

高强度低焊接裂纹敏感性钢焊接热影响区的冲击韧度

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摘 要: 采用埋弧自动焊接方法焊接高强度低焊接裂纹敏感性钢, 分析了高强钢焊接热影响区中不同微区的显微组织特征与冲击韧度之间的关系. 焊接接头粗晶区和细晶区的显微组织分别为粗大的粒状贝氏体和细小的准多边形铁素体组织, 其 $-20\text{ }^{\circ}\text{C}$ 的平均冲击吸收功分别为 45 J 和 170 J . 粗晶区中粒状贝氏体的有效晶界为原始奥氏体晶界, 晶内存在大量的小角度晶界和亚晶界, 有效晶粒尺寸较大, 冲击韧度显著降低; 细晶区中准多边形铁素体的平均有效晶粒尺寸约为 $5.3\text{ }\mu\text{m}$, 大角度晶界可以有效阻碍了裂纹的扩展, 具有较好的冲击韧度.

关键词: 低焊接裂纹敏感性钢; 冲击韧度; 热影响区; 贝氏体

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0 序 言

低焊接裂纹敏感性钢(也称 CF 钢)是一类焊前不需预热, 焊后不进行热处理, 且不产生焊接裂纹的易焊接钢种, 其成分设计的侧重点是保证具有较低的焊接裂纹敏感性指数(P_{cm})^[1]. 但随着钢种强度级别的上升, 微合金元素的增多, P_{cm} 值也相应提高, 这势必会给钢的焊接性能带来一定影响. 对于高强度钢板($R_{0.2} > 620\text{ MPa}$)的焊接接头来说, 母材的显微组织已不再是传统多边形铁素体 + 珠光体组织, 而是具有更高强度的粒状贝氏体、针状铁素体、贝氏体铁素体或是下贝氏体组织^[1, 2]. 这些组织在焊接热循环作用下进一步发生复杂的相变, 会导致焊接热影响区(HAZ)中不同微区的力学性能发生骤变.

通常, 焊接热影响区的宽度很窄, 采用光学显微镜(OM)和透射电镜(TEM)分析热影响区中不同微区的组织特征均有一定局限性, 如 OM 只能从较宏观的尺度来观察显微组织的变化趋势, 而忽视了一些更为微观的信息; TEM 样品薄区的位置对观察结果有很大影响. 近年来, 随着电子背散射衍射技术(EBSD)的发展, 很多关于焊接熔池和焊接热影响区显微组织的研究均采用了该技术^[3]. 该技术的独特优势主要在于制样便捷, 而且可以准确的确定出所需观察范围, 并且可获得各组织之间的晶粒取向

关系. 文中利用 EBSD 对高强 CF 钢焊接热影响区的不同微区组织进行分析, 获得不同微区组织的有效晶粒尺寸、晶粒取向等信息, 并着重分析了微区组织特征与冲击韧度之间的关系.

1 试验方法

采用 TMCP + 加速冷却(ACC)工艺试轧出厚度为 20 mm 的试验钢板, 其主要化学成分(质量分数, %)为 0.053 C , 0.27 Si , 1.2 Mn , 0.02 Al , $0.42\text{ (Cr + Mo + Ni)}$, $0.082\text{ (Nb + V + Ti)}$, $14 \times 10^{-6}\text{ B}$, 裂纹敏感性指数为 0.185% . 试验钢板热轧态的主要力学性能见表 1, 主要显微组织有细小的准多边形铁素体(PF)、针状铁素体(AF)和粒状贝氏体(GB)组织, 如图 1 所示, 粒状贝氏体具有较大的晶粒尺寸, 局部还保留了带状的原始奥氏体晶粒特征.

表 1 试验钢板的主要力学性能

Table 1 Main mechanical properties of tested steel plate

屈服强度 R_{eL}/MPa	抗拉强度 R_m/MPa	断后伸长率 $A(\%)$	冲击吸收功 $A_{kv}(20\text{ }^{\circ}\text{C})/\text{J}$
645	760	17	161

首先对试验钢板开 40° 的 V 形坡口, 两钢板的钝边之间保留 3 mm 间隙. 采用单丝埋弧焊对试验钢板进行 5 道次焊接, 主要焊接工艺参数如表 2 所示. 焊接材料选用 H08MnA 焊丝配合 SJ101 焊剂,

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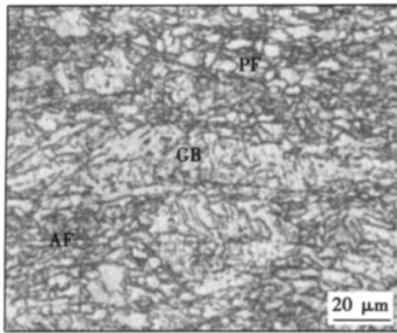


