Materials and Design 63 (2014) 519–530

Contents lists available at ScienceDirect

Materials and Design

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

A comparative study on welding temperature fields, residual stress distributions and deformations induced by laser beam welding and CO_2 gas arc welding

Jiamin Sun, Xiaozhan Liu, Yangang Tong, Dean Deng *

College of Materials Science and Engineering, Chongqing University, No. 174 Shazhengjie, Shapingba, Chongqing 400045, China

ARTICLE INFO

Article history:
Received 22 April 2014
Accepted 24 June 2014
Available online 1 July 2014

Keywords:
Thin plate
Finite element method
Numerical simulation
Geometrical nonlinearity
Welding distortion

ABSTRACT

Welding-induced distortion in thin-plate structure is a serious problem which not only hinders the assembling process but also negatively affects the performance of product. Therefore, how to control welding deformation is a key issue both at design stage and at manufacturing stage. During welding process, there are a number of factors which can significantly affect manufacturing accuracy. Among these factors, the heat input is one of the largest contributors to the final deformation. Generally, when laser beam welding (LBW) is used to join parts the total heat input is far less than that used in a conventional welding method such as gas metal arc welding, so it is expected that LBW can significantly reduce welding distortion especially for thin-plate joints. As a fundamental research, we investigated the welding deformations in low carbon steel thin-plate joints induced by LBW and CO_2 gas arc welding by means of both numerical simulation technology and experimental method in the current study. Based on the experimental measurements and simulation results, we quantitatively compared the welding deformation as well as residual stress induced by LBW and those due to CO_2 gas arc welding. The results indicate that the out-of-plane deformation of thin-plate joint can be largely reduced if CO_2 gas arc welding method is replaced by LBW. Moreover, the numerical results indicate that the residual stresses induced by LBW are superior to those produced by CO_2 gas arc welding both in distribution and in magnitude.

1. Introduction

In automobile industry, it is a current trend in design to adopt thin-plate steel components to achieve weight reduction and fuel savings. Meanwhile, the designers have been forced to use thinner steel or light alloy structures to reduce topside weight for improving fuel economy, and enhance mission capability in shipbuilding industry [1]. Fusion welding technology has been extensively applied to assemble parts both in automobile and in shipbuilding industries owing to its high productivity and flexibility for design. However, when a thin-plate structure is welded by traditional fusion welding processes such as gas metal arc welding (GMAW) and shielded metal arc welding (SMAW), it can be foreseen that welding-induced deformation will be a serious problem because of the relatively small stiffness. If the heat input cannot be reasonably controlled, significant deformation even buckling distortion is apt to occur especially in the welded structure whose thickness is only a few millimeters [2]. In many cases, additional costs and schedule delay are incurred from straightening welding distortion. On the other hand, increasingly, the design of engineering components and structure relies on the achievement of small tolerance. Therefore, controlling welding-induced deformation has become of critical importance.

Welding deformation can be controlled both at design stage and at manufacturing stage [3]. In principle, distortion in a welded structure can be minimized through designing reasonable positions for the joints and/or by adjusting the thickness of plate at the design stage. Meanwhile, controlling heat input and adopting appropriate assembling sequence can reduce the welding-induced deformation to some extent at the manufacturing stage. Recently, the welding processes with high energy density such as laser beam welding [4] and laser-arc hybrid welding [5] have been introduced into manufacturing industry for both improving productivity and reducing welding distortion.

LBW has many advantages over conventional fusion welding methods such as low heat input per unit length, small heat affected zone, high speed and non-contact welding, deep penetration, effective integration with industrial robots and the capability of joining materials by single side access [3,4,6]. On the other hand, LBW involves several complex phenomena like the formation of a keyhole, ionization and vaporization of material, circulation of molten

* Corresponding author. Tel.: +86 23 6512 2079; fax: +86 2365127340.
E-mail address: deandeng@cqu.edu.cn (D. Deng).

http://dx.doi.org/10.1016/j.matdes.2014.06.057
0261-3069/

metal within the weld pool due to buoyancy and Marangoni forces [7], solidification at the liquid–solid interface, and so on. Thus, it is not easy to simulate LBW process with considering all the above factors through using a single numerical model. However, various simplifications are admissible in numerical simulation of welding process with minimal loss in accuracy [8]. Han et al. [9] investigated numerically the temperature field in a thin-plate stainless steel AISI304 joint caused by LBW. Their results suggested that the temperature grads are very large in the fusion zone and its vicinity. Daniel and his co-workers [10,11] studied the distortion and residual stress distribution induced by LBW in a thin-plate AA6065T4 joint by means of both numerical simulation technology and experimental method. Their research indicated that the simulated results matched the experimental measurements well.

