

组合热源模型在焊接数值模拟中的应用

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摘 要: 对不同焊接热源的特征要素进行分析, 焊接数值模拟中采用高斯面热源和双椭球体热源处理焊接加热问题均不能准确地反映焊接熔池形状. 文中提出焊缝表面高斯热源和焊缝内双椭球体热源结合的组合热源模型, 其熔池与实际焊缝熔合线吻合. 应用上述三种热源对马氏体不锈钢平板对接电弧焊的温度场及应力场进行了数值模拟. 结果表明, 使用组合热源进行数值模拟较之单独使用高斯或双椭球热源的残余应力计算值与实测值吻合度更高.

关键词: 数值模拟; 组合热源; 残余应力

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0 序 言

中厚板的焊接过程非常复杂, 利用数值模拟技术预测焊接温度场和应力场的分布情况能够指导工艺优化, 从而得到高质量的焊接结构. 焊接数值模拟技术的应用需要抽象出很多理想化的因素, 其中得到符合焊接热过程的热源模型是焊接温度场模拟的重要条件, 也是应力场模拟的重要影响因素.

按照热源作用方式不同, 焊接热源分为集中热源、平面分布热源和体积分布热源^[1]. 相对于集中热源, 后两者将能量依照一定规律分布于一定空间内, 更加贴近于焊接生产实际. 在焊接数值模拟中通常使用平面分布的高斯热源或体积分布的双椭球热源, 利用这二者人们成功进行了很多焊接结构模拟, 解决了一些工程问题^[2,3]. 但上述两种热源由于片面强调能量的面分布或是体积分布, 热源模拟的焊接熔池形状与实际焊缝熔合线吻合并不理想. 当热源类型为高斯面热源时, 所模拟的焊缝熔宽大, 熔深小, 熔池呈浅碟形, 不能准确反映焊缝内部熔池形状. 当热源类型为双椭球体热源时, 由于考虑了熔滴过渡形成的内热源形式, 这样模拟的熔池形状与实际焊缝熔合线在熔池内部较为吻合, 但是在熔池表面温度较低. 文中分析了高斯热源以及双椭球热源的分布形式, 提出了二者相结合的组合热源模型, 通过组合使模拟的热源模型能够兼顾能量在

熔池表面以及内部分布, 更加接近焊接生产实际. 基于有限元分析软件 MARC 分析了窗形约束焊接试板温度场以及应力场. 模拟得到的残余应力分布与采用盲孔法实测情况对照表明, 采用组合热源提高了焊接应力场分布预测精度^[4,5].

1 组合热源模型的建立

建立热源模型的主要目标是寻找符合相应焊接参数条件下的热流分布形式, 使模拟的熔池(液-固)边界线与试验观测的焊缝熔合线相符, 进而得到与工程实际吻合的温度场.

高斯面热源可以提高高温区的准确性, 但仍未考虑电弧挺度对熔池的影响, 多应用于熔深不大的焊接过程, 因为它将热源按高斯函数在一定的范围内分布^[6], 如图 1 所示. 其函数为

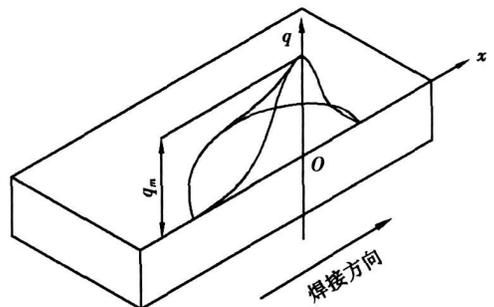


图 1 高斯热源模型

Fig 1 Gauss heat source model

$$q(r) = q_m \exp(-Kr^2) \quad (1)$$

式中: $q(r)$ 为半径 r 处的表面热流; q_m 为热源中心处的热流量最大值; K 为热源集中系数, 是与焊接方法相关的常数; r 为距热源中心的距离。

双椭球体热源多应用于开坡口或大熔深的焊缝, 其热源分布形式^[7]如图2所示, 作用于焊件上的体积热源分为前、后两部分。设双半椭球体的半轴为 (c_1, c_2, a, b) , 设前半部分椭球能量分数为 f_f , 后半部分椭球能量分数为 f_r 且 $f_f + f_r = 2$, Q 为热源总能量, 则在前半部分椭球内热源分布为

$$q_f(x, y, z, t) = \frac{6\sqrt{3}f_f Q}{abc\pi\sqrt{\pi}} e^{-3x^2/c_1^2} e^{-3y^2/a^2} e^{-3z^2/b^2} \quad (2)$$

