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应用三维激光扫描法测量板材的焊接变形

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摘　要: 提出一种应用非接触式三维激光扫描仪测量对接试样焊接变形的新方法. 在板材上钻孔并放置钢珠用于精确定位，焊接前后应用激光扫描仪对板材和钢珠进行扫描，输出相应的点云文件. 应用逆向工程软件 Imageware 对构件焊接前后的点云文件进行分析和处理，最终得到钢珠球心在焊板上的垂直距离的点的三维坐标. 结果表明，该方法解决了由于高温带来的测量点定位困难的问题，可精确计算焊接变形过程中的角变形、弯曲变形等，对于深入研究焊接变形的机理、实现焊接变形的精确控制具有重要意义.

关键词: 焊接变形; 对接试样; 三维激光扫描; 角变形; 弯曲变形
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0　序　　言

焊接作为一种高效的连接方法广泛应用于船舶、桥梁、建筑、航空等制造行业，然而，由于焊接过程本身的复杂性，使得焊接结构的残余变形成为焊接领域一个极其棘手的问题[1,2]. 焊接过程中，材料的局部不均匀受热、板厚方向的热梯度和材料的局部非协调塑性应变是产生各种焊接变形的根本原因[3,4]. 焊接变形的存在不仅可能造成焊接结构形状的改变，而且还会降低构件的承载能力和力学性能，因此如何精确控制和调整焊接变形变得十分重要[5,6].

对焊接变形进行快速、准确的测量，是评价控制和调整焊接变形效果的有效手段. 传统焊接变形的测量方法一般包括两种: 动态测量和静态测量. 动态测量方法一般是利用位移传感器进行接触式的变形测量，可实时测量焊件某点的动态位移，但是由于受高精度传感器的测量量程限制，所以很难用于大变形量的测量，而且对于薄板焊接变形的测量存在局限性. 静态测量一般采用尺寸测量方法，应用于尺寸比较小的构件，对于尺寸较大构件的焊接变形测量难度较大，而且不能实现实时测量[7-9]. 文中研究的目的在于解决三坐标测量机测量焊接变形时存在的缺陷，通过在焊板上打浅盲孔放置钢珠的方式进行测量点的精确定位，应用非接触式三维激光扫描仪测量板材焊接变形.

1　试验方法

焊接试验以 45 钢薄板研究对象，应用焊接机器人进行 CO_2 气体保护焊，制作焊接对接试样，板材尺寸为 400 mm×200 mm×3 mm.

1.1　划线钻孔

应用刻针工具在板材相互垂直的方向上依据一定的刻度划出平行等间距的直线，布局如图 1 所示. 选择了板材上平均分布的 50 个点进行测量，如图 1 中圆圈位置所示. 在 50 个测量点的位置钻浅盲孔，孔的直径和深度约为 1 mm.

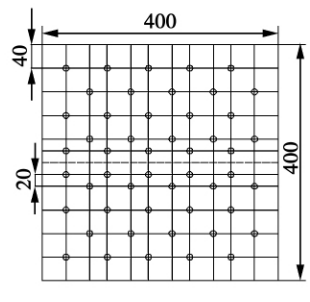

图 1　板材上钻孔的分布(mm)
Fig. 1　Holes distribution on welding plate

1.2　准备工作

钻孔完毕后，将两块板材进行点固焊. 将钢珠平稳地放置在盲孔的位置，如图 2 所示. 然后使用

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显像剂对板材和钢珠进行喷涂,显像剂的作用是降低钢珠及板材的亮度,提高扫描效率. 喷涂完毕后在板材上放置贴片做标识点,用于激光扫描仪的定位,如图3所示.

