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Cr-Mo钢管子局部焊后热处理加热宽度准则的确定

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摘 要：采用粘弹塑性有限元方法从应力释放角度讨论了 Cr-Mo钢局部热处理下各种优化加热条件。研究表明，局部热处理过程产生的瞬态和残余应力受蠕变性能和温度关系弹性模量等因素的影响。当加热宽度足够大时，局部热处理后的应力与炉中热处理的应力接近。通过与现有标准的比较，从应力释放角度位于焊缝中心 $5\sqrt{Rt}$的加热宽度较为合理。提出了考虑焊接冷却过程 Cr-Mo低温膨胀现象的相变模型。给出了焊接残余应力与局部焊后热处理应力的试验结果与模拟结果的对比。

关键词：局部焊后热处理；低温相变；Cr-Mo钢；数值分析
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0 序 言

不同钢种管子局部焊后热处理的标准及其对接头性能的影响是工业生产中亟待解决的问题[1]。局部焊后热处理存在正负两方面的影响。适当的局部焊后热处理可以实现回火和消除焊接应力；反之，引起附加的残余应力。局部焊后热处理必须对许多工艺参数进行优化，如管子尺寸、加热宽度、保温条件、加热速度、均热温度、保温时间、材料蠕变规律等因素都会影响局部焊后热处理的效果。该领域内仍有一些难题有待解决。首先，不同钢种管子局部焊后热处理加热标准的适用范围；其次，各种因素对局部焊后热处理后应力的作用机理也缺乏足够的研究。从而造成各国对于局部焊后热处理的标准存在很大差别[2,3]。Rose[4]和 Burdekin[5]用弹性方法对轴向热应力和热源边界之间的关系进行了研究。近来，人们开始用有限元方法来研究局部焊后热处理条件下接头的力学行为，希望找到一种方法来解决前面提到的难题，并建立确定局部焊后热处理工艺参数的理论基础。提出了直接采用粘弹塑性有限元法来定量评估焊后局部热处理消除应力的效果[6]，该方法同时也应用于确定不同局部焊后热处理条件下的临界加热宽度。建立了管子几何因素和厚度方向温度梯度间的传热学模型，并对厚度方向的温度梯度在局部焊后热处理中消除焊接应力的作用进行了计算[7]。

选用平均应力和弯曲应力来阐明局部热处理条件下的力学行为。采用粘弹塑性有限元法的轴对称模型，讨论了主要参数对局部热处理残余热应力的影响，包括 R/t、保温宽度和加热宽度，计算中没有考虑焊接初始应力。研究了不同钢种管子局部热处理条件下的残余应力，研究表明局部热处理后残余应力的大小很大程度上受到蠕变规律和蠕变参数取值的影响。对 2.25Cr-Mo钢焊接残余应力，以及与加热宽度的关系进行模拟。研究结果为局部热处理加热宽度及其适用性的确定提供了理论依据。

1 模拟方法和计算条件

采用粘弹塑性有限元法对一系列管子的轴对称模型进行了研究，取管子长度的 1/2划分单元网格和计算，局部热处理加热模型见图 1。管子的厚度根据管子特征参数 R/t而有所不同，其主要取值范围为 5.0～22.5，管子的长度为 $L=8\sqrt{Rt}$，R为管子内半径；t为管子厚度。局部热处理中依次取半加热宽度为 $B=0.5B_{cr}$，B_{cr}，$1.6B_{cr}$，$2B_{cr}$，其中临界加热宽度 $B_{cr}=2.5\sqrt{Rt}$；计算中保温宽度 W_{in}均取 $5\sqrt{Rt}$，加热速度控制在 $220\times25/t$ (℃/h)。分别采用低碳钢和 Cr-Mo钢进行计算，即 STPT480，2.25Cr-Mo，9Cr-Mo。使用加热中心的平均应力和弯曲应力来评估局部热处理的效果。低碳钢、2.25Cr-Mo钢和 9Cr-Mo钢的保温温度分别为

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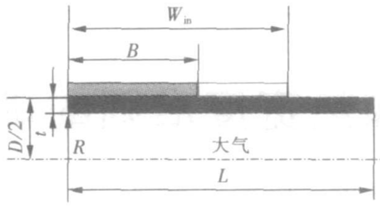

