微钙钢中第二相粒子对焊接 CGHAZ 奥氏体晶粒度及强韧度的影响

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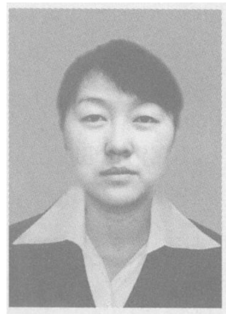

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摘 要：通过向碳素钢中添加微量钙元素，在钢中形成弥散的热稳定的第二相含钙的氧化物粒子。利用扫描电镜、光学电镜、系列冲击试验和显微硬度测试等检测方法，对微钙钢焊接粗晶热影响区（CGHAZ）组织、奥氏体晶粒度及强韧度进行了研究。结果表明，弥散分布的含钙的氧化物粒子，钉扎了焊接热循环过程中 CGHAZ 的奥氏体晶界迁移，限制了奥氏体晶粒的长大，获得较细的焊接 CGHAZ 晶粒度，进而改善了微钙钢焊接 CGHAZ 的强韧度。

关键词：微钙钢；奥氏体晶界；晶粒；韧度
中图分类号：TG456.2 文献标识码：A 文章编号：0253—360X(2007)03—073—04

0 序 言

大量研究表明，向钢中添加合金元素 Ti，使之形成钉扎焊接粗晶热影响区（CGHAZ）奥氏体晶界的 TiN 第二相粒子，能够提高焊接 CGHAZ 强度的同时，提高其韧度。当焊接热输入较大、焊接峰值温度高于 1 350 ℃时，大部分 TiN 发生溶解，导致钉扎奥氏体晶界的作用降低[1]。作者研究了通过向钢中添加稳定高温组织的弥散粒子形成 Ca 元素，使之形成弥散的高熔点的氧化物粒子。利用氧化物粒子的钉扎焊接 CGHAZ 奥氏体晶界的作用，细化焊接 CGHAZ 奥氏体晶粒，从而提高钢的焊接 CGHAZ 强度和韧度[2]。

1 试验材料及方法

1.1 试验材料

试验采用 8 mm 厚微钙钢，其化学成分（质量分数，%）为 C 0.112，Si 0.273，Mn 1.585，P 0.011，S 0.003 2，Nb 0.025，Ca 0.002 3。试验钢的力学性能见表 1。钢的原始组织为铁素体、珠光体和贝氏体，原始组织细小，平均晶粒尺寸约为 3～4 μm，如图 1 所示。

1.2 试验方法

焊接方法为气体保护焊，采用单面带钝边坡口，坡口角度 60°，钝边留 1.5～2.0 mm，跟部间隙与焊丝直径相同。焊接材料采用 H08Mn2Si2A 焊丝，焊丝规格 ϕ1.0 mm。具体焊接工艺参数见表 2。

表 1 钢的力学性能

Table 1 Mechanical properties of steel

屈服强度 R_{eL}/MPa	抗拉强度 R_m/MPa	断后伸长率 A(%)	断面收缩率 Ψ(%)	硬度 (HV)
524	785.6	20.1	52.1	243

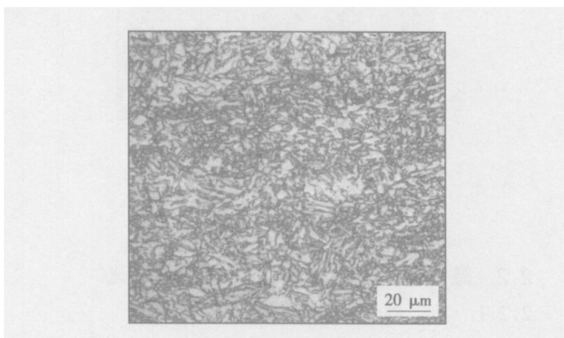

图 1 钢的原始组织

Fig 1 Microstructure of steel

表 2 焊接工艺参数

Table 2 Welding parameters

保护气体	焊接道次	电流 I/A	电压 U/V	焊接速度 v/(cm·min^{-1})	热输入 E/(kJ·cm^{-1})
80%Ar+20%CO_2	第 1 道	150	23	32	6.4
	第 2 道	200	25	32	9.6

收稿日期：2006—10—18

用饱和苦味酸水溶液腐蚀焊接 CGHAZ 的奥氏体晶界，在 LEICAD MIRM 光学显微镜和 PHILIP SXL－30 扫描电镜用截线法测量晶粒平均大小。对焊接 CGHAZ 进行光学显微镜下的金相显微组织观察和显微硬度测试。