同样, 对后半部分椭球内热源分布为

$$q_r(x, y, z, t) = \frac{6\sqrt{3}f_r Q}{abc\pi\sqrt{\pi}} e^{-3x^2/c_2^2} e^{-3y^2/a^2} e^{-3z^2/b^2} \quad (3)$$

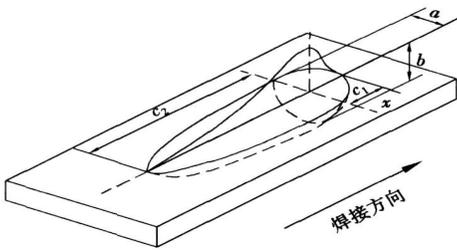


图2 双椭球热源模型

Fig. 2 Double ellipsoid heat source model

所构造的组合热源表面热源采用高斯型热流分布面热源模型, 内部采用双椭球型体热源, 如图3所示。其中面热源控制表面熔池, 体热源反映熔深方向上深层液体层。其模型模拟的熔池形状与实际焊缝熔合线基本吻合。将总的输入功率按一定比例分配, 此时总热流等于表面热流与体积热流两者之和。

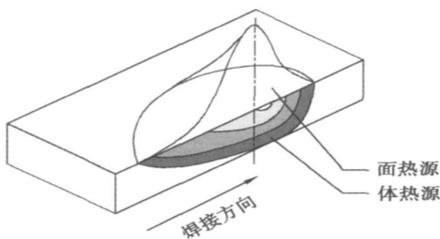


图3 组合热源模型

Fig. 3 Combined heat source model

面热源与体热源的总功率之和与焊接的有效功率 Φ 相等, 即

$$\Phi_s + \Phi_w = \Phi \quad (4)$$

式中: Φ_s , Φ_w 分别为面热源和体热源的功率。将面热源功率所占总有效输入功率的比例系数称为功率分配系数, 用 γ 来表示, 则有

$$\Phi_s = \gamma\Phi, \quad \Phi_w = (1-\gamma)\Phi \quad (5)$$

所构造的模型功率分配系数 γ 为 1/3, 得到了温度场的分布形状符合经典理论^[8], 即 Φ_s 占总功率的 33.3%, Φ_w 占总功率的 66.6%。能量分配系数表征了焊缝横截面上沿深度方向能量沉积的分布规律, 它直接决定了焊缝的深宽比, 这样也就基本决定了焊缝截面形貌特征。

2 有限元模型的建立

研究中模拟焊接试板采用两块 400 mm × 300 mm × 60 mm 规格的 13-5 (0Cr13Ni5Mo) 马氏体不锈钢钢板焊接而成, 试板四周采用窗形约束。两块试板采用马氏体型 HS135 填充材料进行焊接, 其化学成分如表1所示。

表1 材料的化学成分(质量分数, %)

Table 1 Chemical composition of material

材料	C	Si	Mn	S	P	Cr	Ni	Mo
0Cr13Ni5Mo	0.050	0.44	0.56	0.005	0.021	13.98	4.77	0.64
HS135	0.040	0.53	0.61	0.005	0.018	13.18	4.89	0.53

焊接工艺参数为: 焊接电流 200~280 A, 电弧电压 22~32 V, 焊接速度 15~45 cm/min, 焊前预热 100 °C, 层间温度不大于 150 °C。焊接材料热物理参数如表2所示。

表2 材料性能参数

Table 2 Performance parameters for material

温度 $T/^\circ\text{C}$	弹性	屈服	比热容 $c/$	热导率 $\lambda/$	线膨胀系数 $\alpha/ (10^{-5} \text{ } ^\circ\text{C}^{-1})$
	模量 E/GPa	强度 R_{d1}/MPa			
30	210	550	461	68	1.55
200	198	497	514	58	1.65
400	184	442	546	50	1.75
600	165	385	559	45	2.01
1 000	115	322	570	41	2.33
1 400	61	26	576	40	2.40

2.1 几何模型的建立

中厚板多道焊的物理模型, 采用 K 形坡口形

式, 焊接的顺序是正面两道焊接后翻转清根再进行反面焊接, 如图 4 所示.

