M-A 组元对石油储罐用钢粗晶热影响区韧性的影响

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摘 要：利用 Gleeble—3800 热模拟试验机模拟粗晶热影响区（CGHAZ）焊接热循环，研究了大热输入条件下不同石油储罐用钢的粗晶区组织、韧性及其变化规律. 结果表明，各钢粗晶区组织均以贝氏体为主，但由于铁素体、粒状贝氏体等组织的比例差异，韧性差别较大. 同时，随着 M-A 组元面积分数的增加，韧性也呈下降趋势，两者均为先降之后维持较低值. 另外，M-A 组元的形态等也对韧性有影响，块状 M-A 组元对韧性的损害大于条状 M-A 组元. 考虑多种合金元素共同作用对 M-A 组元形成的综合影响，利用多元线性回归的方法对 M-A 组元面积分数做出了预测，对粗晶区韧性评判有一定实际意义.

关键词：热输入；粗晶热影响区；M-A 组元；韧性
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0 序 言

随着大型工程结构的建造，高效率的焊接方法如气电焊、电渣焊等的使用也越来越广泛，但这些方法在提高效率的同时也带来了一个较为严重的问题，就是经过大热输入焊接之后，热影响区特别是粗晶热影响区的韧性会急剧下降，这将会对构件的安全运行造成不利影响.

粗晶区为紧邻焊缝熔合线的区域，在焊接热循环中经历了很高的峰值温度，在大热输入焊接时，从高温冷却下来的时间较长，一方面，高温停留较长的时间会使奥氏体晶粒非常粗大；另一方面，合适的冷却速度也会促使 M-A 组元形成. 研究认为，粗大的奥氏体晶粒与脆性 M-A 组元的存在是粗晶区韧性恶化的主要因素[1,2]. 另外，不同的合金元素，如 C，Si，Al，Mo，Nb 和 V 等对 M-A 组元形成的影响已有报道，但对于不同的合金系统，这些元素是如何相互作用的，对最终 M-A 组元的形成又是如何相互影响的研究较少.

文中针对四种石油储罐用钢在大热输入焊接后粗晶热影响区的组织和韧性，重点研究了 M-A 组元对冲击韧度的影响，提出了 M-A 组元面积分数的预测公式.

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1 试验方法

试验材料为四种石油储罐用低合金高强钢，化学成分见表 1. 其中 A、B 钢为宝钢产，C 钢为日本产，D 钢为国内某钢厂产品. 几种钢均为再加热淬火＋回火热处理.

采用 Gleeble—3800 热模拟试验机模拟粗晶区焊接热循环，试样横向取样，尺寸为 10 mm × 10 mm × 55 mm，在热电偶丝的焊接中心位置开缺口，进行夏比 V 形缺口冲击试验. 模拟热循环加热速率 500 ℃/s，加热峰值温度 1 350 ℃，峰值温度停留时间 3 s，从 800～500 ℃冷却时间 $t_{8/5}$ 为 125 s，这一热循环相当于板厚 20 mm，热输入 100 kJ/cm 时的实际焊接粗晶热影响区.

热模拟试样经磨制、抛光后用 2% 的硝酸酒精溶液腐蚀以观察微观组织形貌，采用两段电解腐蚀法观察粗晶区中的 M-A 组元，腐蚀步骤如下：第一步，乙二胺四乙酸（EDTA）5 g＋NaF 0.5 g＋蒸馏水 100 ml，电解 3 V，10 s，铁素体被腐蚀为灰色；第二步，苦味酸 5 g＋NaOH 25 g＋蒸馏水 100 ml，电解 6 V，60 s，碳化物被腐蚀呈黑色，而 M-A 组元在两步中均未被腐蚀，保持浮突，呈白色. 利用 s—4200 场发射扫描电镜观察 M-A 组元，此时 M-A 组元呈白亮色，碳化物呈黑色，铁素体呈灰色. 利用 Quantiment 600 型图像分析仪对 SEM 照片进行统计，每个试样

所选视场不少于 30 个，测定了M-A 组元的面积分数、长度及长细比等参数.

