Materials and Design 34 (2012) 609–617

Contents lists available at ScienceDirect

Materials and Design

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

Numerical investigation on the variation of welding stresses after material removal from a thick titanium alloy plate joined by electron beam welding

Chuan Liu [a,*], Jianxun Zhang [a], Bing Wu [a,b], Shuili Gong [b]

[a] State Key Laboratory for Mechanical Behavior of Materials, Xi'an Jiaotong University, Xi'an 710049, PR China
[b] National Key Laboratory of High Energy Density Beam Processing Technology, Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, PR China

ARTICLE INFO

Article history:
Received 5 January 2011
Accepted 5 May 2011
Available online 15 May 2011

Keywords:
Non-ferros metals and alloys
Machining
Welding

ABSTRACT

The stress modification after material removal from a 50 mm thick titanium alloy plate jointed by electron beam welding (EBW) was investigated through the finite element method (FEM). The welding experiment and milling process were carried out to experimentally determine the stresses induced by EBW and their modification after local material removal. The modification of as-welded stresses due to the local material removal method and the whole layer removal method was discussed with the finite element analysis. Investigated results showed that with less materials removal from the top, the stresses on the bottom surface remain almost unchanged; after material removal from the top and bottom part, the transverse stress on the newly-formed surface decreases significantly as compared to the as-welded stresses at the same locations; however, the stress modification only occurs at the material removal region in the case of local region removal method; the longitudinal stress decreases with the whole layer removal method while remains almost unchanged with the local region removal method.

1. Introduction

Titanium and its alloys feature a number of superior properties, such as low specific gravity, high strength, good corrosion resistance and heat resistance. These characteristics make this material attractive for numerous applications such as aerospace industry and power generation. The thickness of the titanium alloy components in these important industrial fields keeps growing, and the electron beam welding (EBW) is the preferred technique to join the thick titanium alloy components in that EBW can efficiently offer welds with high depth-to-width ratio. Moreover, EBW is performed in the condition of high vacuum which can effectively prevent the metal from contamination. For example, the spherical titanium alloy gas bottles with wall thickness of 11.2–17.5 mm used in satellite launch vehicles for storing helium gas under very high pressure was joined by EBW [1].

However, as a fusion welding process, residual stresses are definitely generated in the joints with EBW. Ramana et al. [2] found that the transverse residual stress in the Maraging steel weld induced by EBW was compressive, while it was tensile in the medium alloy medium carbon steel weld. The investigation carried out by Lundbäck and Runnemalm [3] shown that the longitudinal residual stress within the joint after EB butt welding of two Inconel 718 plates was highly tensile and the transverse stress was mainly compressive. Their research results also indicated that the residual stress in the weld region at the surface was different from that at a depth of 1 mm. The tensile longitudinal stress and compressive transverse stress were also found in the Inconel 706 weld joined by EBW [4].

Although residual stresses are self-equilibrated systems, their effects on mechanical strength of materials (especially fatigue strength) are often significant. Moreover, the welded components may suffer from various material removal processes regularly, such as milling, grinding, turning and drilling, to prepare specimen or to be assembled. These machining processes would lead to the redistribution of welding residual stresses. In turn, in-service behavior of the welded components can be affected by the redistributed stress. For instance, Liljedahl et al. [5] noticed that the resulting residual stresses when a welded plate was sectioned to a middle tension specimen or a compact tension specimen are remarkably different, and the interaction between the weld stresses and the fatigue cracks is therefore markedly different as well. Altenkirch et al. [6,7] found that subsequent sectioning of the weld into shorter test lengths resulted in a progressive and significant relaxation of the longitudinal residual stress field. Accordingly, it is important to understand the redistributed welding residual stresses so as to facilitate the structure design and life evaluation of welded components.

Numerical and experimental evaluation of welding residual stress distribution has been largely studied [8]. Recently, the redistribution of residual stresses originated by welding after material

* Corresponding author. Tel.: +86 (0) 29 82663115; fax: +86 (0) 29 82668807.
E-mail addresses: mse.chuanliu@gmail.com, chuanliu@stu.xjtu.edu.cn (C. Liu).

0261-3069/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.matdes.2011.05.014

removal has been concerned and studied with experiments and finite element analysis. For example, Zhang et al. [9] investigated the effects of specimen removal on the residual stress redistribution via finite element method when a small specimen was removed from a large girth weld, they found that the overall changes of both axial and hoop stresses were fairly small. Dattoma et al. [10] forecasted the modification and evolution of a residual stress field, which originated by welding and suffered after milling and cutting to prepare the experimental specimens, they found that the residual stresses altered significantly after milling and cutting.

During EB welding, the vapor keyhole will be generated, that is a characteristic of EB welding process. The action of the vapor pressure in the keyhole also serves to drive the molten metal film out from both ends of the keyhole to free space. This leads to the formation of complex topbead and underbead profiles on solidification. Therefore, the welded structure joined by EB must be machined (milled or grinded) to make the surface smooth. The welding residual stresses would be altered due to the material removal after machining process.

