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Material and residual stress considerations associated with the autofrettage of weld clad components

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ABSTRACT

A fatigue-resistant cladding concept confirms the presence of compressive residual stresses in a cylinder weld clad with 17–4 PH stainless steel while tensile residual stresses exist in an Inconel 625 clad layer. In this study, autofrettage of an Inconel 625 thick-walled clad cylinder is investigated with modified residual stress distributions obtained indicating that tensile residual stresses throughout the clad layer are transformed to compressive in nature, discontinuity stresses at the clad/substrate interface are almost entirely eliminated and compressive residual stresses exist to a depth of around 18 mm. An alternative clad material, 17–4 PH stainless steel, is investigated resulting in compressive residual stresses in the clad layer without the need for autofrettage. The complexity of modelling a martensitic stainless steel is discussed and sensitivity studies undertaken to illustrate the influence of coefficient of thermal expansion on resulting residual stresses. Strain hardening effects and the assumption of an idealised interface are discussed. Contour method measurements prove that discontinuity stresses are reduced in reality due to alloying and diffusion effects, highlighting also the need for further characterisation of 17–4 PH. Additional considerations such as the weld clad profile and process parameters are briefly discussed.

1. Introduction

The issue of fatigue failure in weld clad components, such as pipelines utilised in the oil and gas industry, has prompted an investigation into a fatigue-resistant cladding technology to enhance the performance of these components. Fatigue of welded joints and dissimilar material joints have been studied with focus herein placed on weld cladding of 4330 low alloy carbon steel. Two clad materials are investigated, namely nickel-chromium-based superalloy Inconel 625 and 17–4 PH stainless steel.

The application of a coating or cladding to a substrate using a thermal deposition process results in a self-equilibrating residual stress distribution primarily due to the thermal cycle and the associated metallurgical changes during the melting, deposition, solidification and cooling of the material. The arising constraint on differential expansion and associated phase changes results in residual stresses, with material property variation with time and temperature additionally influencing the residual stress state. Dissimilarity in properties between substrate and clad materials further affects the self-equilibrating residual stress field. The nature of the residual stresses in the coating/cladding may be tensile or compressive depending on the characteristics of the dissimilar materials and the process involved. Due to the interest in fatigue performance, the arising residual stress state post-cladding is evaluated.

Tensile residual stresses are commonly induced through many welding and machining processes, therefore providing an undesirable stress state at the surface of the component. It is also common that maximum operational stresses occur at the surfaces of components. Cladding and coating processes often lead to large discontinuity stresses at the interface and fatigue cracking can also occur at this location. Therefore, the aim of this concept is to obtain a compressive residual stress at the component surface and to as great a depth as possible into the clad surface and substrate while reducing or eliminating discontinuity stresses. Finite element models of the weld cladding process, along with experimental validation using the incremental hole-drilling method (ICHD), demonstrate the ability to apply a fatigue-resistant cladding process on 4330 steel using 17–4 PH with compressive residual stresses resulting. However, tensile residual stresses are obtained in

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the case of an Inconel 625 clad [1]. Therefore a post-cladding autofrettage process is under investigation in an attempt to modify these stresses into beneficial compressive residual stresses. Although weld cladding and autofrettage are commonly utilised processes, it appears that there have been no previous studies on the effects of autofrettage of weld cladding [2].

The concept is not limited to the weld cladding of 4330 steel with Inconel 625 or 17–4 PH, with potential applicability to other coatings and claddings applied to substrates for the purposes of improving erosion, corrosion, thermal, optical and other performance measures, particularly where cyclic loading is present. Similar characteristics have been observed in laser cladding using these material combinations, not reported herein.

1.1. Weld clad simulation review

A simplified finite element simulation of a weld clad cylinder was obtained through a two-dimensional axisymmetric model assuming the entire clad layer is deposited on the inner diameter of a cylinder in one step. A thermal transient stress analysis consisted of a pipe pre-heated to one of two temperatures, 150 or 300 °C, prior to the application of the weld material at melt temperature. The entire component was then subjected to slow cooling on the inner and outer surfaces using a convective heat transfer coefficient h = 10 W/m2 K. Latent heat effects were neglected and radial edges of the model were insulated to simulate no axial heat transfer. A bulk temperature of 25 °C was applied, radiation heat transfer was neglected and Poisson's ratio assumed constant with time and temperature. Plane strain conditions were applied on radial lines and an elastic-perfectly plastic material model assumed with the use of temperature dependent thermal and mechanical material properties. These properties were experimentally obtained for clad and heat-affected zone (HAZ) regions to ensure accurate capturing of the material behaviour, most crucially ensuring phase changes are accounted for where relevant.