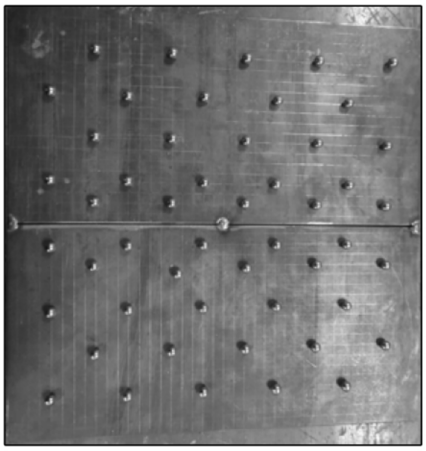


图2 板材放置钢珠的形貌

Fig. 2 Photograph of plate with steel balls

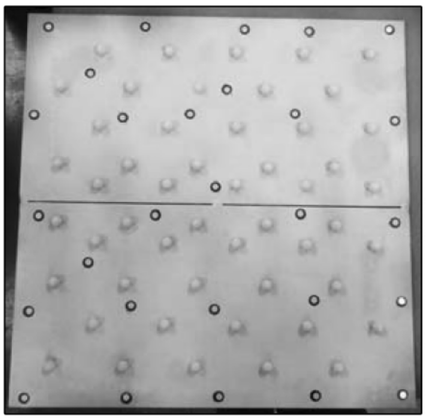


图3 喷涂显像剂及其贴标识点

Fig. 3 Spurted component with adurol and place of targets

1.3 扫描测量

将三维激光扫描仪与电脑相连,实时观测点云文件扫描的过程及其板材和钢珠的点云文件的输出. 扫描时保持扫描仪的平稳,对焊板和钢珠的每个位置匀速扫描,便于获得完整的点云文件,用于后续的计算工作. 图4为应用三维激光扫描仪进行板材和钢珠的扫描测量.

1.4 焊接试验

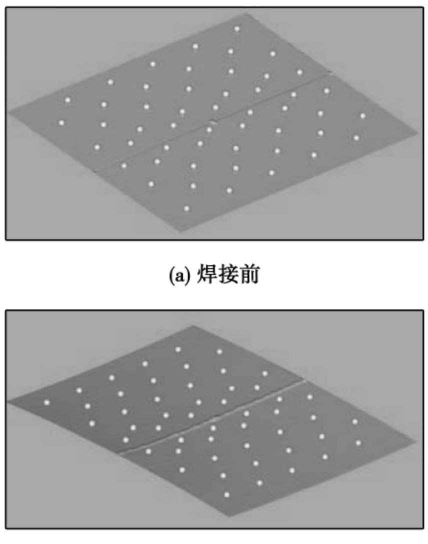
扫描工作结束后,将钢珠取下,清除掉显像剂和标识点贴片,进行焊接试验. 应用焊接机器人进行 CO_2 气体保护焊,焊接速度为 4 mm/s,电源电压为 22 V,电流为 110 A.

图4 应用三维激光扫描仪对构件进行扫描

Fig. 4 Scanning component with three dimensional laser scanner

1.5 焊接后的扫描工作

重复步骤1.2和1.3,对焊接试验后的板材和钢珠再次进行扫描,得到板材焊接变形后的点云文件,图5为构件焊接前后的点云图. 图5a为焊接前构件的点云图,图5b为焊接后构件的点云图.



(a) 焊接前

(b) 焊接后

图5 焊接前后构件的点云图

Fig. 5 Point clouds of component before and after welding

2 结果与分析

应用三维激光扫描仪对板材和钢珠进行扫描后,得到的仅仅是构件整体的点云文件,如何获得板材上测量点的三维坐标值是需要解决的关键问题. 图6为钢珠在焊板上变形前后的位置示意图,图6a

为钢珠焊接前示意图，图 6b 为钢珠焊接后示意图. 需要获得的是测量点焊接前的三维坐标 $A_1(x_1, y_1, z_1)$ 和焊接后的三维坐标 $A_2(x_2, y_2, z_2)$. 然而，直接求得测量点焊接前后的坐标值比较困难，而钢珠球心 O 点坐标的变化和测量点的坐标变化并不一致，因此，首先求出钢珠球心的三维坐标 O_1 和 O_2，然后再计算出球心在板材上的垂直距离的点 A_1 和 A_2 的坐标，即测量点的三维坐标值. 文中研究应用逆向工程软件 Imageware 获得测量点焊接前后的三维坐标，用于计算板材的焊接变形.

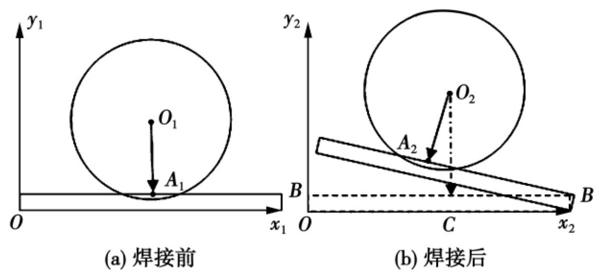


图 6　焊接前后钢珠位置变化示意图

Fig. 6　Position of steel ball before and after welding

2.1　坐标变换

测量点的位移计算是由焊接后测量点的三维坐标与焊接前测量点的三维坐标之差得到. 三维激光扫描仪获得的焊接前和焊接后的点云文件所在的坐标系并不是统一的坐标系. 因此，需要将两个坐标系通过坐标变换统一到相同的坐标系下，才能对测量点的位移进行计算. 焊接前后将板材放于同一水平面内进行扫描，以此扫描平面建立参考坐标系. 首先，将板材所在的面与水平面对齐，然后再对齐板材两条相互垂直的边与水平面内建立的两条相互垂直的线对齐，即作为坐标系的 x 轴和 y 轴.

