The effect of microstructural changes on the thermoelastic response in AISI 316L austenitic stainless steel during the thermoelastic stress analysis of weldments

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Abstract. Thermoelastic stress analysis (TSA) has been proposed as potential method for rapid assessment of residual stresses using portable equipment. Plastic deformation, which contributes to the development of residual stress, also affects the thermoelastic constant of the material. It is proposed that the change can be measured using TSA and linked to residual stress using an iterative finite element technique. In the present study, a series of specimens were made from two different grades of austenitic stainless steel, European standards EN 10027 1.4404 and 1.4435 grades, equivalent to the AISI (American Iron and Steel Institute) 316L designation. Heat treatment to 1150˚C with subsequent cooling has been applied to simulate the heating and cooling experienced by a material during a welding cycle. Three different cooling rates were considered: water quenching, air cooling and furnace controlled cooling at a rate of 100˚C per hour. Micrographs of the specimens were created to observe potential phase transformations in the microstructure. TSA was carried out on the specimens and the influence of the microstructural changes on the thermoelastic response was observed. An assessment was made of the effect of any microstructural changes on the thermoelastic response. The outcome of the work is used to aid interpretation of the thermoelastic response in the vicinity of welds in austenitic stainless steel components and its potential residual stress studies.

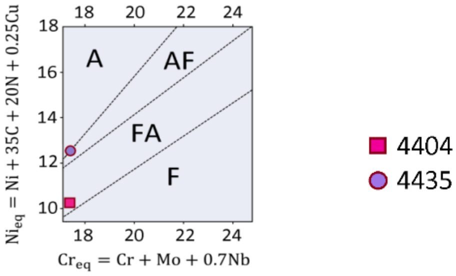
Introduction

Residual stress defines the internal stresses that remain in a structure in the absence of external forces. Welding is one of the predominant causes of residual stresses in structures which must be considered when assessing the structural integrity of a welded component or structure. Residual stresses arise from misfit internal strains resulting from the heating and cooling that occurs during the welding process. Existing methods to evaluate the residual stress in a component can be separated into two categories: destructive and non-destructive methods. Destructive methods can be convenient, but the component is left sometimes severely damaged due to material removal whereas many of the non-destructive methods are expensive and time consuming to apply. TSA has previously been highlighted as a promising non-destructive method, without the disadvantages of traditional non-destructive methods [1]. An infra-red detector is used to measure a small temperature change, ΔT, resulting from cyclic elastic straining. If the change occurs adiabatically, ΔT can be related to the change in the stress invariant $\Delta(\sigma_1 + \sigma_2)$ [2] as

$$\Delta T = -K\, T_0\, \Delta(\sigma_1 + \sigma_2) \tag{1}$$

where T_0 is the absolute temperature and K is the thermoelastic constant $K = \alpha/\rho C_p$ where α is the coefficient of thermal expansion, ρ the mass density and C_p the specific heat at constant pressure of the material. Work on the application of TSA to evaluate residual stress started in 1987 based on an idea from Wong et al. [3]. Recently, further work has been carried out to assess the feasibility of applying TSA on components containing realistic residual stress levels [1]. Two different approaches have been proposed; one approach is based on the mean stress effect, where a small temperature change is dependent on the mean applied stress, however, as steel does not show a mean stress effect, this is not applicable here [4]. The second proposed approach to assess residual stress with TSA is based on the dependence of the thermoelastic constant, K, on the plastic deformation experienced by the material and subsequent changes in microstructure [5]. The change in K can be used to estimate the level of plastic strain experienced by a component [1], it is then possible to derive the residual stress from the level of plastic strain experienced [4]. A focus of the work is welds in AISI 316L austenitic stainless steel components as this material is commonly used on nuclear power plants [6], the proposed application area for the TSA approach. The purpose of the present investigation is to establish the effect on the thermoelastic response of any microdstructural changes that may occur in the material.