加工 5 mm×10 mm×55 mm 的 V 形缺口夏比冲击试样，缺口开在 CGHAZ，每点取 3～5 个试样取平均值。

2 试验结果及分析

2.1 微钙钢 CGHAZ 金相组织

微钙钢原始组织为铁素体、珠光体和贝氏体。经焊接热循环后，焊接 CGHAZ 组织转变为粒状贝氏体和少量板条马氏体组织。这主要是由于微钙钢在焊接过程中加热温度高、加热速度和冷却速度快，原始组织重新奥氏体化，在随后的冷却过程中焊接 CGHAZ 形成上述组织，如图 2 所示。

图 2 CGHAZ 显微组织

Fig. 2 Microstructure of CGHAZ

2.2 微钙钢焊接 CGHAZ 奥氏体晶粒细化

2.2.1 奥氏体晶粒的细化机理

钢在经历焊接热循环后焊接 CGHAZ 晶粒粗大导致韧度下降。因此细化焊接 CGHAZ 晶粒，提高韧度已经成为一大研究方向。研究表明向钢中添加合金元素，使其形成钉扎焊接 CGHAZ 奥氏体晶界的第二相粒子能够有效地阻止奥氏体晶粒长大，使焊接 CGHAZ 的奥氏体晶粒得到细化。第二相粒子对奥氏体晶界的钉扎力由下式确定[3]：$F = K \cdot (f/r)$，其中 K 为常数；f 为单位体积的钢中粒子的体积数；r 为粒子的半径。研究表明钢中的 TiN 第二相粒子能够阻止焊接 CGHAZ 奥氏体晶粒的长大，细化 CGHAZ 晶粒。但是在大热输入焊接条件下 TiN 大部分溶解，使 f 值减小，r 值增大，大大降低了钉扎奥氏体晶界的能力 F，因此对于应用大热输入焊接的钢种向钢中添加合金元素 Ti 来细化 CGHAZ 晶粒效果并不显著。

炼钢过程中通过 Si－Ca 处理向钢中添加 Ca 元素，Ca 元素以蒸气泡方式上升到熔池表面。由于 Ca 元素和 O 元素的结合能力很强，因此在气泡上升过程中溶解 Ca 元素和过剩 Ca 元素与钢液中的 O 元素发生了[Ca]＋[O]＝(CaO)和[Ca]＋[S]＝(CaS)的反应。在 1 600 ℃温度下，CaO 的生成自由能为 849.92 kJ/mol，CaS 的生成自由能为690.82 kJ/mol，所以 CaO 在热力学上比 CaS 更稳定，CaS 依附在 CaO 质点表面析出[4]，如图 3 所示。CaO 的熔点为 2 845 K，是一种热稳定的化合物，即使焊接峰值温度达到 1 400 ℃也不易溶解于奥氏体中。因此 CaO 对 CGHAZ 奥氏体晶界的钉扎力 F 不降低，从而阻止焊接热循环过程中 CGHAZ 奥氏体晶粒的长大，使焊接 CGHAZ 粗晶区奥氏体晶粒得以细化，最终提高焊接 CGHAZ 的韧度[5,6]。

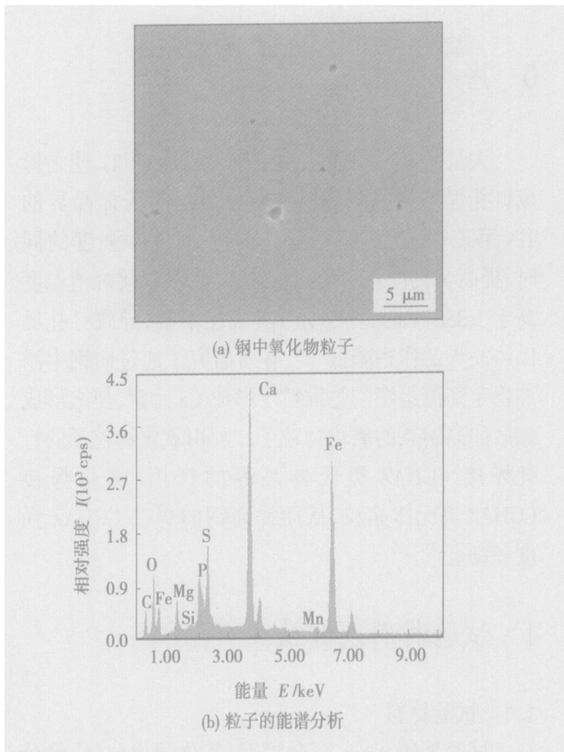

图 3 氧化物形貌及组成分析

Fig. 3 Morphology and chemical compositions of oxide particles in micro-calcium steel

