数值和试验分析同步跟踪冷气热沉方法控制激光焊接 SUS301L 薄板过程中的变形及机制澄清

刘祖国[1]，金湘中[2,*]

[1]湖南大学 汽车车身先进设计制造国家重点实验室，长沙 410082

[2]湖南大学 激光研究所，长沙 410082

*jxz2014@ hnu.edu.cn

摘要：薄板试样的焊接诱导屈曲变形是不可避免的，通过焊后校正和焊中调控不仅增加成本还浪费时间。同时试样变形会严重影响整个部件的装配精度，是一个急需解决的科学问题。本文提出了一种利用涡流管压缩空气制冷与激光源主动控制焊接冷却过程的焊接变形。与常规焊接和其他冷却方式相比，涡流管压缩空气制冷的的方法比较安全，成本低且易于实现。采用冷源辅助作为工艺处理来减轻焊接致屈曲，并用固有应变理论阐明了其机理。建立了一个热弹塑性顺序耦合模型来检测整个焊接过程中的热力学响应。利用三坐标测量了平面外焊接失真结果验证了仿真模型的准确性。然后，在热源尾部施加冷源，建立数值模型实现同步热沉处理。此外，还讨论了热沉强度和位置对减轻焊接致屈曲的影响。热沉位置对减轻焊接致屈曲有决定性的影响，热沉距离越大，不仅没有消除变形，反而增加了变形。结果表明，当热沉强度为 200ml，距离为 d=5mm 时，等效残余应力由 754.78MPa 降低到 693.69MPa，下降了 8.09%，焊接诱导最大变形从 3.51mm 降低到 2.4mm，下降了 31.62%。在冷却过程中，冷源的施加不仅降低了焊缝附近母材的温度场，还使熔池尾部的典型彗星特征消失，变成了一个扁平的温度轮廓，这将有效的改善焊缝区的温度梯度。热沉与激光之间的距离减小时，基材的温升显著被降低，减少了来自基材的自约束，这导致焊缝材料纵向拉伸塑性应变减弱，以减少焊接固有应变和肌腱力。

关键词：激光焊接；同步跟踪冷气热沉；固有应变；肌腱力；焊接变形；残余应力

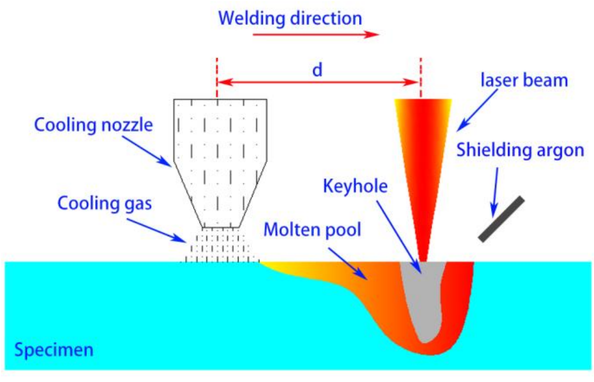

图 1 热沉辅助激光焊接的传热模型。

参考文献

[1] Alizadeh-Sh M, Falsafi F, Masoumi M, Marashi SPH, Pouranvari M. Laser spot welding of AISI 304L: metallurgical and mechanical properties, Ironmak. Steelmak. 2014,41 (3):161-165.

[2] Huang H, Tsutsumi S, Wang JD, Li LQ, Murakawa H. High performance computation of residual stress and distortion in laser welded 301L stainless sheets. Finite Elem Anal Des. 2017,135:1-10.

[3] Li JZ, Sun QJ, Liu YB, Zhen ZY, Sun Q, Feng JC, Melt flow and microstructural characteristics in beam oscillation superimposed laser welding of 304 stainless steel, J Manuf Process. 2020, 50:629-637.

[4] Huang H, Wang JD, Li LQ, Ma NS. Prediction of laser welding induced deformation in thin sheets by efficient numerical modeling, J. Mater. Process. Technol. 2016,227: 117-128.

[5]Baruah M, `Bag S. Influence of heat input in microwelding of titanium alloy by micro plasma arc, J Mater Process Technol. 2016, 231: 100-112.

