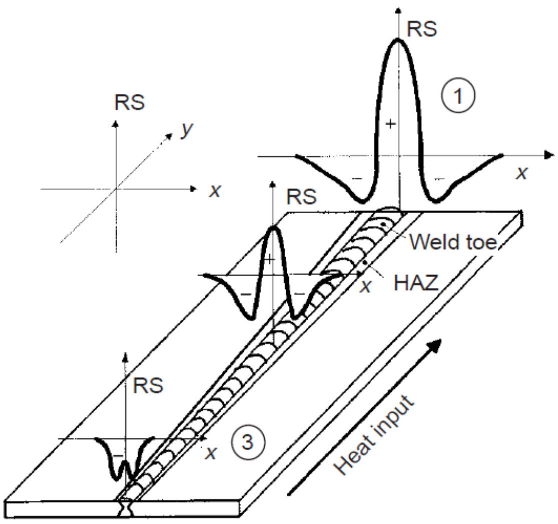

Fig. 1: Influence of heat input on transverse residual stress distribution (RS = residual stress) [6]

Measurement results

The measurement of residual stress in a sample (Fig.2) from high strength steel Domex 700 MC was carried out. Domex 700 MC is a hot-rolled, low-alloy high strength sheet steel with 700 N/mm^2 yield strength. The sheet was welded by laser and then cut into individual samples. The measurement of transverse residual stress was conducted first in base metal sample and subsequently in welded sample on the cut surface (highlighted according to Fig.2) with dimensions (6×6) mm.

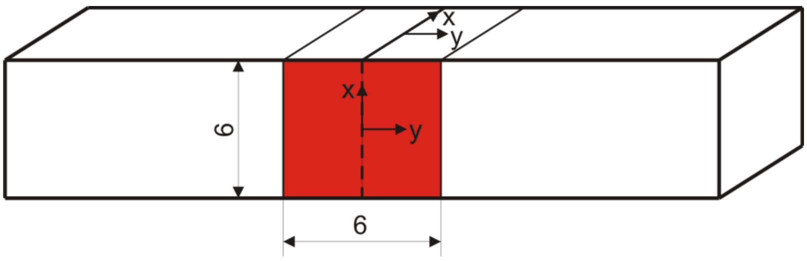

Fig. 2: Schematic representation of a measured sample – highlighted cut surface (transverse)

In Fig. 3, there can be seen high compressive residual stresses (in N/mm^2) in “x” direction (see also Fig. 2) on non-welded cut surface caused by rolling of the material. In Fig. 3b, there is distribution of residual stress along a line y = 0. Fig. 4 shows distribution of normal residual stress in the same direction on welded cut surface and a comparison of these two distributions of residual stress on non-welded and welded cut surface can be seen in Fig. 8a. It is apparent that high compressive residual stresses caused by rolling were released by welding; specifically the highest value of residual stress in “x” direction in non-welded sample cut surface was (according to Fig. 3b)$_{trans}\sigma_x^{nw} = -612$ MPa and the same in welded sample was (according to Fig. 4b) $_{trans}\sigma_x^{w} = -495$ MPa, which means that stress was reduced nearly by 20%. Compressive nature of resulting residual stress after laser welding can be explained by low heat input (see Fig. 1) typical for laser welding.

