

镍基合金 TIG 焊接熔池及热影响区组织模拟

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摘要: 基于枝晶生长动力学和晶粒长大理论, 采用元胞自动机法 (CA) 建立了焊接熔池及热影响区的微观组织演变模型. 通过有限元模型计算了 TIG 焊接过程的温度场分布, 并利用插值算法将热循环曲线应用于 CA 模型, 计算了镍基合金 TIG 焊接熔池凝固过程枝晶生长及热影响区的晶粒长大. 结果表明, 焊缝边缘的晶核主要以柱状晶的形式向焊缝中心生长, 其最终形貌取决于半熔化母材晶粒上的联生结晶及不同取向枝晶间的竞争生长, 焊缝中心为等轴晶组织. 焊接热影响区的晶粒长大使得熔池凝固形成的柱状晶组织粗大. 模拟结果与试验结果吻合较好.

关键词: 元胞自动机; 熔池; 联生结晶; 热影响区; 晶粒长大

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0 序言

在熔焊中, 焊缝微观组织受温度场和热影响区晶粒结构的影响. 在焊接热源高温作用下形成的焊缝与热影响区中的微观组织形貌将影响焊接结构的性能和质量^[1]. 因此, 微观组织的控制是保证焊接接头力学性能的重要因素. 由于焊接是一个高温、瞬时、动态的复杂过程, 采用试验法研究焊接接头组织的演变过程具有一定的限制. 随着计算机技术和材料科学的发展, 通过数值模拟技术已经能够再现焊接熔池枝晶演变和热影响区晶粒长大的动态过程^[2-7].

Pavlyk 等人^[3]首次利用有限差分-元胞自动机 (FD-CA) 模型对惰性气体钨极氩弧焊定向凝固过程中具有相同取向的枝晶生长进行了预测. Zhan 等人^[4]建立 FD-CA 模型对焊接熔池中的柱状树枝晶和等轴树枝晶进行了模拟, 并提出了“对角线模拟角度”方法实现了具有不同结晶学主轴的柱状树枝晶间的竞争生长. Han 等人^[5]模拟了焊接熔池内不同区域的枝晶竞争生长过程, 并研究了基体晶粒尺寸对柱状晶形貌的影响. 张敏等人^[6-7]采用熔池凝固模型实现了焊缝横截面上的枝晶生长模拟. 宋奎晶^[8]基于 CA 模型, 并提出粗网格划分方法和相

似原理实现了钛合金焊接热影响区晶粒长大的多尺度模拟.

目前的焊接接头微观组织模拟主要集中在焊接熔池枝晶生长或者热影响区晶粒长大, 将二者同时考虑的模拟较少. 鉴于此, 针对镍基合金 TIG 焊接过程, 建立了枝晶生长模型与晶粒长大模型来模拟焊接温度场作用下的焊接接头微观组织演变过程.

1 模型建立

1.1 凝固模型

焊接熔池凝固过程主要包括枝晶形核和枝晶生长. 熔池内的晶核数量采用 Rappaz 等人^[9]提出的连续形核模型确定, 单位时间步长内, 形核密度 $n(\Delta T)$ 可表示为

$$n(\Delta T) = \frac{n_{\max}}{\sqrt{2\pi}\Delta T_0} \int_{\Delta T}^{\Delta T + \delta(\Delta T')} \exp\left[-\frac{1}{2}\left(\frac{\Delta T' - \Delta T_N}{\Delta T_0}\right)^2\right] d(\Delta T') \quad (1)$$

式中: $n_{\max}$ 为最大异质形核衬底密度; ΔT_0 为标准曲率过冷度; $\Delta T'$ 为平均形核过冷度; ΔT_N 为最大形核过冷度; $\delta(\Delta T')$ 为单位时间步长过冷度的变化量. 式 (1) 可用于描述熔池边缘与中心的非均匀形核.

