800 MPa 级高强钢焊缝金属热处理组织与性能

赵晓兵[1,2]，何长红[2]，彭　云[2]，田志凌[2]，郑保忠[1]，赵秀柏[3]

（1. 云南大学 物理科学技术学院，昆明　650091；2. 钢铁研究总院 结构材料研究所，北京　100081；3. 辽宁省开原维科容器有限责任公司，辽宁 开原　112300）

摘　要：在 10Ni5CrMoV 高强结构钢焊接中，为了获得良好的强韧性匹配，焊后需要进行热处理来改善焊缝金属的组织和性能。试验采用富氩气体保护焊焊接 10Ni5CrMoV 钢，分析了不同调质热处理工艺下焊缝组织、性能的变化规律。结果表明，焊缝金属焊态的组织主要是贝氏体、少量马氏体和残余奥氏体组织，调质热处理后焊缝组织主要为回火马氏体，随着回火温度的升高，焊缝中残余奥氏体减少，马氏体中碳化物析出长大并有球化趋势。调质态焊缝金属的强度随着回火温度的升高而逐渐降低，而韧性随着回火温度的升高而显著提高。

关键词：焊缝；热处理；显微组织；力学性能
中图分类号：TG457　　文献标识码：A　　文章编号：0253－360X(2007)07－101－04

赵晓兵

0　序　　言

10Ni5CrMoV 钢既具有较高的强度，又具有良好的塑性、韧性和耐磨性，其主要用于工程机械、高压容器和水轮机壳体等，其焊缝及焊接区多承受拉伸载荷。实践表明，在生产中的焊接加工是影响高强度钢结构质量的关键，是生产工艺中的主要问题，而且低合金高强度钢焊接接头的韧性历来都是焊接结构使用性能的主要指标，尤其对 800 MPa 级以上的高强度调质钢的结构，如何提高焊接接头的韧性就更显得非常重要[1]。它关系到产品构件在服役期间的稳定性和安全性。

低碳调质钢是通过调质热处理获得强化效果，但是受焊接热循环的影响，热影响区存在脆化和软化现象，强度级别越高的钢，软化现象越突出。解决的办法[2]，一是焊后不再进行热处理，在焊接过程中严格限制焊接热输入对母材的作用；二是焊后重新调质热处理，以消除应力和改善显微组织，从而获得更优的性能。影响焊缝金属性能的因素是多方面的，除焊缝金属的化学成分、金相组织外，焊接工艺和焊前状态及焊后热处理也是影响因素中的关键问题。试验就是通过对 800 MPa 级 10Ni5CrMoV 钢的焊缝金属进行不同调质热处理来分析焊缝组织、性能的变化规律，确定焊缝金属强度与韧性较佳的匹配点。

收稿日期：2007－01－18

1　试验材料及工艺

试验用 10Ni5CrMoV 钢的化学成分及力学性能如表 1，表 2 所示，其组织主要为回火索氏体，如图 1 所示。焊接方法采用熔化极气体保护焊，焊接设备为 YM－751A 日本产全自动焊机。焊接材料为自行设计冶炼的 Mn－Ni－Cr－Mo－V 系实心焊丝，直径 ϕ1.2 mm。保护气体为 95%Ar 和 5%CO_2，气体流量 22 L/min。层间温度 120～130 ℃，焊接速度 28 cm/min，焊接热输入 18 kJ/cm。

表 1　10Ni5CrMoV 钢的化学成分(质量分数，%)

Table 1　Chemical composition of 10Ni5CrMoV steel

C	Si	Mn	Ni	Cr	Mo	V
0.10	0.19	0.5	1～5	0.4～0.8	0.3～0.7	0.02～0.07

表 2　10Ni5CrMoV 钢的力学性能

Table 2　Mechanical properties of 10Ni5CrMoV 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 Z(%)	冲击吸收功 $A_{kV(-20℃)}$/J
830	925	19.0	63.0	104