2.2　板材和钢珠点云的分离

坐标系统一后，需要将板材和钢珠的点云文件独立地分离出来，才能计算钢珠球心的坐标以及球心在板材上垂直距离点的坐标. 利用选择点工具将每个钢珠的点云从板材中分离出来，如图 7 所示.

2.3　板材和钢珠点云的曲面拟合

板材和钢珠的点云分离后，利用拟合均匀面选项将板材拟合成曲面，利用拟合球体选项将钢珠拟合成球体.

2.4　测量点坐标的获得

最后，利用测量距离选项，将每个球心坐标投影到板材上，即球心到曲面的距离，得到同一位置测量点的三维坐标值.

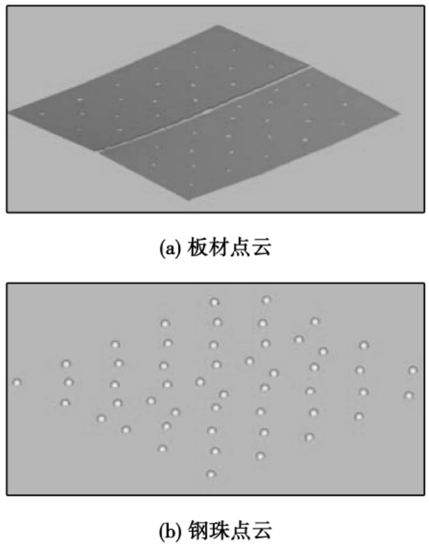


图 7　分离后板材和钢珠的点云图

Fig. 7　Point clouds of welding plate and steel balls

2.5　焊接变形的计算

得到焊接前后各个测量点的三维坐标值以后，将焊接前后的测量点的坐标进行差运算，得到各个测量点的位移，即可计算板材的角变形及其弯曲变形等数据. 图 8 为计算得到的角变形和弯曲变形图，其中图 8a 为垂直焊缝方向的角变形，图 8b 为沿

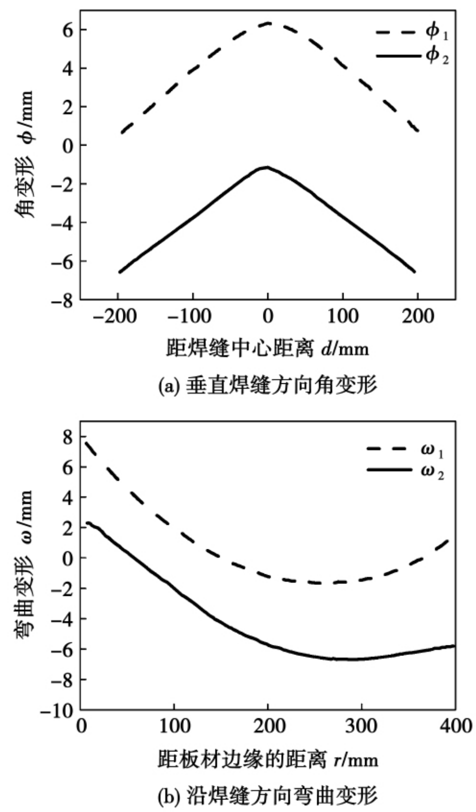


图 8　板材角变形及其弯曲变形图

Fig. 8　Angular and bending deformation of plate

焊缝方向弯曲变形. ϕ_1,ϕ_2 为垂直焊缝方向不同位置的角变形,ω_1,ω_2 为沿焊缝方向不同位置的弯曲变形.

3 结 论

(1) 应用三维激光扫描仪进行测量,利用钢珠进行精确定位,更加准确和快速的获得焊接前后同一测量点的三维坐标,从而可以有效地计算焊接位移和变形.

(2) 该方法克服了传统接触式测量方法的不能精确重复定位的局限性,解决了应用三维激光扫描仪测量时用于定位的标识点(一般为贴标识片的方式)不能耐高温的缺点,为焊接变形的测量和焊接前后同一位置测量点的精确重复定位提供了一种有效的手段.

参考文献:

[1] Wang R, Zhang J X, Hisashi S, *et al*. Study of welding inherent deformations in thin plates based on finite element analysis using interactive substructure method [J]. Materials and Design, 2009, 30: 3474 – 3481.

