International Journal of Pressure Vessels and Piping 146 (2016) 74–86

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

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

A framework for estimating residual stress profile in seam-welded pipe and vessel components part I: Weld region

Shaopin Song, Pingsha Dong*

Welded Structures Laboratory, Department of Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor, MI 48109, USA

ARTICLE INFO

Article history:
Received 3 August 2015
Received in revised form
21 July 2016
Accepted 24 July 2016
Available online 28 July 2016

Keywords:
Residual stresses
Finite element
Seam welds
Residual stress profile
Fitness-for-service
Membrane and bending decomposition
Curved beam

ABSTRACT

A recent comprehensive investigation into residual stress distributions in pipe and vessel longitudinal seam welds is presented in this paper, covering component wall thickness from 1/4″ (6.35 mm) to 10″ (254 mm), component radius to wall thickness ratio from 2 to 20, and linear welding heat input from low (50 J/mm) to high (6000 J/mm). Through the use of a residual stress decomposition technique, two key parameters that govern through-thickness residual stress distributions in terms of their membrane and bending content have been identified. One is component radius to wall thickness ratio (r/t) and the other is a characteristic heat input density ($\hat{Q}$) having a unit of J/mm^3. With these two parameters, a unified functional form for estimating through-thickness residual stress profile in seam welded components is proposed in this paper (Part I) for supporting fitness for service assessment for crack-like flaws in weld region. A curved beam bending theory based model is introduced in Part II as a means of analytically describing through-thickness residual stress profile as a function of circumferential position away from the weld region until residual stresses become zero. The effectiveness of this proposed framework for achieving residual stress profile estimation within weld region (Part I) for longitudinal seam welds in pressure vessel and piping components has been confirmed by finite element residual stress analysis results on a large number of component configurations and different welding conditions.

1. Introduction

Longitudinal (or long) seam welds (see Fig. 1) are often used in manufacture of piping and pressure vessel components in power generation and petroleum refining plants. Structural integrity of these seam welds has always been a major concern, as discussed by Viswanathan [1] and Viswanathan, Dooley, and Saxena [2] on some past major steam piping failures in fossil power plants. Long seam welds are common in high temperature steam lines, piping and other components such as headers, in which creep damage in the form of early crack formation through grain boundary cavitation is of particular concern [1,2]. Such a concern still exists even for the next generation power plant that is designed to operate at ultra-supercritical (USC) temperature [3], in which the demonstration header component is seam-welded. Therefore, a reliable fracture mechanics based structural integrity assessment has become increasingly important for determining a seam welded component's fitness for service (FFS) or need for repair [4]. In performing fracture mechanics based fitness for service assessment, seam weld residual stresses must be considered in fracture driving force calculations in addition to service loads such as operating pressure, as demonstrated by Bryan and Holz [5] in early 1980s on a thick nuclear vessel. Over the past two decades, codified FFS assessment procedures such as BS 7910 [6], API 579 [7], and R6 [8] have incorporated an increasingly detailed guidance on weld residual stress profiles for typical welded components.

For pressure vessel and piping components, residual stress profiles in these procedures [6–8] are categorized in terms of circumferential girth welds and longitudinal seam welds. As far as girth weld residual stress profiles are concerned, a recent critical assessment on their deficiencies is given by Dong et al. [9], in which a shell theory based method was outlined and demonstrated for estimating residual stress profile not only at weld region, but also at any location away from weld until residual stresses completely die out, as presented by Song et al. [10–12] and Dong et al. [13,14]. The key enabler in this process can be attributed to the establishment of a functional dependency of decomposed through-thickness membrane and bending stresses based on pipe geometry and heat input related parameters, as initially proposed by Dong in Ref. [15].

* Corresponding author.
E-mail address: dongp@umich.edu (P. Dong).

http://dx.doi.org/10.1016/j.ijpvp.2016.07.009

Nomenclature and abbreviations

d_p	distance from the weld toe to the boundary of plastic zone, mm
n_p	number of weld passes
Q	linear heat input, J/mm
$\hat{Q}$	characteristic heat input density or intensity, J/mm^3
R	variable in pipe radial direction varying from inner radius r_i to outer radius r_o, mm
r	mean radius of a pipe, mm
r_i	inner radius of a pipe, mm
r_o	outer radius of a pipe, mm
t	pipe thickness, mm
S_y	material yield strength at room temperature, MPa
$\sigma(x)$	residual stress, MPa
σ_m	membrane component of residual stress, MPa
σ_b	bending component of residual stress, MPa
$\sigma_{s.e.}$	self-equilibrating component of residual stress, MPa
$\overline{\sigma}_m$	dimensionless membrane component of residual stress
$\overline{\sigma}_b$	dimensionless bending component of residual stress
$\overline{\sigma}_{s.e.}$	dimensionless self-equilibrating component of residual stress
FEA	finite element analysis
FFS	Fitness-for-Service
ID	inner diameter
OD	outer diameter
SV	Single V
WCL	weld centerline
WT	weld toe

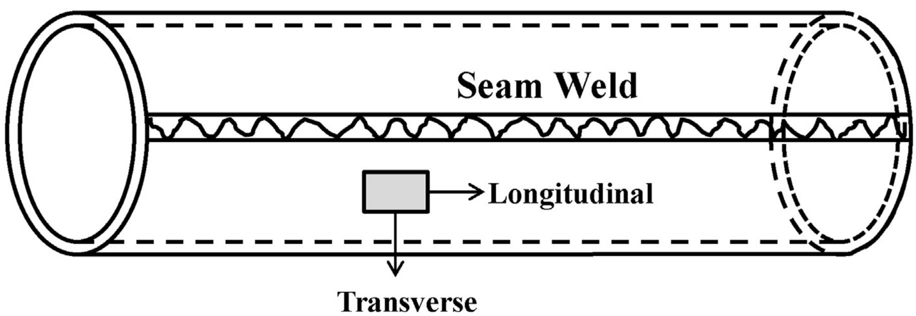

Fig. 1. Longitudinal seam weld and direction definitions.

As for long seam welds, residual stress profiles given by the aforementioned fitness for service procedures [6–8] are rather limited in scope. Both BS 7910 [6] and R6 [7] do not provide residual stress profile particularly for long seam weld, and borrow residual stress profile of butt welded plate for long seam weld. Both codes and standards [6,7] provide a numerically identical transverse residual stress (perpendicular to weld, see Fig. 1) profile for wall thickness ranging from 50 mm to 85 mm and vessel radius to thickness ratio (r/t) larger than 10. This residual stress profile remains constant over a circumferential (transverse to weld) distance of 1.5W from weld centerline, where W is seam weld width. Beyond 1.5W, no information is given in BS 7910 while a linear reduction to zero over a small distance in R6 [7]. API 579 [8] recommends a through-thickness residual stress profile that depends on both r/t ratio and a normalized heat input parameter for circumferential position beyond 0.5W from weld centerline while remains constant within 0.5W with respect to weld centerline. Note that the dependency on circumferential position beyond 0.5W from weld centerline, as given in API 579 [8], was based on a best fit of finite element results. Furthermore, longitudinal residual stress (parallel to seam weld) profile is assumed to be constant at yield magnitude for ferritic steel weldments within a circumferential distance (transverse to weld) of 1.5W from weld centerline in both BS 7910 and R6, while BS 7910 gives no guidance for locations beyond 1.5W and R6 assumes a linear reduction to zero at a small distance. Again, API 579 [8] introduces a similar circumferential variation function to that used for transverse residual stress profiles.

As discussed above, there exist some significant differences in through-thickness residual stress profiles applicable to weld region among the three different FFS procedures [6–8], principally between BS 7910/R6 and API 579. Away from weld region, the differences among the three FFS procedures become more significant, varying from no information given in BS 7910 [6] to a linear variation to zero stress over a small circumference distance in R6 [7] to quadric variation over a circumferential distance in terms of $\sqrt{rt}$ in API 579 [8]. Unfortunately, both detailed experimental residual stress measurements and systematic finite element analyses have been lacking in literature on long seam welded components, particularly on thick wall components, to substantiate or refine some of the assumptions introduced in these codified procedures [6–8]. The current work represents an attempt in addressing some of the inconsistencies in seam weld residual stress profile prescriptions brought forth in the above discussions.

This work is reported in two parts. Part I starts with a brief description of the finite element residual stress modeling procedure adopted in this study, which has been validated previously and used in numerous weld residual stress studies for both girth and seam welds [9–18]. After briefly demonstrating its effectiveness in analyzing a welded mock up component on which experimental residual stress measurements are available, a systematic parametric finite element study is carried out over a wide range of long seam weld geometries and welding heat inputs. Among various parameters investigated, it is found that component geometry in terms of r/t and characteristic heat input having a unit of J/mm^3 play the most dominant role in controlling the membrane and bending components in through-thickness residual stress distributions for all cases studied. Then, a continuous residual stress profile functional form is constructed as a combination of membrane, bending, and self-equilibrating parts for through-thickness residual stress distribution. Membrane and bending components can be determined through a synthesis of parametric finite element results as a function of r/t and a characteristic heat input parameter