焊接接头的调质热处理参数为加热温度 920 ℃，保温 3 h 后用水淬火，回火温度分别为 560，580，600 和 620 ℃，保温 2 h 后空冷至室温。

利用光学显微镜对焊态和热处理态的焊缝组织进行观察和分析，浸蚀剂均为 3% 的硝酸酒精。拉

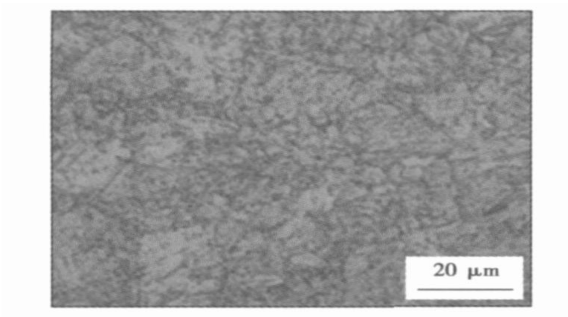

图 1 10Ni5CrMoV 钢组织

Fig. 1 Microstructure of 10Ni5CrMoV steel

伸试验在 AG — 100KNE (50 kN) 及 UH — F50A (250 kN)拉伸试验机上按照国家标准 GB/T2562 — 1989 进行。冲击试验在 JBZ — 300 自动冲击试验机上按照国家标准 GB/T2650 — 1989 进行, 额定冲击能量为 300/150 J。由于对母材和焊缝冲击试验温度的要求不同, 母材冲击试验温度为 −20 ℃, 焊缝冲击试验温度为 −50 ℃。

2 试验结果与分析

2.1 显微组织

图2 所示的是焊缝金属焊态的典型组织。焊缝金属焊态组织主要是贝氏体组织。焊缝金属的化学成分(质量分数, %)为 0.050 C, 0.20 Si, 1.41 Mn, 其余为 Fe, Ni, Cr, Mo。根据相关文献[3-5], 当钢中 C 元素含量降到 0.05%及以下时, 此种钢在经过高温奥氏体化后的冷却过程中, 不再发生奥氏体向铁素体与渗碳体的两相分解, 过冷奥氏体将直接转变成各种形态的铁素体并留下少量富碳的残余奥氏体。也就是说在超低碳条件下, 由于碳含量很低, 钢中所得到的贝氏体组织不同于一般的上、下贝氏体, 而是一种以无碳或少碳贝氏体为主的组织。在试验中, 由于焊缝金属的碳含量已接近超低碳范围, 根据金相分析和透射电镜分析, 焊缝组织由板条状贝氏体(由