图 1　有限元局部热处理加热模型

Fig. 1　Local heat treatment model for FEM analysis

620 ℃、720 ℃、740 ℃。低碳钢和 Cr-Mo 钢分别对应两种不同的蠕变规律，即幂蠕变形式 $\dot{\varepsilon}^c = b\sigma^n$ 和指数蠕变形式 $\dot{\varepsilon}^c = A\exp(B\sigma)$。两种蠕变形式中的参数是依据试验测得的不同应力下应变率的最小值而确定的，见图 2，其中 Cr-Mo 钢 700 ℃以上的蠕变数据为假定值。其余材料性能参数由日本发电设备技检协会（JAPEIC）提供。保温时间控制为 25 h，并且最小保温时间为 1 h。热源位于被加热管子的热源和保温材料覆盖区域的换热系数取为 $\beta = 0.0002 \mathrm{W/cm^2 \cdot ℃}$，其它空冷区域的换热系数为 $\beta = 0.0033 \mathrm{W/cm^2 \cdot ℃}$。

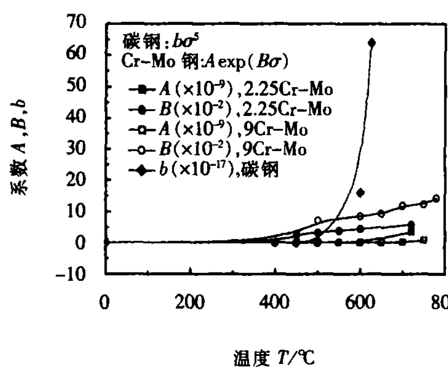

图 2　两种钢的蠕变参量图

Fig. 2　Creep parameters of two types of steel

通过图 2 中所示的蠕变规律和数据，可以计算出不同应力载荷下的应变，见图 3。选取 20～100 MPa 之间的应力载荷来进行比较。研究表明，在小应力载荷时 2.25Cr-Mo 的蠕变应变量比 9Cr-Mo 的值大，而当应力载荷足够大时则 9Cr-Mo 的蠕变应变量比 2.25Cr-Mo 和低碳钢的值要大。

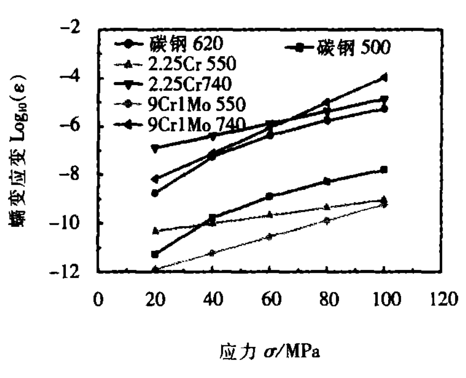

图 3　相关蠕变参数的蠕变应变

Fig. 3　Creep strain under related creep parameters

2　局部焊后热处理应力水平影响因素

2.1　加热宽度的影响

加热宽度会对平均残余应力产生很大的影响。计算中取加热宽度为 $B = B_{cr}$，保温宽度为 $2B_{cr}$。当 R/t 和加热宽度都很小时，平均残余应力很大，当加热宽度窄到与焊缝相当时平均残余应力的值会达到屈服应力。从计算结果可以得出结论，当 R/t 足够大时，如果加热宽度为 B_{cr} 则周向平均应力会在残余应力和加热宽度的共同影响下达到局部的最小值，轴向弯曲应力会随着加热宽度的减小而趋于零，当加热宽度大于 B_{cr} 且 R/t 很小的时候，则轴向弯曲应力会变为正值，见图 4。由以上的计算结果得出从应力角度考虑临界加热宽度 $B_{cr} = 2.5\sqrt{Rt}$ 是合理的。同样，该加热宽度对于 Cr-Mo 钢焊后热处理来

