第 32卷 第 5期　　焊 接 学 报　　Vol.32　No.5
2011年 5月　　TRANSACTIONS OF THE CHINA WELDING INSTITUTION　　May　2011

一种结构焊接变形数值分析方法

陈章兰，　熊云峰
（集美大学 轮机工程学院，厦门　361021）

陈章兰

摘　要：采用结构力学理论与方法，对结构焊接变形进行了有限元数值模拟．将焊缝等效为残余应力与残余应变，其中，将 T形接头视为板条梁，采用热弹塑性有限元分析方法分析了焊后残余应力分布特征和残余应变分布．根据虚功原理将焊缝残余应力等效加载到结构上与焊缝邻近的节点处，采用位移法将残余应变等效加载到结构相应部位．然后采用结构有限元分析方法对焊接结构进行有限元分析，得到其焊接变形数据．方法高效、加载简便，与实际结构生产经验数据比对结果验证了方法的有效性．

关键词：虚功原理；力学位移法；焊接变形；数值分析
中图分类号：TG404　　文献标识码：A　　文章编号：0253－360X（2011）05－0077－04

0　序　言

焊接变形预测是个古老的话题，日本早在 20世纪 70年代开始对其进行研究并取得卓有成效的进展，研究成果已广泛用于造船企业精度控制技术中[1]．中国对这个课题的研究，主要集中在基于热弹塑性力学有限元法和固有应变有限元法两个方面[2]，取得一定的研究成果，但用于实践应用的成果却较少，采用经验数据的生产模式仍很普遍．究其原因，弹塑性力学研究较为准确，但频繁的加热和冷却过程导致的非线性要求单元细化和结构简化使复杂结构的数值计算不太现实；而固有应变有限元法仅考虑到焊缝的应变，忽略焊接残余应力对焊接变形的影响，是一种近似算法[3]．因此，研究如何避开复杂耗时的热弹塑性有限元分析过程，探讨一种焊接变形数值分析的新思路，对推动复杂焊接结构精度控制技术进步和提高企业生产效益具有十分重要的意义[4]．

热弹塑性分析的复杂性和耗时性，焊缝金属的存在导致的结构非线性，都增加模拟收敛的难度．如何充分利用热弹塑性有限元分析的数据，简化焊缝或将焊缝等效，是焊接结构变形模拟技术是否有成效的关键．采用结构力学与热弹塑性力学有限元分析相结合的方法，将焊缝等效为残余应力与残余应变，并将之等效加载在结构模型的相应部位，经过结构有限元分析，得到结构焊接变形分布，从而为焊接结构生产的精度控制提供依据．

1　角焊缝的残余应力力学等效

结构中常见有由对接焊缝连接的接头及由角焊缝连接的 T形接头，其中 T形焊接接头可视为梁结构，把 T形接头独立出来，通过热弹塑性有限元模拟分析其焊后残余应力分布和残余应变分布特点，然后考虑其加载．

1.1　单道角焊缝应力分布特征分析

三维空间中任一弹性体某一点的应力状态可用应力张量表示为

$$[\sigma]=\begin{bmatrix}\sigma_x & \tau_{xy} & \tau_{xz}\\ \tau_{yx} & \sigma_y & \tau_{yz}\\ \tau_{zx} & \tau_{zy} & \sigma_z\end{bmatrix} \tag{1}$$

式中：σ_x，σ_y，σ_z分别为 x，y，z向正应力；τ_{ij}为外法线为 i的平面的 j向应力分量，其中，i，j分别取 x，y，z．

焊接变形一般纵向收缩变形、横向收缩变形、弯曲变形、角变形、波浪变形、扭曲变形和错边变形等 7类．正向应力使结构收缩变形占主导作用，因此，引起结构收缩变形的焊缝空间一点残余应力分量可表示为

$$[\sigma]_w=\begin{bmatrix}\sigma_x & 0 & 0\\ 0 & \sigma_y & 0\\ 0 & 0 & \sigma_z\end{bmatrix} \tag{2}$$

设角焊缝端部受 z向位移约束，长为 200 mm，

收稿日期：2009－12－31
基金项目：李尚大集美大学学科建设基金项目（ZC2010006）

焊脚高度为 8 mm,模块的结构模型如图 1所示. 进行热弹塑性力学分析,可以得到角焊缝与板材连接各节点残余应力分布. 其中,A面各方向残余应力分布如图 2所示.

