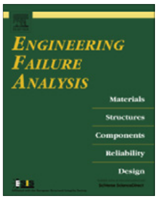
Engineering Failure Analysis 26 (2012) 31–49

Contents lists available at SciVerse ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal



Thermomechanical stress analysis of dissimilar welded joints in pipe supports: Structural assessment and design optimization

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ARTICLE INFO

Article history:
Received 22 March 2012
Received in revised form 23 July 2012
Accepted 25 July 2012
Available online 3 August 2012

Keywords:
Structural integrity assessment
Dissimilar welds
Creep resistant steel
Coupled thermomechanical FEA
Stress linearization

ABSTRACT

In this paper, the authors apply the ASME Boiler & Pressure Vessel Code to the structural assessment and design optimization of dissimilar welded joints subjected to transitory thermo-mechanical loads. The verification is based on the finite element stress linearization methodology. A large number of dissimilar P22/P91 steel welded joints of a power generation plant are taken into consideration. The joints vary in geometrical and operational conditions. In comparison with experimental investigations on some damaged structures, the methodology proves to be feasible, easily implemented, and reliable. Further, a second relevant result is obtained using the validated method to perform an optimization of the geometry of the joints for a safer design.

1. Introduction

Metal arc welding is a joining technology very much used to assembly parts and structures. With the refinement of materials and heat treatment, welding is taking the place of the traditional methods of joining components operating even at high temperature. Recently, it has begun to be employed to make fast and economic connections in the technology of power generation plants, for pipelines, heaters and boilers.

Generally, in applications in which the temperature ranges between 500 and 600 °C, high mechanical strength, good corrosion/oxidation resistance, and high structural stability of the materials are desired. High chromium ferritic steels are preferred for their high creep strength and low cost. However, long-term experimental results show that at high temperatures there is a significant reduction in their creep strength and hence an overestimation of their service life [1]. Since power plants are expected to operate under severe service conditions for several decades, an efficient structural design, an appropriate construction, and adequate monitoring are crucial in order to avoid downtime or even worse damage.

Nowadays, a very common technological problem is the combination of steels with different grades and microstructures. In fact, it may be necessary to join bainitic steels with martensitic or ferritic–pearlitic steels, bainitic steels with low-alloy steels, and, generally speaking, ferritic steels with austenitic steels [2,3]. Such heterogeneous joints can create a number of technological problems, e.g., the selection of the filler material, and even more, the selection of the postweld heat treatment cycle (PWHT). Premature creep failures in the weld zone may have several causes: (a) incompatibility of the mechanical properties of the base materials [4], (b) reactive diffusion of carbon at the interface when there is a clear difference in chromium content [5], (c) fragile phase precipitation or metallurgical problems weakening the weld heat affected zone (HAZ), (d) residual stresses in the weld, and (f) working conditions, oxidation, and other factors [6,7].

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http://dx.doi.org/10.1016/j.engfailanal.2012.07.002

The assessment of the integrity of these structures is conducted by schematizations and verifications that are generally based on analytical methods. As an outstanding example of this, we may consider the lifetime assessment factors of welded components, which are always implemented in specific design codes and guidelines. In recent years, general and/or more specific standards have been rapidly developing. As a matter of fact, many of the proposed design approaches imply a stress calculation in the weldments or in their proximities in order to achieve a correct and reliable joint design [8–15]. There are a few other important methods which have been developed over the last decades employing various design curves and failure assessment diagrams; among these are the "reference stress method" and its derivatives, the "MPC Omega Method", the "Engineering Treatment Model (ETM)", and the recent "European flaw assessment method SINTAP" [16–20].

The estimation of stress and/or strain concentrations at the weldments for dissimilar joints of pressure vessels is, in general, worked out via a finite element analysis. The most detailed calculations take into account the creep properties and the crack propagation resistance of the weldment constituents: the weld, the HAZ, and the base metal. As a matter of fact, a huge number of experimental studies have focused on the high temperature and creep resistance of steels; these, in accordance with the ASTM 335 standard, are designed from grades P1 to P911 depending on the Chromium and Molybdenum content. Many of these studies concern P22 (2.25Cr1Mo) and P91 (9Cr1Mo) grade steels [21–27], commonly used for the most exposed parts of steam power plants, such as turbines, boilers, and pressure pipes, and which are the steels treated in this work.