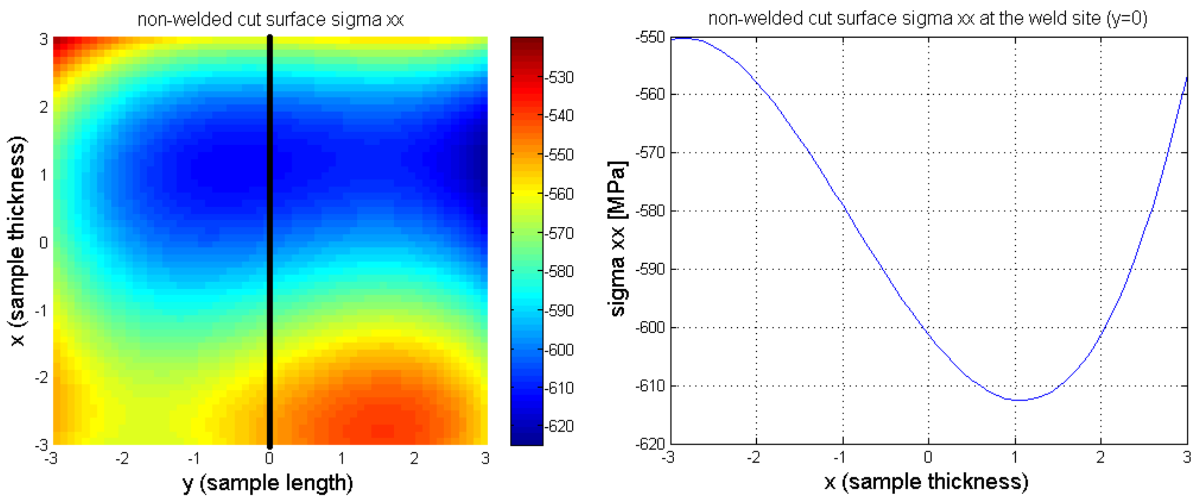

Fig. 3: a) Distribution of normal residual stress in “x” direction on non-welded cut surface and b) distribution of normal residual stress in “x” direction on line y = 0 on non-welded cut surface

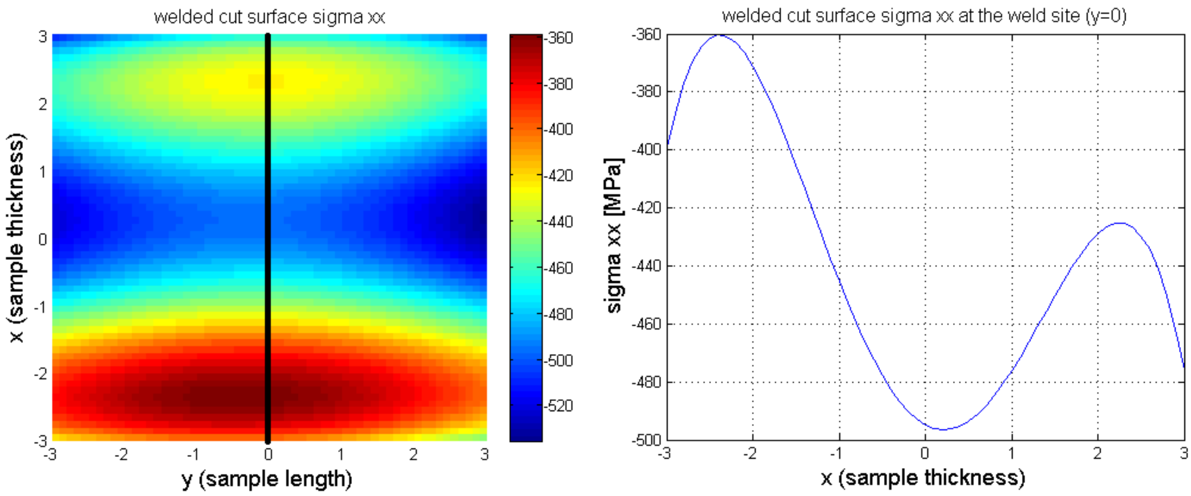

Fig. 4: a) Distribution of normal residual stress in “x” direction on welded cut surface and b) distribution of normal residual stress in “x” direction on line y = 0 on welded cut surface

The next step was measurement of longitudinal residual stress, again first in base metal sample and thereafter in welded sample on the unworked surface (highlighted according to Fig.5) with dimensions (6×6) mm.

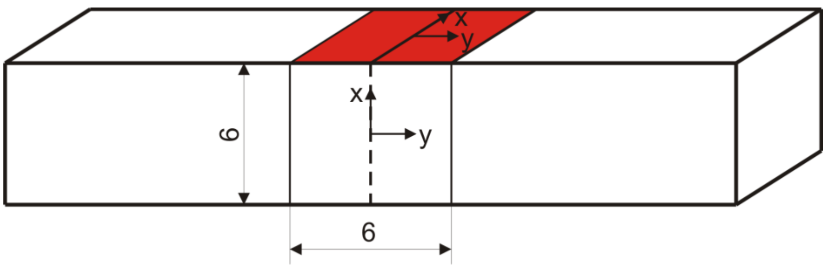

Fig. 5: Schematic representation of a measured sample – highlighted unworked surface (longitudinal)

In Fig. 6, one can see approximately zero normal residual stress in “x” direction on non-welded unworked surface near the middle of sample thickness and low values of compressive residual stress near the edges, which can be caused by cutting the sheet into samples.

