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Measurement and modeling of residual stress in a welded Haynes® 25 cylinder

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Abstract

An experimental and simulation study of residual stresses was made in the vicinity of a gas tungsten arc weld, used to join a hemispherical end cap to a cylinder. The capped cylinder is used in a satellite application and was fabricated from a Co-based Haynes® 25 alloy. The cylinder was 34.7 mm in outer diameter and 3.3 mm in thickness. The experimental measurements were made by neutron diffraction and the simulation used the implicit Marc finite element code. The experimental resolution was limited to approximately 3 mm parallel to the axis of the cylinder (the weld was 6 mm in the same direction) and comparison over the same volume of the finite element prediction showed general agreement. Subject to the limited spatial resolution, the largest experimentally measured tensile residual stress was 180 MPa, located at the middle of the weld. However, the predictions suggest that there are regions in the weld where average tensile residual stresses as much as 400 MPa exist. One qualitative disparity between the model and the experiments was that the measurement included a larger degree of asymmetry on either side of the weld than predicted by the model.
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1. Introduction

The use of welding to join metals generally leaves residual stresses in the vicinity of the weld, since the solidification and contraction of molten material during cooling is constrained by the surrounding metal. The existence of such residual stresses can significantly affect subsequent lifetime by augmenting or impeding fatigue or creep failure events [1]. Consequently, for an accurate assessment of engineering lifetimes, there is a need to determine residual stress profiles. A variety of techniques such as neutron, X-ray and synchrotron X-ray diffraction, hole drilling, curvature measurements and instrumented indentation are available (e.g., refs. [2–4]). Amongst these, neutron diffraction is advantageous because it is non-destructive and residual stresses can be determined from the bulk in the component. Neutron diffraction is widely used to determine residual stresses due to welding (e.g., refs. [3,5–7]).

Experimental determinations of residual stresses due to welding are often accompanied by computational approaches in order to provide additional insights as to the origins of the experimental data and offer predictive capabilities (e.g., refs. [8,9]). A successful model has to consider thermal, mechanical and microstructural parameters—parameters that evolve during the welding process. This coupled problem is usually solved using finite element (FE) models where the thermal and mechanical analyses are either performed simultaneously or staggered. In the staggered approach, time steps first solve for temperature and the geometry is updated in subsequent mechanical analysis. Alternatively, the mechanical analysis may precede the thermal analysis or even iterate between the two in order to reduce out-of-phase effects. In the simultaneous approach, the simultaneous solution of temperatures and displacements can lead to an unsymmetric system of coupled nonlinear equations. Since this coupling is weak for ordinary welding problems, this approach is not considered worthwhile [10].

Progress in computational modeling and increased availability of material properties have resulted in increased

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residual stress modeling of welded materials [11]. For example, of relevance to this study, a model of multi-pass arc welded steel pipes is available [12]. The results show tensile axial weld stresses at the inner surface of the pipe, which decrease and become compressive away from the weld center. The opposite was found at the outer surface of the pipe in the axial direction. The hoop weld stresses were tensile at the inner surface and then decreased, quite abruptly, to compressive further from the weld. The outer surface stresses in the hoop direction were smaller and varied between compression and tension.

Here we report on spatially resolved measurements using neutron diffraction in a welded cylinder for a satellite application. Concerns relating to precipitation aging following long term exposure to heat in the application lead us to assess the fabrication induced residual stress profile. These measurements were performed during commissioning of the Spectrometer for Materials Research at Temperature and Stress (SMARTS) [13], at the Manuel Lujan Jr. Scattering Center at Los Alamos National Laboratory. We also present complementary results from FE analysis. The Marc code [14] was used to model the two-pass weld. A preliminary implementation of this code helped in the selection of optimum locations for neutron diffraction measurements, thereby making efficient use of neutron beam time. The FE model gave information about strains at different depths below the surface and therefore complemented the neutron diffraction measurements that average over the thickness of the cylinder.

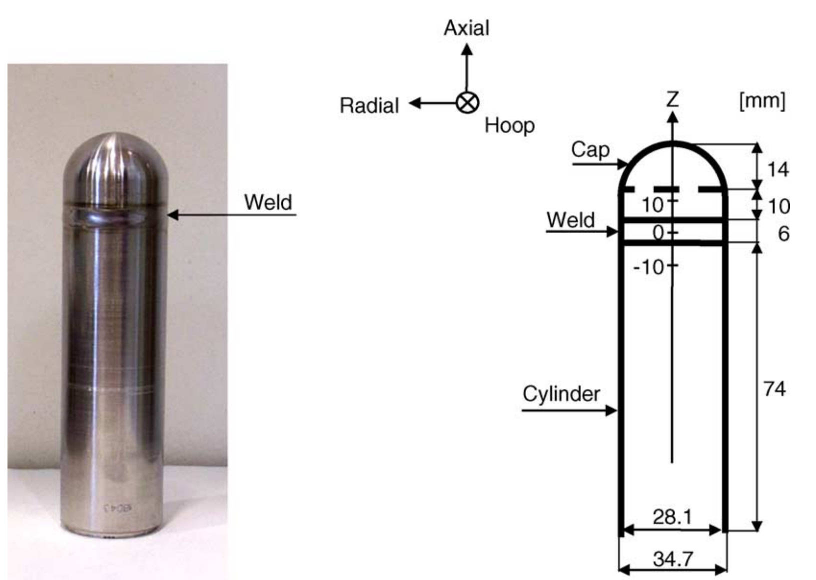
In addition to demonstrating the SMARTS capability for spatially resolved measurements on a cobalt rich alloy, these results are a quantitative estimate of residual stresses in a Haynes® 25 alloy weld. Haynes® 25 metal has unfavorable nuclear properties for diffraction. This is principally because cobalt has a low coherent scattering cross section and a large absorption cross section. The coherent scattering length, coherent cross section, incoherent cross section, absorption cross section, and macroscopic attenuation length were calculated and presented in Table 1, for Haynes® 25, and for iron as a comparison. The nominal documented composition was used and the elements' properties were taken from Windsor [15]. It can be seen that the coherent cross section for the alloy is about five times smaller and the macroscopic attenuation length is twice that of iron. The long attenuation length implies that, for a path length of neutrons through two walls of Haynes® 25 metal, only 10% of the scattered neutrons emerge. This high degree of attenuation, together with the small coherent cross section, makes the measurements difficult.

Table 1
Comparison of scattering parameters between Haynes® 25 and Fe at 1.8 Å

Property	Haynes® 25	Fe
Average coherent scattering length (cm)	0.4×10^{-12}	0.95×10^{-12}
Coherent cross section (cm^2)	2.1×10^{-24}	11.4×10^{-24}
Incoherent cross section (cm^2)	4.7×10^{-24}	0.2×10^{-24}
Absorption cross section (cm^2)	22.5×10^{-24}	2.5×10^{-24}
Macroscopic attenuation length (cm^{-1})	2.6	1.2

2. Sample preparation

A photograph and a schematic with the dimensions of the sample are shown in Fig. 1. The specimens were fabricated by welding a hemispherical end cap to an open cylinder that was about 74 mm long. The end cap consisted of a 10 mm long cylindrical section with a 14 mm high hemispherical



(a) (b)

Fig. 1. (a) The welded Haynes® 25 sample. (b) Dimensions of the welded sample, including the *z*-axis.

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