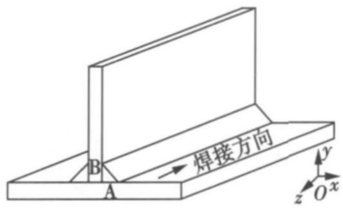
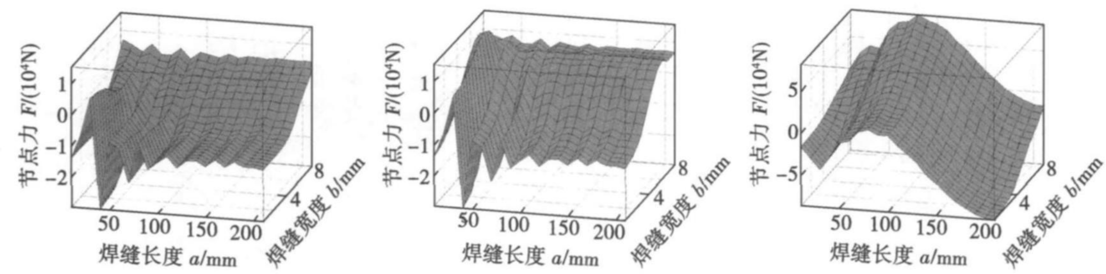


图 1 结构模型

Fig. 1 Structure model of fillet weld

从图 2a,b显示的 A面残余应力分布可以看出,起焊点位置由于热-应力的严重非线性,节点力变化非常剧烈,并出现奇异点,但中后部变形趋于平缓;水平面焊缝节点力在 x和 y向分布的变化趋势基本相同. 通过数值比较还可以发现更多的规律性. A面 y向节点力分布趋势与立面 x向节点力分布趋势、大小基本相同;立面 y方向节点力分布与水平面 x向焊缝部位节点力大小和分布趋势基本相同. 另外,两个面的 z向节点力相同,且在焊缝首尾端为负,在中部为正. 数值模拟得出的节点力分布与理论计算十分吻合.



(a) A面x方向节点力分布 (b) A面y方向节点力分布 (c) A面z方向节点力分布

图 2 角焊缝残余应力分布

Fig. 2 Residual stress distribution of T-shape joint

由于焊缝起始长度和终止长度所占焊缝长度较小,提取焊缝残余应力时,仅取中段焊缝分析. 对水平面 y向节点力进行统计,发现正向节点力与反向节点力之和为一很小数字,剔除由于加热和冷却急剧变化过程中导致的非线性导致出现奇异节点力的点,可以认为正向节点力与反向节点力之和为零. 这一点也与应力自平衡理论分析一致.

将焊缝加长,再进行热弹塑性数值模拟,这种应力分布的规律性更加明显. 由于变化剧烈部位处于焊缝端部,对结构整体变形影响较小,因此,取变化较平缓部位作为残余应力简化模型.

1.2 角焊缝应力分布对称性分析

结构中角焊缝一般对称布置,处于对称角焊缝中心的节点两侧焊缝对称,两侧加载的 3个主应力大小相等,方向有差异,其中同向应力叠加,反向应力由于作用点不在同一位置,会引起结构的局部变形,但不会引起结构整体变形,因此,在板两侧的反向应力可相互抵消. 如结构 y向焊缝,在焊接工艺参数相同时,处于对称中心的节点 i,j左侧焊缝节点施加的 x方向残余应力 $(\sigma_x)_{ij}$与右侧对称节点 k施加的 x方向节点力 $(\sigma_x)_{ik}$大小相等,方向相反,即有 $(\sigma_x)_{ij}=-(\sigma_x)_{ik}$,两者可以互相抵消,因而加载时只需考虑 $(\sigma_y)_{ij}$,$(\sigma_y)_{ik}$,$(\sigma_z)_{ij}$与 $(\sigma_z)_{ik}$即可. 同样,在结构 x向焊缝和 z向焊缝,加载的处理方法与上相同.