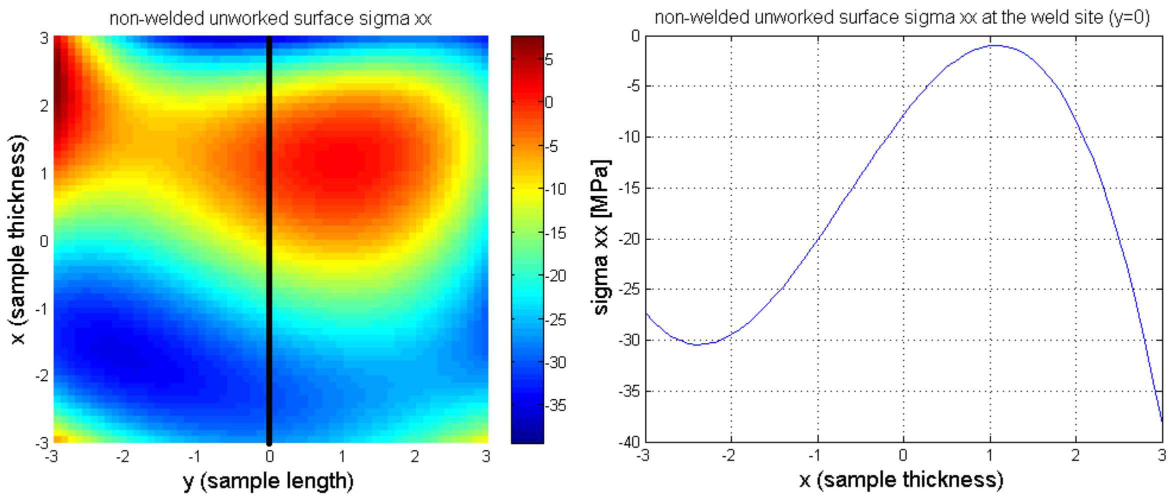

Fig. 6: a) Distribution of normal residual stress in “x” direction on non-welded unworked surface and b) distribution of normal residual stress in “x” direction on line y = 0 on non-welded unworked surface

In Fig. 7, there can be seen relatively high values of compressive residual stress after welding, mainly near the middle of sample length and also thickness – in the weld spot. Comparison of residual stress before and after welding is illustrated in Fig. 8b. In contrast to the above results of transverse residual stress in cut surface, there can be seen increase of compressive residual stress by welding from nearly zero to maximum value of -192 MPa.

