ESRF	**Experiment title:** Influence of a trailing heat sink on the welding residual stress distribution	**Experiment number**: MA46
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Report:

Introduction - The residual stresses that develop due to the welding process are the result of the non-uniform temperature cycle of heating and cooling. It is commonly known that welding produces high tensile stresses near the weld zone, and compressive stresses further away. When welding thin plate structures, the compressive stresses are the source for buckling distortion to appear. A method to eliminate the buckling distortion is by applying a heat sink at a short distance behind the welding heat source, a process also known as Dynamically Controlled Low Stress No Distortion (DC-LSND) welding.[1] The results obtained by this method are promising: plates that show severe buckling due to conventional welding remain nearly flat when a heat sink is applied. The elimination of the buckling distortions can be correlated to changes of the compressive residual welding stress when an active cooling source is applied. Unfortunately, there is still a lack of experimental data to show in what way the cooling source affects the residual stress distribution.
To increase the insight, finite element (FE) models were developed at Delft University of Technology and the Netherlands Institute of Metals Research. They predict both a reduction, and a redistribution of the welding stresses when a cooling source is applied. In addition, analytical models were derived to predict under what residual stress conditions the welded plates will buckle, and how buckling could be avoided. By combining these models, information can be obtained on how the active cooling source should be applied to prevent buckling distortion.
The aim of this experiment is to measure the longitudinal and transverse residual stress distributions on samples that were welded with and without a trailing heat sink, and with various welding parameters. The purpose is twofold. Firstly, the results should provide insight into the influence of the welding and cooling parameters on the residual stress distribution. It will lead to a better understanding of how the cooling source should be applied, to obtain a maximum reduction in the buckling distortion. Secondly, the results will be used for FE model validation. Once validated, the models are a powerful tool to further study the effect of the cooling source on the residual stress distribution.

Experimental method - Welded samples were prepared in advance at Delft University of Technology. The samples consist of AISI 316L austenitic stainless steel plates, with three different sample sizes, i.e. (*thickness*, *width*, *length*) = (1.5×100×200), (2×100×200), and (2×120×100) mm. In addition, two dual phase steel (DP600) plates of (1.5×100×200) mm were investigated. Welds were made along the whole plate length, in full penetration mode. Several sets of welding parameters were investigated, by varying the welding current and welding speed in such way that the weld geometry remained the same for all welds. For every set of welding parameters, one sample is conventionally welded (CONV), and one is welded with a trailing heat sink (DC-LSND). The residual stresses in the plates are assumed to be bi-axial, with zero stress in the thickness direction. The stresses were determined along a line perpendicular to the welding direction, at the centre of the plate. Duplicate samples were welded to measure the temperature histories during welding, and for microstructural analysis.
Synchrotron X-ray diffraction experiments were conducted at beam line ID31 to study the longitudinal and transverse residual stress state of the welded samples, using traditional 2θ-scanning in transmission mode. The stresses were determined by performing a strain scan in two perpendicular directions.[2] A 60 keV beam was used. Diffraction measurements were performed at the Fe <311> planes, which for a wavelength of 0.2068 Å, results in (stress free) diffraction angles of around $2\theta = 10.946°$. The receiving (vertical) slit size was set to 2 mm. The incoming beam slits were set to (*horizontal*×*vertical*) = (1×2) mm for the longitudinal measurements, and to (*horizontal*×*vertical*) = (2×1) mm for the transverse measurements. This resulted in a gauge length of 8 mm for the transverse measurements, and 10.5 mm for the longitudinal measurements, which is larger than the plate thickness, so that measurements over the whole plate thickness were obtained. The plates were clamped with help of clamping devices provided by the FaMe38 lab. Clamping resulted in good fixture of the plates, while applying minimum clamping forces, so that the stress state of the plates was not affected.

