Materials Characterization 133 (2017) 196–205

Contents lists available at ScienceDirect

Materials Characterization

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

Correlation between softening mechanisms and deformation non-uniformity of laser-welded titanium alloy tube during gas bulging process

Kehuan Wang[b,c,*], Gang Liu[a,b,*], Denis J. Politis[c], Liliang Wang[c]

[a] State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China
[b] School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China
[c] Department of Mechanical Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, UK

ARTICLE INFO

Keywords:
Softening mechanism
Deformation uniformity
Laser beam welding
Titanium alloy tube
Gas bulging

ABSTRACT

In this paper, post-weld annealing was carried out to adjust the flow stress difference between weld seam and base material (BM). Deformation non-uniformity of laser-welded titanium alloy tubes before and after annealing was evaluated by gas bulging at 800 °C. Results show that after double annealing (950 °C/2 h, air cooling + 600 °C / 2 h, air cooling), weld seam and BM had similar peak stress at first during tensile test at 800 °C, 0.001 s^{-1}, then the flow stress difference between them changed dynamically due to different softening rates. The maximum flow stress difference ratio was reduced from 36% to 17% after annealing. Deformation uniformity of the bulged tube was improved by 24.6% after annealing, but the higher softening rate of BM during gas bulging confined its further improvement. At early stage of gas bulging of the annealed tube, the main softening mechanism for weld seam was dynamic recovery and that for BM was globularization of secondary α and phase transformation of α to β. At middle-late stage of gas bulging, the main softening mechanism for weld seam was partial globularization of lamella α and that for BM was wide dynamic recrystallization.

1. Introduction

Titanium alloys are widely used in the aerospace, marine, chemical, energy and transportation industries due to their outstanding properties including superior strength-to-weight ratio and excellent corrosion resistance [1,2]. In order to further improve the performance of aircraft, manufacturers have sought to increase the power output of aircraft systems by increasing the working pressures for fuel and hydraulic pipe systems. This has brought new challenges to produce titanium alloy tubular sections for these systems capable of withstanding the adverse operating conditions [3]. One of the greatest challenges which has limited their widespread application is the difficulty to fabricate seamless medium or high strength titanium alloys tubes economically due to their high strength and low ductility at room temperature [4]. Solutions to overcome these challenges include hot rolling, multiple cold rolling with intermediate annealing, hot extrusion or the use of seamed titanium alloy tube. Seamed titanium alloy tube produced to withstand working loads can be produced at relatively low cost with increased flexibility of geometry [5]. A means of producing seamed titanium tube is Laser Beam Welding (LBW), which as a mature welding technology has seen widespread application in the production of seamed steel tubes [6] and has been demonstrated in the literature to provide considerable flexibility for the joining of titanium alloys [7].

Weld joint deformation has been subject to intense study in the metal forming sector due to its unique deformation non-uniformity characteristics which have challenged established forming practices. Specifically, studies have found that the weld joint results in a decrease in formability of the sheet material by trigging inhomogeneous deformation [8]. The weld joint can be roughly divided into several categories according to the joint material and thickness such as joint with the same or different materials, joint with the same or different thickness and joint with different materials and different thickness [9]. Extensive research has been conducted to study the mechanical and microstructure properties, formability and failure of the aluminum alloys joints [10] and steel joints [11], which can be found in Merklein's review [9]. In order to reduce the local deformation and improve formability, Abbasi et al. [12] modified the forming parameters including thickness ratio, rolling direction with respect to the weld line and direction of major stress with respect to the weld line and found that maximum formability occurred when the major stress and rolling direction were along the weld line. Babu et al. [13] employed solution treatment to improve the formability of the tailor welded blanks of two different materials, namely AA6061 and AA2014. Gnibl et al. [14] improved the formability of the friction stir welding aluminum sheets

* Corresponding authors at: School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China.
E-mail addresses: kehuan.wang@imperial.ac.uk (K. Wang), gliu@hit.edu.cn (G. Liu).

http://dx.doi.org/10.1016/j.matchar.2017.10.002
Received 11 August 2017; Received in revised form 28 September 2017; Accepted 2 October 2017
Available online 03 October 2017
1044-5803/

by combination of increasing the forming temperature to 150 °C and by a heat treatment between 200 and 350 °C.

As for the titanium alloys joint, after LBW, the joint has a higher strength than the base material as is also found in steel joints. However, in contrast to the forming of steel components, which are generally produced through cold forming, titanium alloys parts are usually formed at elevated temperature. Wang et al. [15] have investigated the superplasticity of TC4 butt-welded plates produced by LBW through hot tensile tests and superplastic bulging tests. It was found that the TC4 butt-welded plates had good formability and the maximum bulge height can be up to 1.8 times as the internal radius of the female die. Kashaev et al. [16] have studied the formability of the laser beam welded joints between fine-grained and standard TC4 sheets. They concluded that superplasticity can be observed in the fine-grained TC4 sheet without crack formation in the heat-affected zones or the fusion zone, but the weld seam of the dissimilar fine-grained-standard butt joint is resistant to superplastic deformation. Similar results were also reported by Wang et al. [17], where the laser-welded joint resisted deformation when the tensile stress was vertical with the weld line. Although the LBW titanium alloy joint has good formability at elevated temperature, the deformation non-uniformity problem remains. According to Zhan et al. [18] who conducted a review on plastic forming of welded tubes, there have been limited studies on the inhomogeneous deformation and coordination mechanism of plastic forming of titanium alloy joints, especially for the plastic forming of welded titanium alloy tube.