图1 试验钢板的显微组织

Fig. 1 Microstructure of tested steel plate

可见焊缝熔敷金属的强度明显低于母材. 试验的目的主要是分析母材在经历多道次焊接热循环后热影响区中不同微区的微观组织特征及其冲击韧度. 为了分别检测焊接接头中不同微区的冲击韧度, 根据国家标准 GB/T2650—2008 和焊接热影响区的分布情况, 将冲击试样的夏比 V 形缺口根部分别开在紧靠熔合线附近的粗晶热影响区和距熔合线约 1.5 mm 处的细晶热影响区, 冲击试样尺寸为 10 mm × 10 mm × 55 mm, 冲击试验温度为 -20 °C.

表2 焊接工艺参数

Table 2 Parameters of welding process

电流 <i>I</i> /A	电压 <i>U</i> /V	焊接速度 <i>v</i> /(mm·min ⁻¹)	热输入 <i>E</i> /(kJ·cm ⁻¹)	层温 <i>T</i> /°C
600	30	400	27	180~200

采用浓度为 4% 硝酸酒精溶液腐蚀焊接金相试样, 在 LEICA-MIRM 光学显微镜下观察焊接热影响的显微组织变化. 为了分析热影响区中不同微区组织的晶粒取向与冲击韧度之间的关系, 采用高氯酸 + 酒精溶液电解腐蚀制备 EBSD 试样. 在 FEI-Quanta600 扫描电镜配备的 EBSD 装置中观察不同显微组织的晶粒取向.

2 试验结果及分析

2.1 显微组织

图 2 为焊接热影响区中不同微区的显微组织形貌. 粗晶区紧靠熔合线, 经历的焊接热循环温度高, 奥氏体晶粒发生粗化. 在 27 kJ/cm 的热输入条件下形成以粒状贝氏体为主的显微组织, 如图 2a 所示. 粒状贝氏体中分布着大量 M/A 岛, 其形态有长棒状和小块状. 所观察的棒状 M/A 岛最大长宽比

可达 25. 块状 M/A 岛随机分布在基体上. 图 2b 为细晶区的显微组织, 以细小的准多边形铁素体(或块状铁素体)为主, 同时含有少量针状铁素体. 晶粒尺寸非常细小, 且形状不规则, 很难在金相图片中准确地测量出平均晶粒尺寸.

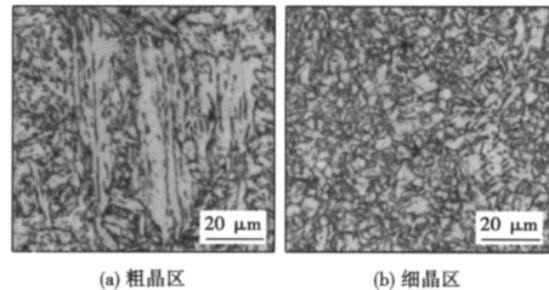


图2 焊接热影响区中不同微区的组织形貌

Fig. 2 Microstructures at different regions of HAZ

2.2 冲击韧度以及断口形貌

对不同微区的冲击韧度进行分析. 粗晶热影响区的平均冲击吸收功为 45 J, 而细晶热影响区的平均冲击吸收功为 170 J, 且三个值的波动范围很小. 细晶热影响区的冲击韧度明显高于粗晶热影响区. 从冲击断口可以看出, 如图 3a 所示, 粗晶热影响区的冲击断口出现约 90% 的脆性准解理断面区, 较大的单元解理小刻面尺寸可达 40 μm, 表明微裂纹扩展过程中近直线扩展的距离大, 导致冲击吸收功减小. 细晶热影响区冲击断口以韧度断面为主, 平均纤维断面率约占整个断面面积的 60%, 如图 3b 所示. 细小的韧窝能够吸收大量冲击功, 有利于提高冲击韧度. 由于细晶区和粗晶区是紧密相连的, 裂纹在细晶区的扩展阻碍大, 在冲击断口的根部, 裂纹扩展路径明显向粗晶区偏转而形成局部解理断裂面, 同时也可能存在小部分未完全相变区的显微组织对细晶区冲击韧度的影响.

