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覆材厚度对不锈钢复合板焊接接头应力应变影响的数值模拟分析

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摘要：采用钨极气体保护焊 (gas tungsten arc welding, GTAW) 制备了基材厚度为 13 mm, 覆材厚度分别为 0.3, 1.0, 2.0 mm 的 304/Q355 复合板焊接接头. 采用数值模拟法, 分析了覆材厚度对 304/Q355 复合板焊接接头应力应变的影响, 揭示了不同覆材厚度的不锈钢复合板焊接过程中残余应力及应变的演变特征. 结果表明, 随着覆材厚度的增加, 304/Q355 复合板焊接接头截面区最大残余应力逐渐减小, 残余应力区宽度逐渐增大, 在基层焊缝向过渡层焊缝焊接过程中, 应力集中区逐渐向过渡层焊缝区收缩, 最高应力集中区均位于过渡层焊缝区, 最大应力接近材料屈服强度. 焊后变形量随覆材厚度的增加而增大, 覆材厚度 2.0 mm 的复合板变形量比覆材厚度 0.3 mm 的复合板变形量大约 2 mm, 变形最大的方向为焊缝厚度方向.

创新点：(1) 通过数值模拟方法详细分析了不同覆材厚度的 304/Q355 复合板焊接接头应力应变分布.
(2) 通过应力应变场分析结果, 阐明了不同覆材厚度的 304/Q355 复合板焊接接头应力应变演变特征.

关键词：覆材厚度; 复合板; 应力应变; 数值模拟

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0　序言

随着现代工业不断推进, 金属板材应用工况愈发复杂, 单一金属板材已无法满足多元化的服役要求, 发展趋势从单一性能向着综合性能方向发展[1-3], 双金属复合材料是通过各种复合工艺将热物理、力学等性能不同的金属结合, 兼具两种金属的优异性能[4-5], 既满足工业上对结构与性能需求, 也可以削减材料成本, 因而在汽车、石油化工、能源等领域得到广泛的使用. 不锈钢复合板具有耐腐蚀、高强度、性价比高等优点, 目前被广泛应用于装备制造领域[6], 焊接是重大装备的关键加工技术, 因此成为金属复合材料应用的关键制造技术. 焊缝金属由基层焊缝、覆层焊缝、过渡层焊缝组成[7], 3 层焊缝金属间化学成分、热物理性能差异较大, 易产生焊接应力与应变, 应力应变是影响焊接接头质量的重要因素, 焊接区域附近过大的残余应力及应变, 通常是焊接接头失效的直接原因[8], 而复合板覆材厚度与其焊缝成分及应力、应变有关系, 因此研究复合板覆材厚度对其焊接接头应力与应变的影响, 具有重要工程实际意义[9-11].

采用 304/Q355 复合板为研究对象, 采用钨极气体保护焊制备了基材厚度为 13 mm, 覆材厚度分别为 0.3, 1.0, 2.0 mm 的复合板焊接接头. 利用数值模拟与试验相结合的手段研究了复合板焊接接头表面残余应力, 分析了不同覆材厚度对 304/Q355 复合板焊接接头应力应变的影响, 揭示了不同覆材厚度的不锈钢复合板焊接过程中残余应力及应变的演变特征, 研究结果为不锈钢复合板焊接接头应力应变的控制和优化提供理论参考.

1　试验方法

焊接过程分基层、过渡层、覆层 3 层焊接, 基层焊缝填充材料为 ER50-6, 过渡层焊缝填充材料为 ER309, 覆层焊缝填充材料为 ER308, 母材及焊接

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填充材料化学成分见表 1, 焊接工艺参数见表 2. 试验选用 304/Q355 双金属复合板作为模型材料, 基材 Q355 厚度均为 13 mm, 覆材 304 厚度分别为 0.3,1.0,2.0 mm(A 组模型, B 组模型, C 组模型), 试板尺寸为 300 mm × 200 mm, 焊接坡口形式 V 形, 如图 1 所示.

表 1 母材和焊材的化学成分 (质量分数，%)

Table 1 Chemical composition of base material and welding materials

材料	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	N
304	0.08	1.00	2.00	0.045	0.03	8.00	18.00	—	—	0.1
Q355	0.2	0.55	1.60	0.025	0.025	0.30	0.30	—	0.40	—
ER308	0.08	1.00	0.50	0.040	0.03	7.00	22.00	0.75	0.75	—
ER309	0.15	1.00	0.5	0.040	0.03	12.00	18.00	0.75	0.75	—
ER50-6	0.105	0.975	0.163	0.015	0.013	0.016	—	0.06	—	—

表 2 焊接工艺参数

Table 2 welding parameters

焊缝道次	焊接电流 I/A	电弧电压 U/V	焊接速度 v/(mm·s^{-1})	适用模型
①～③	100～140	8～10	2	A/B/C
④～⑤	150	12～15	2	A/B/C
⑥～⑦	135	8～11	2	C

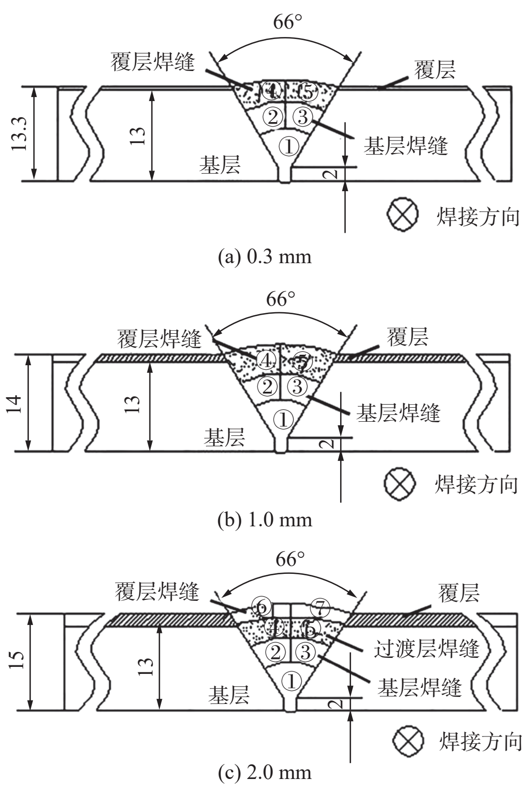


图 1 不同覆材厚度的坡口形式及焊道布置 (mm)

Fig. 1 Groove form and pass arrangement. (a) 0.3 mm; (b) 1.0 mm; (c) 2.0 mm

2 有限元计算方法

利用 ANSYS 软件, 基于有限元理论建立 304/Q355 不锈钢复合板模型, 按照上述焊接工艺进行模拟, 根据焊接时所用材料和模型确定材料性能参数、热边界条件和约束条件, 模拟温度场并将温度载荷通过间接耦合的方式传输到应力场, 从而研究应力应变场的规律.