[6] James MN. Residual stress influences on structural reliability. Eng Failure Anal. 2011;18(8):1909-1920.

[7] Zerbst U. Integrity of thin-walled light-weight structures - concepts and applications foreword, Eng Fract Mech. 2009, 76(1): 1-2.

[8] Zhan XH, Wu YF, Kang Y, Liu X, Chen, XD. Simulated and experimental studies of laser-MIG hybrid welding for plate-pipe dissimilar steel, Int J Adv Manuf Tech. 2019,101(5-8): 1611-1622.

[9] Deng D, Zhou YJ, Bi T, Liu XZ. Experimental and numerical investigations of welding distortion induced by CO2 gas arc welding in thin-plate bead-on joints, Mater Design. 2013, 52: 720-729.

[10] Tolle F, Gumenyuk A, Backhaus A, Olschok S, Rethmeier M, Reisgen U. Welding residual stress reduction by scanning of a defocused beam, J Mater Process Technol. 2012, 212(1): 19-26.

[11] Zhang W, Fu H, Fan JK, Li RJ, Xu HY, Liu FJ, Qi BJ. Influence of multi-beam preheating temperature and stress on the buckling distortion in electron beam welding, Mater Design. 2018,139: 439-446.

[12] Xu HL, Guo XY, Lei YP, Lin J, Fu HG, Xiao RS, Huang T, Shin Y. Welding deformation of ultra-thin 316 stainless steel plate using pulsed laser welding process, Opt Laser Technol. 2019,119: 1-8.

[13] Benyounis KY, Olabi AG, Hashmi MSJ. Effect of laser welding parameters on the heat input and weld-bead profile, J Mater Process Technol. 2005, 164: 978-985.

[14] Islam M, Buijk A, Rais-Rohani M, Motoyama K. Simulation-based numerical optimization of arc welding process for reduced distortion in welded structures, Finite Elem Anal Des. 2014, 84: 54-64.

[15] Jiang P, Wang CC, Zhou Q, Shao XY, Shu LS, Li XB. Optimization of laser welding process parameters of stainless steel 316L using FEM, Kriging and NSGA-II, Adv Eng Softw. 2016, 99:147-160.

[16] Prabakaran MP, Kannan GR. Optimization of laser welding process parameters in dissimilar joint of stainless steel AISI316/AISI1018 low carbon steel to attain the maximum level of mechanical properties through PWHT, Opt Laser Technol. 2019, 112:314-322.

[17] Mehrpouya M, Gisario A, Huang H, Rahimzadeh A, Elahinia M. Numerical study for prediction of optimum operational parameters in laser welding of NiTi alloy, Opt Laser Technol. 2019, 118: 159-169.

[18] Zhan XH, Liu JT, Chen JC, Peng QY, Wei YH, Zhao YQ. Parameter optimization of multi-pass multi-layer MIG welded joint for invar alloy, Int J Adv Manuf Tech. 2016, 87(1-4): 601-613.

[19] Zhou Q, Wang Y, Choi SK, Cao LC, Gao ZM. Robust optimization for reducing welding-induced angular distortion in fiber laser keyhole welding under process parameter uncertainty, Appl Therm Eng. 2018, 129: 893-906.

[20] Rong YM, Lei T, Xu JJ, Huang Y, Wang CM. Residual stress modelling in laser welding marine steel EH36 considering a thermodynamics-based solid phase transformation, Int J Mech Sci. 2018,146: 180-190.

[21] Xu JJ, Chen CM, Lei T, Wang WB, Rong YM. Inhomogeneous thermal-mechanical analysis of 316L butt joint in laser welding, Opt Laser Technol. 2019, 115: 71-80.

[22] Deng D, Murakawa H, Liang W. Numerical simulation of welding distortion in large structures. Comput Method Appl M. 2007, 196(45-48):4613-4627.

[23] Han Q, Kim D, Kim D, Lee H, Kim N. Laser pulsed welding in thin sheets of Zircaloy-4, J Mater Process Tech. 2012, 212(5): 1116-1122.