1.3 残余应力的等效移置与加载

结构单元的划分对有限元计算效率有较大影响,若网格大小的划分与焊缝的相同,则焊后焊缝的节点力可直接加载在结构相应单元的节点上. 但若采用过小网格,与焊缝相比,由于结构尺寸大得多,其单元数与节点数都会大幅增加,计算时间也会大大增加,这种加载方法无法实用. 下面介绍节点力等效移置方法,即将焊缝处节点力等效移置到结构单元的邻近节点上.

由前述可知,角焊缝 T形接头的残余应力不是常数,且是面力. 以 z向应力为例,设接头 A区域为 $M_1M_2M_3M_4$,焊缝宽度为 b,长度为 a,对应纵向残余应力设为 σ'',如图 3所示.

先将面力等效转化为 M_2M_3上线力 σ_z',即

$$\int_0^a \sigma_z' \mathrm{d}v = \int_0^a\int_0^b \sigma_z'' \mathrm{d}u\mathrm{d}v \quad (0 \leqslant u \leqslant b, 0 \leqslant v \leqslant a) \tag{3}$$

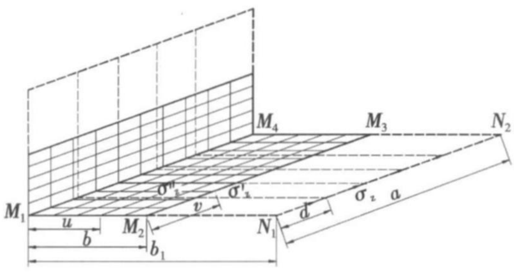


图 3　焊缝载荷向结构载荷等效转化示意图

Fig. 3　Transferring of inherent stress from original loads to initial loads

再将线力 σ_z转化为具有结构单元宽度为 d与中心距离为 b_1的结构的 M_1处的节点力 σ_z为

$$\sigma_z = \frac{d}{a}\int_0^a \sigma_z{}' \, db \qquad (4)$$

同理，可求得其它两个方向节点力分力，组成节点力向量$\{\sigma\}$.

应用虚功原理将 M_1处节点力等效移置到结构单元的节点 N_1处．设在节点力作用下，M_1处发生虚位移为$\{\delta_M\}$，在等效节点力$\{\sigma_e\}$作用下，N_1处发生虚位移$\{\delta_N\}$，则节点力$\{\sigma\}$对虚位移$\{\delta_M\}$所作虚功与等效节点力$\{\sigma_e\}$对虚位移$\{\delta_N\}$所做虚功应相等，即

$$\{\sigma_e\} = \frac{\{\sigma\}\{\delta_M\}^T}{\{\delta_N\}^T} \qquad (5)$$

显然，$\{\delta_M\}/\{\delta_N\}$大小由 b_1/b确定．联接式（3）~式（5），可解出加在结构上的与焊接残余应力等效的节点力$\{\sigma_e\}$.

2　残余应变模型

与残余应力分析相同，这里考虑收缩变形，三维空间任一点残余应变张量可简化为

$$[\varepsilon]_w = \begin{bmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix} \qquad (6)$$

2.1　单道角焊缝残余应变分布特征分析

热弹塑性力学有限元分析结果是节点位移，若计算残余应变$[\varepsilon]$还需根据节点位移进行计算．提取 T形接头热弹塑性有限元分析结果数据，计算得到残余应变分布数据．数据的准确性通过多点测量残余应变值得到验证．角焊缝各点的残余应变如图 4所示，可以看出，残余应变 ε_x，ε_y值基本一致，且变化不大，残余应变 ε_z自焊缝起点至终点缓慢增大，但增幅并不大，整个长度内不到 9%．ε_z值较 ε_x和 ε_y小些．为方便加载，将图 4中各方向残余应变曲线采用最小二乘常数拟合，即加载固定的初始位移值，以模拟将焊缝做结构简化后产生的残余应变 ε.