2.1 模型建立及网格划分

建立的有限元模型如图 2 所示, 在设计网格划分时, 网格密度与计算精确度呈现正相关, 网格越密集, 其结果越精确, 在保证计算结果精度前提下, 对远离焊缝区域网格划分相对稀疏. 利用 Hypermesh 软件将模型网格划分成焊缝处较密, 母材处相对稀疏的形式, 二者之间利用笛卡尔网格划分方式进行疏密过渡, 由于需要计算不同场的结果, 不同网格适应的不同物理场自由度. 在 ANSYS 软件中, 计算温度场使用 Plane55 单元或 Solid70 六面体单元, 应力场使用 Plane55 和 Solid45 六面体单元, 图 2 为 3 种模型的网格划分, 上述网格划分的单元总数分别为 32 200、28 840 和 27 580, 在 3 个有限元计算模型中使用了三点自由约束的形式, 如图 3 所示.

2.2 材料模型

焊接过程是典型的非线性瞬态分析, 在进行温度场分析需要的参数有热导率 (thermal conductivity)、密度 (density)、比热容 (specific heat), 进行应力场分析则需要的参数有屈服强度 (yield strength)、热膨胀系数 (thermal expansivity)、泊松比

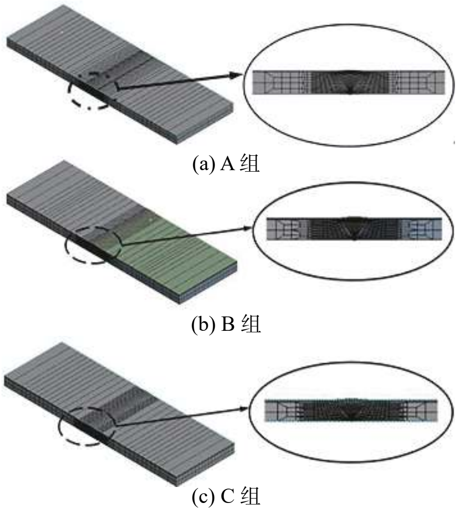


图 2　网格划分模型及局部放大

Fig. 2　Meshing model and local magnificatio. (a) A; (b) B; (c) C

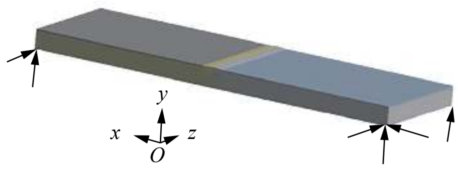


图 3　约束条件

Fig. 3　Constraints condition

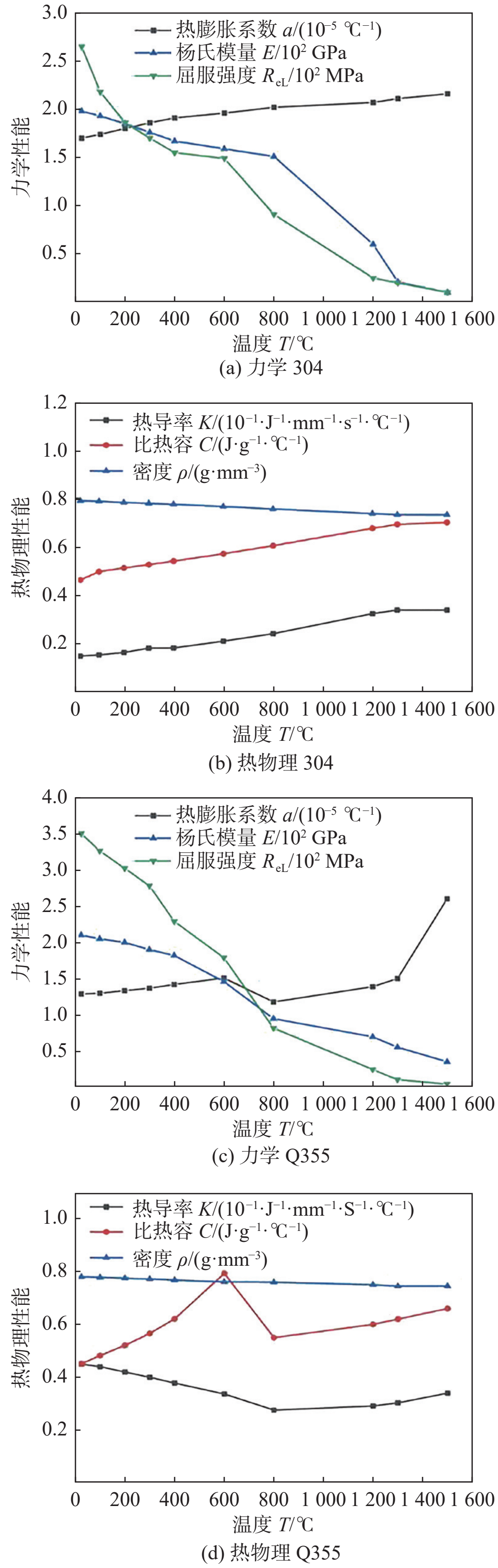


图 4　304 和 Q355 力学—热物理性能参数

Fig. 4　Mechanical — thermophysical performance parameter of Q355 and 304. (a) mechanical 304; (b) thermal physics 304; (c) mechanical Q355; (d) thermal physics Q355

(poisson's ratio) 和弹性模量 (young's modulus). 由于部分材料在高温时处于熔化状态，其高温下的物理性能较难测量，对于 304 奥氏体不锈钢需要考虑加工硬化和退火软化[12-14]. 通过 JMatProV7.0 软件计算材料性能参数，304 和 Q355 合金随温度变化的热物理性能和力学性能参数如图 4 所示，初始温度为 25 ℃，泊松比设置为恒定值 0.3，切线模量设为杨氏模量的 1/10.

2.3　温度场计算

采用 Goldak 双椭球体热源来模拟各单条焊道的焊接过程，热流分布包括前后两个部分

$$q_f(x,y,z)=\frac{6\sqrt{3}f_fQ}{a_fbc\pi\sqrt{\pi}}\exp\left(-\frac{3x^2}{a_f^2}-\frac{3y^2}{b^2}-\frac{3z^2}{c^2}\right) \tag{1}$$

$$q_r(x,y,z)=\frac{6\sqrt{3}f_rQ}{a_rbc\pi\sqrt{\pi}}\exp\left(-\frac{3x^2}{a_r^2}-\frac{3y^2}{b^2}-\frac{3z^2}{c^2}\right) \tag{2}$$

式中：x, y, z 为热源中心为原点的横、纵、竖坐标值；b, c 为形状参数；a_f, a_r 为前，后半轴圆长轴；Q 为有效热输入；f_f 和 f_r 分别是熔池前部和后部总输入功率的能量分布系数为 1.4 和 0.6. 双椭球热源模型如图 5 所示[15].