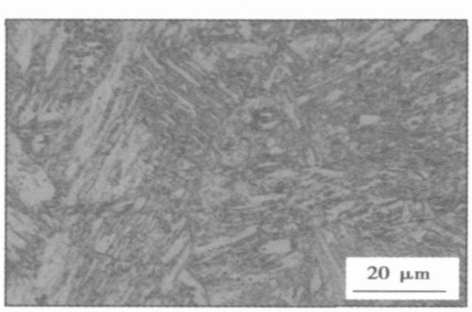

图 2 焊缝金属焊态组织

Fig 2 Microstructure of weld metal

板条状贝氏体铁素体及板条间的残余奥氏体组成)、部分下贝氏体和 M−A 组元组成。

焊缝金属经过 920 ℃保温 3 h 淬火, 组织主要为板条马氏体和少量残余奥氏体。图 3 所示的是调质后的焊缝组织, 组织主要为回火马氏体。图4a, b

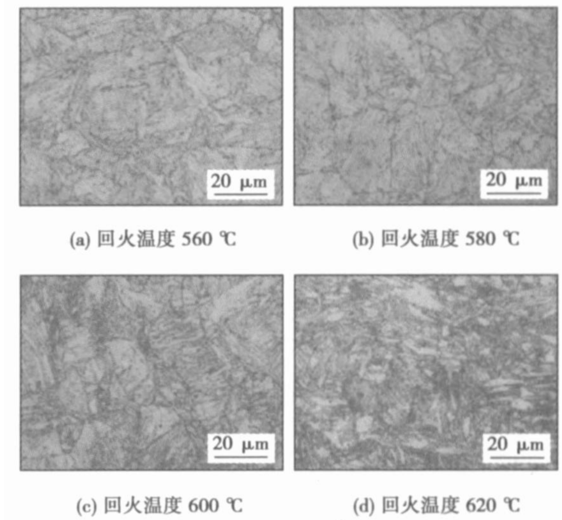

图 3 焊缝调质态组织

Fig. 3 Microstructure of weld metal after different heat treatment

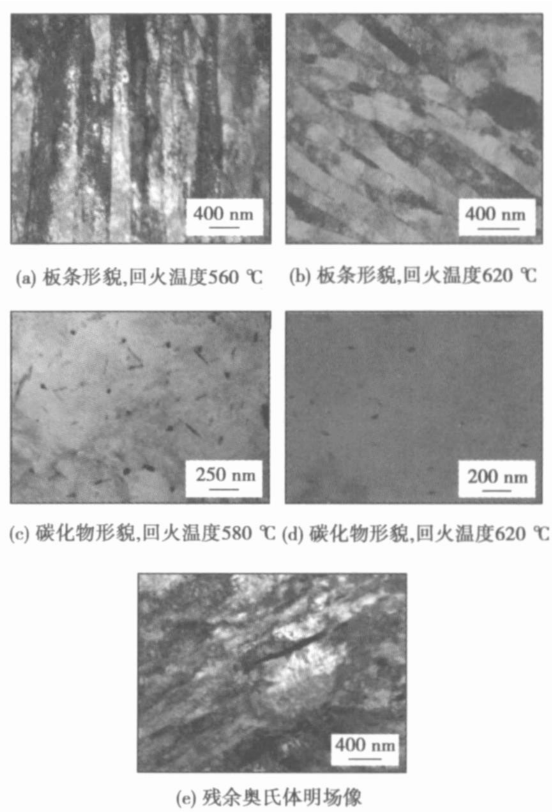

图 4 焊缝透射照片

Fig. 4 Microstructure of weld metal after different heat treatment (TEM)

为不同回火温度时透射电子显微镜形貌照片, 由于回火温度较高, 保温时间较长, 位错密度也大幅度降低; 随着回火温度的升高, 焊缝中马氏体中的碳化物析出长大并有球化趋势(图 4c, d)。但仍有少量残余奥氏体未分解(图 4e)。图 5 所示的是光学显微镜下, 焊态和调质态(回火温度为 560 ℃)的焊缝组织(试样抛光后, 采用 Lepera 试剂, 4%苦味酸酒精与 1% $Na_2S_2O_4$ 1∶1 的比例混合, 浸蚀约 15～20 s)。从图 5 中可以看出, 焊态焊缝组织中的 M－A 组元较多, 而经过调质热处理后, 焊缝中部分的 M－A 组元已经发生分解, 但仍有一定数量的 M－A 组元断续存在于焊缝中。随着回火温度的提高, 焊缝 M－A 组元数量减少, 碳化物数量增加。

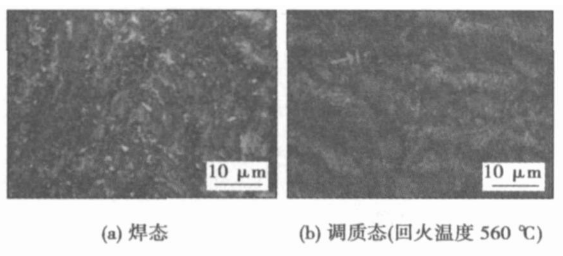

图 5　焊缝中的 M－A 组元

Fig. 5　Microstructure of weld metal with M－A constituent

2.2　力学性能

调质态焊缝的强度和韧性随回火温度变化的趋势主要是由调质态焊缝的组织决定的。图 6a 所示的是焊态和调质态焊缝的屈服强度和抗拉强度。焊态焊缝的屈服强度为 810 MPa, 抗拉强度为 1 100 MPa。调质态焊缝的屈服强度均高于焊态, 而抗拉强度均低于焊态。与调质态焊缝相比, 随着回火温度的升高, 其屈服强度和抗拉强度均有不同程度降低, 屈服强度最大为 945 MPa, 最小为 840 MPa, 抗拉强度最大为 1 010 MPa, 最小为 895 MPa。图 6b 所示的是焊态和调质热处理态焊缝的硬度变化趋势。焊态焊缝的硬度为 340 HV1。560 ℃回火时, 焊缝硬度为 335 HV1, 随着调质热处理的回火温度的升高, 硬度逐渐降低, 620 ℃回火温度, 其焊缝硬度为 290 HV1。随着回火温度的升高, 焊缝金属的硬度逐渐降低。当回火温度升高时, 焊缝组织中马氏体中的碳化物析出并长大, 板条中的位错密度降低。焊缝组织中碳化物(图 4c, d)的球化和 M－A 组元的分解, 这些因素都使得焊缝金属强度和硬度降低。