表 1 试验用钢的化学成分(质量分数，%)

Table 1 Chemical composition of steels

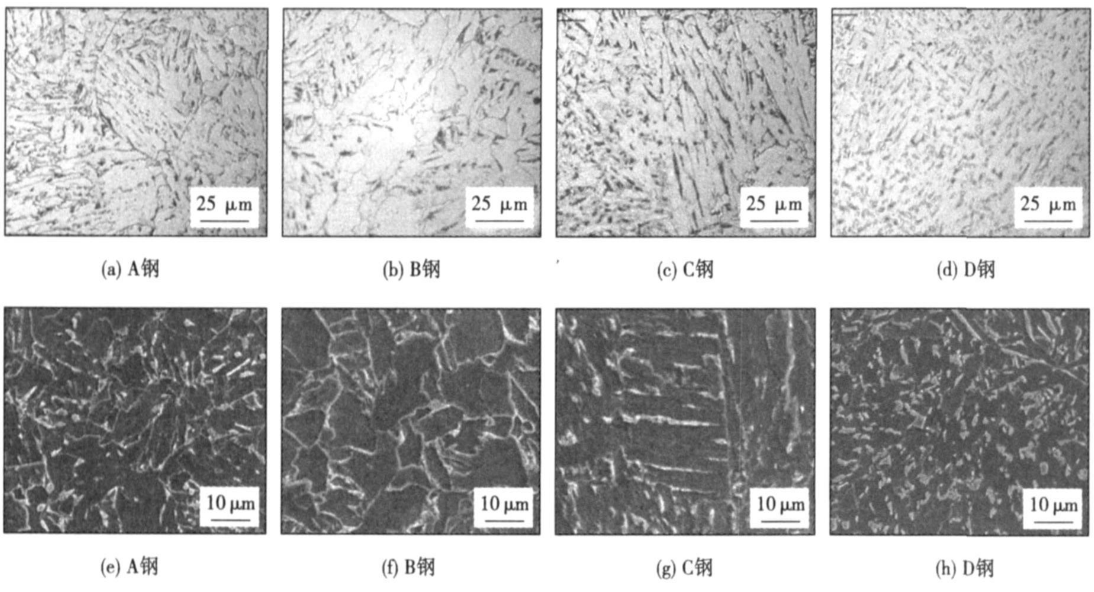
材料	C	Si	Mn	P	S	V	Nb	Ti	N(10^{-4})
A	0.074	0.23	1.41	0.005	0.002 5	0.044	0.026	0.01	42
B	0.073	0.21	1.34	0.004	0.001 6	0.042	—	0.012	36
C	0.082	0.18	1.38	0.014	0.003 0	0.041	0.024	0.009	27
D	0.12	0.28	1.45	0.018	0.004 0	0.041	<0.002	0.012	18

其它：Ni，Cr，V，Mo 和 Al 等

2 结果与讨论

2.1 粗晶热影响区微观组织

由于热输入较大(100 kJ/cm)，冷却速度缓慢，高温停留时间长，因此，粗晶区组织以一些易于在较高温度生成的组织为主，如铁素体、上贝氏体、粒状贝氏体等. 试验钢的显微组织形貌如图 1 所示. A 钢以粒状贝氏体和上贝氏体混合组织为主，奥氏体晶界明显且平直；B 钢以铁素体与贝氏体组织为主，原奥氏体晶界完全消失，被在奥氏体晶界形核并长大的晶界铁素体所取代，铁素体的大量萌生有利于韧性提高；C 钢中大多为上贝氏体组织，贝氏体铁素体板条较宽，渗碳体呈长条状有序排列；D 钢组织为较典型粒状贝氏体，M-A 组元及碳化物均匀密集分布于铁素体基体之上.