[2] 刘 川, 王 蕊, 张建勋. 堆焊角变形动态过程试验与数值分析 [J]. 西安交通大学学报, 2007, 41(9): 1017 – 1021.
Liu Chuan, Wang Rui, Zhang Jianxun. Numerical simulation and testing of dynamic welding angular distortion for overlayer [J]. Journal of Xi'an Jiao Tong University, 2007, 41(9): 1017 – 1021.

[3] 李晓延, 巩水利, 关 桥, 等. 大厚度钛合金结构电子束焊接制造基础研究 [J]. 焊接学报, 2010, 31(2): 107 – 112.
Li Xiaoyan, Gong Shuili, Guan Qiao, *et al*. Fundamental research on electron beam welding of heavy section titanium alloy structures [J]. Transactions of the China Welding Institution, 2010, 31(2): 107 – 112.

[4] 汪建华, 陆 皓. 焊接残余应力形成机制与消除原理若干问题的讨论 [J]. 焊接学报, 2002, 23(3): 75 – 79.
Wang Jianhua, Lu Hao. Some discussions on principle of causing and relieving welding residual stress [J]. Transactions of the China Welding Institution, 2002, 23(3): 75 – 79.

[5] 田锡唐. 焊接结构 [M]. 北京: 机械工业出版社, 1997.

[6] 中国机械工程学会焊接学会, 焊接手册(第三卷) [M]. 2 版, 北京: 机械工业出版社, 2001.

[7] 李 玲. 焊接变形光学测量技术研究 [J]. 光学技术, 2010, 36(6): 825 – 828.
Li Ling. Study on the rapid three-dimension optical measurement for welding deformation of sheet structure [J]. Optical Technique, 2010, 36(6): 825 – 828.

[8] 阮星谊, 包晔峰, 石忠贤. 焊接变形测量方法 [J]. 电焊机, 2005, 35(5): 55 – 57.
Ruan Xingyi, Bao Yefeng, Shi Zhongxian. Measuring methods of welding deformation [J]. Electric Welding Machine, 2005, 35(5): 55 – 57.

[9] 蔡志鹏, 鹿安理, 施光凯, 等. 焊接变形实时测量系统的建立与应用 [J]. 机械工程学报, 2001, 37(2): 63 – 65.
Cai Zhipeng, Lu Anli, Shi Guangkai, *et al*. Establishment and application of a welding real time displacement surveying system [J]. Chinese Journal of Mechanical Engineering, 2001, 37(2): 63 – 65.

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会 讯

中国机械工程学会第十次全国会员代表大会在武汉隆重召开

2011 年 11 月 15 日,中国机械工程学会第十次全国会员代表大会在湖北省武汉市隆重召开。全国人大常委会副委员长、第九届理事会理事长路甬祥,候任理事长、中国工程院院长周济,第九届理事会常务副理事长宋天虎,副理事长王玉明、包起帆、卢秉恒、李忠海、李培根、李新亚,与来自中国机械工程学会各专业分会、各省区市机械工程学会及港澳台地区的会员代表和列席代表共计 400 余人,齐聚华中科技大学管理学院学术报告厅,以高度的责任感认真履行代表的职责,圆满完成了大会的全部议程。会议选举产生了中国机械工程学会第十届理事会和第一届监事会,并召开了中国机械工程学会第十届理事会第一次会议和中国机械工程学会第一届监事会第一次会议。

经全体到会正式代表投票,大会选举出了新一届理事会理事和第一届监事会监事,中国机械工程学会第十届理事会由 175 名理事组成,第一届监事会由 5 名监事组成。在随后举行的中国机械工程学会第十届理事会第一次会议上,经全体到会理事投票,中国工程院院长周济当选中国机械工程学会第十届理事会理事长,卢秉恒、包起帆、任洪斌、李培根、李新亚、杨海成、张彦敏、陈钢、林忠钦、钟志华、郭东明、蔡惟慈、谭建荣当选副理事长,张彦敏兼任秘书长。经投票产生的还有第十届理事会的常务理事会,本届常务理事会由 55 名常务理事组成。第一届监事会全体监事列席了第十届理事会第一次会议。在中国机械工程学会第一届监事会第一次会议上,宋天虎当选首届监事会监事长。 中国机械工程学会秘书处供稿

MAIN TOPICS, ABSTRACTS & KEY WORDS

Prediction of weld appearance of electron beam deep penetration welding based on visual sensing ZHANG Binggang[1], SHI Mingxiao[2], CHEN Guoqing[1], FENG Jicai[1] (1. State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China; 2. State Key Laboratory of Gansu Advanced Non-ferrous Metal Materials, Lanzhou University of Technology, Lanzhou 730050, China). p 1 – 4, 36