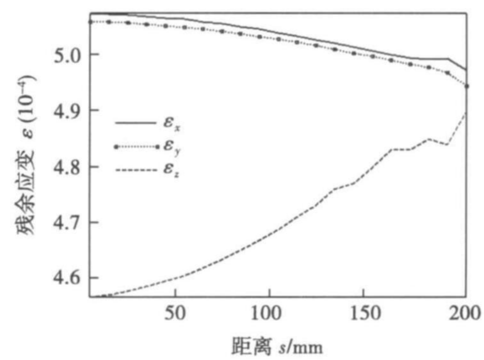


图 4　角焊缝各方向残余应变分布

Fig. 4　Residual strain distribution of T-shape joint in three directions

2.2　残余应变的等效计算与加载

根据结构力学位移法，当板端（焊缝）节点发生初始应变 ε_0后，可解析求得与端点距离为 s的任一截面处，引起应变 ε_s为

$$\varepsilon_s = \varepsilon_0 \left(\frac{3s^2}{l^2} - \frac{2s^3}{l^3}\right) \qquad (7)$$

式中：s为结构上与焊缝邻近的节点与焊缝中心距离；l为结构间距．

式（7）中应变 ε_s由两个方向焊缝初始应变引起，且距离另一侧焊缝的影响由于距离远可忽略不计，这样就可确定邻近节点处的应变值．同样，在不细化网格或增加单元与节点数量的前提下，将焊缝部位初始应变等效加载到结构上邻近焊缝的节点处．

3　基于残余应力与应变的焊接变形模拟方法的应用

船体结构是复杂焊接结构之一，船舶建造精度控制技术重要内容就是对分段结构的焊接变形进行预测．以某散货船双层底中部分段为例进行有限元数值模拟，分段 Y向长 5 m，布置 5道间距为 0.8 m的肋板．X向长 3.5 m，具有 3道纵桁和上下 4道共 8道纵骨，纵桁间距 1.5 m，纵骨间距 0.5 m．内、外底板厚 12 mm，桁材、肋板、骨材板厚为 10 mm．Z向焊缝有 28道，X向焊缝 20道，Y向焊缝 220道．其中大量焊缝是对称布置的，如 Y向焊缝全部为对称设置．分段有限元结构的网格划分如图 5所示．

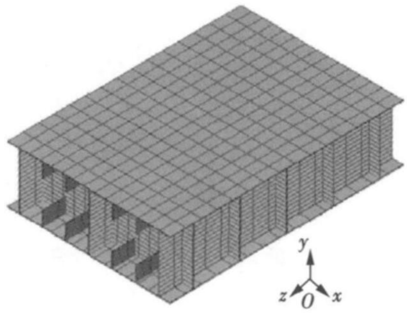


图 5　分段有限元结构的网格划分
Fig. 5　Mesh of hull block

焊缝数量太多, 节点捕捉效率就非常重要. 程序开发时充分考虑对称性和程序的自动化程度, 采用了参数化设计语言. 程序设计时首先是采用近似坐标捕捉节点, 结果节点选择总为空. 后改用 node 函数捕捉节点, 先测试 node 函数捕捉节点的精度, 确认函数捕捉的节点与输入的坐标一致后, 编制各道焊缝的自动捕捉程序, 如 z 向某道焊缝, x, y 坐标不变, 仅 z 坐标不同, 可将 node 函数中 z 向坐标设为参数, 设计自动循环程序, 捕捉该道焊缝上各节点. 实现准确高效加载, 把繁杂的加载工作变为程序自动运行, 加载工作也不容易产生遗漏, 大大减少加载工作量.

取 $\varepsilon_{x0}=\varepsilon_{y0}=5\times10^{-5}$, $\varepsilon_{z0}=4.7\times10^{-5}$, 进行数值模拟, 提取收缩量结果, 其中结构 x, z 向收缩量如图 6 所示.

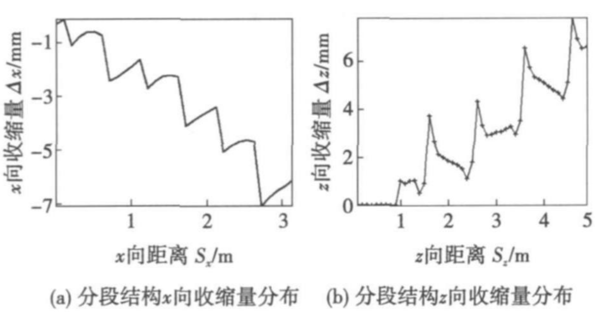


图 6　分段收缩量分布
Fig. 6　Distribution of shrinkage amount of hull block

图 6a 为 x 向收缩量分布, 由于内部骨架结构的存在, 收缩量呈曲折形增大, 这一点与实践经验相符. 处于边缘位置的节点收缩值约为 7.1 mm, 与工厂经验数据 7.6 mm 接近; 图 6b 为分段 z 向收缩量, 收缩变形呈波浪形态增大, z 收缩量约为 6.3 mm, 与经验数据 5.7 mm 接近.