(a) A钢 (b) B钢 (c) C钢 (d) D钢

(e) A钢 (f) B钢 (g) C钢 (h) D钢

图 1 热输入 100 kJ/cm 时模拟粗晶热影响区显微组织形貌

Fig 1 Optical and SEM micrographs of simulated CGHAZ at 100 kJ/cm

2.2 粗晶热影响区冲击韧度

热输入 100 kJ/cm 时模拟焊接粗晶热影响区夏比V 形缺口冲击吸收功如图 2 所示，试验温度为 −15 ℃. 由图可知，B 钢 CGHAZ 冲击韧度最高，三个冲击试样平均值为 219 J，D 钢最低，仅为 37 J. 几种钢母材基体的冲击韧度并不差，均为−15 ℃时 200 J 以上，但大热输入焊接之后韧性下降幅度却差别很大，这主要归因于焊接过程中组织转变的差异，下降幅度大的钢种在焊接过程中产生了一些对韧性有害的微观组织，如M-A 组元等.

2.3 M-A 组元对冲击韧度影响

M-A 组元对冲击韧度危害很大，其形成通常认为必须有合适的冷却速度与合适的碳及合金元素含量. 试验中焊接大热输入(100 kJ/cm)，高温冷却速度较缓慢，有利于高温碳的扩散，使碳不易在 γ/α 界面聚集，抑制渗碳体的形成，冷却至较低温度时富碳的未转变 γ 相一部分转变为马氏体，另一部分残留下来成为残余奥氏体，形成 M-A 组元. 图 3 为经两步电解腐蚀之后的M-A 组元形貌. 未被腐蚀的白色小岛为M-A 组元，铁素体基体呈灰色，碳化物呈黑

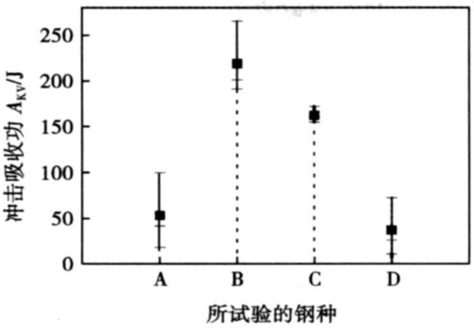


图 2　不同钢在 100 kJ/cm 时粗晶热影响区冲击韧度

Fig. 2　Charpy impact energies of simulated CGHAZ for different steels

色, 可以看出不同钢中 M-A 组元的尺寸、数量、分布、形态等均有不同. 块状 M-A 组元一般沿晶界或相界分布, 而细长状 M-A 组元倾向于沿贝氏体板条边界分布. Li 等人[2] 的研究中也观察到了同样的现象. 由图 3 显示, A 与 D 钢 M-A 组元分布密集且尺寸较大, B 与 C 钢 M-A 组元较为稀少, 且尺寸较小.