焊接过程中，复合板内部的热量传递以热传导为主，而复合板表面与周围环境介质的热量传递则以热辐射和热对流为主，其中，在焊缝周围热辐射

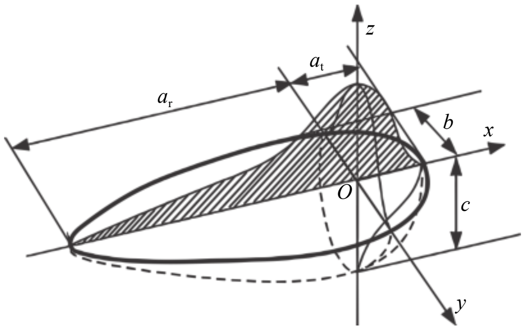


图 5 双椭球热源模型

Fig. 5 Double ellipsoidal heat source model

损失占主要地位，而远离熔池的母材区域热对流则占主导地位[16-17].

(1) 热对流系数：指的是物体间相互接触，表面温度传递一种能力，一般而言，焊接填充材料与母材的热对流可采用考虑下式，即[18]

$$q_c = -h_c(T_s - T_0) \tag{3}$$

式中：h_c 为热对流系数为 15 W/(m^2·℃)；T_s 为复合板的表面温度；T_0 为环境温度为 25 ℃.

(2) 热辐射系数：高于−273.15 ℃ 的物体均对外产生辐射，随着温度升高辐射能量也增强，表示辐射能量的能力就是热辐射系数.

$$h_r = \sigma\varepsilon F\left(T^2 + T_r^2\right)(T + T_r) \tag{4}$$

$$q_r = -\sigma\varepsilon F\left\{(T_s+273)^4 - (T_0+273)^4\right\} \tag{5}$$

式中：q_r 为热流密度；σ 为斯蒂芬—玻尔兹曼常数 (5.64×10^{-14} J/mm^2·s)；ε 为辐射发射率 0.85；F 为配置因子；h_r 为对流系数；T_r 为辐射温度；T 为瞬时温度；T_s 为复合板表面温度；T_0 为环境温度.

2.4 应力场计算

基于热弹塑性理论研究焊接应力场需遵循 Von Mises 屈服准则和流动准则，将温度载荷导入应力场中，并以热应变的形式来计算应力应变，一般情况下，每个材料节点的总应变，即

$$\varepsilon = \varepsilon^{\varepsilon} + \varepsilon^{p} + \varepsilon^{th} \tag{6}$$

式中：弹性应变$\varepsilon^{\varepsilon}$遵循 Hookean 定律；塑性应变$\varepsilon^{p}$为各向同性硬化模型；$\varepsilon^{th}$ 为热应变.

根据 Hookean 定律，弹塑性应力应变关系为

$$\{d\sigma\} = [D]\{d\varepsilon\} - \{C\}dT \tag{7}$$

式中：$[D]$ 为弹塑性矩阵；$\{C\}$为温度相关向量；$\{d\sigma\}$为内应力增量；$\{d\varepsilon\}$为塑性应变增量；dT 为单位时间.

根据各节点和单元的状态，将集中节点力与位移载荷为总刚度矩阵与总载荷量，平衡方程式为

$$K\{d\sigma\} = \{dF\} \tag{8}$$

式中：K 为总刚度矩阵；$\{dF\}$为载荷总量；$\{d\sigma\}$为位移载荷矩阵.

总载荷量表达式为

$$\{dF\} = \sum(\{dF\}^e + \{dR\}^e) \tag{9}$$

式中：$\{dR\}^e$为等效节点力的增量，当不存在外部载荷条件时，每个单元内节点力相互平行，即 $\Sigma\{dF\}^e = 0$，$\{dF\} = \Sigma\{dR\}^e$；$\{dF\}^e$为等效节点载荷增量；$\{dF\}$为载荷总量.

基于上述理论计算焊接残余应力，将模型整体划分网格，通过各节点温度，将温度载荷导入应力场，这种方法因不考虑材料的相变应力，具有计算精度高，收敛性好的优点，既简化了模型，也可以得出相对精确的结果. 通过式 (10) 能够求出节点的位移增量$\{d\delta\}$，得到应变—位移方程如下

$$\{d\varepsilon\}^e = [B]\{d\delta\}^e \tag{10}$$

式中：$\{d\varepsilon\}$为等效节点塑性应变增量；$[B]$ 网格的个数矩阵；$\{d\delta\}^e$ 为节点的位移增量，把式 (10) 代入式 (7) 中计算出应力增量，来求解其应力应变过程.

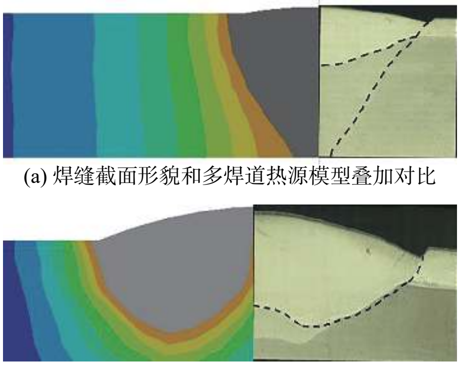
3 结果与讨论

3.1 熔池形貌

为验证所建立的有限元模型和采用的热源模型的准确性，采用覆材厚度为 1.0 mm 的 304/Q355 复合板温度场进行验证，图 6 为焊缝截面形貌和多焊道热源模型叠加对比，及盖面截面形貌和单道热源模型对比，可见熔池形貌与实际焊缝相近，说明经过校核的双椭球热源模型是合理准确的.

3.2 残余应力分析

图 7 为覆材厚度为 0.3, 1.0, 2.0 mm 的 304/Q355 复合板的残余应力分布. 可知，304 侧横向残余应力最大值位于焊趾处，呈对称分布，覆材厚度从 0.3 mm 增大到 2.0 mm 时应力变化不大，纵向残余应力在焊缝及热影响区应力均较高. 覆材 304 侧横向应力远低于纵向应力，说明焊接过程，接头受到的横向拘束比纵向拘束小，这是由于在垂直于焊缝方向上，焊缝和热影响区在加热冷却后，受到周围温度较低金属的拘束，在局部区域产生很大的横向及纵向残余应力，而在垂直于焊缝方向 (纵向)，由于覆材 304 的室温屈服强度比 Q355 低约