4　结　　论

(1) 焊缝尺寸和刚度很小, 对焊接结构影响不大, 可将焊缝尺寸舍去, 简化为残余应力与残余应变进行加载.

(2) 将角焊缝视为 T 形梁, 经过热弹塑性分析后提取两直角边残余应力数据, 并对其三维分布特征进行了分析. 应用虚功原理将焊缝应力进行等效并加载到结构上邻近焊缝区域的节点上.

(3) 提取节点位移值并计算出残余应变作为结构加载的初始应变, 并根据结构力学位移法将焊缝区域的残余应变等效到结构邻近节点上.

(4) 采用基于残余应力与应变的有限元数值模拟方法, 成功模拟了某散货船双层底分段焊接变形, 新方法数值计算结果与经验数据基本吻合.

参考文献:

[1]　国家计委、船舶总公司“加快船舶工业发展研究”课题考察组. 日本、德国船舶工业考察报告[J]. 船舶工业技术经济信息, 2001, 5: 4－10.
Staff of investigation on “prompting research on shipbuilding industry development” from planning commission of the state and China state shipbuilding corporation. Investigation report of Japanese and German shipbuilding industry[J]. Technology and Economy Information of Shipbuilding Industry, 2001, 5: 4－10.

[2]　汪建华, 陆　皓, 魏良武. 固有应变有限元法预测焊接变形理论及其应用[J]. 焊接学报, 2002, 23(6): 36－40.
Wang Jianhua, Lu Hao, Wei Liangwu. Prediction of welding distortion based on theory of inherent strain by FEM and its application[J]. Transactions of the China Welding Institution, 2002, 23(6): 36－40.

[3]　陈建波, 罗　宇, 龙　哲. 大型复杂结构焊接变形热弹塑性有限元分析[J]. 焊接学报, 2008, 29(4): 69－72.
Chen Jianbo, Luo Yu, Long Zhe. Analysis on welding distortion of large complicated structure by thermal elastic-plastic finite element method[J]. Transactions of the China Welding Institution, 2008, 29(4): 69－72.

[4]　曾　志, 王立君, 张　涵. 采用子结构与子模型结合方法的三维焊接应力变形数值模拟[J]. 焊接学报, 2009, 30(7): 89－93.
Zeng Zhi, Wang Lijun, Zhang Han. Application of substrucure and submodelling on 3D numerical simulation of welding[J]. Transaction of the China Welding Institution, 2009, 30(7): 89－93.

作者简介: 陈章兰, 女, 1970 年出生, 硕士, 副教授. 主要从事船舶焊接精度控制技术的科研和教学工作. 发表论文 10 余篇. Email: chenzhanglan@163.com

tent of (Ti+C) is more than 30% during argon arc cladding the fine TiC particles of 1 5 μm in size can be completely synthesized The uniform and continuous excellent metallurgical bonding without defects between the coating and the ZL104 substrate was obtained and the particles were dispersively distributed in the coating The microhardness of the coatings enhanced by the TiC particles can reach 650 HV0 2 which is about 7 times higher than that of the ZL104 alloy

Key words argon arc cladding in-situ synthesis TiC composite coating

Numerical analysis on deformation of welded construction

CHEN Zhanglan XIONG Yunfeng (Facility of Marine Engineering Jimei University Xiamen 361021 China). p77—80