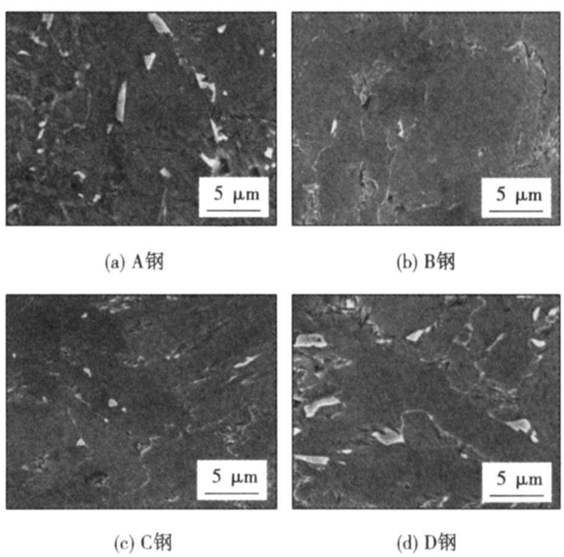


图 3　粗晶热影响区 M-A 组元形貌

Fig. 3　SEM micrographs of M-A constituent of simulated CGHAZ

M-A 组元的面积分数与冲击韧度的关系如图 4 所示. 随 M-A 面积分数的增加, 冲击韧度值先下降, 之后保持平稳, 维持较低值. 当 M-A 面积分数从 0.614%增大为 2.845 5%时, A_{kv} 值从219 J降为53 J, 下降幅度非常大, 之后随 M-A 面积分数的增加, 韧度值只有小幅波动. 这种趋势说明 M-A 面积分数的增加的确能恶化粗晶区冲击韧度, 但存在一个临界值, 超过这个临界值之后, 随 M-A 面积分数的增加, 韧性变化不明显. 在试验所用钢板及焊接热循环条件下, 这一临界值大约为 2.8%左右.

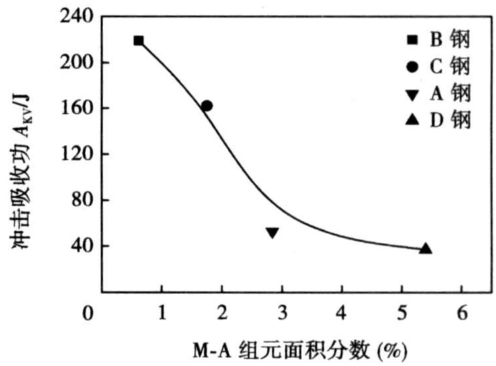


图 4　M-A 组元面积分数与冲击韧度的关系

Fig. 4　Relationship between area fraction of M-A constituents and Charpy impact energy

很多研究指出, 不仅 M-A 组元的面积分数, 而且它们的形态差异等也对冲击韧度有影响[3]. 文中利用图像分析仪对 M-A 组元颗粒的面积分数、长度、长细比进行了统计. 为了更精确地接近实际结果, 经过对图像的仔细对比与分析, 把 $L>0.35$ μm 的颗粒计入统计总数, 认为 $L<0.35$ μm的颗粒是由于抛光腐蚀等方面的原因, 在表面存在的一些与 M-A 灰度差别很小的极细小的颗粒, 它们的数目占了颗粒总数的大部分, 但分析认为这些颗粒并非 M-A 组元, 因此把它们排除出去. M-A 组元的形态可由其长度和长细比确定. 图 5 为热输入 100 kJ/cm 时 D 钢粗晶区 M-A 组元的形态分布. 长度大于2 μm的颗粒称为大颗粒, 把长度大于2 μm, 长细比大于 4 的组元归为长条状组元, 而把长度大于2 μm, 长细比小于 4 的组元归为块状组元. D 钢的块状组元面积分数远大于长条状组元面积分数, 按照这种统计方法, 分别把 A, B 和 C 钢的 M-A 组元形态进行了统计.

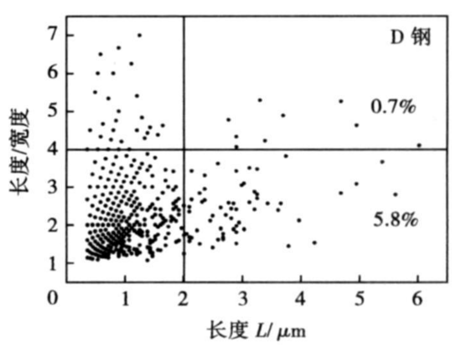


图 5　D 钢粗晶热影响区中不同形态 M-A 组元分布

Fig. 5　Distribution of M-A constituents in CGHAZ of D steel

结果可知, 大块状M-A 组元对冲击韧度的影响是占主导地位的, 文献[4, 5] 都认为大块状的 M-A 组元对韧性有非常显著的危害. 文献[6] 指出, 在有着大块M-A 组元颗粒的情况下, 微裂纹首先发生在大块M-A 组元颗粒与铁素体基体的界面上. 因此, M-A 组元的存在使脆性裂纹的萌生及扩展行为发生了变化, M-A 组元在这里起到了应力集中源的作用, 在它与基体的界面上产生脆性断裂的显微裂纹, 并且脆性断裂的二次裂纹也是沿 M-A 组元边界扩展.