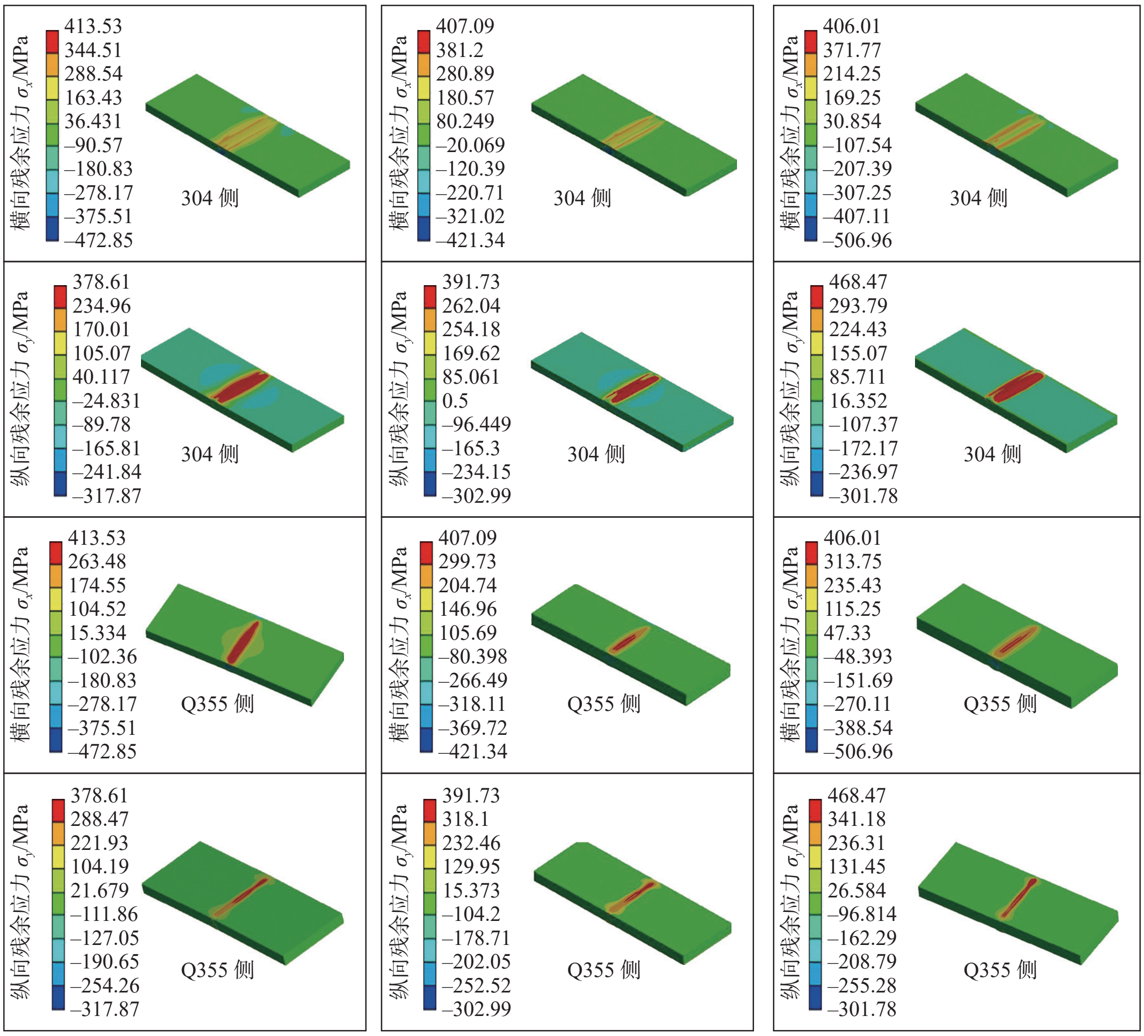
(a) 焊缝截面形貌和多焊道热源模型叠加对比

(b) 盖面截面形貌和单道热源模型对比

图 6　模拟熔池与实际熔池形貌对比

Fig. 6　Comparison of simulated melt pool with outual-melt pool morphology (a) superimposed comparison of macroscopic morphology of weld section and multi-pass welding; (b) comparison between simulation results of cover welding and macroscopic morphology of weld section

131%,而其线膨胀系数却是 Q355 的 170%,在加热过程中具有较强的塑性变形趋势,但在冷却过程会受到 Q355 材料的强烈约束,覆材 304 和基材 Q355 之间巨大的热物理性能的差异,使焊接加热冷却后,覆材 304 侧纵向残余应力较大. 而 304 侧横向未受到异种材料物理性能差异的影响,因此表现出的应力较低,但热影响区两侧应力较高,这是由于热影响区在加热冷却后受到周围温度较低金属的拘束作用产生. 304 侧纵向残余应力随覆材厚度的增加,焊缝两端应力减小,这可能有两方面原因:①焊缝两端为自由端,在焊接冷却收缩过程中受到的约束减小;②随着覆材厚度的增加,受到基材和覆材热物理性能差异的影响减小. Q355 表面最大纵向和横向残余应力均分布在焊缝及其热影响区,这是由于坡口形式为 V 形,坡口根部位于 Q355 侧,Q355 侧焊缝较窄,因此焊缝残余应力宽



(a) 0.3 mm　　(b) 1.0 mm　　(c) 2.0 mm

图 7　不同覆材厚度复合板残余应力

Fig. 7　Residual stress distribution of composite plate with different thickneos of cladding matericaI. (a) 0.3 mm; (b) 1.0 mm; (c) 2.0 mm

度相对 304 侧较窄, 焊缝横向残余应力高于纵向残余应力, 说明 Q355 侧焊缝受到的横向拘束比纵向拘束大.

在焊缝中间垂直焊缝方向上, 作一截面观察复合板焊接过程, 每一道焊缝截面的残余应力分布如图 8~图 10 所示. 覆材厚度 0.3 mm 的 304/Q355 复合板接头横截面见图 8, 可见随着焊接道次的增加, 等效应力分布范围越来越宽, 在焊接过程中, 近焊缝区由于受热影响大, 产生的热应力较大, 远离焊缝的母材受热影响较小, 热应力较低. 在冷却过程中, 受热部位冷却收缩大, 所以在焊缝及近缝区应力较大; 覆材厚度 1.0 mm 的复合板焊接横截面见图 9, 其中第一道焊缝、第二道焊缝、第三道焊缝焊后最大等效应力约为 340 MPa, 第四道焊缝、第五道焊缝焊后最大等效应力约为 355 MPa, 与材料屈服强度相接近, 同时, 不同道次的焊缝横截面应力最大均集中在焊缝中间部位; 覆材厚度 2.0 mm 的 304/Q355 不锈钢复合板焊缝横截面应力见图 10,

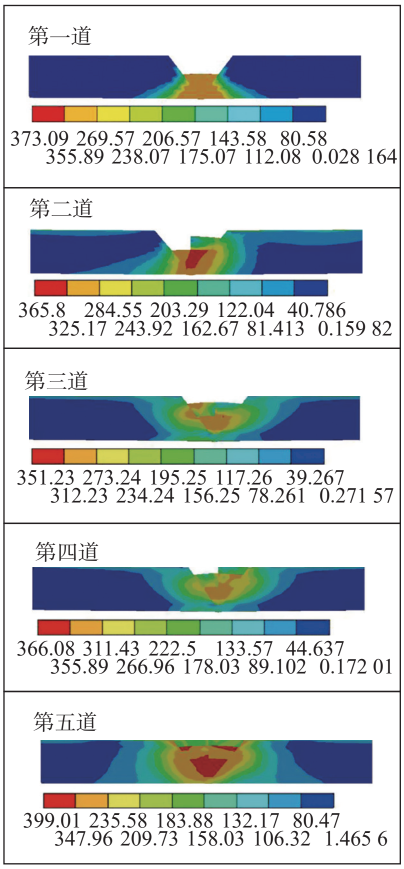


图 8 覆材厚度 0.3 mm 的 304/Q355 不锈钢复合板焊缝横截面应力云图 (MPa)