晶核形成后, 开始进入生长阶段. 考虑成分过冷和曲率过冷, 固/液界面处液相的溶质浓度可表

示为

$$C_L^* = C_0 - \frac{1}{m_L}(T_L - T - \Gamma \kappa f(\varphi, \theta)) \quad (2)$$

式中: m_L , T_L , Γ 为常数; T 为局部温度; κ 为界面曲率; $f(\varphi, \theta)$ 为各项异性函数^[10].

模型中假设固/液界面存在局部平衡, 通过式 (3) 进行溶质分配.

$$C_S^* = k C_L^* \quad (3)$$

式中: k 为溶质分配系数; C_S^* 和 C_L^* 分别是固/液界面两侧固相和液相中的溶质浓度.

固/液界面生长态元胞中的液相溶质浓度为

$$C_L = C_L^* - \frac{1}{2}(1 - f_S)\Delta x G_L \quad (4)$$

式中: f_S 为固相分数^[10]; Δx 为元胞尺寸; G_L 为液相溶质浓度梯度.

浓度梯度的存在使溶质发生扩散, 液相和固相中溶质扩散控制方程为

$$\frac{\partial C_L}{\partial t} = \frac{\partial}{\partial x} \left[D_L \frac{\partial C_L}{\partial x} \right] + \frac{\partial}{\partial y} \left[D_L \frac{\partial C_L}{\partial y} \right] \quad (5)$$

$$\frac{\partial C_D}{\partial t} = \frac{\partial}{\partial x} \left[D_D \frac{\partial C_D}{\partial x} \right] + \frac{\partial}{\partial y} \left[D_D \frac{\partial C_D}{\partial y} \right] \quad (6)$$

式中: C_S 为固相中的溶质浓度; C_L 为液相中的溶质浓度; D_S 为固相中的溶质扩散系数; D_L 为液相中的溶质扩散系数.

1.2 热影响区晶粒长大模型

热影响区晶粒长大是通过晶界迁移实现的, 通常晶界迁移速度可通过晶界迁移率 M 和晶界迁移驱动力 F ^[11] 计算.

$$v = MF \quad (7)$$

考虑到相邻晶粒的位向差, 晶界迁移率 M 可表示为

$$M = \begin{cases} M_0 \left(\frac{\theta}{\theta_m} \right)^5, & \theta < \theta_m \\ M_0 = \frac{A_2 n_1 v_1 V_m^2}{N_a R T} \exp \left(-\frac{\Delta G_A}{RT} \right), & \theta > \theta_m \end{cases} \quad (8)$$

式中: A_2 为晶粒接纳原子的概率; n_1 为单位面积上

处于有利跳跃位置的原子数; v_1 为原子跳跃频率; V_m 为原子摩尔体积; N_a 为阿伏伽德罗常数; R 为气体常量; ΔG_A 为激活能; θ 为晶粒的取向差, θ_m 取 15° .

晶界迁移驱动力可通过晶界曲率表示为

$$F = \gamma \cdot \kappa \quad (9)$$

式中: γ 为单位面积的晶界能; κ 为晶界曲率. 其中 γ 服从 Read-Shockley 公式, κ 可通过等效模型法计算得到^[12].

中心元胞状态转变为邻居元胞状态的概率 P 为

$$P = \begin{cases} 0, & G_{T,i} < \Delta G_A - \sum \Delta G_i \\ \frac{M_i F_i}{M_{\max} F_{\max}}, & G_{T,i} > \Delta G_A - \sum \Delta G_i \end{cases} \quad (10)$$

式中: $G_{T,i}$ 为元胞内能; $\sum \Delta G_i$ 为元胞转变前后的自由能差. 给元胞赋予随机数 r ($0 \leq r \leq 1$), 若 $P > r$, 则元胞状态发生转变.

