第32卷第10期 焊 接 学 报 Vol. 32 No. 10
2011年10月 TRANSACTIONS OF THE CHINA WELDING INSTITUTION October 2011

激光冲击对X70管线钢焊接接头H_2S应力腐蚀断口的影响

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摘 要：利用激光冲击波对X70管线钢焊接接头进行了改性处理，通过慢应变速率法(SSRT)研究了其在NACE(national association of corrosion engineers)标准饱和H_2S溶液中应力腐蚀的敏感性，并对其断口进行SEM观察，分析了激光冲击处理对X70管线钢焊接接头抗H_2S应力腐蚀开裂(SCC)行为的影响. 结果表明，原始状态的X70管线钢焊接接头为脆性断裂，断口为应力腐蚀裂纹；经激光冲击处理后X70管线钢焊接接头，韧窝尺寸与深度变小，断口形式为韧性断裂；SCC是X70管线钢焊接接头应力腐蚀断裂的主要机制，激光冲击处理降低了氢致开裂和SCC的倾向，提高了焊接接头抗H_2S应力腐蚀的能力.

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关键词：X70管线钢；焊接接头；激光冲击处理；应力腐蚀
中图分类号：TG115.28 文献标识码：A 文章编号：0253-360X(2011)10-0013-04

0 序 言

X70管线钢螺旋焊管是天然气、石油输送主要方式之一，应力腐蚀开裂(stress corrosion cracking，SCC)已经对输送管道构成重大威胁[1]. 硫化氢是石油和天然气中最具腐蚀作用的有害介质之一[2,3]，严重地影响着油气输送管线的使用寿命. SCC是在应力和腐蚀介质共同作用下产生的一种极其危险的低应力破坏形式[4]，其中焊接接头是管线钢结构中SCC的最敏感部位[5]. 现有的研究成果表明[6-8]，管线钢焊接接头对氢脆断裂很敏感，抗应力腐蚀性能较低. 目前对管线钢焊接接头的处理方法主要有喷丸强化、表面纳米化、超声冲击等[9,10]，而激光冲击强化处理管线钢焊接接头的研究尚未见报道. 利用激光冲击波对X70管线钢焊接接头进行了表面改性处理，采用SSRT法研究了激光冲击处理对X70管线钢焊接接头应力腐蚀的影响，为提高X70管线钢应力腐蚀性能提供了试验基础.

1 试验方法

X70管线钢焊接工艺为埋弧自动焊，焊接速度为1.0～1.2 m/min. 采用WQ-1，ϕ4 mm焊丝，CHF101焊剂，X形坡口，双面焊接，试样尺寸及形状如图1所示. 激光冲击强化试验在大功率KQ开关钕玻璃脉冲激光装置上进行，其输出波长为1 054 nm，脉宽为23 ns左右，最大的有效光斑直径为8 mm，激光脉冲功率为2.0×10^9 W. 腐蚀试验为24 ℃±3 ℃，压力为试验溶液的饱和蒸气压，试验介质为NACE饱和H_2S溶液. 试验设备采用SERT-5000-D9H型恒慢应变速率应力腐蚀试验机，对应力、应变及速度进行自动测量. 试验选用应变速率为500×10^{-6}/s作为研究SCC的应变速率，试验前测量并记录试样的原始尺寸，然后在NACE饱和H_2S溶液中进行慢拉伸试验，直至试样断裂. 用超声波清洗后用SEM观察断口形貌，确定试样是否为腐蚀断裂.