图 7 所示的是焊态和调质态焊缝的低温冲击试验结果。－50 ℃条件下, 焊态焊缝的冲击吸收功为 40 J。随回火温度的升高, 调质态焊缝的低温冲击吸收功提高, －50 ℃冲击吸收功最大为 102 J, 最小为 29 J。图 8 所示是的调质态焊缝冲击断口形貌。当回火温度为 560 ℃时, 断口为解理, 对应着最低的韧性; 当回火温度为 580 ℃时, 断口为解理和少量韧窝, 对应着较低的韧性; 当回火温度为 600 ℃时, 断口为韧窝和少量解理, 对应着较高的韧性; 当回火温度为 620 ℃ 时, 断口为韧窝状, 对应着最高的韧性。因此, 调质态焊缝的冲击断口形貌也可反映出焊缝冲击吸收功随回火温度的变化趋势。对于韧性来说, 尽管奥氏体的分解降低了焊缝的韧性, 但是回火马氏体中碳化物充分析出和长大以及 M－A 组元的

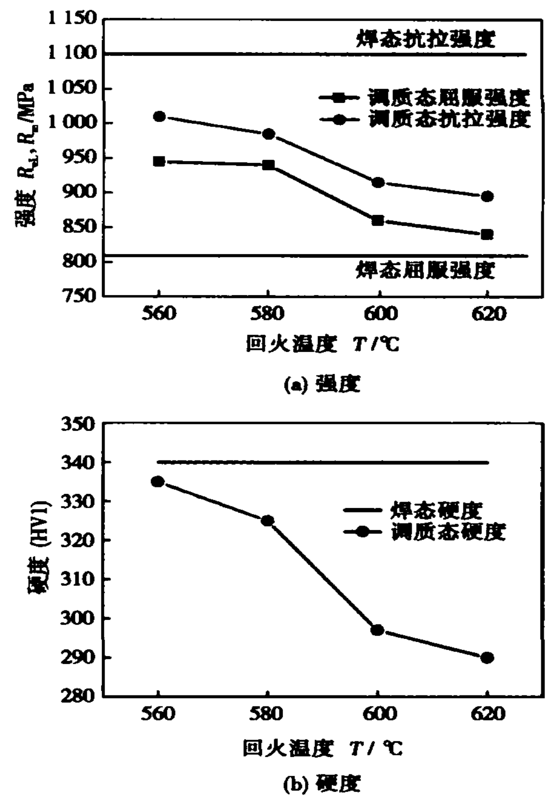

图 6　焊缝的强度及硬度

Fig. 6　Strength and hardness of weld metal

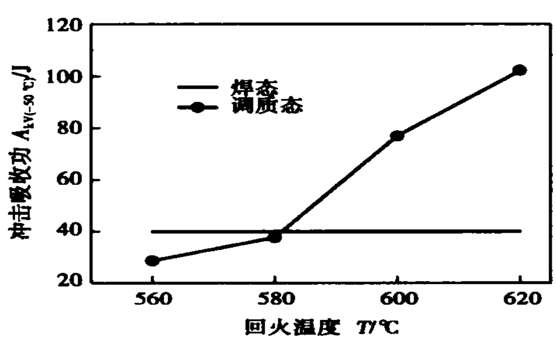

图 7　焊缝的冲击吸收功(－50 ℃)