Fig. 8 Stress cloud diagram of weld section of 304/Q355 stainless steel composite plate with 0.3 mm thickness of cladding material

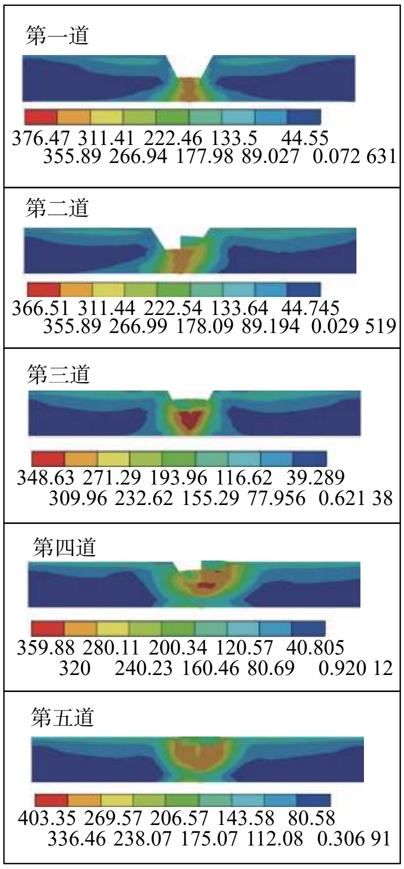


图 9 覆材厚度 1.0 mm 的 304/Q355 不锈钢复合板焊缝横截面应力云图 (MPa)

Fig. 9 Stress cloud diagram of weld section of 304/Q355 stainless steel composite plate with 1.0 mm thickness of cladding material

由于 304 和 Q355 两种材料的物理和化学性能不同, 在焊接加热的过程中, 其冷却和受热速率不同, 在两种材料的交界处存在着应力不连续的情况, 可以看到, 每道焊缝横截面的最大应力均在材料的屈服强度附近. 总体观察, 从基层焊缝到覆层焊缝焊接过程, 焊缝截面应力集中区逐渐向过渡层焊缝区收缩.

此外, 观察复合板焊接最终状态的截面残余应力分布特征可以发现, 3 种不同覆材厚度的复合板焊接接头的残余应力分布特征类似, 最大残余应力均集中在过渡层焊缝内, 这与其他研究报道的坡口形式对双金属复合板多层多道焊接头残余应力分布特征一致[19-22], 主要是由于碳钢和不锈钢热膨胀系数差别大, 304 不锈钢热膨胀系数是 Q355 低合金高强钢的 170%, 同时由于多层多道焊, 中间部位的温度传递主要通过金属间的热传导, 能通过空气对流等方式的区域少, 由于这些原因, 该区域等效应力较高, 而高应力集中对于复合板的安全服役存

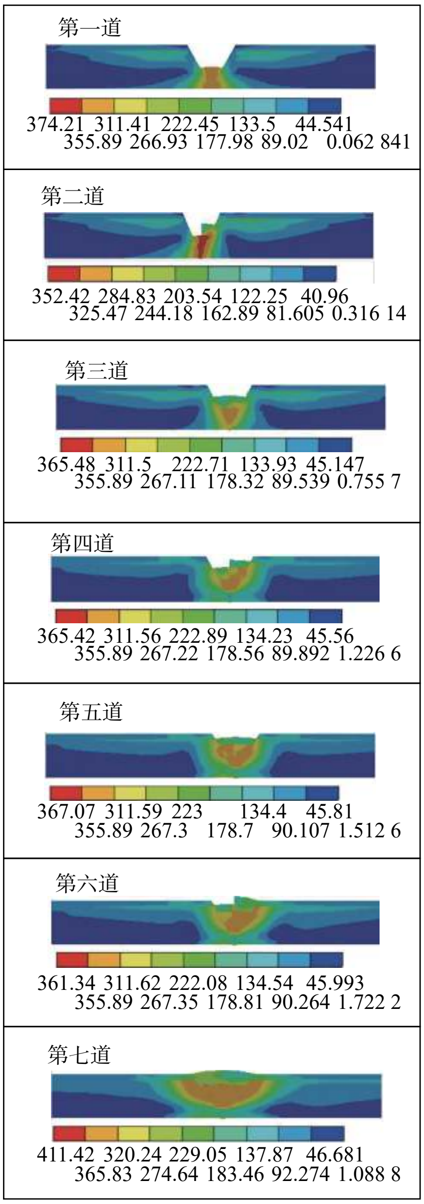


图 10　覆材厚度 2.0 mm 的 304/Q355 不锈钢复合板焊缝横截面应力云图 (MPa)

Fig. 10　Stress cloud diagram of weld section of 304/Q355 stainless steel composite plate with 2.0 mm thickness of cladding material

在巨大的隐患,另外观察最后一道焊缝焊接完成后,全厚度焊缝截面的应力分布,可知随着覆材厚度的增加,复合材料界面位置的应力逐渐降低.

3.3　残余变形分析

焊接残余变形一般可分为纵向收缩变形、横向收缩变形、弯曲变形、角变形、波浪变形、错边变形、扭曲变形 7 类. 在焊接过程中,焊接变形使得部分残余应力得到释放,但变形会影响到工件的尺寸精度,所以研究焊接变形很有必要[23-24].

图 11 是不同覆材厚度下的复合板焊接残余变形模拟结果. 可以看出,焊接残余变形最大的区域位于焊缝及其热影响区处,其中覆材厚度为 0.3 mm 的复合板变形区间为 0 ~ 4.67 mm,覆材厚度为 1.0 mm 的复合板变形区间为 0 ~ 6.4 mm,覆材厚度为 2.0 mm 的复合板变形区间为 0 ~ 7.02 mm,随着覆层厚度的增大,焊接残余变形也随之增大.