As for welding deformation of thin-plate joint induced by traditional arc welding process, Wang and his co-workers [12] studied the characteristics of welding distortion in a bead-on-plate weld performed by metal inert gas welding process. Deng et al. [13] investigated the influence of heat input on welding distortion in a thin-plate joint induced by CO_2 gas arc welding by means of both thermo-elastic–plastic FEM and experimental method. Recently, several experimental mock-ups and numerical models have been used to study welding residual stresses and deformations in thin-plate joints, however, very limited literatures have quantitatively compared the deformation and residual stress distribution induced by LBW with those induced by a traditional fusion welding method such as CO_2 gas arc welding in a thin-plate joint or welded structure, especially in a weldment whose thickness is less than 3.0 mm [14]. Theoretically, it is easy to qualitatively distinguish the welding distortion induced by LBW and that due to CO_2 gas arc welding in a given joint. However, to help choosing a reasonable welding method with balancing manufacturing cost and dimensional accuracy, it is necessary to quantitatively clarify the differences between the welding distortion and residual stress caused by LBW and those produced by CO_2 gas arc welding. In addition, the comparison can provide fundamental knowledge for welding engineers.

As a fundamental research, the objective of the present study was to compare the welding deformation and the residual stress distribution induced by LBW with those due to CO_2 gas arc welding in a thin plate joint. First, experiments were carried out to measure the transverse shrinkages and the deflection (out-of-plane deformation) induced by LBW and CO_2 gas arc welding. Then, based on the commercial software MSC.Marc code [15], a Thermo-elastic-plastic finite element method with considering moving heat source, material nonlinearity and geometrical nonlinearity was developed to simulate welding temperature field, residual stress distributions and distortions for thin-plate joints. In the developed computational approach, we made certain efforts to design moving heat sources and to select their corresponding parameters for modeling the heat inputs of both LBW and CO_2 gas arc welding. Moreover, we clarified the difference between the welding deformation predicted by large deformation theory and that computed by small deformation theory in a low carbon steel thin-plate joint performed by LBW. Finally, we quantitatively compared the welding deformation and the residual stress distribution induced by LBW and those caused by CO_2 gas arc welding in thin-plate joints with 2.3 mm thickness. It is hoped that the present study will provide both designers and practicing engineers with a method to control welding distortion.

2. Experimental procedure

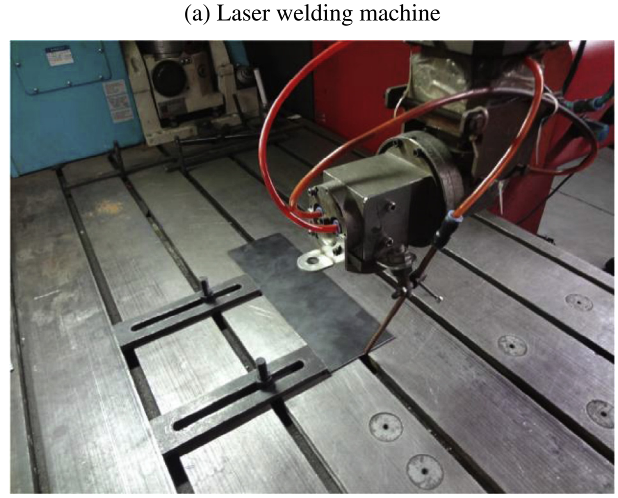
To compare the welding deformations induced by LBW and CO_2 gas arc welding, we carried out experiments to measure the deformations in two thin-plate joints. The base metal is low carbon steel (Q235), and its chemical components are shown in Table 1. The dimension of each weld specimen is 300 mm × 100 mm × 2.3 mm. All of the specimens were welded without any external restraint. In the LBW, the laser beam was used to only melt the plate, and no filler metal was added to the plate. The laser beam welding system used in the current study is shown in Fig. 1, and the welding parameters used in the experiment are summarized in Table 2. The joint type performed by CO_2 gas arc welding is a bead-on joint, and the wire is YGW16 with 1.2 mm diameter. The CO_2 gas arc welding was performed by a Panasonic TAWERS TA-1400 arc welding robot as shown in Fig. 2, and the welding conditions are shown in Table 3.

To measure the transverse shrinkage, six holes were drilled in each specimen, and their locations are shown in Fig. 3. Here, we take hole *a* and hole *b* (location 1) which are a pair as an example to explain how to measure the transverse shrinkages on both the top surface and the bottom surface. Before welding, the distances between hole *a* and hole *b* on the top surface and the bottom

Table 1
Chemical composition of Q235 (low carbon steel).

Material	C	Si	Mn	S	P	Cr	Fe
Q235	0.17	0.26	0.46	0.007	0.009	0.02	Bal.

(a) Laser welding machine



(b) Weld specimen and torch of laser machine

Fig. 1. Laser beam welding system. (a) Laser welding machine. (b) Before welding.