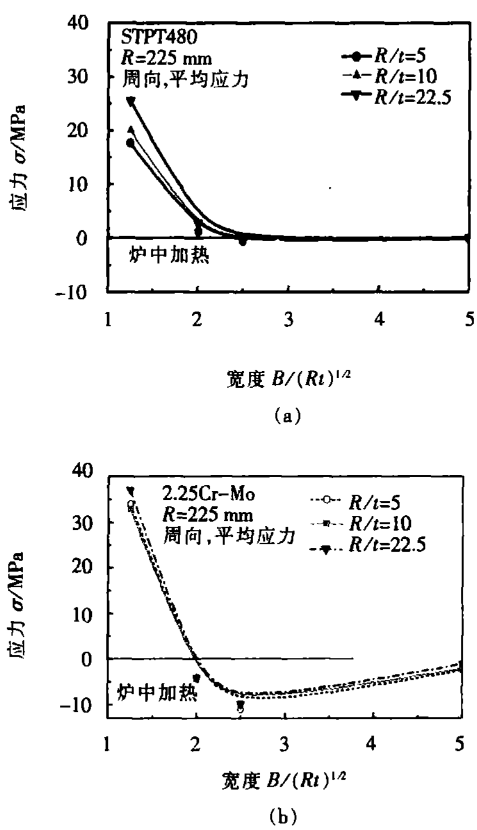

图 4　加热宽度对残余应力的影响

Fig. 4　Effect of half heated band width on residual stress

说已经足够。至于当 R/t非常小的时候,局部热处理后的残余应力是管子约束(R/t)和局部加热两方面作用的结果,管子厚度方向温差和管子轴向温差引起的周向平均残余应力相互抵消。在 R/t较小的情况下,从轴向弯曲应力角度考虑过大的加热宽度是不合适的。当 R/t介于 1.8~5之间时,残余应力水平上升,应力绝对值而言较小。

2.2　保温宽度的影响

对保温宽度与热应力的关系也做了研究,保温宽度与加热宽度的比之间的关系表明当保温宽度为 $2B_c$时,轴向弯曲应力通常小于 20 MPa,对周向平均应力的影响通常小于 10MPa,可以忽略不计。

2.3　蠕变规律和蠕变参数取值的影响

不同钢种的实际局部热处理的温度均存在一定的范围,假定 2.25Cr-Mo钢和 9Cr-Mo钢的均热温度都是 720 ℃,并且局部热处理的加热速度、保温时间是一致的。当 R/t较小时 9Cr-Mo钢的轴向弯曲应力比 2.25Cr-Mo钢的要小,当 R/t较大时则趋于零,残余应力因蠕变参数的不同而存在一定差异,2.25Cr-Mo钢产生了压缩残余应力。该现象与 2.25Cr-Mo钢在局部热处理时的应力载荷下的应变率(图 3)有关,2.25Cr-Mo钢和 9Cr-Mo钢在小应力载荷下采用了不同的蠕变参数取值。不同类型钢种因蠕变规律和蠕变参数差异,导致局部热处理的周向平均应力降为零的过程不同,而对于 Cr-Mo钢,加热宽度为 $B_{cr}=2.5\sqrt{Rt}$已足够大。

3　焊接和局部焊后残余应力试验结果比较

3.1　焊接应力计算中的低温相变模型

对于 Cr-Mo钢,在焊接冷却过程存在低温非扩散性相变,导致压缩应变。该压缩应变对于不同 Cr-Mo钢,其大小不一样。常用的处理方式是改变冷却过程的材料性能参数,如弹性模量和屈服强度。另一种方法是将试验测得的冷却阶段的应变 β_I导入粘弹塑方程得式(1)[3]。文中对 2.25Cr-Mo钢采用改变性能参数的方法,对 9Cr-Mo钢采用式(1)进行残余应力计算

$$\{\mathrm{d}\sigma\}=[D^{ep}]\left(\{\mathrm{d}\varepsilon\}-\{\alpha\}\mathrm{d}T-\frac{\partial[D^e]^{-1}}{\partial T}-\mathrm{d}T\right)-[D^{ep}]\sum_{I=1}^{N}(\alpha_I\mathrm{d}T+\beta_I)\mathrm{d}\xi_I\{I\}-\frac{1}{S_0}\left\{\frac{\partial F}{\partial\sigma}\right\}\left(\frac{\partial F}{\partial T}\mathrm{d}T+\sum_{I=1}^{N}\frac{\partial F}{\partial\xi_I}\mathrm{d}\xi_I\right)。\quad(1)$$