[24] Tsirkas SA, Papanikos P, Kermanidis T. Numerical simulation of the laser welding process in butt-joint specimens. J Mater Process Technol. 2003, 134 (1), 59–69.

[25] Zain-ul-Abdein M, Nelias D, Jullien JF, Deloison D. Prediction of laser beam welding induced distortions and residual stresses by numerical simulation for aeronautic application. J Mater Process Technol. 2009, 209 (6), 2907–2917.
[26] Chen GQ, Shu X, Liu JP, Zhang BG, Feng JC. A new method for distortion calculations in additive manufacturing: Contact analysis between a workpiece and clamps, Int J Mech Sci. 2020, 171: 1-10.
[27] Ma NS, Huang H, Murakawa H. Effect of jig constraint position and pitch on welding deformation, J Mater Process Technol. 2015, 221:154-162.
[28] Kumar B, Bag S. Phase transformation effect in distortion and residual stress of thin-sheet laser welded Ti-alloy, Opt Laser Eng. 2019, 122: 209-224.
[29] Huang CC, Chuang TH. Effects of post-weld heat treatments on the residual stress and mechanical properties of laser beam welded sae 4130 steel plates. Mater Manuf Processes. 1997;12(5):779-797.
[30] Marques M, Ramasamy A, Batista A, Nobre J, Loureiro A. Effect of heat treatment on microstructure and residual stress fields of a weld multilayer austenitic steel clad, J. Mater. Process. Technol. 222 (2015) 52-60.
[31] Liu C, Yan Y, Cheng XH, Wang CJ, Zhao Y. Residual stress in a restrained specimen processed by post-weld ultrasonic impact treatment, Sci Technol Weld Joi. 2019,24(3):193-199.
[32] Guan Q, Guo DL, Li CQ. Low stress non-distortion (LSND) welding-a new technique for thin materials. Transactions of the China Welding Institution. 1990,11(4): 160.
[33] Li J, Guan Q, Shi YW,Guo DL. Stress and distortion mitigation technique for welding titanium alloy thin sheet, Sci Technol Weld Joi. 2004,9(5): 451-458.
[34] Li J, Guan Q, Shi YW, Guo DL, Du YX, Sun YC. Studies on characteristics of temperature field during GTAW with a trailing heat sink for titanium sheet, J Mater Process Technol. 2004,147(3):328-335.
[35] Yegaie YS, Kermanpur A, Shamanian M. Numerical simulation and experimental investigation of temperature and residual stresses in GTAW with a heat sink process of Monel 400 plates, J Mater Process Technol. 2010,210(13):1690-1701.
[36] Kala SR, Prasad NS, Phanikumar G. Studies on multipass welding with trailing heat sink considering phase transformation, J Mater Process Technol. 2014,214(6):1228-1235.
[37] Zhang Y, Ying YY, Liu XX, Wei HY. Deformation control during the laser welding of a Ti6Al4V thin plate using a synchronous gas cooling method, Mater Design. 2016,90:931-941.
[38] Bajpei T, Chelladurai H, Ansari MZ. Mitigation of residual stresses and distortions in thin aluminium alloy GMAW plates using different heat sink models, J Manuf Process. 2016,22:199-210.
[39] Pariona MM, Teleginski V, dos Santos K, de Lima AAOC, Zara AJ, Micene KT, Riva R. Influence of laser surface treated on the characterization and corrosion behavior of Al-Fe aerospace alloys, Appl Surf Sci. 2013, 276: 76–85.
[40] Pariona MI, Teleginski V, dos Santos K, Machado S, Zara AJ, Zurba NK, Riva R. Yb-fiber laser beam effects on the surface modification of Al-Fe aerospace alloy obtaining weld filet structures, low fine porosity and corrosion resistance, Surf Coat Technol. 2012,206(8-9): 2293–2301.
[41] Ostuni S, Leo P, Casalino G. FEM simulation of dissimilar aluminum titanium fiber laser welding using 2D and 3D Gaussian heat sources. Metals 2017; 7(8); 1-15.
[42] Chen L, Mi GY, Zhang X, Wang CM, Numerical and experimental investigation on microstructure and residual stress of multi-pass hybrid laser-arc welded 316L steel, Mater Design. 2019, 168: 1-12.
[43] Yazdian N, Derakhshan ED, Kovacevic R. Numerical prediction and experimental analysis of the residual stress fields and generated distortion in hybrid laser/arc welded thick plates of high-strength steels,