1.3 初始条件

温度场模型中采用的构件尺寸为 $100 \text{ mm} \times 50 \text{ mm} \times 2 \text{ mm}$, 材料为镍基合金 GH3039, 计算所用的热物性参数详见文献 [13]. 焊接方式为 TIG 焊, 焊接电流为 75 A, 电弧电压为 10 V, 焊接速度为 2 mm/s. 针对薄板 TIG 焊, 选用高斯热源模型, 通过商业有限元软件计算获得焊接温度场, 并将节点热循环曲线通过双线性插值计算得到元胞自动机模型中温度条件.

CA 模型中选择焊缝横截面上的微观组织演变过程作为研究对象, 选取的计算域尺寸为 $1 \text{ mm} \times 2 \text{ mm}$. 母材晶粒结构通过等轴晶形核和生长获得, 其中母材晶粒尺寸设为 $32 \mu\text{m}$ (该值由试验测量得到). 晶粒取向总数设为 48, 其值在 $1 \sim 48$ 之间随机给出, 晶粒的择优生长取向随机赋予 $-45^\circ \sim 45^\circ$ 之间的角度. 热影响区晶粒长大模型中的元胞尺寸设为 $4 \mu\text{m}$, 凝固模型中的元胞尺寸设为 $2 \mu\text{m}$, 时间步长设为 0.000 1 s. 凝固枝晶生长模型中的初始参数如表 1 所示^[14].

表 1 微观组织模拟参数

Table 1 Parameters used in the Microscopic Simulation

液相线温度 T_L/K	液相线斜率 m_L	溶质分配系数 k	液相扩散系数 $D_L/(\text{m}^2 \cdot \text{s}^{-1})$	固相扩散系数 $D_S/(\text{m}^2 \cdot \text{s}^{-1})$	Gibbs Thomson系数 $\Gamma/(\text{K} \cdot \text{m})$	初始溶质浓度 $C_0(\%)$
1 640	-2.1	0.714	2.0×10^{-9}	3.7×10^{-12}	2.0×10^{-7}	20

2 结果与讨论

2.1 温度场模拟结果

图 1 为宏观有限元模型计算得到的焊接过程某一时刻构件上表面、焊缝横截面及微观组织计算区域内插值后的温度场分布情况。为了将熔池部分区分出来,将高于熔池边界温度的区域用灰色表示,熔池边界温度为 $1\,367\text{ }^{\circ}\text{C}$ 。由构件上表面温度场云图可以看出熔池呈现椭圆形,熔池前方的等温线较为密集,温度梯度大,熔池后端的等温线稀疏,温度梯度较小。由图 1b 中的温度分布可以看出不同区域的温度分布和最大温度梯度方向是不一致的。选取图中黑色线框中的区域作为微观组织的计算范围,将该区域中节点的热循环曲线进行双线