The work in this paper investigates the deformation non-uniformity that occurs on a titanium LBW joint during gas bulging. The welded TA15 titanium alloy tube was fabricated by hot U-O forming process combined with LBW. U-O refers to two successive forming operations from a plate to a tube, namely U-forming and O-forming with further details of the U-O forming process found in the authors' previous publication [4]. To improve the deformation uniformity, post-weld annealing treatment was conducted. Finally, microstructure characterization was conducted to reveal the effect of softening mechanism on deformation non-uniformity.

2. Experimental Procedures

2.1. Laser Beam Welding and Annealing Process

TA15 is a near-α titanium alloy with chemical composition of Ti–6.5Al–2Zr–1Mo-1V (in wt%). A hot rolled TA15 sheet with thickness of 2 mm was employed in this study. The TA15 titanium alloy tubes were fabricated from the same rolled sheet. The LBW was performed with a diffusion cooling carbon dioxide laser of 3.0 kW rated power (ROFIN-SINAR DC030). To reduce the constraint of weld seam on the welded tube during deformation, different welding parameters were tested to reduce the width of the weld seam. It was found that the width of the weld seam increased with the heat input and incomplete penetration would occur when the heat input was insufficient. Satisfied joints with full penetration and relatively small width of weld seam can be achieved with output power and welding speed of 1 kW and 1.2 m/min, respectively. The corresponding focus length and spot size were 192 mm and 0.15 mm, respectively. The same welding parameters were used to weld both the sheet and tube. Argon gas shielding was used during welding to prevent oxidation.

The transverse section view of a LBW sheet joint in the as-welded condition is shown in Fig. 1, in which three distinct regions can be identified: the fusion zone (FZ), heat-affected zone (HAZ), and the base material (BM). Fig. 1(b) shows the microstructure in FZ, which consists of coarse columnar grains with fine α′ martensitic structure in the matrix. The microstructure of HAZ is more complex than that of FZ, which contains a mixture of α′, primary α phase, β phase and transformed β phase, as shown in Fig. 1(c). The microstructure of the tube joint is similar to the sheet joint, as found in the study performed by Wang et al. [4].

Due to the huge difference in microstructure between the BM and weld joint, there will be strength gradient between them which will lead to non-uniform strain distribution during the deformation. In order to improve the deformation uniformity, vacuum annealing treatments were carried out. The α → β transformation temperature of the present Ti-alloy is ~980 °C. Three different vacuum annealing treatments were selected: two recrystallization annealing and one double annealing. The two recrystallization annealing processes are 850 °C/2 h, air cooling (AC) and 900 °C/2 h, AC, respectively; and the double annealing process is 950 °C/2 h, AC + 600 °C/2 h, AC.

2.2. Gas Bulging

The gas bulging of the welded TA15 titanium alloy tubes before and after annealing treatment was performed on a dedicated high pressure gas forming platform, with experimental apparatus and dimension of the forming tools shown in Fig. 2. The length of the bulging zone was 48 mm, or 1.2 times of the outer diameter of the tube. Moreover, the die entrance radius was 4 mm. Thermocouple and displacement sensor measurements were made on the tube to monitor and record the instantaneous temperature and bulging height. Once uniform tube temperature was achieved, the tube was expanded via pressurized gas. Bursting tests were conducted to investigate the formability of the TA15 titanium alloy tubes and interrupted bulging tests were carried out to study the deformation uniformity. Once formed to the bulged shape, the tubes were quenched in cold water immediately. The bulging ratio was calculated by eq. 1.

$$\varnothing = \frac{l_d - l_0}{l_0}{}^{*}100\% \tag{1}$$

Where l_d is the perimeter of the middle section from tube after bulging deformation and l_0 is the initial perimeter of the tube.

2.3. Microstructure and Property Examination

Microstructures of the materials before and after both of the heat treatment and bulging deformation were examined by optical microscopy (OM) and electron backscattered diffraction (EBSD). The OM examination was performed on a Leica BMI-3000M microscope. The samples for optical microscopy examination were prepared by standard titanium metallographic procedures and etched with a solution consisting of 7% HF, 13%HNO_3 and 80% H_2O (vol%). The EBSD was performed on a Zeiss Supra55 scanning electron microscope (SEM) operated at 20 kV with a step size of 0.2 μm. The EBSD data was processed by HKL Channel 5. The samples for EBSD measurement were prepared by electro-polishing with a solution of 6% perchloric acid, 34% butanol and 60% methanol (vol%) at − 40 °C with a potential of 30 V and current of 0.8 A. In the bulged region of the deformed tube, each section exhibited varying degrees of deformation. Hence, samples from the tube (BM and weld joint) were taken from these sections of the bulged tube and the samples from the middle section are shown in Fig. 3. Microstructure examination was conducted on the RD-TD surface.

The microhardness of the weld joints before and after annealing treatment were tested by a Vickers microhardness machine with load of 450 N and holding time of 15 s at room temperature. Tensile tests were conducted on an INSTRON 5500R test machine at 800 °C. The dimensions of the dog-bone shaped tensile specimens were 20 mm in gauge length, 4 mm in width, 6 mm in the corner radius and 2 mm in thickness. The average width of weld seam in the parallel specimen was 3 mm, and the total width of the parallel specimen was 4 mm, so the ratio between weld and BM is 3:1. After the tensile test, the specimen was water quenched immediately.