2.2.2 奥氏体晶粒的细化效果

相同焊接工艺参数条件下，未加钙钢(其它化学成分相近)的 CGHAZ 奥氏体晶粒平均尺寸约为 100 μm左右，晶粒度为 3～4 级，如图 4a 所示。微钙钢焊接 CGHAZ 奥氏体晶粒平均尺寸约为 40 μm 左右，

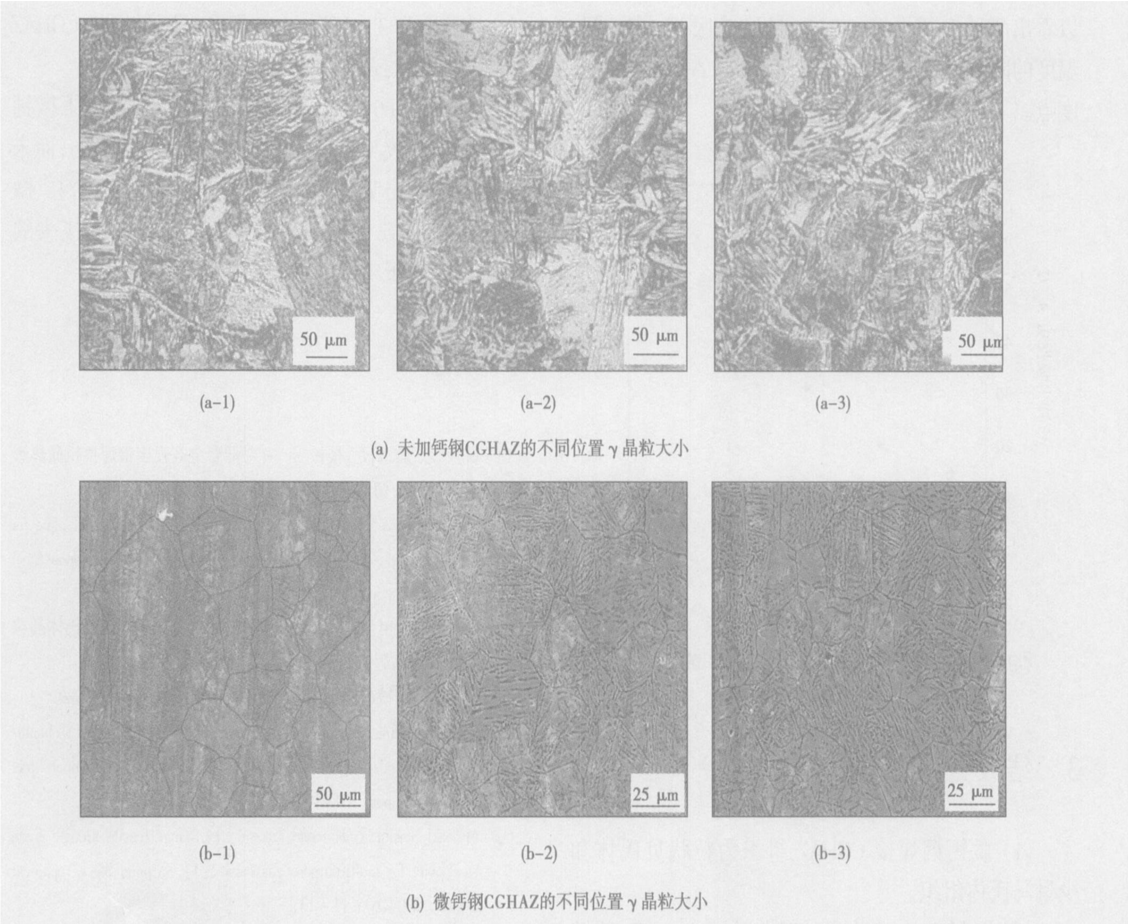

图 4　焊接 HAZ 奥氏体晶粒大小

Fig 4　γ grain size in CGHAZ

晶粒度为 6～7 级，如图 4b 所示。通过比较可知，微钙钢焊接 CGHAZ 奥氏体晶粒要比未加钙钢的焊接 CGHAZ 奥氏体晶粒细小，说明 CaO 粒子有细化晶粒的效果。