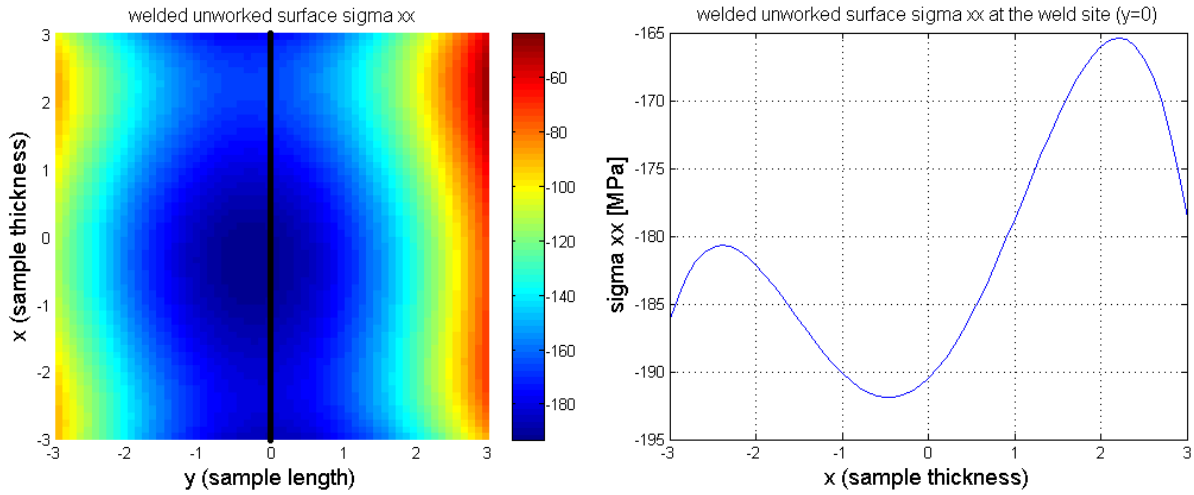

Fig. 7: a) Distribution of normal residual stress in “x” direction on welded unworked surface and b) distribution of normal residual stress in “x” direction on line y = 0 on welded unworked surface

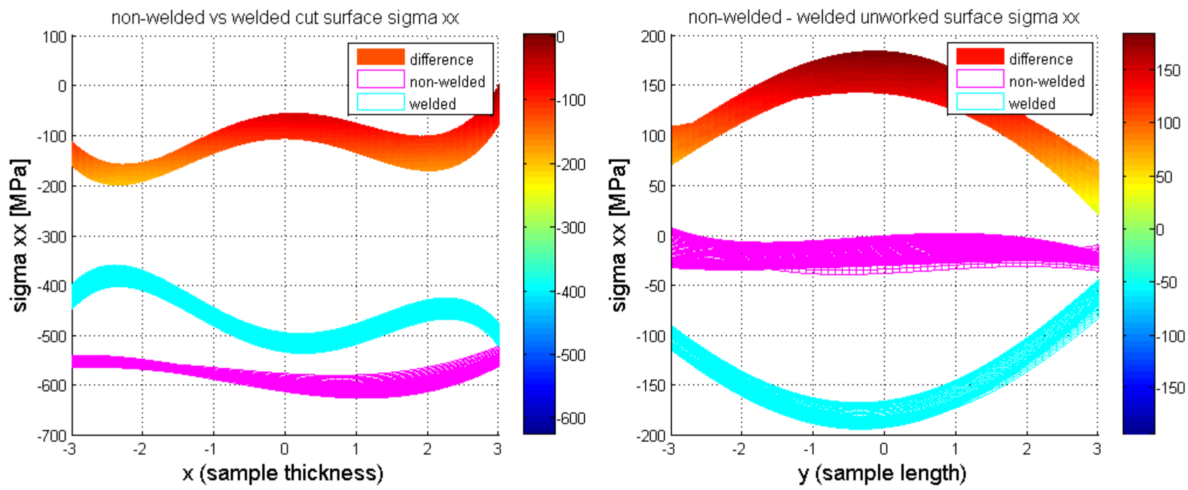

Fig. 8: a) Comparison of normal residual stress in “x” direction on non-welded and welded cut surface and b) comparison of normal residual stress in “x” direction on non-welded and welded unworked surface

In Fig. 8, there are two comparisons – of transverse and longitudinal residual stress before and after welding. It should be noted that in Fig. 8a, stress distribution varies in a direction of the sample thickness whilst in Fig. 8b, stress distribution changes with sample length.

Conclusion

The aim of this paper was to conduct experimental measurement of residual stress in high strength steel sample before and after laser welding by X-ray method, process the data and compare and evaluate the results. Residual stress was determined in transverse and longitudinal direction across the sample thickness before and after laser welding; data was processed in program Matlab, where surfaces of stress distributions were created and smoothened by polynomial functions. Before welding, transverse residual stress was compressive with maximum value of -612 MPa resulting from rolling of the material and was reduced after welding to maximum value -495 MPa. This means that welding caused nearly 20% decrease of compressive transverse residual stress. Longitudinal residual stress before welding was negligible and after welding was increased to maximum value of -192 MPa. Results showed compressive character of normal residual stress both in transverse and longitudinal direction after laser welding due to the low heat input typical for this technology. This fact is favourable as compressive residual stress can enhance fatigue resistance of material, which will be verified in later research.

Acknowledgement

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