Chinese Journal of Aeronautics, (2016), 29(2): 305–315

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

REVIEW ARTICLE

Advances and trends in plastic forming technologies for welded tubes

Zhan Mei *, **Guo Kun**, **Yang He** *

State Key Laboratory of Solidification Processing, School of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, China

Received 29 June 2015; revised 31 July 2015; accepted 7 September 2015
Available online 2 November 2015

KEYWORDS

Constraint effects;
Deformation coordination;
Finite element modeling;
Forming;
Forming limit;
Inhomogeneous deformation;
Material characteristics;
Welded tube

Abstract With the implementation of environmental protection, sustainable development and conservation-oriented policies, components and parts of thin-walled welded tubes have gained increasing application in the aircraft and automotive industries because of their advantages: easily achieving forming and manufacturing process at low cost and in a short time. The current research on welded tube plastic forming is mainly concentrated on tube internal high-pressure forming, tube bending forming, and tube spinning forming. The focuses are on the material properties and characterization of welded tubes, finite element modeling for welded tube forming, and inhomogeneous deformation behavior and the mechanism and rules of deformation coordination in welded tube plastic forming. This paper summarizes the research progress in welded tube plastic forming from these aspects. Finally, with a focus on the urgent demand of the aviation, aerospace and automotive industries for high-strength and light-weight tubes, this paper discusses the development trends and challenges in the theory and technology of welded tube plastic forming in the future. Among them, laser tailor-welded technology will find application in the manufacture of high-strength steel tubes. Tube-end forming technology, such as tube flaring and flanging technology, will expand its application in welded tubes. Therefore, future studies will focus on the FE modeling regarding how to consider effects of welding on residual stresses, welding distortions and microstructure, the inhomogeneous deformation and coordination mechanism of the plastic forming process of tailor-welded tubes, and some end-forming processes of welded tubes, and more comprehensive research on the forming mechanism and limit of welded tubes.

* Corresponding authors. Tel.: +86 29 88460212 805 (M. Zhan), +86 29 88495632 (H. Yang).
E-mail addresses: zhanmei@nwpu.edu.cn (M. Zhan), gkyike@163.com (K. Guo), yanghe@nwpu.edu.cn (H. Yang).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

1. Introduction

Compared with seamless tubes, welded tubes have advantages, such as low production cost, high production efficiency, stable quality and variety, etc. With the implementation of environmental protection, sustainable development and

http://dx.doi.org/10.1016/j.cja.2015.10.011
1000-9361

conservation-oriented policies and the rapid development of lightweight structure forming manufacturing technology in the aviation, aerospace and automotive industry, all types of thin-wall welded tube parts and components are finding increasingly extensive application.[1–4] Especially in the aviation industry, the tubing system is the core part of the aircraft. Because of high material utilization rate, high production efficiency, and the properties of expanding and bending forming having little difference with seamless tube, welded tube is finding wide application in aircraft environmental control and drain line system. From the perspective of plastic forming, welded tube plastic forming belongs to the category of inhomogeneous materials forming. The welded tube forming process is similar to that of homogeneous tubes with wrinkling, cracking and other possible defects, while inhomogeneous materials and the performance of the parent metal, the weld seam (weld line or weld bead) and the heat-affected zone (HAZ) of welded tubes lead to a complicated nonlinear materials problem. The width of the weld seam and the HAZ and their positions in the plastic forming process will result in a complicated geometrical nonlinear problem. Material and performance differences among the weld seam, the HAZ and the parent metal in the plastic forming process may also lead to a complex contact with the tool and die and boundary nonlinear conditions. These nonlinear problems and their coupling effects enhance the restriction of the weld (including the weld seam and the HAZ) on the plastic forming quality of welded tubes and make the plastic forming quality and forming performance/forming limit of welded tubes more sensitive to the rules of constraints and deformation coordination among the weld seam, the HAZ and the parent metal. When the effect of inhomogeneous deformation among these zones is so strong that they cannot deform in a coordinated fashion, defects such as wrinkling and fracture may occur. Furthermore, these defects will constrain the normal plastic forming process of welded tubes and the improvement in their forming performance. When each zone of the welded tubes can be deformed in a coordinated fashion, it is likely that the plastic forming process can be carried out smoothly, thereby improving the forming quality of the welded tubes and fully exploiting the tubes' deformation potential and improving their forming performance. These characteristics make the plastic forming behavior of welded tubes different from those of homogeneous tubes. Therefore, it is important to perform research on welded tube plastic forming theory and technology. This research will provide a practical engineering theory basis for improving the quality of plastic forming of welded tubes and for exploring the deformation potential of these tubes. It is significant and important for improving the level and capability of the high-quality, low-cost, and short-cycle manufacturing technology of welded tubes.