Unfortunately, not much data on the long-term creep in dissimilar joints is available today; what there is, is restricted to very specific applications. From the experimental point of view, an obstacle to the prediction of a long lifetime is the fact that in creep tests, the service relevant failure modes for dissimilar joints are achieved only after a very long test duration, hence long term prediction is somewhat unreliable for this regime [28,29].

In this paper, the authors take a method of calculation from the ASME Code and apply it to assessing the structural integrity of welded joints with dissimilar steel grades. The welds play a structural role in a set of pipes support of a steam pressure line operating in a power generation plant. The assessment procedure, which turns out to be perfectly compliant with the normative guidelines, is based on a finite element determination of the elastic stress field near the weld critical zones. These calculated stress state pictures are in accordance with the available failure data of experimental, non-destructive tests.

2. Failure analysis of joints

This study focuses on piping supporting frames used in two pipelines of saturated steam conduction, working in high and low pressure circuits, of, respectively, 12″ and 24″ diameters. It is worth noting that the pressure in these pipelines does not play any significant role in our study. Hence, from now on, we shall simply refer to them as steam pipelines or steam circuits. All the pipes are made of grade P91 ferritic steel.

One of these supporting structures is represented in Fig. 1. In the construction of these circuits, several transversal branches are applied to the main pipes in order to be suspension supports. These branches are then fixed to the ground frames via elastic/dumping elements, thus constituting a "real dynamic suspension". The above-mentioned branches are fixed to the main pipe by 4-side fillet welds on rectangular pads. The applied pads and the weld filler material is grade P22 ferritic steel. An explicatory scheme of these supporting frames is shown in Fig. 2. Hereinafter, this scheme will be useful for distinguishing the geometrical parameters of the supports.

From a routine in-service inspection of the thermal power plant, some localized structural problems were detected by non-destructive diagnostics: an ultrasonic inspection revealed the presence of extensive cracks in some of the supporting structures, all originating from the pipeline. The images in Fig. 3 show one of these damaged supports. Fig. 3a illustrates the location of a crack in the P91 pipe a few millimetres from the weld, within the HAZ. The surface of the pipe was mechanically ground. Fig. 3b and c shows details of this crack, which has been analyzed using the method of metallographic replica.

An ultrasonic analysis was also conducted to investigate the depth of the crack: it reported a crack depth of 1.5 mm perpendicular to the thickness of the pipe, extending under the weld bead. Other weaker echoes indicated other, sub-superficial lesser damage; investigations conducted with focused longitudinal waves probes confirmed the presence of sub-superficial small cracks.

From this, it is clear that the cracks originated within the pipe HAZ, at about 45° with the pipe axis, and emanated from the volume below the weld. A metallographic investigation was conducted with the replica method, in order to detect any possible structural change or deterioration. The technique of investigating microstructures to correlate the material evolution and creep exposure has been extensively used in metallographic observations of specimens after creep tests, and the microstructural investigation on actual in-service components is usually performed with this technique [30].

Here, the analysis revealed tempered, fine-grained martensitic structures, which are shown in Fig. 4. The structure of the base material, Fig. 4a, shows dispersed carbides and precipitation along the grain boundaries: these are typical signs of thermal aging that causes a deterioration of the mechanical properties of components operating at high temperature, such as carbide-induced embrittlement, temper embrittlement, and softening of the matrix [31–33]. The same structure was found in the HAZ of the pipe, Fig. 4c. The weld fusion zone, Fig. 4b shows a dendritic structure of acicular ferrite with dispersed carbides and precipitation at the grain boundaries. Between the pass welding, some coarse ferritic islands are also detected.

The microstructural analysis lets us ascribe the crack damage to a high temperature or thermal fatigue phenomenon combined with thermal stress. Hardness tests conducted in different zones of the joints, see Fig. 5, confirmed a structural degradation, revealing a hardness drop to about 180–190 in the base material, from the expected VHN of above 200.