3.2　2.25Cr-Mo钢加热宽度与残余应力关系

对不同加热宽度下的 2.25Cr-Mo钢焊后局部热处理计算表明,随加热宽度的增加,残余应力逐渐下降,并接近零。计算时采用了焊接残余应力水平较高的内壁周向应力分量。见图 5,当半加热宽度为 110 mm时,残余应力已接近零,$B_{cr}=2.5\sqrt{Rt}$可以满足 Cr-Mo钢焊后局部热处理加热的要求。

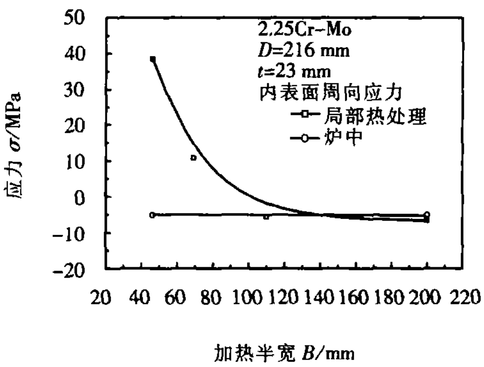

图 5　2.25Cr-Mo局部焊后热处理加热宽度与残余应力的关系

Fig.5　Relation between B and welding residual stress in local PWHT of 2.25Cr-Mo steel

3.3　试验结果与计算值比较

焊接和局部焊后热处理后的应力采用应变片进行了测量。测量所用管子的尺寸、局部焊后热处理的工艺参数和化学成分见表 1和表 2。用有限元方法进行了焊接残余应力和局部焊后热处理后应力的计算并与试验结果进行了了比较。计算中采用了指数形式的蠕变方程,计算结果见图 6。结果表明,有限元分析方法模拟的应力大小与试验结果相当的吻合。

表 1　局部热处理工艺和测试的管子规格

Table 1　Local PWHT process and test pipe dimension

尺寸/mm			加热速度	保温温度	保温时间	冷却速度	绝热宽度	加热半宽
D	t	$2L$	v_H/(℃·h^{-1})	T_h/℃	t_H/h	v_c/(℃·h^{-1})	W_{in}/mm	B/mm
216	23	1 900	220	720	1	275	220	110

表 2 2.25Cr–Mo化学成分(质量分数, %)

Table 2 Chemical components of 2.25Cr–Mo

C	Si	Mn	Cr	Mo	Fe
0.06~0.13	0.26~1.5	0.45~0.98	1.92~2.35	0.52~1.27	余量

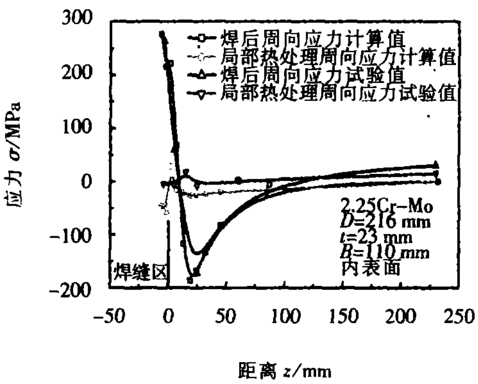

图 6 2.25Cr–Mo钢的试验结果与计算值比较

Fig. 6 Comparison of experimental and computational results of 2.25Cr-Mo steel

4 结 论

(1)局部热处理后的残余应力受到 R/t的很大影响, 当 R/t足够大时局部热处理后的平均残余应力不会很大。

(2)对于 Cr–Mo钢, 当加热宽度为 B_{cr}时可以得到平均应力的局部最小或趋于零。

(3)蠕变参数的取值对局部热处理后的计算残余应力有相当大的影响, 局部焊后热处理后残余应力主要受低应力载荷下的蠕变数据控制。

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MAIN TOPICS, ABSTRACTS & KEY WORDS

Characteristic parameter describing appearance of aluminum alloy weld in electron beam welding WU Qing-sheng, HE Jing-shan, FENG Ji-cai (National Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p1 – 4