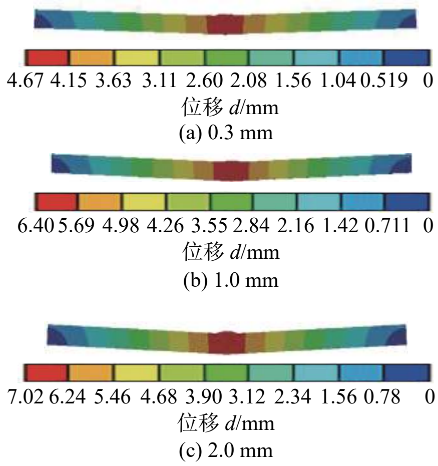
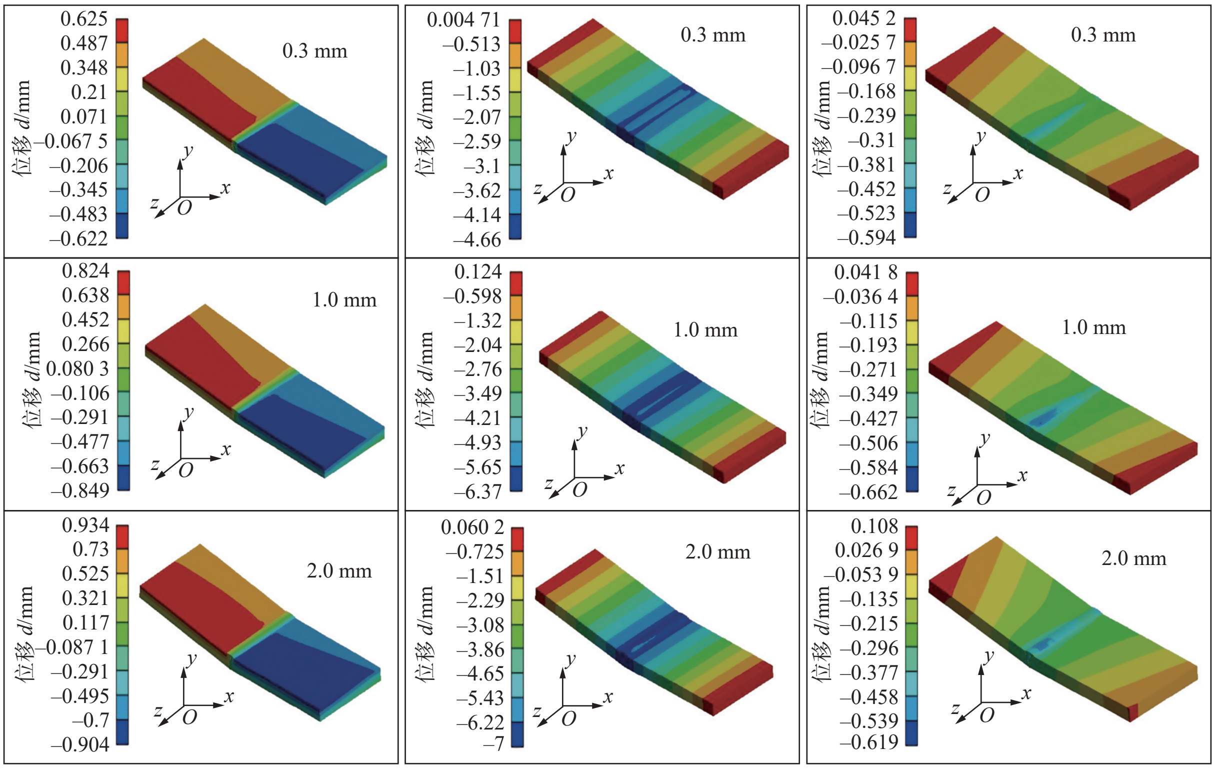


图 11　不同覆材厚度复合板总变形对比

Fig. 11　Comparison of total deformation of composite plates with different thickness of cladding material. (a) 0.3 mm; (b) 1.0 mm; (c) 2.0 mm

图 12 为 x, y, z 方向的焊后变形云图,可见 z 方向变形相对较小,但随着覆材厚度的增大,z 方向的变形量增大,这里横向收缩变形指 x 方向变形量和 y 方向变形量相互叠加后的变形量,覆材厚度为 0.3, 1.0, 2.0 mm 复合板焊接后在 x 方向的变形分别为−0.6 ~ 0.6, −0.8 ~ 0.8, −0.9 ~ 0.9 mm,由于约束形式是自由约束,所以在 x 方向变形基本呈现对称式分布,可见覆材厚度对 x 方向的焊接残余变形影响较小;在 y 方向的变形分别为−4.66 ~ 0.0, −6.37 ~ 0.12, −7.0 ~ 0.06 mm,可见覆材厚度对 y 方向的焊接残余变形影响较大;在 z 方向的变形分别为−0.59 ~ 0.04, −0.66 ~ 0.04, −0.62 ~ 0.10 mm,覆材厚度对 z 方向的焊接残余变形影响较小.

图 13、图 14 分别为不同覆材厚度的 Q355 及 304 表面垂直焊缝方向横向残余应力分布曲线. 从图 13 可以看到,Q355 表面垂直焊缝方向横向残余应力峰值均低于或近似于屈服强度,焊缝区域呈现拉应力,焊缝或焊趾处应力出现峰值. 随着离焊缝中心线距离越远,应力降低,在板边缘处应力值趋于零. 其中覆材厚度为 0.3 mm 的复合板应力峰值为 301 MPa,覆材厚度为 1.0 mm 的复合板应力峰值为 321 MPa,覆材厚度为 2.0 mm 的复合板应力



(a) x 方向 (b) y 方向 (c) z 方向

图 12 不同覆材厚度复合板 x，y，z 方向变形云图

Fig. 12 Deformation cloud image in x, y, z direction of composite plate with different thickness of cladding materical. (a) x; (b) y; (c) z

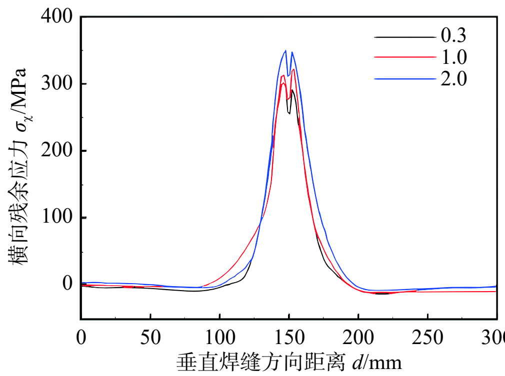


图 13 Q355 表面垂直焊缝方向横向残余应力分布

Fig. 13 Transverse residual stress distribution in the vertical weld direction of Q355 side

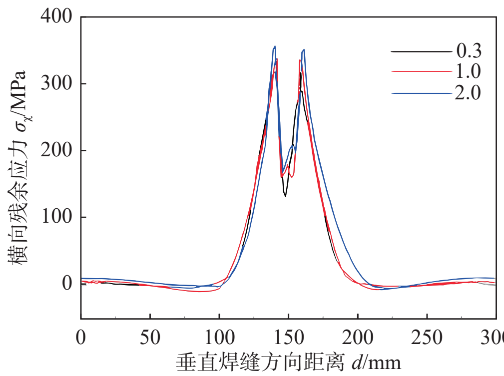


图 14 304 表面垂直焊缝方向横向残余应力分布

Fig. 14 Transverse residual stress distribution in the vertical weld direction of 304 side

峰值为 345 MPa，随着覆材厚度的增加，Q355 表面的应力也随之增大，其应力峰值接近材料屈服强度，这主要是因为材料自身性能的限制，以及多道焊的过程中，低合金高强钢表面为先焊区域，前道焊缝对后道焊缝有预热的作用，从而消除了材料的加工硬化的影响，使应力峰值在一个合理区间. 复合板两侧应力值趋于零，主要是由于横向和纵向收缩的叠加，而板边缘外侧应力得到释放，从而应力值趋于零.