2.4 M-A组元面积分数的回归分析

前已所述, 粗晶区韧性随 M-A 组元面积分数的增加而减小, 那么, 如果能够对 M-A 组元的面积分数做出较为精确的预测, 粗晶区的韧性也就能够做出相应的判断. 在焊接热循环一定的前提下, M-A 组元的形成只与合金元素添加量的多少有关. 文献[7, 8] 等研究了 C, Si, Al, Mo, Nb 和 V 等元素对M-A 组元形成的影响, M-A 组元中的碳含量虽然独立于基体组织的碳含量, 但M-A 组元的数量却随碳含量的增加而大幅增加; 硅含量增加也有利于M-A 组元形成, 由于在贝氏体相变中, 硅在渗碳体中溶解度很低, 因此聚集于渗碳体与未转变奥氏体的表面, 加剧了未相变 γ 相中碳的浓化过程, 阻碍渗碳体长大, 有利于奥氏体稳定化和 M-A 组元形成; 在中到大热输入情况下, 铌减少晶界铁素体促使有着长条状M-A 组元的粗化铁素体的形成, 提高硬度值.

钢中同时含有这些合金元素, 各个元素之间相互作用, 构成一个复杂的系统, 对 M-A 组元的形成有一个综合的影响. 回归分析就是一种处理变量间相互关系的数理统计方法. 把M-A 组元的面积分数作为因变量, 比较四种钢合金元素含量的差异, 从中选取了三个质量分数差异较大的元素作为自变量, 分别为 C, Si, Nb, 建立多元线性回归方程. 线性回归分析模型为

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3$$

式中: β_0, β_1, β_2, β_3 为待定系数; x_1, x_2, x_3 为 C, Si, Nb 的质量分数. 回归分析结果为

$$S_{MA} = -9.748 + 59.002C + 28.831Si + 61.38Nb$$

式中: S_{MA}为M-A 组元面积分数.

复相关系数 R 与决定系数R^2 均为 1 时, 回归方程有效, 并且显著性良好, 因此可用它来进行预测. 这个方程适合大热输入的低合金高强钢粗晶热影响区M-A 组元面积分数的预测, 在给定组分和焊接条件的情况下, 是评判 M-A 组元含量及粗晶区韧性的有用工具.

3 结 论

(1) 在大热输入(100 kJ/cm)焊接时, 粗晶区组织以贝氏体为主, 但各钢中铁素体, 粒状贝氏体等的比例不同, 从而冲击韧度差异较大.

(2) 随粗晶区 M-A 组元面积分数的增加, 韧性也呈下降趋势, 同时, M-A 组元的形态对韧性也有影响, 块状M-A 组元对韧性的损害大于条状 M-A 组元.

(3) 综合合金元素对 M-A 组元形成的影响, 提出了M-A 组元面积分数的多元线形回归方程, 对预测粗晶区韧性有实际意义.

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study compositions and microstructures of the coating. The oxidation resistance of the ceramal composite coating was investigated under the testing condition of 900 ℃ and 50 hours. The results indicate that the excellent oxidation resistance of the coating is mainly attributed to the relatively continuous oxide scales which mainly consist of Cr_2O_3 and Fe_2O_3, and the oxide scales can prevent the inner part of the composite coating from being further oxidized.

Key words: reactive plasma cladding; high-chromium iron-based composite coating; precursor; microstructure; oxidation resistance

Resistance spot welding microstructure proportion simulation and experiment analysis on two aluminium alloys TANG Xinxin, SHAN Ping, LUO Zhen, LUO Baofa (College of Material Science and Engineering, Tianjin Key Laboratory of Advanced Jointing Technology, Tianjin University, Tianjin 300072, China). p96—100

Abstract: AA5754 and AA6082 aluminium alloy are two kinds of aluminius alloys with different strengthen modes. In the processing of the resistance spot welding, the microstructure of the two aluminium alloys changes in different types. By two different numerical models, the microsturcture proportion in the nuggets of the two aluminium alloys was simulated and pridicted. Conpared with the experimental results, the two simulation models are effective to predict some important phenomenas in terms of the phase transformation of the nuggets. Both the simulation results and the experimental results show that there are marked different features in the phase transformation of the two kinds of aluminium alloys.