Fig 7　Impact absorbing energy of weld metal

进一步分解都将提高焊缝的低温韧性[6-8]。因此调质处理态焊缝的韧性随回火温度的升高而提高。

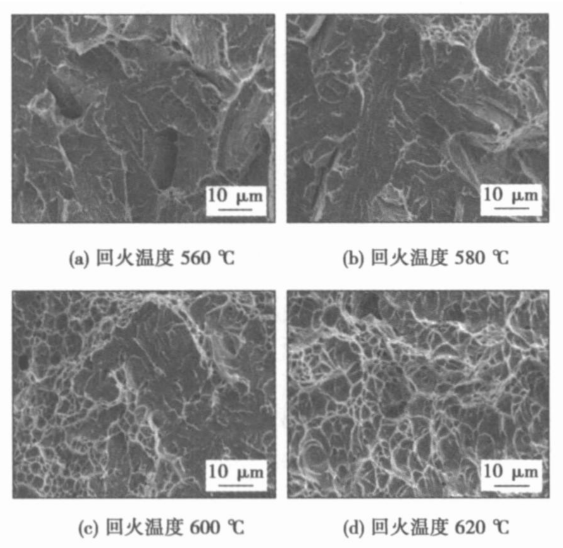

图 8 调质态焊缝冲击断口形貌

Fig. 8 Fracture surface of weld metal after different heat treatment

3 结 论

(1) 10Ni5CrMoV 钢焊缝金属焊态组织为板条状贝氏体(由板条状贝氏体铁素体及板条间的残余奥氏体组成)、下贝氏体和少量粒状贝氏体的混合组织。调质后的焊缝组织为高温回火马氏体。随着回火温度的升高,焊缝金属中碳化物析出并长大,残余奥氏体和 M-A 组元含量均减少。

(2) 调质态焊缝的强度随回火温度的升高而降低,韧性随回火温度的升高而提高,这是由于组织中的板条位错密度的降低、M-A 组元的分解造成的;调质态焊缝的硬度随回火温度的升高而降低,这是由于组织中碳化物的析出和位错密度降低的影响结果。

参考文献:

[1] 李亚江, 王 娟, 刘 鹏. 低合金钢焊接及工程应用[M]. 北京: 化学工业出版社, 2003.

[2] 李亚江. 焊接组织性能与质量控制[M]. 北京: 化学工业出版社, 2004.

[3] 翁宇庆, 田志凌, 彭 云, 等. 超细晶粒钢——钢的组织细化理论与控制技术[M]. 北京: 冶金工业出版社, 2003.

[4] 武会宾, 尚成嘉, 杨善武, 等. 超细化低碳贝氏体钢的回火组织及力学性能[J]. 金属学报, 2004, 40(11): 1143-1150.

[5] Wang X M, He X L, Yang S W, *et al*. Refining of intermediate transformation microstructure by relaxation processing[J]. International, 2002, 42(12): 1553-1559.

[6] Chen J H, Kikuta Y, Araki T, *et al*. Micro-fracture behavior induced by M-A constituent (island martensite) in simulated welding heat affected zone of HT80 high strength low alloyed steel[J]. Acta Metail, 1984, 32(10): 1779-1788.

[7] Matsuda F, Ikeuchi K, Liao J. Weld HAZ toughness and its improvement of low alloy steel SQV-2A for pressure vessels (Report 1)[J]. Transactions of Joining and Welding Research Institute, 1993, 22(2): 271-279.

[8] Matsuda F, Fukada Y, Okada H, *et al*. Review of mechanical and metallurgical investigations of martensite-austenite constituent in welded joints in Japan[J]. Welding in the World/Le Soudage Dans Le Monde, 1996, 37(3): 134-154.

作者简介: 赵晓兵, 男, 1977 年出生, 硕士研究生。主要从事焊接技术及焊接材料的研究工作。发表论文 3 篇。

Email: zxb0810@163.com

joints were examined by means of Olympus optical microscope and scanning electron microscope. And the Vickers microhardness profiles were measured by Vickers microhardness tester. The crack resistance in Y-groove welded joints was also compared. The experiment results showed that the crack resistance of the welded joint using H10MnSi wire was better than that of the weldment using H08Mn2Si wire, which is mainly due to the fine crystal grain in the weld metal and the more content of acicular ferrite.