图 14 可以看出，横向残余应力为驼峰状，驼峰宽度与覆层表面焊缝宽度接近，应力最大位于焊趾处，主要是由于母材和焊接填充材料的冷却过程不一致，从而形成强约束. 随着离焊缝中心距离越远，应力降低，在垂直于焊缝的模型边缘处应力趋近于零，在覆层厚度变化过程中，0.3 mm 和 1.0 mm 的热影响区宽度变化不明显，2.0 mm 的热影响区宽度相对较宽，这是因为同温度下 304 不锈钢的热导率远小于 Q355 的热导率（常温下 Q355 的热导率约为 304 的 3 倍），覆材厚度 2.0 mm 模型的焊接道次增多，热输入有明显增大. 此外，应力最大均出现

在驼峰处, 其中覆材厚度为 0.3 mm 的复合板应力峰值为 316 MPa, 覆材厚度为 1.0 mm 的复合板应力峰值为 338 MPa, 覆材厚度为 2.0 mm 的复合板应力峰值为 356 MPa, 随着覆材厚度的增大, 304 表面横向残余应力也随之增大.

3.4　试验结果与数值模拟结果对比和分析

采用无损检测 X 射线衍射法, 对覆材厚度 2.0 mm 的 304/Q355 复合板焊后表面残余应力进行测量, 与模拟值比较分析. 图 15为测量焊接残余应力的取点位置, 图 16 为实测值与模拟值的对比图. 通过对横向残余应力和纵向残余应力的实测值与模拟值比较可知, 实测值呈现中间区域为拉应力, 两边为压应力的特征. 对于横向残余应力, 在热影响区的测量值分布在模拟曲线附近, 说明实测值与模拟结果有较好的一致性. 在焊缝区, 测量值大部分点大于模拟值, 其中最大相差 95 MPa, 主要是由于在工业实际中焊缝区的材料屈服强度稍高于母材, 而在计算时对焊接填充的材料属性做了简化处理导致的. 对于纵向残余应力, 其最大误差为 11.6%, 最小误差为 1.12%, 其中最大差值也出现在焊缝区, 但就整体趋势而言, 实测值和模拟值拟合较好, 说明模拟值具有一定的参考价值.

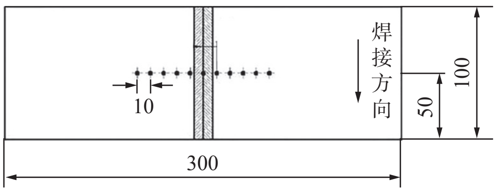


图 15　测量焊接残余应力的取点位置 (mm)

Fig. 15　Location of the point for measuring welding residual stress

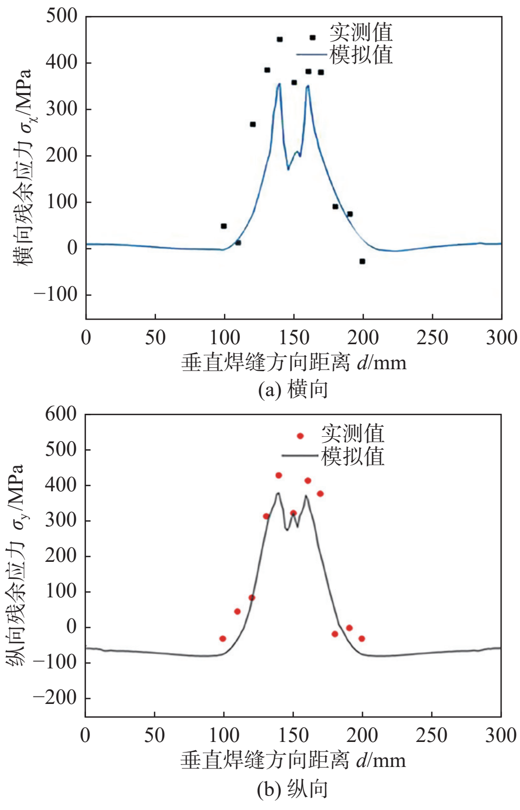


图 16　横向和纵向残余应力实测值与模拟值的对比

Fig. 16　Comparison of measured and simulated residual stress in horizontal and rertical. (a) horizontal; (b) rertical

4　结论

采用数值模拟与试验手段相结合的方法, 通过对比覆材厚度 1.0 mm 的 304/Q355 复合板焊后焊缝截面形貌和多焊道热源模型叠加, 及盖面截面形貌和单道热源模型, 模拟熔池形貌与实际焊缝形貌相近, 验证了经过校核的双椭球热源模型的准确性.

随着覆材厚度的增加, 304/Q355 复合板焊接接头截面区最大残余应力逐渐减小, 残余应力区宽度逐渐增大, 复合材料截面位置的应力逐渐减小, 在基层焊缝向过渡层焊缝焊接过程中, 应力集中区逐渐向过渡层焊缝区收缩, 最后最高应力集中区均位于过渡层焊缝区, 最大应力接近材料的屈服强度.

随着覆材厚度的增大, 焊接残余变形逐渐增大, 焊接残余变形最大的区域位于焊缝及其热影响区, 覆材厚度 0.3 mm 的复合板变形量为 0 ~ 4.67 mm, 覆材厚度 1.0 mm 的复合板变形量为 0 ~ 6.4 mm, 覆材厚度为 2.0 mm 的复合板变形量为 0 ~ 7.02 mm, 随着覆材厚度的增加, Q355 及 304 表面的应力随之增大, 其应力峰值接近材料屈服强度.

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parameters to achieve better droplet transfer.