For thick titanium alloy welded component joined by EWB, few literatures are available about the variation of the EBW induced residual stress field suffering after material removal process. In the present study, the welding residual stress modification after successively milling in a 50 mm thick TA15 titanium plate joined by EWB was investigated. Welding experiment, milling process to remove local material, stress measurement both on the surfaces of as-welded plate and the newly-formed surfaces were implemented to experimentally determine the as-welded residual stresses and their variation after milling a local region. Finite element analysis was performed to highlight the difference in stress distribution after welding and milling. In addition, the stress variation after local material removal and whole layer removal was discussed with the numerical simulation.

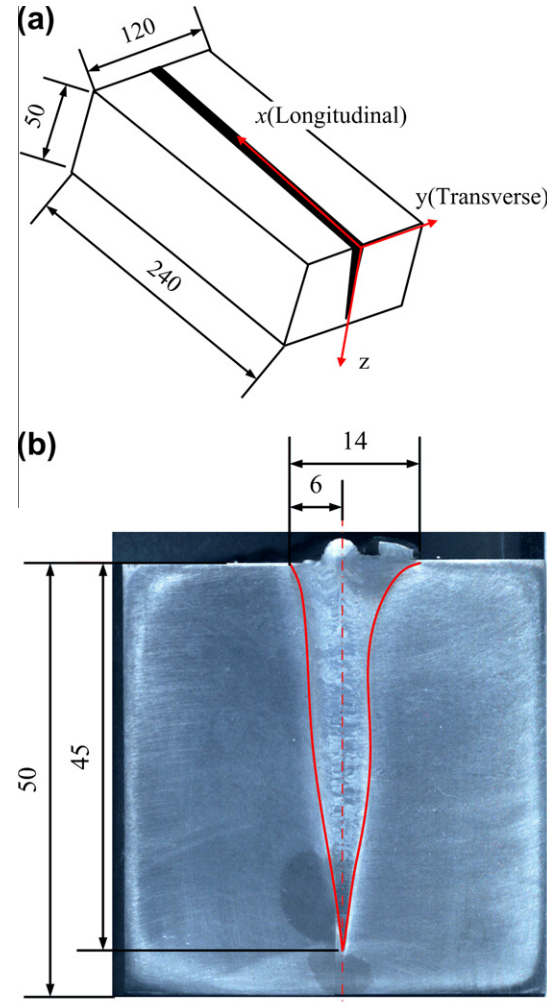

Fig. 1. (a) Dimensions of the welded plate, and (b) Fusion zone profile.

2. Experimental procedure

2.1. Welding experiment

Autogeneous bead-on-plate and single pass EBW of TA15 (Ti–6Al–2Zr–1Mo–1V) titanium alloy plates were performed using CV65M EBW system, operating in vacuum at 3.0×10^{-2} Pa. The electron beam was consistently focused on the top surface with 150 kV welding voltage, 70 mA welding current and a welding speed of 5 mm/s. In our research, five experiments were carried out on the 50 mm thick plates to investigate the proper welding parameter, effects of material removal on residual stress, effects of heat treatment on welding residual stress, the profile of fusion zone and the microstructure of the welding zone, respectively. Only one of the welded specimens was milled to investigate the effect of material removal on the welding residual stress and will be introduced in this paper.

The dimensions of the plate investigated in the present study are 240 mm × 120 mm × 50 mm, as shown in Fig. 1a. The profile of the welded joint is shown in Fig. 1b.

2.2. Residual stress measurement and materials removal with end-milling

After welding, the hole drilling method was employed to measure the surface residual stress. A strain gauge rosette of type BE120-2CA-K was attached on the carefully polished surface and a hole of diameter 2.0 mm was drilled using a drilling tool in the center of the strain gauge rosette, YJ-18 type static strainer was used to record the release strain. This kind of stress measurement method was also used by Barroso et al. [11] to evaluate the welding residual stresses.

The surface residual stresses were measured for the four welded specimen among the five experiments, as shown in Ref. [12]. Only one of the welded specimens was used to investigate the effect of material removal on the welding residual stress. Because the titanium block of such thickness is expensive and the machining is also costly, the local material removal method was used to avoid fully destroying the block and the materials left can be used for other purposes. In addition, the finite element method can be used to investigate the residual stress modification after the whole layer removal when it is verified by the experiments of local material removal. It is economic and effective to investigate the welding phenomena by means of large number of finite element simulations integrating with a few experiments.

Based on the above ideas, the local materials removal method was selected during milling experiments and the effects of the whole layer removal on residual stress were investigated by the finite element method.

The milling process was used to remove local regions from the top and the bottom of the welded plate alternatively until 10 mm material left in the thickness. An ordinary vertical milling machine with a taper shank end milling cutter was used to perform to milling process. The diameter of the cutter is 18 mm. The coolant was adopted to prevent the thermal stress during milling process.

The stresses were measured on newly-formed surface using hole-drilling method when 4 mm thick local material had been