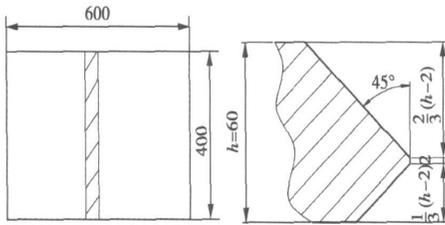


图 4 焊接平板几何模型 (mm)

Fig. 4 Schematic of weld geometric model

2.2 网格划分

焊接过程是一个不均匀加热的过程, 在焊缝处温度梯度变化很大. 划分网格时采用的是不均匀网格划分, 在焊缝及其附近的部分采用加密的网格, 在远离焊缝的区域, 温度分布梯度变化相对较小, 网格划分较粗, 网格划分结果如图 5 所示.

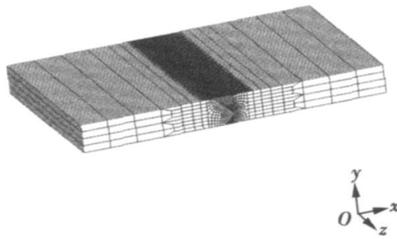


图 5 模型网格划分示意图

Fig 5 Elements mesh of model

2.3 数值模拟

焊接模拟要通过热力耦合计算. MARC 软件计算焊接温度和应力场时有两种处理方法: 一种被称为间接耦合, 即首先进行热传导分析, 得到焊接过程中的温度场分布, 再将求得的节点温度作为载荷施加在同一几何模型上进行应力分析; 另一种是直接进行耦合分析, 此时采用的单元具有温度和位移两种自由度, 分析计算完成后同时得到温度场和应力应变场. 文中采用直接耦合方法进行计算.

2.4 “生死”单元技术

在中厚板对接焊过程中, 焊接材料不断填充而形成焊缝, 这一过程可以通过 MARC 中“生死”单元技术体现. 前处理时将这些单元杀死, MARC 中将单元杀死并不是真正将这部分单元移走, 而是将它们的热传导系数变为很小的值, 在保证刚度矩阵稳定的前提下, 将这部分单元的作用减至最小, 这样在

实际计算中就相当于这部分单元不存在. 在焊接过程中再按一定的速度逐步将这部分单元激活. 即将它们的热传导系数恢复原值, 相当于这部分材料被逐步填充入焊道. 激活的判断标准为方盒子法.

3 对接焊数值模拟及其结果分析

3.1 温度场结果分析

高斯热源、双椭球热源、组合热源在 31.5 s 时的热源模型及温度场结果, 如图 6 所示.