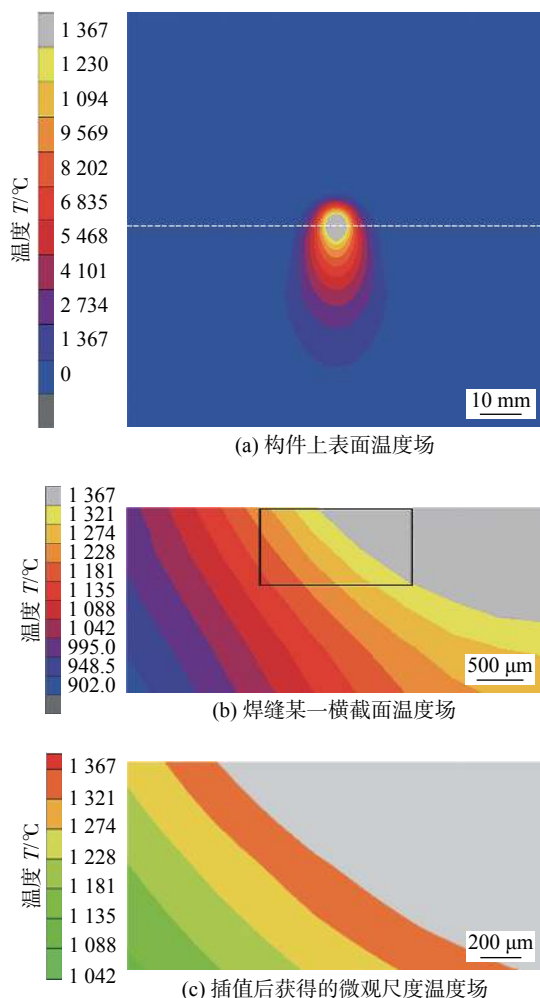


图 1 焊接过程温度场云图

Fig. 1 Temperature field during the welding process. (a) temperature field on the upper surface of the workpiece; (b) temperature field of the weld cross-section; (c) temperature field in the calculation domain obtained by interpolation

性插值可以得到任意时刻任一元胞的温度值,某一时间步微观尺度上的温度场分布如图 1c 所示。

2.2 焊接接头微观组织模拟结果

焊接接头微观组织模拟结果如图 2 所示。图 2a 表示焊接构件横截面上的母材晶粒分布情况。随着热源的靠近,母材熔化形成熔池,如图 2b 中深色区域所示。熔池附近的晶粒在热作用下开始长大,距离熔合线越近,晶粒生长越明显。当晶粒长大到一定程度后将基本不再变化,如图 2c 所示。晶粒生长过程主要是通过大晶粒吞噬小晶粒完成的。随着热源的离开,构件的整体温度逐渐下降,熔池开始凝固。由于熔池边缘散热较快且易于形核,在此处率先形成的晶核开始以柱状树枝晶的形式向熔池中心生长。图中用不同灰度表示具有不同择优生长取向的晶粒,这些具有不同取向的枝晶在生长过程中逐渐靠近并发生竞争生长,择优取向与最大温度梯度方向相近的枝晶更易于生长,竞争优势较弱的枝晶在生长过程逐渐被挤压,直至停止生长,如图 2d 所示。由同一母材晶粒联生结晶形成的枝晶簇具有相同的择优生长方向,其凝固后在焊缝中表现为完整的柱状晶粒。当熔池中的最大过冷度增大到足以形成新的晶核时,大量具有随机取向的晶核在柱状晶前沿形成并阻碍柱状晶的生长,因此在凝固后焊缝中心形成了连续的等轴晶区,如图 2e 所示。图 2f 为联生结晶与柱状晶向等轴晶转变过程。熔池内的柱状晶结构和宽度主要与热影响区中的晶粒取向和尺寸有关,热影响区的晶粒粗化现象越明显,熔合线附近的母材晶粒数量越少,由同一晶粒联生结晶形成的柱状树枝晶数量增多,使得焊缝中的柱状晶变得粗大。

为了验证模拟结果的可靠性,选取 2 mm 厚的 GH3039 镍基合金进行 TIG 焊接试验,选用的焊丝牌号为 HGH3039。通过金相试验获得的焊接接头微观组织如图 3 所示。由图 3a 可以看出,熔池内部主要的枝晶形态为柱状树枝晶和等轴树枝晶。柱状树枝晶前沿为大量的等轴晶组织。由图 3b 可以看到热影响区的晶粒与母材相比发生了明显的粗化,通过截线法测量得到该区域的晶粒平均尺寸约为 $132\text{ }\mu\text{m}$ 。同理可得模拟的热影响区晶粒平均尺寸约为 $129\text{ }\mu\text{m}$,模拟结果与试验结果吻合较好,说明了该模型可用于焊接熔池及热影响区的微观组织演变过程模拟。

