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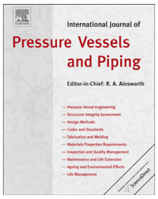

Analysis of residual stress relief mechanisms in post-weld heat treatment

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ABSTRACT

This paper presents a recent study on weld residual stress relief mechanisms associated with furnace-based uniform post-weld heat treatment (PWHT). Both finite element and analytical methods are used to quantitatively examine how plastic deformation and creep relaxation contribute to residual stress relief process at different stages of PWHT process. The key contribution of this work to an improved understanding of furnace based uniform PWHT can be summarized as follows:

(1) Plastic deformation induced stress relief during PWHT can be analytically expressed by the change in material elastic deformation capacity (or elastic deformation limit) measured in terms of material yield strength to Young's modulus ratio, which has a rather limited role in overall residual stress relief during furnace based uniform PWHT.
(2) The most dominant stress relief mechanism is creep strain induced stress relaxation, as expected. However, a rapid creep strain development accompanied by a rapid residual stress reduction during heating stage before reaching PWHT temperature is shown to contribute to most of the stress relief seen in overall PWHT process, suggesting PWHT hold time can be significantly reduced as far as residual stress relief is concerned.
(3) A simple engineering scheme for estimating residual stress reduction is proposed based on this study by relating material type, PWHT temperature, and component wall thickness.

1. Introduction

Post-weld heat treatment (PWHT) is often required for pressure vessel and piping components for relieving residual stresses and/or improving weldment properties, as summarized in a comprehensive review by McEnerney and Dong [1]. Stipulations for performing PWHT are given in various design codes and standards such as ASME Division 2 [2], API 579 RP [3], EN 13445 [4], among others as discussed in Ref. [1]. All these codes share a set of rather similar PWHT requirements in terms of PWHT ramp-up heating rate, hold temperature, and hold time, depending upon the type of steel and wall thickness involved. However, there is little information available in the literature on how these stipulated PWHT conditions were determined, as illustrated by Fidler [5,6] and Smith and Garwood [7]. Experimental investigations like these on selected weldment geometries seem to support an estimate of residual stress reduction at about 30% of material yield strength, as adopted by various defect assessment procedures such as API 579 RP [3] and BS 7910 [8].

As far as residual stress relief is concerned, some recent investigations have shown that code-specified PWHT procedures could be excessively conservative, particularly in terms of hold time for thick vessels. For instance, MeEnerney and Dong [1] reviewed various national/international codes and standards including industrial reports such as the report by Sangdahl and Rebenack [9] on thick section vessel PWHT experiences. Dong and Hong [10] and Zhang et al. [11] reported a series of finite element residual stress and PWHT study using Omega creep model by Prager [12] on different PWHT hold temperature and hold time for vessel wall thickness up to 100 mm. They [1,10,11] found that for furnace based PWHT, the code required hold time can be significantly reduced for achieving an expected residual stress reduction as long as a

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reasonable PWHT temperature is achieved, which can result in significant economic benefits. A very recent study by Takazawa and Yanagida [13] on a laboratory weld mockup specimen using both Norton and Norton–Bailey creep models confirmed a rather similar trend as discussed above, particularly when PWHT temperature is close to or at coded-specified temperature level. It is worth noting that the aforementioned investigations involve three different types of creep models. Takazawa and Yanagida [13] considered both primary and steady-state creep behavior in the form of Norton Bailey model and pure steady-state creep behavior based on classical Norton model, while Dong and Hong [10] and Zhang et al. [11] used a tertiary creep model widely used by petroleum industry [3]. These previous investigations seem to suggest that as far as general residual stress relief behavior in PWHT of weldments is concerned, computational results are not that sensitive to which type of creep models used, as long as sufficient material properties for a given application are available.