The assumptions made in terms of model geometry and behaviour are consistent with the experimental weld cladding process, reflected in the results discussed.

Fig. 1 shows the clad cylinder dimensions in millimetres and the associated axisymmetric finite element model. Fig. 2 shows the results for the as-clad self-equilibrating residual stress distribution along the axisymmetric model for an Inconel 625 clad on 4330 steel.

The clad model initially produces high biaxial tensile residual stresses in the clad layer and into the substrate. Hoop stresses in the clad layer are tensile for both substrate pre-heat temperature values and the effect due to pre-heat temperature is seen to be negligible. Due to the dissimilarity in the materials, a discontinuity stress will also invariably exist at the interface between the cladding/coating and the substrate. The discontinuity stress can be significantly higher than the stress in the clad material, as is also shown to be the case here. From a fatigue viewpoint, cracks may develop at either the clad/coating surface or the interface as mentioned previously, depending on the nature of the combined residual and operational stress distributions and the fatigue strength of the as-deposited materials involved.

2. Validating ‘as-clad’ residual stresses

Limited validation of simulation residual stresses to a depth of 1 mm was obtained using the incremental centre hole drilling (ICHD) method. ICHD is a relaxation method which measures strains in the vicinity of a drilled hole through the application of a strain gauge rosette on the surface of the component [3]. These strain values are then converted into stresses, with the comparison between simulation and experimental hoop stress values shown in Fig. 3. Results are shown for a 4330 steel cylinder with pre-heat temperature 300 °C externally clad with Inconel 625, with the same dimensions and clad thickness as an internally clad cylinder.

Machining of the weld profile was required to enable the strain gauge rosette to be laid on the surface of the weld clad cylinder and these surface effects can be seen in hoop stress values in the first 200 microns from the clad surface. Overall, however, correlation between hoop stress values obtained through simulation and experimental means is good. Experimental measurements also established the axisymmetric nature of the results.

Further model validation included autofrettage predictions for a pressurized plain cylinder, for which good agreement with theory was obtained as presented herein.

3. Modifying ‘as-clad’ residual stress distribution

In terms of the NACE International regulations [4], the use of Inconel 625 as a weld clad material presents no issues in compliance with the regulations. The beneficial properties of erosion and corrosion resistance provided by Inconel 625 are recognized and therefore post-cladding processes are investigated with a view to improving the residual stress state and ultimately the fatigue-resistance in the case of 4330 steel clad with Inconel 625.

There are three characteristics of the typical as-clad residual stress distribution shown in Fig. 4 that could be modified in a manner that would improve the fatigue performance of the component:

A: Transformation of the tensile residual stress to a compressive residual stress, with as high a magnitude as possible, throughout the thickness of the clad. This would reduce the likelihood of surface cracks initiating and propagating, with this protection offered in an erosive/corrosive environment until the clad thickness has been removed.

B: Elimination, or at least a decrease in the level, of tensile discontinuity stress at the interface, leading to the reduction of the likelihood of cracks initiating and propagating at the interface between the clad and substrate.

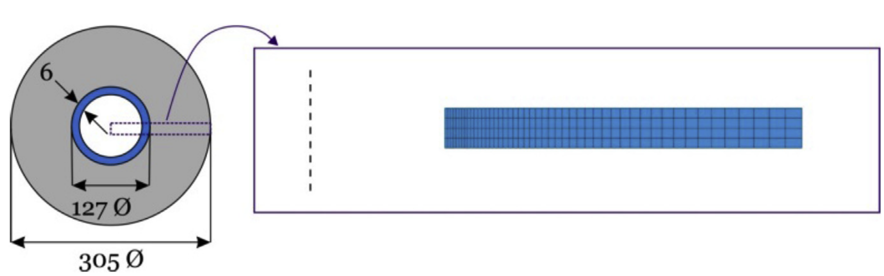

Fig. 1. Axisymmetric finite element model – clad deposition on inner diameter of cylinder (dimensions in mm).