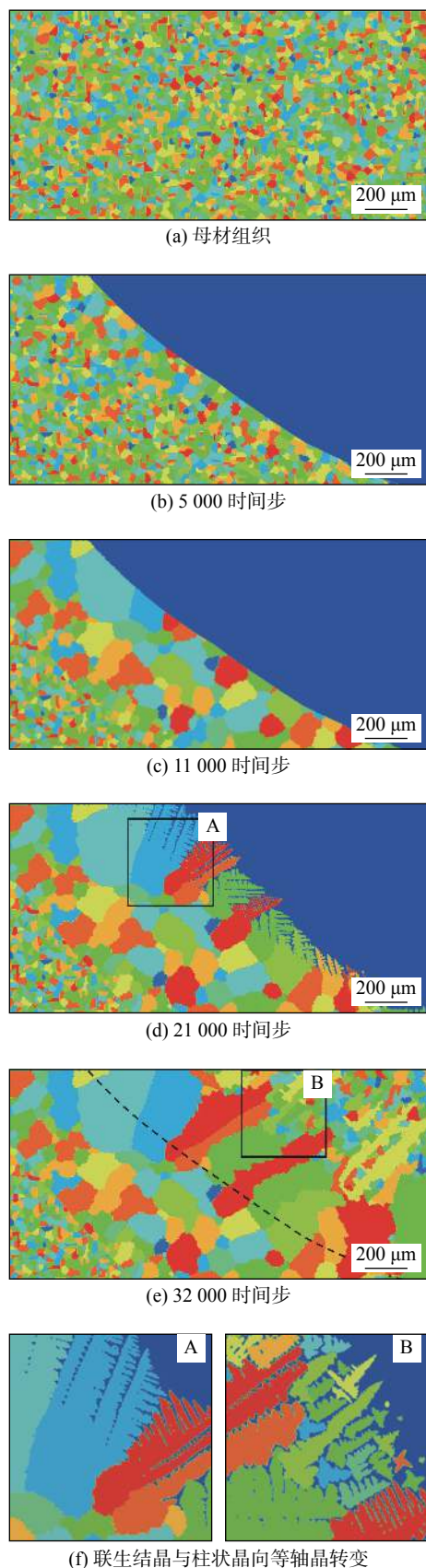


图2 不同时刻焊接接头微观组织形貌

Fig. 2 Microstructure of welded joint at different times. (a) predicted grain distribution of the base metal; (b) 5 000 CAs; (c) 11 000 CAs; (d) 21 000 CAs; (e) 32 000 CAs; (f) epitaxial solidification and the columnar to equiaxed transition

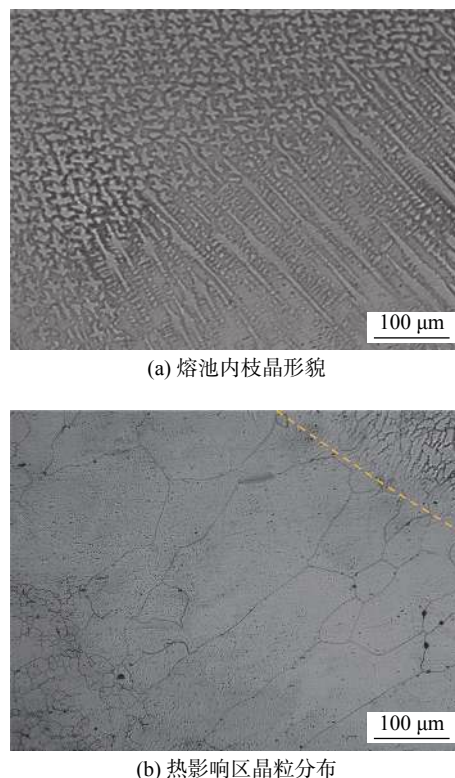


图3 焊接接头微观组织分布

Fig. 3 Micrographs of welded joint. (a) dendrite morphology of the molten pool; (b) grain distribution of the heat-affected zone

3 结论

(1) 所建立的热影响区晶粒长大模型能够较好的模拟热作用下的晶粒粗化过程.