2.3　焊接接头的强度和韧度

2.3.1　焊接接头的强度

分别对微钙钢和未加钙钢的焊接接头进行拉伸试验。试验结果是，微钙钢拉伸后断裂部位均在母材处，而未加钙钢拉伸后断裂部位均在热影响区。由此可以得出微钙钢焊接接头的强度要高于未加钙钢焊接接头的强度。分析其原因为以下几点：(1) 未加钙钢 CGHAZ 晶粒度为 3～4 级，晶粒粗大和组织粗大导致焊接接头出现软化区域致使其在热影响区处断裂。(2) 微钙钢内的 CaO 粒子对奥氏体晶界的钉扎作用使焊接热影响区的晶粒度为 6～7 级，晶粒和组织细化，最终提高焊接接头的强度。通过对微钙钢焊接接头的显微硬度试验可以看出热影响区的硬度明显高于母材，如图 5 所示，这与微钙钢的拉伸结果是对应的。

2.3.2　焊接接头的韧度

微钙钢和未加钙钢在不同试验温度下焊接

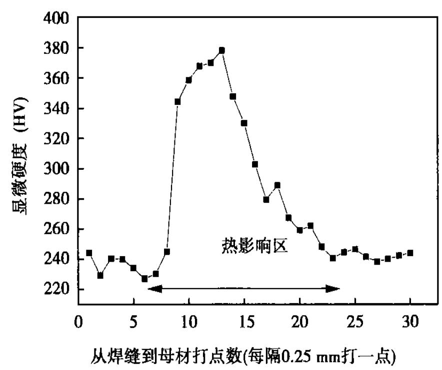

图 5　显微硬度曲线

Fig 5　Curve of micro-hardness

CGHAZ 的冲击韧度如图 6 所示。从图 6 中可以看出不同温度下微钙钢焊接 CGHAZ 处的冲击韧度均高于未加钙的钢焊接 CGHAZ 的冲击韧度。由 Hall—Petch 公式可知细化晶粒不但可以提高材料的强度，同时还可以改善材料的塑性和韧性[7]。因此微钙钢中 CaO 粒子的钉扎奥氏体晶界、细化奥氏体晶粒的作用改善了焊接 CGHAZ 的韧度。从图中还可

以看出两种钢的焊接 CGHAZ 的冲击吸收功随试验温度的降低而逐渐降低,且没有明显的韧脆转变温度点。

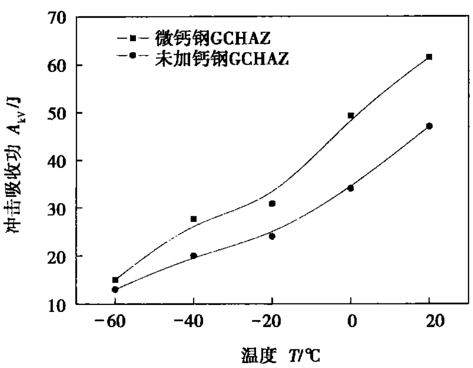

图 6 CGHAZ 系列冲击曲线

Fig. 6 Impact absorbing energy curves of CGHAZ

3 结 论

(1)微钙钢焊接 CGHAZ 组织为粒状贝氏体和少量马氏体组织。

(2)通过 Si—Ca 处理向钢中添加 Ca 元素,能够得到稳定高温组织的第二项粒子 CaO。

(3)微钙钢焊接 CGHAZ 奥氏体晶粒细小,奥氏体平均晶粒尺寸约为 40 μm,晶粒度为 6 ~7 级;未加钙钢的 CGHAZ 奥氏体晶粒平均尺寸约为 100 μm 左右,晶粒度为 3 ~4 级。CaO 粒子有明显细化 CGHAZ 奥氏体晶粒的效果。

(4)在—60,—40,—20,0,20 ℃试验温度下微钙钢的冲击吸收功分别为 15,27.6,30.8,49,62 J,而未加钙钢的冲击吸收功分别为 13,20,24,34,47 J。微钙钢中 CaO 粒子的细化晶粒的作用使焊接接头的强韧度要优于未加钙钢的焊接接头。

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tent is 24.5%—25.5%, B content is 1.30%—1.40%, W content is 3.9%—4.2%, V content is 3.0%—3.2%.

Key words: alloy element; iron-base; hardfacing alloy; grinding abrasion

Effect of second phase particles on γ grain size and toughness and strength of CGHAZ in micro-calcium steel JIA Kunning, GAO Cairu, DO Linxiu, WANG Guodong (The State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110004, China). p73—76

Abstract: The thermal-stable particles of oxide containing Ca can be formed in micro-calcium steel which can be obtained by appending Si-Ca powder into carbon steel. The microstructure, γ grain size, strength and toughness of coarse grain heat affected zone(CGHAZ) in micro-calcium and no micro-calcium steels were studied by SEM, microscope, tensile test and series impact experimental. The research show that the second phase particles have strong pinning force to γ grain boundary of CGHAZ in micro-calcium steel. It can retard γ grain growth in the course of welding, and fine γ grain in the CGHAZ, and improve the strength and toughness of CGHAZ in micro-calcium steel.