Results – The measurements have resulted in valuable data that served as FE model validation[3] and that increased the insight into the process of welding with a trailing heat sink. These data contribute to a PhD Thesis on the DC-LSND process.[4] A summary of the measurement results is given here.
Figure 1(a) shows the large difference in buckling deformation between a conventional weld (CONV) and an actively cooled weld (DC-LSND). The buckling inevitably affects the residual stress state of the samples. To investigate what the stresses in the welded samples must have been before buckling, one of the conventionally welded sample was pressed flat again. Figure 1(b) clearly shows that the residual stress in a buckled sample is lower then the stress in the same sample when it is pressed flat. Important to note is that the stress measured in the flat sample is the stress that causes the buckling deformation. Figure 1(c) shows that the transverse stress in the 200 mm long samples is low.

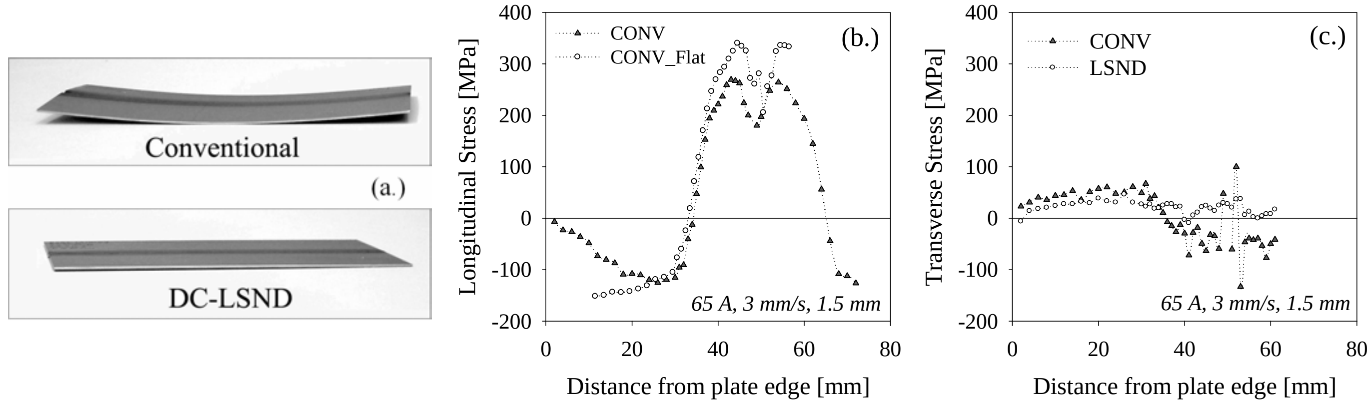

Figure 1.(a) Difference in buckling deformation for a conventional and an actively cooled sample. (b) Residual welding stresses for a conventionally welded sample in a buckled state (CONV) and when pressed flat (CONV_Flat); (c) Transverse residual stress in a 1.5×100×200 mm sample.

The longitudinal residual stress measurement results for the 200 mm long 316L steel samples are plotted in Figures 2(a) to (d), for varying welding parameters. It can be seen that the welding parameters do not significantly affect the residual stress state of the conventional welds (Figs 2(a) and (c)). When the active cooling is applied (Figs 2(b) and (d)), the longitudinal stress is reduced. The amount of stress reduction largely depends on the welding speed: at higher speeds, the effect of the active cooling source deceases. The reduction in buckling deformation for the actively cooled samples can be explained by the reduction of the compressive residual stress near the plate edges.

Figures 2(e) and (f) show the results for the 2×120×100 mm 316L steel samples. Due to their relatively thick and wide geometry, these samples show little deformation, even after conventional welding. However, the stresses in these samples are higher than for the 200 mm long samples. The conventional weld in Fig. 2(f) shows a high transverse stress. For these samples, the active cooling source does not only effectively reduce the longitudinal stress, but also the transverse stress.