To date, the welded tube plastic forming research mainly concentrates on three aspects, including internal high pressure forming, bending forming and spinning forming. The focus is on material properties and the characterization of welded tubes, finite element modeling for welded tube forming, and inhomogeneous deformation behavior in welded tube plastic forming and the mechanism and rules of deformation coordination. Based on these aspects, this paper summarizes the research progress in welded tube plastic forming.

2. Material properties and constitutive modeling of welded tubes

Different welding technologies and processes will produce weld seams and HAZs with different appearances, sizes and mechanical properties. This has a significant effect on the forming performance. Therefore, it is necessary to perform research on welded tube performance and its characterization.

2.1. Weld characteristics of welded tubes

The appearance, size, mechanical properties and plastic forming performance of the weld line and the HAZ are closely related to the welding process, the speed, the temperature, the extrusion force and the thickness of the tube. Through metallographic analysis and tensile testing, Chen[5] investigated the mechanical non-uniformity of a 304 (SUS304) austenitic stainless steel welded joint of tailor-welded tubes that were made using tungsten inert gas (TIG) welding technology. He analyzed the variations and differences in the microstructure and mechanical properties of different zones of welded joints and ascertained that the width of the weld was approximately 5 mm, and divided the welded joints into four regions, including parent metal, HAZ, fusion zone (or in some cases only a fusion line) and weld seam. Khalfallah[6] ascertained that the weld seam width of a low-carbon steel S235JR tube welded by high-frequency induction welding was approximately 1 mm and that the width of each HAZ was approximately 2 mm. The weld region in their study was characterized by much higher hardness (approximately HV = 198) than that of the parent metal (approximately HV = 115). The yield and tensile strength stresses of the weld specimen were higher than those of the parent metal, whereas the strain hardening exponent and the uniform elongation were lower for specimens containing the weld than those of the parent metal.[6] Ghoo et al.[7] and Panda et al.[8] also obtained similar findings. Yang et al.[9] ascertained that the weld width of a QSTE340 welded tube produced by resistance welding was 4 mm and the width of each HAZ was 6 mm by analyzing the weld joint microstructure and microhardness distribution. For high-frequency electric resistance welding (HF-ERW)[10] and extrusion welding[11], the weld is always funnel-form. Ren et al.[12] observed the weld shape to be like a typical drum by means of microhardness distribution and microstructure analysis. They found that the difference among the parent material, the HAZ and the fusion zone was apparent and determined that the weld seam width of 60 mm × 4.0 mm ($d \times t$:d-tube outside diameter, t-wall thickness) and 78 mm × 2.7 mm QSTE340 HF ERW tubes were both 0.4 mm and the width of the HAZ of both tubes was 2.4 mm. Li et al.[13] used tensile tests and microhardness tests to study the mechanical performance of a CP3 pure titanium thin-walled welded tube which would be used in the drain line system of a civil aircraft. Their results show that compared with the parent metal, the yield strength and tensile strength of the weld were higher, but the elongation of the weld was obviously lower, and a large hardness gradient appeared in the HAZ. Ren[14] also obtained similar conclusions in the research on QSTE340 steel welded tubes. A large number of studies show that welding caused a change in the hardness of the weld area. For example, in laser welding, the weld area hardness increased by 50%[15] to