Although the aforementioned investigations provided an improved understanding on the mechanics of residual stress relief during PWHT, there exist a number of questions that are of both practical importance and fundamental in nature. For example, can PWHT hold time be prolonged to compensate the use of a lower PWHT temperature to achieve the same stress relief effects? A limited experimental study on a low carbon steel weldment by Olabi and Hashimi [14] seem to support this proposition, while the investigations both by Dong and Hong [10] and by Takazawa and Yanagida [13] seem to point out that hold time has no significant effect on residual stress relief. Therefore, a lower PWHT temperature may not be substituted with a longer hold time to achieve a similar residual stress relief effect. This finding seems to be supported by another recent study by Yaghi et al. [15] in which the authors reported that more than half of the residual stress reduction already occurred during the first 30 min after reaching PWHT temperature by considering a 100 hour of PWHT hold time. It should be noted that in the latter study [15] creep relaxation was assumed negligible during the temperature ramp up stage during which studies by Dong and Hong [10], Zhang et al. [11], and Takazawa and Yanagida [13] all showed that most of residual stresses are already relieved when PWHT temperature is reached.

Another question is if residual stress relief occurs in any significant manner without even triggering creep relaxation mechanism when a component is heated up to a PWHT temperature? Stout [23] postulated that a residual stress reduction without creep relaxation can be measured by the ratio of material yield strength at PWHT temperature to its room temperature value, which could be significant, depending upon material yield strength dependency on temperature. Such a postulation has served as a basis for justifying some of codified PWHT procedures even to this day, e.g., in ASME Div 2 [2]. To the authors' best knowledge, a quantitative assessment on plastic deformation effects as a result of yield strength and Young's modulus change during PWHT is still not available in the literature except some preliminary results reported by the authors [10,11]. For instance, Yaghi et al. [15,17] stated that stress relaxation occur when yield stress and elastic modulus reduce to their values at PWHT temperature, but without qualifying how and to what an extent such a phenomena would contribute to plastic strain development in relieving residual stresses. The study by Takazawa and Yanagida [13] did not separate such effects from creep relaxation effects on residual stress relief in their computational analyses.

With the above discussions, this paper is structured to address the following specific questions, after presenting a validation study on a girth welded component on which the computational modeling results using the procedures adopted in this work are compared with measurement results:

(a) What is the dominant stress relief mechanism during furnace based PWHT
(b) How does plasticity deformation caused by the change in yield strength and Young's modulus during heating play a role in stress relief, if any?
(c) How to quantitatively inter-relate PWHT temperature, hold time, component wall thickness, and material type so that a more consistent "Time–Temperature-Thickness" relationship can be develped for residaul stress relief purpose?

It should be emphasized that this paper is focused upon residual stress relief. In addition to residual stress relief, material property improvement is another main objective for using PWHT in practice, which is currently being investigated in an on-going study, to be published separately in due time.

2. Analysis procedure

Analysis of weld residual stress relief during PWHT involves modeling of both weld residual stress development process as a result of welding and residual stress relaxation process during PWHT when an as-welded component is subjected to a controlled heating, holding, and cooling cycle.

2.1. Weld residual stress modeling procedure

A comprehensive discussion on requirements and effective methodologies for computational modeling of weld residual stresses for structural integrity assessment purposes are given in Dong and Hong [14], Dong [15], and most recently by Song et al. [16] to which the present study is a continuation of the same research program that is on-going at University of Michigan. As a result, detailed residual stress modeling procedures used in this study (see Ref. [16]) will not be repeated here due to space limitation. Instead, a validation example for demonstrating the validity of both residual stress modeling and creep relaxation modeling procedure will be presented here to provide a basis for supporting the discussions and observations to be presented in this paper.

A P91 pipe girth weld mockup (see Fig. 1a) was taken from Yaghi et al. [17], on which both experimental residual stress measurements both under as-welded and after PWHT are also available. By using the welding conditions and materials properties given in Ref. [17], the same residual stress modeling procedure documented by the same authors in Ref. [16] is used to estimate the resulting residual stress state after welding. The finite element model (axisymmetric) details showing individual pass profiles are shown in Fig. 1b. The final through thickness residual stress distributions along weld centerline are shown in Fig. 1c and compared with Deep Hole Drilling (DHD) measurements given in Ref. [17]. It is evident that the agreement between the modeling results and measurement results is rather reasonable (see further discussions on such a comparison in Ref. [16]).

The same modeling procedure is used throughout this paper for generating weld residual stress information for seam-welded pipes to be used for PWHT stress relief analyses. Note that analysis of PWHT stress relief with a focus on pipe girth welds as a part of this same study has already been reported by Zhang et al. [11].

2.2. Creep relaxation modeling procedure

With the weld residual stress state generated in the previous section (e.g., see Fig. 1c), PWHT procedure follows the following steps: