Materials and Design 56 (2014) 782–790

Contents lists available at ScienceDirect

Materials and Design

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

Experimental and numerical assessment of mechanical properties of welded tubes for hydroforming

Ali Khalfallah *

Laboratoire de Génie Mécanique, Ecole Nationale d'Ingénieurs de Monastir, Av. Ibn El-Jazzar, Monastir 5019, Tunisia
Institut Supérieur des Sciences Appliquées et Technologie de Sousse, 4003 Sousse, Tunisia

ARTICLE INFO

Article history:
Received 7 September 2013
Accepted 21 November 2013
Available online 8 December 2013

Keywords:
Welded tube
Heat-affected zone
Rule of mixtures
Tensile test
Microhardness test
Free tube hydroforming test

ABSTRACT

The identification of welded tubes properties considering the weld bead and Heat Affected Zone (HAZ) is important for reliable and accurate finite element simulation of tubular plastic forming processes such as tube hydroforming and rotary draw bending processes. Therefore, a simplified method is proposed to extract the weld bead and HAZ properties. Full size standard tensile specimens cut from the welded tube and comprising the weld parallel to the load direction are extended to failure. Mechanical properties obtained from uniaxial tensile test are correlated with the microhardness data measured across the welded specimen and by using the rule of mixtures; the constitutive model parameters of weld bead and HAZ regions are identified. Accuracy of the proposed method is assessed by comparing finite element simulation predictions to experimental measurements obtained from two mechanical tests: the first one is the uniaxial tensile test performed on specimens comprising the weld line perpendicular to the loading direction and the second test is the free bulge hydroforming test achieved on seamed tubular samples. This investigation has shown that the presented method is practical in use and sufficiently accurate to extract the weld metal properties of seamed tubes.

1. Introduction

The Welded tubes are becoming widely employed in automotive and aerospace industries owing to their attractive manufacturing low cost and mass production capacity [1]. For instance, over the last few decades, tube hydroforming and rotary draw bending processes are the chief consumers of welded thin-walled structures. Nowadays, around two thirds of the steel tube production in the world is accounted for by welding processes [2]. Tubes with a variety of cross sectional shapes are generally, the raw materials used for the tube hydroforming and rotary draw bending processes which are ones of the current active fields of development in the lightweighting deed of automotive and aerospace industries. The welding process has shown an influence on the size, microstructure and mechanical properties of the weld zone due to local metallurgical modifications that affects the tube characteristics [3–6]. The inhomogeneous effect of heating during the weld process influences the non-uniform material properties in the heat-affected zone (HAZ). Several researches have been carried out to characterize the mechanical behavior of inhomogeneous weld joint on the basis of uniaxial tensile tests [7–9]. Some tensile specimens have been specially designed comprising only the weld bead [10], others were a subsized tensile specimens cut from standards gauge samples [11–13]. However, the manufacture of such miniature samples and its testing are very subtle and complicated. On the other hand, microhardness test has traditionally been used for the measurement of local mechanical properties of tiny samples or thin regions. Indeed, microhardness testing has been a widespread technique for the mechanical characterization of weldment zone. Furthermore, the indentation test is a non-destructive method which involves the same testing principle as that used in hardness test and the load-unload curve obtained from indentation test is usually used to determine the mechanical properties and local stress–strain relationship of weld materials [14–16]. As for methods to determine the characteristics of material properties, the digital image correlation (DIC) is an efficient technique to obtain local mechanical properties of weld bead and HAZ. This method was initially used by Reynolds and Duvall [17] and since then, it is widely used to determine mechanical properties of laser and friction stir welding [18–20].

Zhan et al. have established a method to determine the constitutive models for welded tubes based upon a mixed tensile test, microhardeness test and the use of rule of mixtures. Nevertheless, their proposed method has not been experimentally verified [21]. Saunders and Wagoner have used similar method to determine

---

* Address: Laboratoire de Génie Mécanique, Ecole Nationale d'Ingénieurs de Monastir, Av. Ibn El-Jazzar, Monastir 5019, Tunisia. Tel.: +216 73 50 05 11; fax: +216 73 50 58 66.

E-mail addresses: ali.khalfallah@gmail.com, ali.khalfallah@enim.rnu.tn

0261-3069/$ - see front matter © 2014 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.matdes.2013.11.051

the weld properties of steel and aluminum of tailor welded blanks (TWBs) [12]. They have used standard full-size specimens and smaller sub-size samples for tensile test experiment. Similar method has been used by Abdullah et al. to obtain the mechanical properties of TWBs [11]. Likely, Lee et al. have extracted the average properties of weld bead and HAZ of TWBs using sub-sized tensile specimens combined with the rule of mixtures [22]. Recently Song et al. have proposed a method to characterize the mechanical properties of laser welding beams by using the micro-Vickers hardness test combined with the rule of mixtures [23]. Experimental validation of their proposed method by other tests was missing, but only instrumented indentation tests using the same samples as for the identification were conducted to verify the measured inhomogeneous properties of weld materials. Hence, from the above literature review, it can be concluded that up to date, many studies have been performed on the determination of plastic behavior of tailor welded blanks (TWB) [8,9,22,23]. Nevertheless few works were published on the constitutive relationship of welded tubes [6,21].

This work is a contribution among the few studies which focus on the determination of mechanical properties of welded tubes. The purpose of this paper is to put forth a simplified analytical and reliable method for determining the necessary mechanical properties to model the weld zone comprising weld bead and HAZ region of welded tubes. This method uses correlation relationships between standard tensile test properties (i.e. yield stress, ultimate tensile strength and strain hardening exponent) and microhardness measurements which are combined with the rule of mixtures. The conjunction of rule of mixtures with these relationships addresses the determination of material weld properties.

The accuracy assessment of this method is based on the comparison of numerical predictions attained by finite element simulations which use material parameters as input data and the experimental measurements obtained from two mechanical tests. Namely the tensile test and the free bulge hydroforming test. The first test is performed on specimen containing the weld in its transversal direction while the latter one is achieved on a seamed tube sample. This study has shown that the presented method is practical in use and efficient to determine the weld metal properties of welded tubes.

2. Experimental set up

2.1. Material

Studied tubes were made from low carbon steel S235JR. This material was provided by the steel tube manufacturer company RAF-Rades in Tunisia. These tubes were manufactured according to the EN 103 05-03 Standards by sheet slip rolling process and welded by high frequency induction welding. The weld zone width is about 5 mm along the axial tube. The outside tube diameter is 50 mm and the wall thickness is 1.2 mm. Table 1 depicts the chemical composition of the tube material.

2.2. Tensile test

Tensile specimens were machined from the S235JR welded tubes in the axial direction with respect to ASTM: E8/E8M standards. In fact three sets of standard size specimens were cut from the welded tube. The tensile specimens of the first set contain the weld joint in the middle and along the axial direction. The second set represents the specimens of the parent metals which were cut in the opposite location to the first ones. Fig. 1 shows the tube where the specimen 1 and specimen 2 were cut from. In the third set, the tensile specimens enclose the weld bead in the center and along the transversal direction. These samples were cut from a flatten sheet obtained from the tube. It is worth to denote that the experimental tests related to the specimen that encloses the weld bead in the axial direction and the parent metal specimen were used to identify the mechanical welding zone properties. Whereas the specimen 3 is used to validate in a first approach the proposed method. Fig. 2 shows the three specimen-types used for the tensile tests. The experiments were performed on six specimens of each type. They were extended to failure in a Shimadzu universal materials testing machine at a stoke rate of 5 mm/min and the displacements were measured in the gauge zone by an extensometer with a range of 50 mm. An average of the six tensile curves was calculated to represent the flow stress curve of the material in each region where the specimen was cut from. Fig. 3 represents the experimental three curves corresponding to the different tensile test specimens. They are plotted using engineering stress–strain measurements. One can see the significant influence of the weld zone on the mechanical properties of the parent material. It can be observed that the strength of the specimens with weld zone parallel to loading direction is higher that of the parent metal specimen. The weld also decreases the elongation of the tested material even when it is perpendicular to the loading direction. This influence of the weld on mechanical properties depends on the orientation of weld zone relative to the tensile direction.

Table 1
Chemical composition of the base material of the low carbon steel S235JR.

%C	%Mn (max)	%P (max)	%S (max)	%N (max)	%Fe
0.21	1.50	0.055	0.055	0.011	Balance

2.3. Microhardness test

The microhardness measuring method using standards ASTM: E92-82 is applied to obtain the microhardness profile of the tested samples. An arc cross-section specimen is cut around the weld line comprising the weld bead, the HAZ and the parent metal.

The samples are enrobed with resins and polished to obtain perfectly mirror-like surfaces. Vickers microhardness tester is used to measure the microhardness along the transversal cross-section direction of the specimen and along the thickness direction. The displacements along the two directions are controlled by screw-micrometers. Depending of the measured region the intervals of reading microhardness along transversal direction vary from 0.25 mm to 0.15 mm. Along the thickness direction, an average of five measurement points is obtained to represent the microhardness for a given position in the transversal direction. The measurements

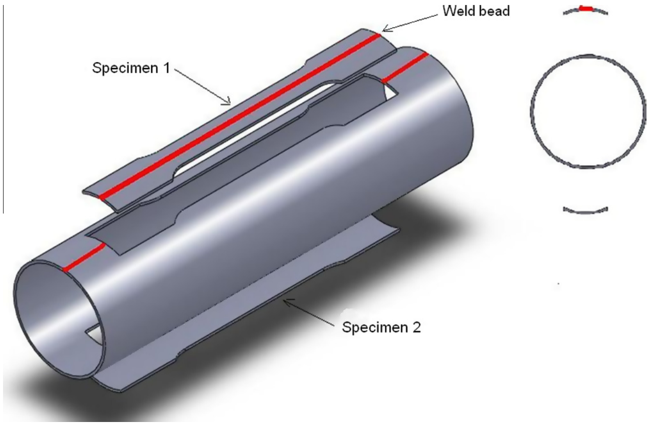

Fig. 1. Tensile test specimens and its cut locations.