Abstract: Basing on visual sensing method, the electron beam welding molten pool image of titanium alloy was obtained. The binary morphological image processing algorithm was used to process the molten pool image for getting the molten pool edge, moreover, the molten pool width was obtained by using a suite of processing programs for molten pool extraction. The correspondence relationship between the fluctuation of molten pool width and weld appearance is found, i. e. the weld appearance is poor when the fluctuation of molten pool width is relatively large, but the weld appearance is good when the fluctuation of molten pool width is relatively small. Based on analysis, the coefficient of variation CV was proposed as characterization to describe the weld appearance. The results show that the developed image processing algorithms are reliable, and the detected errors are less than 0.1 mm, at the same time the whole extraction process of molten pool width only needs approximately 30 milliseconds, which could meet the needs of real time detection. The coefficient of variation can reflect the quality of weld appearance and it can be used as a parameter to control the weld appearance.

Key words: visual sensing; electron beam welding; binary morphology; weld appearance; characterization

Analysis of characteristics of plasma image during high-power disk laser welding GAO Xiangdong[1], LV Weixing[1], YOU Deyong[1], KATAYAMA Seiji[2] (1. Faculty of Mechanical and Electrical Engineering, Guangdong University of Technology, Guangzhou 510006, China; 2. Joining and Welding Research Institute, Osaka University, Osaka 567-0047, Japan). p 5 – 8

Abstract: A new approach for detecting and analyzing the deep welding quality in high-power disk laser welding based upon the plasma plume images is presented. During the laser butt-joint welding of 304 austenitic stainless steel plate with a high power 10 kW disk laser, an ultraviolet and visual sensitive high-speed video camera was used to capture the dynamic images of the plasma plume. The area and height of a plasma image were calculated as the characteristic parameters of plasma image using the image processing techniques. The weld bead width was defined as the parameter reflecting the stability of welding process. Moreover, the variation in the weld bead width and the plasma images in the welding process were monitored to research the correlation between the characteristics of the plasma image and the welding stability. To obtain the statistics of the characteristic parameters of plasma images that reflect the welding stability, the average and the percentage with different threshold values about the fluctuation of consecutive frames images for the plasma area and height at different parts of weld bead were studied. The actual laser welding experimental results showed that the stability of a high power disk laser welding process could be monitored and estimated by the defined characteristic parameters of the plasma images.

Key words: high-power disk laser; plasma plume image; welding process stability; 304 austenitic stainless steel

A method to measure welding deformation of plate by three dimensional laser scanner HE Hongwen, ZHAO Haiyan, NIU Wenchong, WANG Peng (Key Laboratory for Advanced Materials Processing Technology, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China). p 9 – 12

Abstract: A new method was proposed to measure the welding deformatioin of the butt-welding joints by using the non-contact three-dimensional laser scanner. The steel balls were placed onto the drilled holes for the purpose of accurate positioning. Before and after welding experiment, the butt-welding joints and steel ball were scanned by the laser scanner to gain the corresponding point cloud files. After being analyzed by the imageware software, the final three dimensional coordinates of the steel balls on surface of the plate would be obtained. Results indicated that this method could solve the difficult positioning problem because of high temperature, which might calculate the angular distortion and deflection deformation during welding process. It also contributed to understand the mechanism of welding deformation and realize the accurate positioning.

Key words: welding deformation; butt-welding sample; three dimensional laser scan; angular deformation; bending deformation

Mechanism of cold welding cracks in 30CrMnSi steel joints welded by TIG method YANG Jianguo, HUANG Luyong, ZHANG Yong, FANG Hongyuan (State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China). p 13 – 16

Abstract: As a kind of the medium-carbon quenching and tempering steel (MCQTT), 30CrMoSi has been used widely in some industrial fields. However, just like some MCQTT, this steel faces such problems as cold cracking in the welded joints. In this research, the fracture and microstructure of the joints of 30CrMoSi steel welded by TIG method were studied by scanning electron microscopy (SEM) and optical microscopy (OM), respectively. More attention has been paid to the mechanism of the cold welding crack in 30CrMoSi steel. The results show that the hot welding cracks formed at high temperature are prone to inducing cold welding cracks. The potential method to control the cold welding crack in 30CrMoSi steel was discussed as well.

Key words: 30CrMoSi steel; TIG; cold welding crack; hot welding crack

Fuzzy-PI algorithm of load system of friction welding ma-