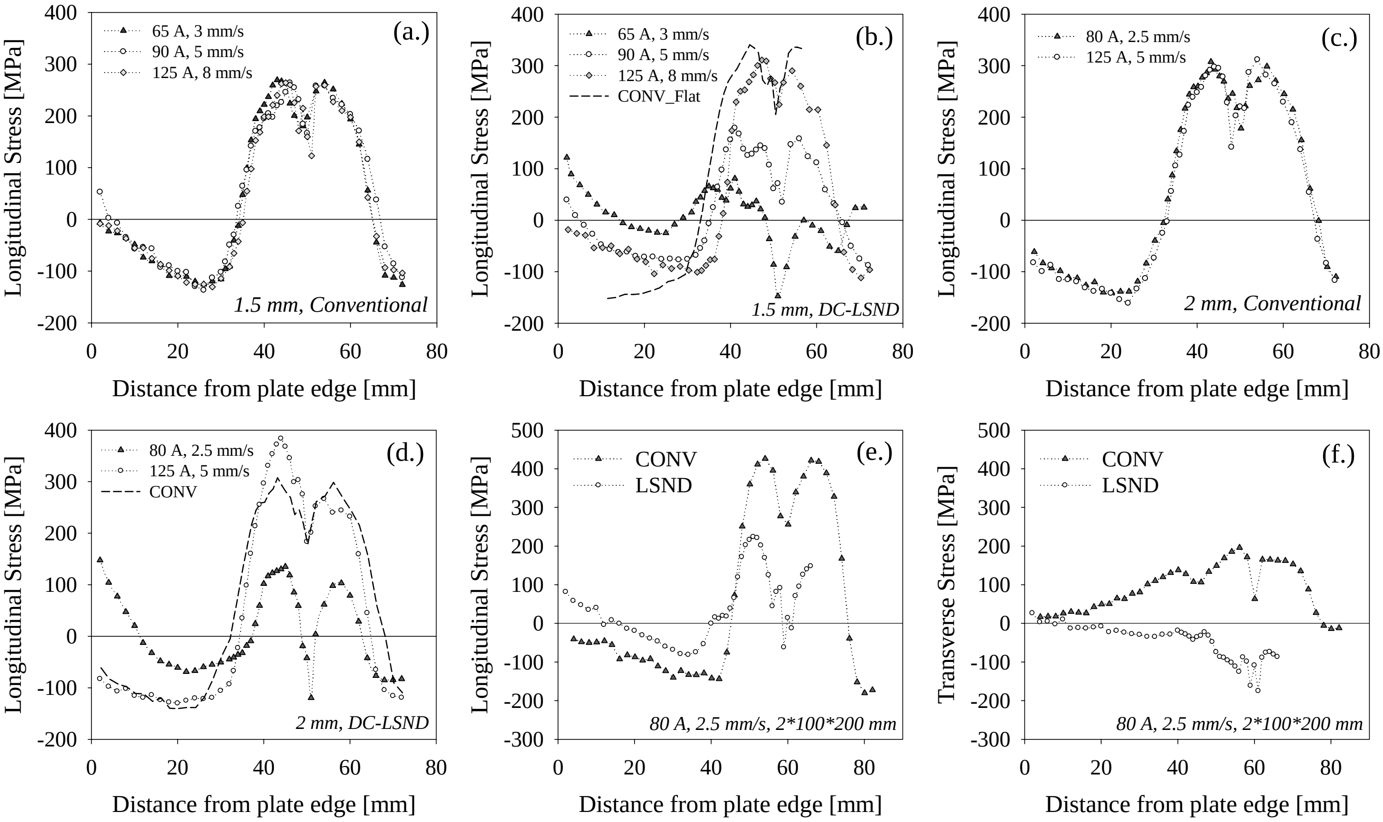

Figure 2. Residual stress results for the 316L stainless steel samples with dimensions: (a,b) 1.5×100×200 mm, (c,d) 2×100×200 mm, and (e,f) 2×120×100 mm.

The measurements on the DP600 steel plates show similar results as those on the 316L steel plates. However, due to the solid state phase transformations that took place during welding, the stress results in the heat affected zone could not be determined with high accuracy.

Conclusions – The results obtained with this experiment are very valuable for both the insight into the DC-LSND welding process, and for validation of the FE models. The influence of the active cooling during welding under various conditions was clearly shown. The active cooling is most effective at lower speeds and its influence decreases for increasing speeds. The effect of buckling on the residual stress distribution was also shown. The buckling deformation that appears in the conventionally welded plates after releasing the plates from the clamp after welding causes a relaxation of the stresses, which was quantified experimentally.

References

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