(2) 所建立的枝晶生长模型能够对焊接熔池凝固过程中半熔化母材边缘的联生结晶, 不同枝晶间的竞争生长和熔池中心的等轴晶生长过程进行模拟, 可以完整的再现焊接接头微观组织的动态演变过程.

(3) 模拟结果能够较好的体现焊接热影响区晶粒尺寸与焊缝柱状晶宽度之间的关系.

(4) 模拟得到熔池微观组织和热影响区晶粒分布与试验结果吻合较好, 由此验证了模型的可靠性.

参考文献

- [1] Wei H L, Elmer J W, Debroy T. Origin of grain orientation during solidification of an aluminum alloy[J]. Acta Materialia, 2016, 115: 123 – 131.
- [2] Li X Q, Hao B H, Chen Y X, *et al.* The microscopic mechanical performance for nonuniform welded joint of nickel-based alloy

- with nanoindentation[J]. China Welding, 2019, 28(2): 29 – 34.
- [3] Pavlyk V, Dilthey U. Simulation of weld solidification micro-structure and its coupling to the macroscopic heat and fluid flow modelling[J]. Modelling and Simulation in Materials Science and Engineering, 2004, 12(1): 33 – 45.
- [4] Zhan X H, Dong Z B, Wei Y H, *et al.* Simulation of grain morphologies and competitive growth in weld pool of Ni-Cr alloy[J]. Journal of Crystal Growth, 2009, 311(23–24): 4778 – 4783.
- [5] Han R H, Dong W C, Lu S P, *et al.* Modeling of morphological evolution of columnar dendritic grains in the molten pool of gas tungsten arc welding[J]. Computational Materials Science, 2014, 95: 351 – 361.
- [6] 张敏, 徐嵩彦, 汪强, 等. Fe-C 合金焊接熔池凝固过程 CET 转变的数值模拟 [J]. 焊接学报, 2016, 37(2): 5 – 8.
Zhang Min, Xu Aiyun, Wang Qiang, *et al.* Numerical simulation of CET transformation in the solidification of Fe-C alloy weld pool[J]. Transactions of the China Welding Institution, 2016, 37(2): 5 – 8.
- [7] 张敏, 周玉兰, 薛覃, 等. Ti-45Al 合金焊接熔池凝固过程数值模拟 [J]. 焊接学报, 2018, 39(3): 6 – 10.
Zhang Min, Zhou Yulan, Xue Qin, *et al.* Numerical simulation of solidification process of Ti-45Al alloy weld pool[J]. Transactions of the China Welding Institution, 2018, 39(3): 6 – 10.
- [8] 宋奎晶. TA15 钛合金 TIG 焊热影响区组织模拟及力学本构关系研究 [D]. 哈尔滨: 哈尔滨工业大学, 2014.
- [9] Rappaz M, Gandin Ch A, Desbiolles J L, *et al.* Prediction of grain structures in various solidification processes[J]. Metallurgical and Materials Transactions A, 1996, 27(3): 695 – 705.
- [10] Gu C, Wei Y H, Liu R P, *et al.* Effect of temperature and fluid flow on dendrite growth during solidification of Al-3 Wt Pct Cu alloy by the two-dimensional cellular automaton method[J]. Metallurgical and Materials Transactions B, 2017, 48(6): 3388 – 3400.
- [11] He Y Z, Ding H L, Liu L F, *et al.* Computer simulation of 2D grain growth using a cellular automata model based on the lowest energy principle[J]. Materials Science & Engineering A, 2006, 429(1-2): 236 – 246.
- [12] 金朝阳, 俞栋华, 吴欣桐. 热挤压态纯镁晶粒长大的元胞自动机模拟 [J]. 塑性工程学报, 2016, 23(6): 216 – 222.
Jin Zhaoyang, Yu Donghua, Wu Xintong. Simulation of grain growth behavior of hot-extruded pure magnesium by cellular automata[J]. Journal of Plasticity Engineering, 2016, 23(6): 216 – 222.
- [13] 陈晶, 李少华, 颜飞雪, 等. JMatPro 软件在 GH3039 真空扩散焊工艺研究中的应用 [J]. 热加工工艺, 2018, 47(11): 232–235.
Chen Jing, Li Shaohua, Yan Feixue, *et al.* Application of JMatPro software in research of GH3039 vacuum diffusion welding process[J]. Hot Working Technology, 2018, 47(11): 232–235.
- [14] Dong Z B, Song K J, Wang S J, *et al.* Solute redistribution with shear flow in molten pool of Ni-Cr alloy[J]. Journal of Materials Science & Technology, 2011, 27(2): 183 – 188.