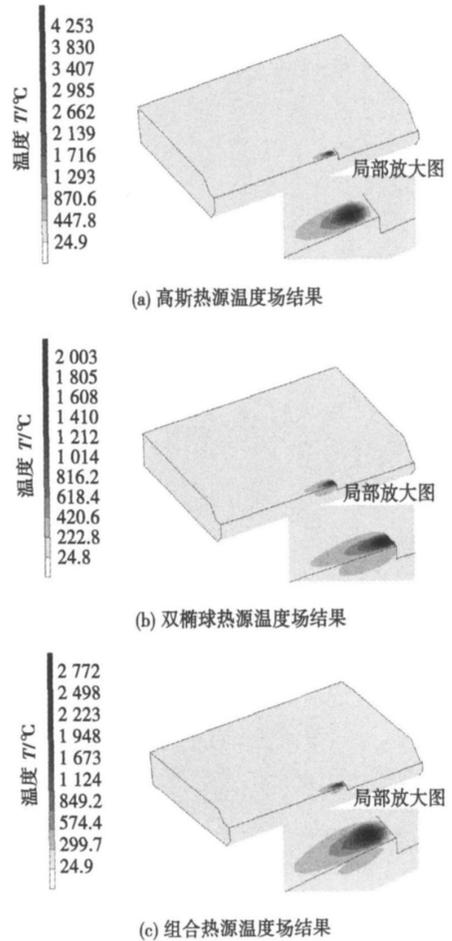


图 6 焊接过程温度场

Fig 6 Distribution temperature field

当选用高斯热源时温度场分布范围小, 局部温度过高, 表面最高温度达到 4 253 °C, 且只在表面加热, 坡口底部的部分单元都没有被加热而只是通过热传导升温; 双椭球热源将热量平均施加在焊缝上, 导致温度场的分布范围大, 最高温度偏低, 最高温度为 2 003 °C. 组合热源的温度场的分布范围和最高温度都介于高斯面热源和双椭球体热源之间,

最高温度为 2 772 °C, 既考虑到电弧对母材的加热, 又考虑到焊缝坡口形式对温度场的影响. 运用组合热源来模拟中厚板平板对接电弧焊接热源. 根据坡口的形状选择表面热源和体热源的能比, 体现坡口形式对温度场的影响, 更符合电弧焊的传热特点, 得到的温度场更符合实际情况.

3.2 应力场结果分析

利用盲孔法在焊后的试板上进行应力的测试. 应力测量装置是机械工业部郑州研究所生产的 YC—II 型应力测量仪.

焊后应力测量位置沿垂直焊缝方向共测 15 个点, 如图 7 所示, 其中点 7 位于焊缝区域, 点 1 到点 6 位于试板 1 上, 从焊缝到距焊缝 120 mm 的区域且距离平均分配. 点 8 到点 15 位于试板 2 上, 分布同点 6 至点 1.

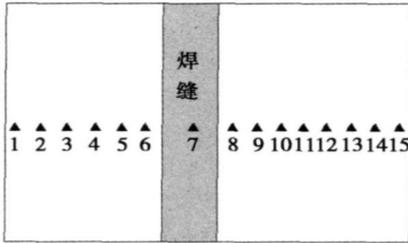


图 7 焊后应力测量位置分布图

Fig 7 Measurement position of residual stress

图 8 可以看出三种热源模型下得到的焊接件上表面残余应力趋势一致, 残余应力最高点均接近焊缝中心. 计算所得到的残余应力值均小于实测值, 这是因为计算所采用的参数中常温屈服强度为该材料的标准值 550 MPa, 试板经残余应力测试后取样得到的屈服强度为 648 MPa, 由于屈服强度的差异

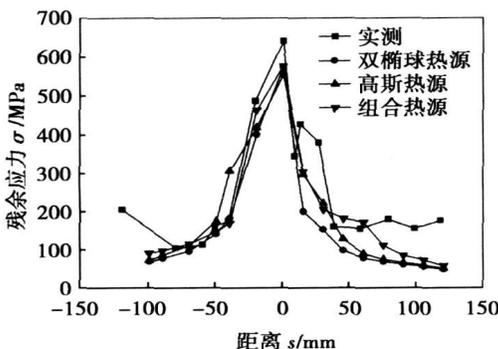


图 8 沿垂直焊缝方向表面残余应力随距离变化曲线

Fig. 8 Curve of transverse residual stress changing with distance

造成了计算值低于测试值. 采用双椭球热源计算得到的表面高应力分布区域更窄一些, 而采用高斯热源计算得到的表面应力集中程度较低, 采用组合热源模型的计算结果介于二者之间. 三种热源模型下的温度场分布状况不同, 高斯热源在表面能量分布较宽; 双椭球热源将热量分布施加在焊缝上, 能量分布在熔深方向较大而表面分布较窄; 组合热源的焊接温度场的分布范围和最高温度都介于高斯面热源和双椭球体热源之间, 既考虑到电弧对母材的加热, 又考虑到焊缝坡口形式对温度场的影响, 表现在表面残余应力分布的情况如图 9 所示.

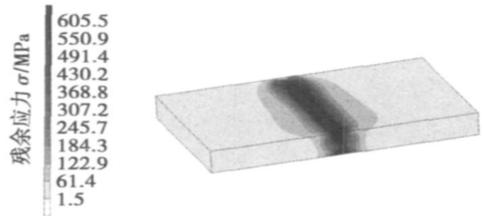


图 9 焊后残余应力分布云图

Fig 9 Distribution of residual stresses

4 结 论

(1) 以高斯面热源和双椭球体热源两种类型热源相结合构造了组合热源模型. 模拟的最高温度为 2 772 °C, 熔池形状与实际焊接温度场相符.