It is understood that the composition range of many grades of austenitic stainless steels is sufficiently broad to allow different solidification modes to occur [7]. The AISI composition restrictions of 316L austenitic stainless steel allow several grades from different steel designations to belong to the 316L category, such as the EN 10027 1.4404 and 1.4435 grades. The heat cycle observed during the welding of grade 1.4404 is expected to produce a primary ferrite microstructure, whereas a austenite to primary austenite microstructure is expected of grade 1.4435 as can be seen in in Fig. 1, where A, AF, FA and F stands respectively for fully austenitic, primary austenite, primary ferrite and fully ferritic solidifications. A, AF and FA solidification modes are illustrated in Fig. 2. The cooling rate may also affect the recrystallisation of the material. These microstructural changes can lead to dislocation and plastic deformation, which may influence the thermal expansion coefficient [6], and therefore, the thermoelastic behaviour.



EN 10027grade /chemical component [wt %]	C	Mn	Cr	Ni
1.4404	0.02	≤2.0	17.2	10.1
1.4435	0.02	≤2.0	17.3	12.6
EN 10027 grade / chemical component [wt %]	**Mo**	**N**	**Fe**	
1.4404	2.1	≤0.1	Balance	
1.4435	2.6	≤0.1	Balance	

Figure 1 : Solidification mode diagram based on the WRC-1992 diagram [8] (left) and EN 10027 grades 1.4404 and 1.4435 austenitic stainless steel compositions [6].

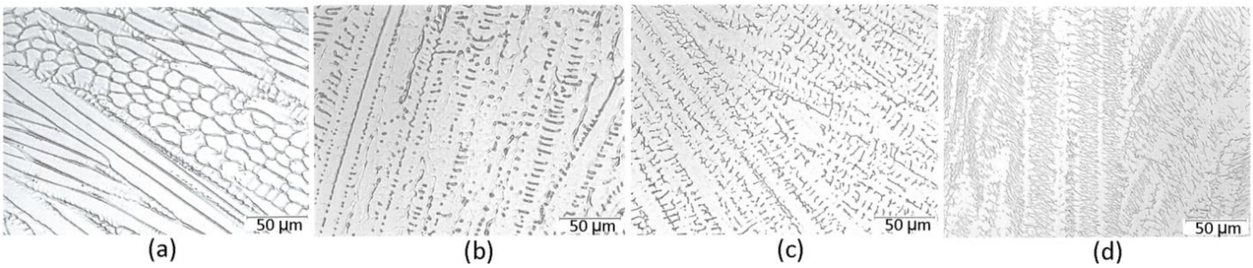


Figure 2: Fusion zone microstructure resulting from solidification mode A (a), AF (b) and FA, skeletal ferrite morphology (c) and lathy ferrite morphology (d) [7]

Experimental work

To observe the possible microstructural changes in AISI 316L due to heating and cooling and thus evaluate the effects on the thermoelastic response of the material. A series of specimens were created in both EN 10027 grades 1.4404 and 1.4435. The specimens were manufactured with dimensions of 150 mm by 20 mm by 2 mm to ensure a uniform microstructure through the thickness. Different heat treatments were applied to specimens to capture a range of possible microstructural changes. Twelve specimens of each grade were obtained, three of which were kept as reference specimens and the others were heat treated in a furnace up to 1150˚C, the annealing temperature of AISI 316L. Three cooling rates were applied to three sets of specimens: water quenching, air cooling and furnace controlled cooling at a rate of 100˚C per hour. Micrographs of the specimens were made to confirm the solidification mode and resulting microstructure. TSA was then applied to investigate the effects of the microstructural changes on the thermoelastic response. Tensile specimens were cyclically loaded at 10 Hz, with a load amplitude of ± 3 kN (120 MPa) about a mean load of 5 kN (200 MPa) and the thermoelastic constant of each specimen was calculated using Eq. 1 and compared to that of the reference specimen.

Conclusion

The microstructural changes due to different cooling applied were observed and compared with predictions. According to the influence of microstructure on thermoelastic constant, feasibility of using TSA on AISI 316L stainless steel weldments was determined.

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