Abstract: Based on visual image sensing method, variation of the rear part of the length (L_R) and the width (W) of the feature zone in electron beam welding of aluminum alloy were investigated. The characteristic parameters describing the appearance of the aluminum alloy weld in electron beam welding were determined by analyzing the relationship between the appearance of weld and the fluctuation of RL and W. The results show that the appearance of weld can be described successfully by the variation coefficient of L_R (υ_{RL}) and the variation coefficient of W (υ_W) as the characteristic parameters, because the fluctuation of RL and W are the dependent variable and the independent variable of the variation of the welding pool respectively. The effect that the appearance of weld is described by both the characteristic parameters is the same.

Key words: electron beam welding; appearance of weld; characteristic parameter; image sensing; aluminum alloy

Determination of heated band width criterion of local postweld heat treatment for CrMo steel pipe LU Hao, WANG Jian-hua, MURAKAWA Hidekazu (1. Materials School, Shanghai Jiaotong University, Shanghai 200030, China; 2. Welding and Joining Research Institute of Osaka University, Osaka 567-0047, Japan). p5 – 8

Abstract: Optimum heating conditions for local post weld heat treatment (PWHT) of CrMo steel pipe were discussed from the point of view of residual stress using thermal-visco-elastic plastic finite element method (FEM). The whole history of the stress relaxation during local PWHT could be clarified through FEM analysis. The investigation showed that the transient and residual stresses induced by local PWHT were significantly affected by creep behavior and temperature dependency of Young' s modulus. The stresses decreased quickly in the heating stage, with decreased yield strength. They continued to decrease slowly according to the creep law in the holding stage and increased slightly due to recovery of Young' s modulus when the cooling stage started. The residual stress after PWHT decreased with increase of heated band width. When the heated band width was large enough, the residual stress after local PWHT become close to that of the uniform PWHT. Compared with the existing codes, it was found that the heated band width of $5\sqrt{Rt}$ on center of the weld seems reasonable from the residual stress point of view. A new phase transformation model was proposed considering the low temperature expansion during the cooling stage of welding of CrMo steel pipe. Experiment results of welding residual stress and the stress after local postweld heat treatment are compared with numerical simulation.

Key words: local postweld heat treatment; low temperature phase transformation; CrMo steel; numerical analysis

Microstructure and mechanical properties of 2219 Al alloy heat affected zone with twin wire welding MENG Qing-guo, FANG Hong-yuan, XU Wen-li, JI Shu-de (National Key Laboratory of Advanced Welding Production technology, Harbin Institute of Technology, Harbin 150001, China). p9 – 12

Abstract: Microstructure and mechanical properties changing rules of 2219 Al alloy HAZ (heat affected zone) with twin wire welding were studied using welding thermal simulation method. The result shows that the temperature interval of soften zone is 400 – 500 ℃ for 2219 Al alloy twin wire welding, and 450 ℃ is the most serious temperature. The minimum strength is only 60% of the base metal with normal cooling rate. And property of HAZ is damaged more seriously with slower cooling rate, so increasing cooling rate can be used to strengthening HAZ. Effect of peak temperature on fracture type is small, and the alloy fractures are all ductile rupture.

Key words: thermal simulation; microstructure; 2219 Al alloy

Numerical simulation on vibration in ultrasonic welding SHEN Jie, JIN Xian-long, GUO Yi-zhi (School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200030, China). p13 – 16

Abstract: A new finite element method was proposed, which was used to identify the cause of product failure due to vibration in ultrasonic welding. According to the principle of welding machine, the complex welding system was simplified. For the simulation, the loading method and transforming mechanism of energy transmission was given and verified by temperature distribution in the joint calculated by the thermal mechanical coupled model. Based on the idea proposed in this paper, a 3D finite element model was established for analyzing the vibration of cell phone battery during ultrasonic welding, and experiments proved its favorable effect.

Key words: ultrasonic welding; finite element method; analysis of vibration

Improvement on numerical simulation precision of GTAW weld pool geometry ZHAO Ming, WU Chuan-song, ZHAO Peng-cheng (The MOE Key Laboratory of Liquid and Heredity of Materials, Shandong Uni-