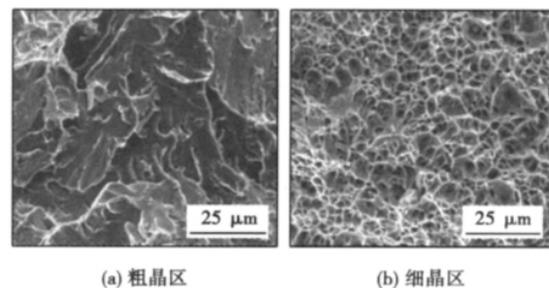


图3 焊接热影响区中不同微区的断口形貌

Fig. 3 Fractographs at different regions of HAZ

2.3 EBSD 分析有效晶粒尺寸与冲击韧度

图 4 为焊接熔合线附近粗晶区的 EBSD 分析结果。从粗晶区的 EBSD 质量图可以看出, 粒状贝氏体具有较大相同取向的晶畴尺寸, 而针状铁素体和多边形铁素体的晶畴尺寸比较细小。根据相关研究^[4], 定义取向角大于 15° 的晶界为有效晶界。在晶界取向分布图中采用蓝粗线表示大角度晶界(即有效晶界), 红细线表示小角度晶界(取向角在 2° ~ 15°)。对比图 4a、b 可以看出, 粒状贝氏体的大角度晶界属于原始奥氏体晶界, 由于粗晶热影响区受到高温焊接热循环的作用, 原始奥氏体晶粒尺寸显著粗化, 使得粗晶热影响区的有效晶粒尺寸变大。根据 EBSD 结果可知, 粗晶热影响区的平均有效晶粒尺寸约为 13.5 μm, 最大有效晶粒尺寸可达 35 μm。有效晶粒尺寸增加意味着解理裂纹的单元小刻面的尺寸增大。

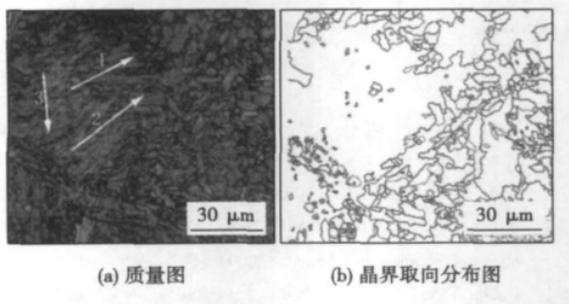


图 4 粗晶热影响区的 EBSD 分析结果

Fig. 4 EBSD analysis of coarse grained HAZ

解理裂纹在粗晶热影响区的扩展可分为三个阶段^[4]: 第一阶段是显微裂纹源在局部应力集中微区形成(如夹杂物、M/A 岛等硬相组织), 第二阶段是显微裂纹穿越硬相组织扩展到基体组织中, 直到遇到晶界, 第三阶段是显微裂纹穿越晶界继续向周围组织扩展并与其它裂纹合并造成断裂。当显微裂纹形成后, 大角度晶界可以使显微裂纹的扩展路径发生偏转而形成新的解理断裂小刻面, 此时需要消耗冲击吸收功, 从而能够提高冲击韧度。

同时, 根据韧脆转变温度与有效晶粒尺寸的关系可知, 如式(1)所示^[4, 5], 当有效晶粒尺寸增大时, 材料的韧脆转变温度会明显上升。所以粗大的有效晶粒尺寸会明显恶化了粗晶热影响区的韧脆转变温度。

$$T_{DBTT} = A - K \ln d^{-\frac{1}{2}} \quad (1)$$

式中: T_{DBTT} 为韧脆转变温度; d 为有效晶粒尺寸; A 、 K 分别为材料常数。

为了进一步分析粗晶区中具有粗大有效晶粒尺寸的粒状贝氏体内部的亚晶界或小角度晶界的分布情况, 在粒状贝氏体内选取三条不同路径的线, 如图 4a 中的白色箭头所示。沿箭头方向, 对比所经过点的取向差, 采用点对点的取向差变化规律和点对起始点的变化规律来表示, 如图 5 所示。