Key word: micro-calcium; γ grain boundary; γ grain size; toughness

Deformation control of complex space curve welded joint WANG Junheng[1], GAO Hongming[1], ZHANG Guangjun[1], XIE Meirong[2], WU Lin[1] (1. National Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China; 2. Capital Aerospace Machinery Corporation, Beijing 100076, China). p77—80

Abstract: A type work-piece has some features such as thin wall, dense space curve welded joint, easy to deform when heated, a high demand of gap and unfitness and so on. According to the structure characteristic and the states of heating and stress for the welding parts, the distortion mechanism of the work-piece has been further investigated and subsection linear control strategy for current to suppresses the distortion has been proposed. Based on the relationship between the gap and the welding current, the subsectioo linear control strategy for the current has been implemented by using the signals of virtual ARC _ON/OFF companied by the current-control signals produced by PLC. It has been approved that the control strategy can be successfully applied in the actual welding production and improves the quality and productivity of the work-piece.

Key words: space curve welded joint; arc welding robot; PLC; subsection linear current control

Analyze and design of RC snubber circuit in full-bridge inverter main circuit TIAN Songya, LI Wangang, SUN Yan, Wu Dongchun (The College of Mechanical & Electrical Engineering Hohai University, Changzhou 213022, Jiangsu, China). p81—84

Abstract: A great change of load occurs by freewheeling diode turning on and turning off in freewheeling circuit, it acts great quality of di/dt on main circuit. Voltage surge happens at the action of transformer leakage, induction of snubber and circuit induction, and harms IGBT by high voltage, and influences IGBT reliable work. If freewheel diode is in state of turning off, over high voltage will not produce, and it is good switching trace. Match model of IGBT U_{ce} and U_{ce} voltage equation is derived during turning off, and it shows that the less transformer leakage, the less voltage surge. According to main circuit parameter, R is calculated in good switching trace, and capacitance is calculated at the requirement of resistance power in snubber circuit and switching trace, and model is testified by the experiment. Reliability of main circuit is improved in full bridge inverter.

Key words: full bridge inverter main circuit; switching trace; RC snubber circuit; voltage surge

Microstructure in Fe—Cr—C hardfacing alloys with high C and Cr YANG Wei, WEI Jianjun, HUANG Zhiquan (Zhengzhou Research Institute of Mechanical Engineering, Zhengzhou 450052, China). p85—88

Abstracct: The effects of C and Cr on microstructures of Fe-Cr-C hardfacing alloys were studied. While the content of carbon is about 6.0%, the content of chromium changed, and while the content of chromium is about 40%, the content of carbon changed. The results show that C and Cr can both increase quantity of (Cr, Fe)$_7$C$_3$ primary carbide. With the content of Cr and C increasing, the shape of the primary carbide of Fe—Cr—C hardfacing alloy layers become more and more integrate, and the distributing of the primary carbide also becomes more and more dense。The size of the respective primary carbide gets bigger. The content of Cr in (Cr, Fe)$_7$C$_3$ primary carbide become more when the content of Cr are increased under the C content of 6.0%; but with the Cr content of about 40% the carbon content increasing makes the content of Cr in (Cr, Fe)$_7$C$_3$ primary carbide fewer.

Key words: high-chromium cast iron; hardfacing alloy; primary carbide (Cr, Fe)$_7$C$_3$; microstructure; submerged arc welding

Microstructure and mechanical property of cast iron spray-welding LEI Ali, FENG Lajun (School of Materials Science and Engineering, Xi'an University of Technology, Xi'an 710048, China). p89—92

Abstract: In order to avoid chill and quenched structure, spheroidal graphite iron was spray-welded using oxyacetylene spray torch with self-fluxing alloy powder F101 and Ni60. It was also welded using arc welding with cast iron electrode Z308. The tensile strength, hardness and metallurgical structure of samples were inspected. The results indicate that chill, quenched structure and crack were appeared in the welds of arc cold welding. The hardness of fusion zone of using Ni60 alloy powder increased up to 701 HV, and it is badly harder than that of base metal. The hardness of heat-affected zone and weld using F101 alloy powder is almost the same as that of base metal. Metallurgical structures indicate that there exists