Key words: armoured steel; CO_2 shielded arc welding; microstructure; crack resistance

Development of gas metal arc welding wire for X80 pipeline steel LI Ran[1,2], WEI Jinshan[1], PENG Yun[1], TIAN Zhiling[1], SHI Zhe[2] (1. State Key Laboratory of Advanced Steel Processes and Products, Central Iron & Steel Research Institute, Beijing 100081, China; 2. Faculty of Materials and Metallurgical Engineering Kunming University of Science & Technology, Kunming 650093, China). p97—100

Abstract: The developed wires are used for gas metal arc welding. The chemical composition, microstructure, impact toughness, strength, hardness and tensile strength of welded joint are investigated. The microstructure is composed of acicular ferrite and a little proeutectoid ferrite and a little granular bainite. The fractured surfaces of impact specimen are analyzed by scanning electron microscope, and the microstructures of weld metal are analyzed by transmission electron microscope. Experiment results indicated that it was effective to resist proeutectoid ferrite and make fine homogeneous acicular formation by adding microcontent Ti—B elements in the wire. It had been found that alloy element in weld metal could be the nucleating-centers of acicular ferrite as long as they formed fine disperse inclusion. It is effective to prevent crack propagation and improve impact toughness because there are lots of dislocation agglomerating in acicular ferrite.

Key words: X80 pipeline steel; gas metal arc welding; low-temperature toughness; acicular ferrite; inclusion

Microstructure and property of PWHT weld metal of 800 MPa grade low alloy steel ZHAO Xiaobing[1,2], HE Changhong[2], PENG Yun[2], TIAN Zhiling[2], ZHENG Baozhong[1], ZHAO Xiubai[3] (1. School of Physic Science and Technology, Yunnan University, Kunming 650091, China; 2. Institute for Structural Materials, Central Iron & Steel Research Institute, Beijing 100081, China; 3. Kaiyuan Weike Pressure Vessel Co., Ltd, Kaiyuan 112300, Liaoning, China). p101—104

Abstract: In order to achieve good toughness and strength in welding 10Ni5CrMoV steel, heat treatment is usually carried out to improve the mechanical properties of the weld metal. 10Ni5CrMoV steel was welded with rich Ar shielding gas, and the microstructure and mechanical properties of the weld metal were investigated after different heat treatment. The results indicate that the microstructures of the weld metal are bainite, martensite and a small amount of retained austenite. After quenching and tempering, the microstructure of the weld metal is tempered martensite. The amount of retained austenite in the weld metal decreases and the size of carbide in the martensite increases with tempered temperature increasing. The strength of the weld metal decreases as tempered temperature increases, and the toughness is improved when tempered temperature is increased.

Key words: weld metal; heat treatment; microstructure; mechanical properties

Study on inner expulsion in resistance spot welding of magnesium alloy WANG Yarong[1], ZHANG Zhongdian[2], FENG Jicai[2] (1. Institute of Mechanical Manufacturing Technology, China Academy of Engineering Physics, Mianyang 621900, Sichuan, China; 2. State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p105—108

Abstract: Expulsion is highly undesirable during the resistance spot welding for it decreases the weld quality. An axisymmetric finite element model was creates to study the distribution of temperature and the plastic deformation to investigates interior expulsion happening during the resistance spot welding of AZ31 magnesium alloy, employing a contact resistance model based on the micro-contact theory. Because of high thermal conductivity, low melting point, small specific heat and large linear thermal expansion coefficient of AZ31 magnesium alloy, expulsion is most encountered problem due to the application of high current in short welding time, compared with Al alloy and mild steel. And it is connected with the increased pressure in the nugget due to melting so that the surrounding solid material cannot hold the liquid phase and the molten metal break through the constriction of peripheral boundary, which leads to expulsion.

Key words: expulsion; magnesium alloy; resistance spot welding; finit element method

Finite numerical simulation of temperature field in multi-pass laser cladding MA Lin, YUAN Jinping, ZHANG Ping, ZHAO Junjun (National Key Laboratory for Remanufacturing, Academy of Armored Force Engineering, Beijing 100072, China). p109—112

Abstract: The main effective factor of temperature field was analyzed and the calculation model of temperature field in multi-pass laser cladding was built. In the model the main consideration was given to the thermal boundary conditions and heat source. And the temperature field of three passes cladding process on plate were calculated. The temperature variations of the three points at the center of each pass were obtained. The analysis results show that the temperature variation curves of the three center points were serrate and their peak values were different. Moreover, under the multi-pass condition the lowest temperatures of the three points before their temperature ascending went up gradually during the cladding process and the trend was similar to the parabola. The results are reasonable, and could make preparations for studying the stress and strain variation.

Key words: laser cladding; temperature field; multi-pass laser cladding