(2) 分别采用高斯热源、双椭球热源以及组合热源仿真的应力场与试板实测的残余应力的分布均基本符合. 组合热源所得到的应力分布在最大值以及高应力区分布与实测值吻合度更高, 可以为焊接工艺参数的选择提供依据.

(3) 模拟焊接温度场及残余应力场表明所构造的组合热源模型能够较准确地反映焊接实际.

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acteristic harmonic

Intelligent inspection of soldered joint based on artificial neuron network

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Abstract As electronic components get smaller and the board densities become more compact, it is necessary for automatic inspection in electronic manufacturing. The automatic optical inspection (AOI) system is demanded more precise and intelligent. The traditional inspection methods require large quantity samples of all types to train the inspector, or do some complicated setting. To overcome the disadvantages, an intelligent method was proposed. Firstly, a series of features of soldered joints were defined. Then, an automatic boundary setting method based on statistic was introduced. Finally, the neural network was established to classify the soldered joints. The performance of the method was verified by the experiment.

Key words: solder joint; neural networks; machine vision; inspection

Application of combined welding heat source in arc welding simulation

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Abstract: Factors of various welding heat sources were analyzed. It is found that Gaussian heat source and double ellipsoidal heat source can not indicate welding molten pool exactly in weld simulation. The combined welding heat source which combined Gaussian face heat source with double ellipsoidal body heat source was used in welding simulation. The welding molten pool calculated with the combined welding heat source consists with practice fusion line. The temperature field and stress field of stainless steel by arc welding were simulated with these three kinds of welding heat sources. The residual stress field simulated using the combined welding heat source is in good agreement with test and more exactly than those using the other two heat sources.

Key words: simulation; combined heat source; residual stress

Microstructure and high temperature abrasion resistance of Ni-based WC composite layer deposited by plasma arc

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Abstract: The Ni-based alloy powder with 60% WC was deposited on the surface of 15CrMo by plasma arc surfacing. The microstructures, hardness and wear resistance of the layer were analyzed. The results show that the layer has good external appearance and the WC particles which maintain its high hardness and exhibit few refusion distributes uniformly across the section of the layer. The layer also has high hardness and wear-resistance at elevated temperature, which is 5 times than that of 45 normalized steel.

Key words: plasma transferred-arc; WC particle; microstructure; wear-resistance at elevated temperature

Effect of Ag and Ni on melting temperature and spreadability of Sn-Sb-Cu solder alloy

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Abstract In order to improve the properties of the Sn-10Sb-8Cu solder alloy, two new lead-free solders (Sn-Sb-Cu-Ag and Sn-Sb-Cu-Ni) were made by adding small amounts of Ag and Ni into Sn-10Sb-8Cu solder alloy. Results show that the melting temperatures of the Sn-Sb-Cu-Ag solder alloys decrease and the spreading areas increase compared with those of the matrix solders, which are related to the increase of the superheat degree, the dispersed distribution of SnAg phase with low melting point and the decrease of the surface tension of the melting solder. The melting temperatures of the Sn-Sb-Cu-Ni solder alloys decrease and the spreading areas of the Sn-Sb-Cu-Ni solder alloys are slightly less than those of the matrix solders. It is because the viscous and the surface tension of the Sn-Sb-Cu-Ni melting solder increase and the Cu₆Sn₅ is covered by the polyhedron-shape (Cu, Ni)₆Sn₅ which is adverse to the spreadability of the solder by adding small amount of Ni.

Key words: Sn-Sb-Cu alloy; lead-free solder; melting temperature; spreadability

Numerical simulation on temperature field in on-site induction brazing of tubes

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Abstract Considering the characteristics of on-site induction brazing of tubes, the FEM model was built. Based on the electromagnetic and thermal coupled finite element method, the temperature distribution on tubes was simulated by ANSYS. The results show that temperature distribution on tubes is nonuniform. Using a six-point synchronous temperature measurement system with thermocouples,