Key words: aluminium alloy; resistant spot welding; numerical simulation; welding microstructure

Fabrication and characterization of nanocrystructured surface layer of J507 weld by ultrasonic impact peening LI Dong, FAN Zhao, LIAO Libao, ZHANG Li, XU Hong (State Key Laboratory of Chemical Engineering, School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, China). p100—104

Abstract: A nanostructured surface layer was fabricated on a J507 weld metal by. ultrasonic impact peening (UIP). The refined microstructure in the top surface layer was characterized by means of X-ray diffraction and transmission electron microscopy (TEM), and the microhardness variation along the depth of the treated sample was examined. Experimental results show that, after the UIP treatment, the microstructure of the surface layer may be refined into 21. 25 nm. Grains refinement involves formation of dense dislocation walls (DDWs) and dislocation tangles (DTs) in coarse grains, transformation of DDWs and DTs into subboundaries, and evolution of subboundaries to highly misoriented grain boundaries. The strengthened thickness of the layer is 100 μm after UIP treatment. The microhardness of nanocrystalline surface layer is enhanced significantly after the UIP treatment compared with that of the original sample.

Key words: J507 weld; ultrasonic impact peening; surface nanocrystallization; microhardness

Analysis on the tendency of welding hot cracks of aluminum alloy increased by longitudinal pre-tension ZHOU Guangtao[1], LIU Xuesong[1], YANG Jianguo[1], FANG Hongyuan[1,2] (1. State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China; 2. Institute of Astronautical Technology, Shenyang Institute of Aeronautical Engineer, Shenyang 110034, China). p105—108

Abstract: Numerical simulation calculation of TIG welding of thin wall aluminum cylinder by the thermo-elastic FEM has been conducted. Based on the generating of analysis model, the values and distribution at the centre of weld seam for transverse tensile stress and strain produced by pre-tension upon the solidification metal at the back of molten pool. Experiments were performed to verify the simulation results. It can be drawn that, for weld metal just solidified at the joint pre-tension load can produce transverse tensile stress, which increases the tendency of welding hot cracks. And with the increasing of pre-tension load, the transverse tensile stress increases. When the pre-tension stress is 60, 120, 150 and 210 MPa, the crack length in specimens is 5. 2 mm、8. 1 mm、8. 9 mm and 10. 6 mm, respectively. The tests results indicates the reliability of simulation results.

Key words: pre-tension; numerical simulation; residual stress; hot cracks

Effects of M-A constituent on toughness of coarse grain heat-affected zone in HSLA steels for oil tanks ZHANG Yingqiao[1], ZHANG Hanqian[1,2], LIU Weiming[1] (1. Department of Materials Science and Engineering, Shanghai Jiaotong University, Shanghai 200030, China; 2. Research Institute for Advanced Structural Steel, R&D Center, Baoshan Iron and Steel Limited Company, Shanghai 201900, China). p109—112

Abstract: Microstructure and impact toughness of CGHAZ in HSLA steels for oil tanks under high heat input (100 kJ/cm) have been investigated. Bainite is main microstructure in CGHAZ for four steels, but there is a significant difference in impact values due to different proportion of ferrite and granular bainite. Toughness values decrease with the increase of area percentage content of M-A constituents. The effects of morphology of M-A constituents on toughness have also been studied, and the harm of massive M-A constituent is more severe than that of long strip. Considering the influence of alloy elements on the formation of M-A constituents, area percentage contents of M-A constituents are predicted by the method of multiple linear regressions, which is helpful for evaluating the toughness of CGHAZ.

Key words: heat input; coarse grain heat-affected zone; M-A constituent; impact toughness