Int J Adv Manuf Tech. 2018,98(9-12):2725-2735.
[44] Zhan XH, Li YB, Ou WM, Yu FY, Chen J, Wei YH. Comparison between hybrid laser-MIG welding and MIG welding for the invar36 alloy, Opt Laser Technol. 2016,85: 75-84.
[45] H. Martin, Heat and mass transfer between impinging gas jets and solid surfaces, Adv. Heat Tran. 1997,13: 1-60.
[46] Deng D, FEM prediction of welding residual stress and distortion in carbon steel considering phase transformation effects, Mater Design. 2009,30(2):359-366.
[47] Baruah M, Bag S. Influence of pulsation in thermo-mechanical analysis on laser micro welding of Ti6Al4V alloy. OptLaser Technol. 2017, 90:40-51.
[48] Bhatti AA, Barsoum Z, Murakawa H, Barsoum I. Influence of thermo-mechanical material properties of different steel grades on welding residual stresses and angular distortion. Mater Design. 2015, 65:878-889.
[49] Deng D, Liu XZ, He J, Liang W, Investigating the influence of external restraint on welding distortion in thin-plate bead-on joint by means of numerical simulation and experiment, Int J Adv Manuf Tech. 2016,82(5-8):1049-1062.
[50] Ueda Y, Murakawa H, Ma N. Welding Deformation and Residual Stress Prevention. Butterworth-Heinemann Publishing, United Kingdom, Oxford, 2012.
[51] Ueda Y, Murakawa H, Nakacho K, Ma N. Establishment of computational welding mechanics. Weld Surfacing Rev 1997,24:73-86.
[52] Sun JM, Liu XZ, Tong YG, Deng D. A comparative study on welding temperature fields, residual stress distributions and deformations induced by laser beam welding and CO2 gas arc welding, Mater. Des. 63 (2) (2014) 519-530.
[53] Wang JC, Zhao HQ, Zou JS, Zhou H, Wu ZF, Du SZ. Welding distortion prediction with elastic FE analysis and mitigation practice in fabrication of cantilever beam component of jack-up drilling rig, Ocean Eng. 2017,130: 25-39.
[54] Yi B, Wang JC. Mechanism clarification of mitigating welding induced buckling by transient thermal tensioning based on inherent strain theory, J Manuf Process. 2021,68: 1280-1294.
[55] Wang JC, Yin XQ, Murakawa H. Experimental and computational analysis of residual buckling distortion of bead-on-plate welded joint, J. Mater. Process. Technol. 2013,213(8): 1447-1458.
[56] Wang J, Yi B, Zhou H. Framework of computational approach based on inherent deformation for welding buckling investigation during fabrication of lightweight ship panel. Ocean Eng. 2018,157:202-10.
[57] Wang JC, Ma N, Murakawa H. An efficient FE computation for predicting welding induced buckling in production of ship panel structure. Mar. Struct. 2015, 41, 20-52.
[58] Wang J, Yi B, Zhang C, Zhou H, Shu Y. Experiments of double curvature plate bending with induction heating and processing parameters investigation by computational analysis. Ocean Eng. 2019,192:1-13.
[59] Bonakdar A, Molavi-Zarandi M, Chamanfar A, Jahazi M, Firoozrai A, Morin E. Finite element modeling of the electron beam welding of Inconel-713LC gas turbine blades, J Manuf Process. 2017, 26: 339-354.
[60] Liang W, Murakawa H, Deng D. Estimating inherent deformation in thin-plate Al alloy joint by means of inverse analysis with the help of cutting technique. Adv Eng Softw. 2016, 99:89-99.
[61] Luo Y, Murakawa H, Ueda Y. Prediction of welding deformation and residual stress by elastic FEM based on inherent strain. I. Mechanism of inherent strain production. Trans JWRI 1997;26(2):49–57.