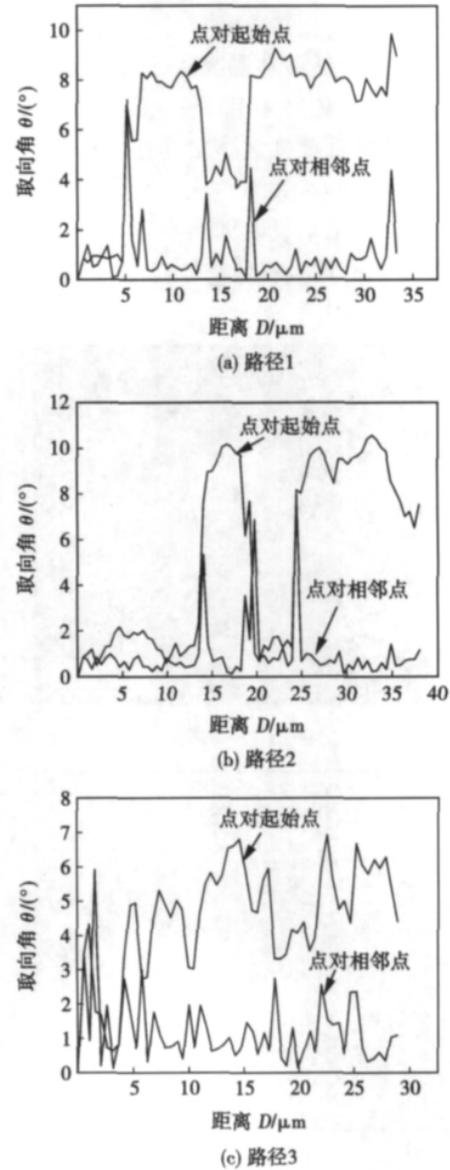


图 5 粒状贝氏体内的不同路径上的取向角分布

Fig. 5 Misorientation of different lines in granular bainite

所选路径 1 和路径 2 的方向近似平行于熔合线, 而路径 3 近似垂直于熔合线。所有路径上点对点的取向角变化非常频繁(取向角在 1° 附近波动), 表明粒状贝氏体中存在大量的亚晶界或高密度的位错。路径 1 在距起始点约 5 μm 处取向角发生约 6° 的突变, 随后点对起始点的取向差维持在 8° 附近, 对路径 2 来说这种情况出现在距离起始点约 14 μm

处表明这两条路径都穿过了一条取向差约为 6° 的亚晶界。这些亚晶界主要是由于焊接残余应力和相变应力所引起的。焊接残余应力使得焊缝区和热影响区的高温奥氏体组织中存在大量亚结构;而非平衡相变使得产物中含有高密度位错。

图6a和6b分别为细晶热影响区的质量图和晶界取向角分布图。大部分细小准多边形铁素体晶粒均有独立的晶畴,使得晶畴尺寸非常细小。从图6b可看出准多边形铁素体晶界属于大角度晶界,同时含有少量有效晶粒尺寸相对较大的粒状贝氏体和针状铁素体。相邻针状铁素体之间往往存在小角度晶界,所以细晶区的有效晶粒尺寸会大于质量图中晶畴尺寸。EBSD结果表明细晶热影响区的有效晶粒尺寸为 $5.8\ \mu\text{m}$,最大有效晶粒尺寸为 $13\ \mu\text{m}$ 。根据

式(1)可知,由于有效晶粒尺寸非常细小,细晶热影响区的韧脆转变温度比粗晶热影响区要低。同时,大量的大角度晶界对解理裂纹扩展的阻碍作用,即使在低温冲击也会表现出较好的高韧度行为。

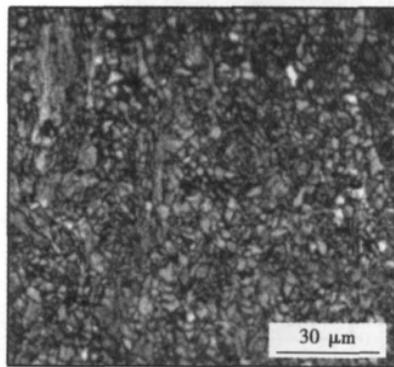
3 结 论

(1) 在多道次焊接后,粗晶热影响区和细晶热影响的主要显微组织分别为粒状贝氏体和准多边形铁素体组织,其冲击吸收功分别为 $45\ \text{J}$ 和 $170\ \text{J}$ 。

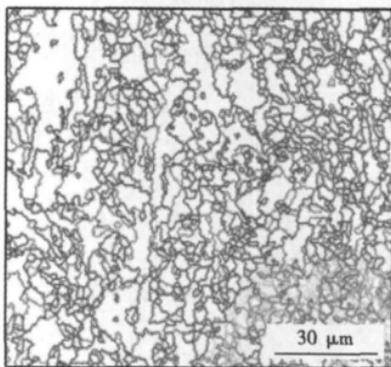
(2) EBSD分析表明粗晶热影响区中粒状贝氏体的有效晶粒尺寸粗大,晶内含有大量的亚晶界,导致冲击韧度降低;细晶热影响区中准多边形铁素体的有效晶粒尺寸非常细小,能够很好地阻碍裂纹的晶界扩展,所以韧度较好,同时细小的晶粒尺寸也决定了细晶热影响区具有良好的韧脆转变温度。

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(a) 质量图



(b) 晶界取向分布图

图6 细晶热影响区的EBSD分析结果

Fig. 6 EBSD analysis results of fine grained HAZ

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sheets.