Abstract Some theories and methods of structure mechanics were applied to simulate the efficiently welding deformation Since the seam size is too small to contribute itself to the strengthen of huge construction it can be replaced by residual strain and stress in complicated welded structure in order to improve the quality of ANSYS meshing and save calculating time Residual stress and strain distributions obtained by thermal elastic and plastic finite ANSYS method were analyzed respectively The principle of virtual work and the displacement method were used to load the residual stress and strain of weld seam on the corresponding node in welded structure which made the stress and strain loading process more convenient and useful The deformation of welded structure in simulation was proved by comparing the experience data It was proved that the method to simulate the welding deformation based on the principle of virtual work and the displacement method can be used to predict the deformation of complicated welded structure

Key words principle of virtual work displacement method welding deformation numerical analysis

Analysis on single arc welding with twin electrode of TE4303

LI Liying ZOU Zengda HAN Bin LI Chaowen (1. School of Mechanical and Electronic Engineering China University of Petroleum (East China) Dongying 257061 China 2 School of Materials Science and Engineering Shandong University Jinan 250061 China). p81—84

Abstract Single arc welding with twin electrode (TE4303) was studied from the welding efficiency and energy saving microstructure mechanical properties and fracture morphology The results show that melting coefficient and deposition coefficient of TE4303 single arc welding are as two times higher as that of the traditional single electrode (E4303) arc welding Compared with E4303 arc welding TE4303 single arc welding can save electrical energy about 20% ~ 30% to melt per unit weight of electrode metal Meanwhile its welding heat input is low to get the small fusion ratio The columnar grains in weld are much slimmer at the same welding current It is also found that both the compositions and mechanical properties of the deposited metal meet the requirements of standards The analysis on fracture appearance shows that it is ductile fracture with dimple mode and the inclusions are oxides which are analyzed by electron probe microscope

Key words twin electrode single arc welding efficiency and energy saving microstructure mechanical properties

Heat source model for partial penetration lap laser welding of stainless steel railway vehicles

SHI Chunyuan GU Guochen WANG Hongxiao 2 JIN Cheng WANG Chunsheng (1. School of Materials Science and Engineering Dalian Jiaotong University Dalian 116028 China 2 Changchun Railway Vehicles Ltd Co Changchun 130062 China). p85—88

Abstract It is an optimum method to solve the problem on the appearance quality and tightness of stainless steel car body by replacing resistance spot welding with lap laser welding But in the experiments of partial penetration lap laser welding the shape of molten pool was found to be similar with a vase in the common processing parameters which was different from the normal laser conductive welding or the laser deep penetration welding By using the software of ABAQUS the welding temperature fields were simulated with different heat source models such as Gauss heat source Gauss heat source + conical heat source and 3-D conical heat source + inverted conical heat source + ellipsoid heat source The results indicate that the shapes of molten pool simulated by using 3-D conical heat source + inverted conical heat source + ellipsoid heat source agree well with the experimental results

Key words stainless steel railway vehicles lap laser welding heat source model numerical simulation

Nonlinear combination neural network model of intelligent prediction on electrode properties

HUANG Jun XU Yuelan (School of Materials Science and Engineering Nanjing University of Science and Technology Nanjing 210094 China). p89—92

Abstract The elongation after fracture and impact energy of the deposited metal by electrode were tested by experiments A nonlinear combination neural network model to predict the deposited metal mechanical properties by electrode was built by taking predicted data acquired by such single models as BP RBF and adaptive fuzzy neural network as input parameters 42 groups of experimental samples were used to train and verify the model The results show that the average relative prediction errors of both elongation after fracture and impact energy are less than 5% and it satisfies the demands of practical production An intelligent prediction system of electrode properties was developed by Matlab and visual C++ and it can correctly predict the elongation after fracture and impact energy of deposited metal by electrode according to the raw material components It provides a new simple and effective way to predict and control the electrode quality

Key words adaptive fuzzy neural network deposited metal carbon steel electrode nonlinear combination prediction

Metallographic sample preparation of Ti_3Al alloy laser welded joints for EBSD

SONG Zhihua WU Aiping ZOU Guisheng WANG Guoqing 2 REN Jialie (1 Department of Mechanical Engineering Tsinghua University Beijing 100084 China 2 China Academy of Launch Vehicle Technology Beijing 100076 China). p93—96

Abstract Research of the microstructure and texture of laser welded joints of Ti_3Al based alloy plays an important role in improving the properties of the joints while the technique of electron backscatter diffraction (EBSD) is an attractive method