Key words: droplet transfer; Swing arc; MIG welding; Narrow gap welding

Study on sensitization characteristics of TP347H stainless steel welded joints LI Chengan[1], FENG Daochen[1], ZHANG Lin[2], ZHENG Wenjian[1], CHENG Mao[3], LU Xianjing[3], YANG Jianguo[1](1. Zhejiang University of Technology, Hangzhou, 310014, China; 2. CFHI Dalian Nuclear Power and Petrochemical Equipment Co. ,Ltd. , Dalian 116113, China; 3. Zhejiang Academy of Special Equipment Science, Hangzhou, 310020, China). pp 64-72

Abstract: In order to clarify the sensitization characteristics of TP347H stainless steel welded joints, the welded joints were heat treated at different temperatures, and the changes of sensitization degrees at different temperatures were studied. The results showed that an obvious sensitization trend was observed in the heat-affected zone(HAZ) of welded joints. During the sensitization process, because the binding energy of Nb atoms on the grain boundary is higher than that of Cr atoms, coarse primary niobium carbon compounds are formed first, and then fine secondary niobium carbon compounds are formed. When the temperature is kept at 700 ℃, the sensitization degree of the HAZ of the welded joint shows a trend of first increasing and then decreasing. When the temperature reaches 800 ℃ and above, heat treatment no longer increases the sensitization degree of the HAZ of the joint. Comparing with the sensitization characteristics of F347H joints with 21 000 h in the actual production line, it is confirmed that the sensitization limit can be reached by holding the welded joints of TP347H at 650 ℃ for 100 h. The reason is that the content of Nb is several times that of C, most of C combines with Nb to form NbC, and the diffusion of C in the grain has been fully combined with Cr. The resulting sensitization reaches an equilibrium state.

Highlights: (1) Confirmed that TP347H stainless steel welded joint was heat treated at 650 for 100h can reach the sensitization limit.

(2) In the process of sensitization, because the binding energy of Nb atoms on the grain boundary is higher than that of Cr atoms, the coarse niobium carbon compound will be formed first, and then the fine niobium carbon compound will be formed.

(3) When the TP347H stainless steel welded joint was heat treated at 700 ℃, the sensitization degree in the theat affected zone of the welding joint shows a trend of increasing first and then decreasing.

Key words: TP347H stainless steel; sensitization; welded joint; heat treatment; corrosion resistance

Numerical simulation of the influence of thickness of cladding material on stress and strain of welded joint of stainless steel composite plate FENG Yulan, WU Zhisheng, SUN Zhiyu(Taiyuan University of Science and Technology, Taiyuan, 030024, China). pp 73-82

Abstract: GTAW technology has been used to fabricate welded connections on composite plates consisting of 304 and Q355 materials. Base material thickness was 13 mm, while cladding material thicknesses ranged from 0. 3 mm to 2. 0 mm. The influence of different thicknesses of cladding material on the stress and strain of 304/Q355 composite plate welded joint was analyzed by numerical simulation method, and the evolution characteristics of residual stress and strain during welding of stainless steel composite plate with different thicknesses of cladding material were revealed. The results show that the X-ray diffraction test results are in good agreement with the numerical simulation results. With the increase of the thickness of the cladding material, the maximum residual stress value of the welded joint section of 304/Q355 composite plate gradually decreases, and the width of the residual stress zone gradually increases. During the welding process from the base weld to the transition weld, the stress concentration zone gradually shrinks to the transition weld zone. Finally, the highest stress concentration area is located in the weld zone of the transition layer, and the maximum stress value is close to the yield strength of the material. In addition, the deformation after welding increases with the increase of the thickness of the cladding material, and the deformation of the composite plate with the thickness of the cladding material 2. 0 mm is about 2 mm higher than that of the composite plate with the thickness of the cladding material 0. 3 mm, and the direction of the largest deformation is the direction of the weld thickness.

Highlights: (1) The stress and strain distribution of 304/Q355 composite plate welded joints with different thickness of cladding material were analyzed in detail by numerical simulation.
(2) The stress-strain evolution characteristics of 304/Q355 composite plate welded joints with different thickness of cladding material are described by the results of stress-strain field analysis.

Key words: cladding materials thickness; composite plate; stress and strain; numerical simulation

Analysis of side-deflection behavior mechanism of GMAW weld section of cable type welding wire YANG Zekun[1,2], XU Kai[2,3], YANG Zhanli[2], ZHANG Yan[2], FEI Dakui[2], ZHOU Kun[2], YANG Yongbo[2](1. China Academy of Machinery Science and Technology Group Co. Ltd., Beijing, 100048, China; 2. Harbin Welding Institute Co. Ltd., Harbin, 150028, China; 3. Harbin Welding Institute Co. Ltd., Harbin, 150028, China). pp 83-87

Abstract: The side-deflection of weld section in cable type welding wire GMAW will lead to poor fusion of welded joints. Therefore, based on droplet force analysis and the principle of minimum voltage, the mechanism analysis of the change rule of the side-deflection of weld section was carried out. The results show that the current is the key factor affecting the side-deflection of the section. The unique stranded structure of the cable type welding wire causes arc rotation, which leads to the phenomenon of uneven force on the droplet. The transition direction of the droplet is at an angle with the axis of the welding wire, resulting in the phenomenon of side -deflection of the weld section under the action of the droplet impact force. The droplet transition direction gradually tends to the axis, so the side-deflection trend of weld section decreases with the increase of current.

Highlights: Based on the principle of minimum voltage, the characteristics of alternating arc-starting of cable type welding wire are analyzed, and it is found that the uneven force of droplet caused by rotating arc is the fundamental cause of the side- deviation of weld section, and the trend of the side- deviation of section decreases with the increase of current.

Key words: cable type welding wire; GMAW; weld section side-deviation; droplet transition; the principle of minimum voltage

Weld recognition based on key point detection method
GUO Zhongfeng, LIU Junchi, YANG Junlin(Shenyang University of Technology, Shenyang, 110870, China). pp 88-93

Abstract: In order to ensure the quality of automatic welding and improve the accuracy and adaptability of weld identification, a key point detection method for weld feature extraction is proposed. A weld feature extraction network was designed based on the convolutional neural network. The network extracted weld feature by convolution and pool operation. The feature map from deep layer is sampled up, and then the feature map from deep layer and shallow layer are fused to improve the accuracy of weld feature extraction. The feature point position of weld seam is predicted by the thermal image of weld seam, and the recognition and location of many kinds of groove weld seam are realized, and eliminating the need for non-maximum suppression algorithm, which improves the feature extraction speed. The network model is trained by collecting different weld feature images. The experimental results show that the root mean square error of weld feature point location is 0.187 mm. The network model designed in this research has high detection accuracy in the weld feature point recognition task, and has strong adaptability and generalization, and meets the requirements of automatic welding.

Highlights: (1) Weld feature extraction network, deep weld seam feature maps are sampled up and shallow weld seam feature maps are fused to improve feature extraction accuracy.
(2) The thermal image of weld seam is output to predict the position of weld feature points, which does not require non-maximum suppression and improves the speed of feature extraction.

Key words: image processing; deep-learning; weld recognition; feature fusion

Study on microstructure and mechanical properties of 6061 aluminum alloy prepared by oscillating laser-arc hybrid welding ZHANG He[1], JIN Jun[2], JIANG Ping[2], ZHANG Fengdong[1], ZHANG Zhenpeng[1], ZHOU Zhikai[3](1. CRRC Qingdao Sifang Co., Ltd., Qingdao, 266111, China; 2.