Key words: three layers; resistance spot welding; nugget size; welding lobe

Influence of heat sink on welding residual deformation and optimization analysis of parameters of heat sink

ZHAO Lihua , ZHANG Kailin (Traction Power State Key Laboratory , Southwest Jiaotong University , Chengdu 610031 China) . pp 37 -40

Abstract: The numerical simulations have been done for both the conventional metal active-gas welding (MAG) and the dynamically controlled low stress no-distortion (DC-LSND) MAG welding , and the measurement has been done for the DC-LSND experimental weldment as well , it is found that the simulating result is basically consistent with the measured data. Subsequently , the welding residual deformation of the partial side beam of bogie frame was selected as a research object , the optimization analysis of parameters of the heat sink had been done with the numerical simulation combining with optimization algorithm , and the according optimum scheme was obtained. The results showed that the control effect of welding residual deformation was obvious by the DC-LSND MAG welding with the optimum parameters.

Key words: dynamically controlled low stress no-distortion (DC-LSND) welding; heat sink; numerical simulation; optimization analysis; residual deformation

Toughness of welding heat affected zone in high strength steel with low welding crack susceptibility

LAN Lianyun , QIU Chunlin , ZHAO Dewen , GAO Xiuhua (The State Key Laboratory of Rolling and Automation , Northeastern University , Shenyang 110819 , China) . pp 41 -44

Abstract: In this study , the submerged arc auto-welding technique was employed to weld the high strength steel with low welding crack susceptibility. The relationship between microstructural feature and toughness in different sub-zones of heat affected zone was analyzed in details. The results showed that the main microstructures in the coarse grained zone and fine grained zone are coarse bainite and fine quasi-polygonal ferrite , respectively. And corresponding average impact absorbed energy is 45 and 170 J , respectively. Electron back scattering diffraction (EBSD) analysis showed that the effective grain boundary of coarse bainite is prior austenite grain boundary and a number of sub-boundaries and dislocation exist inside the grain. The coarse effective grain size reduces the toughness of coarse grained zone. On the contrary , the average effective grain size of quasi-polygonal ferrite in the fine grained zone is about 5.3 μm . High angle grain boundary inhibits the propagation of crack and improves the toughness.

Key words: low welding crack susceptibility steel; toughness; heat affected zone; bainite

Effect of boron on microstructure and properties of high-boron iron-based alloy by plasma transferred arc

LIU Zhengjun , LI Lechen , SU Yunhai , Zong Lin (School of Material Science and Engineering , Shenyang University of Technology ,

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Abstract: The iron-based composite materials of Fe-Cr-B-C hardfacing alloys were deposited on the surface of 20g steel by using plasma transferred arc (PTA) . The effect of different B contents on microstructure and properties of surfacing layer was investigated by means of the X-ray diffraction (XRD) , optical microscope (OM) , scanning electron microscope (SEM) , Rockwell hardness tester and wet sand abrasion tester. The result shows that the microstructure of the surfacing layer consists of supersaturated α -Fe dendrite solid solution , eutectic boride and carbides. The hard phases in the surfacing layer include Cr_2B , CrB_2 , Fe_2B , Cr_7C_3 and B_4C etc. The amount of borides significantly increased with B content increasing , and the hardness and wear resistance of surfacing layer reached optimum value when B contents reached 5% . The hardness is 66.1 HRC and the weight reduction is 0.383 g. The wear resistance of surfacing layer decreased with the amount of boron further increasing.

Key words: plasma transferred arc; surfacing; boride; wear resistance

Prediction model of bead geometry shaped by rapid prototyping based on pulsed PAW

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Abstract: In this paper , rapid prototyping based on pulsed PAW technology is introduced. The Taguchi method is applied to design single bead forming experiments properly and then multi-group experimental data of weld width and height are obtained. The prediction model of bead geometry is developed by applying BP neural network based on genetic algorithm. It turns out that the model holds high prediction accuracy and generalization ability verified by error analysis and linear regression , which can predict single and multiple beads geometry accurately.

Key words: pulsed PAW; rapid prototyping; Taguchi method; genetic algorithm; BP neural network

Design of lower stress and flexible CCGA solder joints and reliability expectancy

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Abstract: To improve the interconnect reliability of large-die area array package and reduce the stress concentration in solder joints under service load , the flexible interconnect structure for CCGA (ceramic column grid array) package and its solder joints shape are designed based on mechanics principle. Mechanical behaviors of the lower stress and flexible CCGA interconnect structure under shear load are studied by finite element method. Results showed that the designed copper tapered-funnel in both ends of copper column subjected to peak stress