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Abstract: Diffusion bonding between Tungsten and Steel using Co powder/Ni foil composite interlayer was carried out under the condition of 10 MPa in vacuum at 800 °C, 900 °C and 1 000 °C for 120 minutes. The microstructure, composition, fracture characteristic and shear strength of the joints were studied. The results showed that less intermetallic compound is formed in tungsten matrix/interlayer interface of the joints bonding at 800 °C and 900 °C, the shear strength of the corresponding joints is 186 MPa and 172 MPa, respectively. The shear fracture of the joints, which is typical cleavage fracture morphology, are located in tungsten matrix near interface. When the bonding temperature is up to 1 000 °C, a continuous intermetallic compound layer less than 2 μm is formed in the tungsten/interlayer interface, the shear strength of the joints reduced significantly to 115 MPa. The shear fracture of the joints bonding at 1 000 °C is also located in tungsten matrix near interface. Most of which exhibits intergranular fracture morphology.

Key words: tungsten; cobalt; bonding; shear strength

3D reconstruction of laser scanning at weld surface defects

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Abstract: The surface defects of the workpiece weld bead were detected using a point laser displacement sensing method. Firstly, the data of weld defect surface was collected and the original data was filtered by Gaussian filtering. Then the Delaunay triangulation was applied for the processed data points and reconstruction of a three-dimensional model with the spatial coordinates. Experimental results showed that the 3D reconstruction method based on the point laser displacement sensing and the surface defect images of the weld bead can accurately judge the appearance of welds.

Key words: laser ranging; weld defect; triangulation; 3D reconstruction

Simulation of microstructure evolution of weld pool and heat-affected zone during TIG welding of nickel-base alloy

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Abstract: Model for microstructure of molten pool and HAZ was developed based on the dendritic growth kinetics and the grain growth theory using the cellular automaton method. The temperature field during TIG welding process was calculated by the finite element model. And the thermal cycle curves were applied to the CA model to calculate the dendrite growth in the molten pool and grain growth in the heat-affected zone. The simulation results showed that the nuclei at the fusion boundary mainly grows in the form of columnar dendrite toward the center of the weld. The final morphology depends on the partially melted grains of base metal at the fusion boundary and competition growing between dendrite arrays with different orientation. The microstructure at the center of the molten pool was equiaxed dendrites. The grain growth in the heat-affected zone results in the columnar structure of the molten pool coarser. The simulation results agree well with the experimental results.

Key words: cellular automata; molten pool; dendrite arrays; heat-affected zone; grain growth

Apparent defect recognition of gas metal arc welding based on infrared vision

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Abstract: The visual monitoring of welding process and welding defect identification are vital to the intelligent control of welding processes. In this paper, a mid-wave infrared CCD was used to acquire the infrared images of the welding pool on-line during the welding process. The images captured are preprocessed by the improved filtering algorithm and image enhancement algorithm. To obtain the temperature distribution information of the welding pool, the relationship between the gray value in infrared image and the temperature is established based on temperature calibration of the used thermocouple. The improved edge extraction algorithm is used to extract the characteristic parameters of the welding pool. Then the identification algorithm of welding defect is developed. The results of verified experiments show that the proposed algorithm has good practicability and accuracy in the on-line identification of welding shape, burn-through and