2 试验结果与分析

2.1 SSRT拉伸曲线

图2为X70管线钢焊接接头慢拉伸应力—应变曲线，其变化具有一定的规律性，空拉时无论是抗拉强度还是断裂时间都最大. 在激光冲击波加载下管线钢焊接接头具有较强的变形抗力和变形能力，其应力—应变行为具有明显的应变率效应，即呈现出较明显的增强增塑现象，最大承受拉伸载荷为激光冲击波处理的试样，激光冲击处理试件的断裂时

收稿日期：2010-08-31
基金项目：江苏省自然科学基金资助项目(BK2009104)；江苏省普通高校研究生科研创新计划项目(XM2011-388)

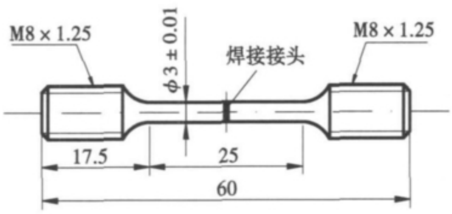


图1 试样尺寸示意图(mm)

Fig. 1 Sketch of sample by laser shock processing

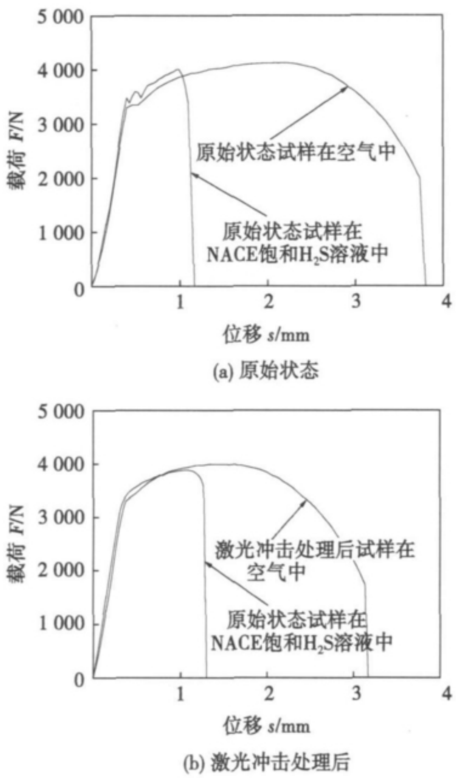


图2 X70管线钢焊接接头应力—应变曲线

Fig. 2 Stress-strain curves of X70 pipeline welded joints

形变比原始状态更大. 这是由于激光冲击处理在材料表面产生了塑性形变,使得材料的塑性性能有所提高.

表1为图2中X70管线钢焊接接头慢拉伸的应力腐蚀敏感指数处理结果. X70管线钢焊接接头原始状态试样在NACE饱和H_2S溶液中有应力腐蚀倾向,表现为虽然屈服强度、抗拉强度均没有明显的下降,但断后伸长率、断面收缩率均有明显下降,图2a中拉伸试验曲线反映出的内积功应力大,这表明腐蚀敏感性指数I_{SCC}也大. 经激光冲击处理后X70管线钢焊接接头在NACE饱和H_2S溶液中也有一定的应力腐蚀倾向,表现为图2b中断后伸长率和断面收缩率均有下降,拉伸试验曲线反映出的内积功应力腐蚀敏感性指数I_{SCC}稍大,但是屈服强度、抗拉强度没有明显下降,这表明激光冲击处理后X70管线钢焊接接头没有明显的应力腐蚀特征.

表1 X70管线钢焊接接头慢拉伸结果

Table 1 Slow strain test results of X70 pipeline steel welded joint

试验状态	腐蚀环境	屈服强度 R_{eL}/MPa	抗拉强度 R_m/MPa	断后伸长率 A(%)	内积功 A_n/J
原始状态	空气中	490	603	15.20	260
	NACE饱和H_2S溶液	510	586	4.66	135
激光冲击处理	空气中	485	587	12.67	210
	NACE饱和H_2S溶液	505	572	5.20	170

2.2 断口形式

图3为慢拉伸的断口形式. X70管线钢焊接接头试样慢拉伸的断口位置均发生在焊缝区,原始试样断口形式如图3a所示,断口为脆性+剪切型,断口面3/4相对于应力方向垂直,1/4断口面与应力方向成45°. 断口形式从韧性断裂向脆性断裂转变,其方式为混合断裂. 激光冲击处理后试样慢拉伸断口,其断裂面与基准平面成45°斜面,说明发生了剪切断裂,断裂形式为韧性+剪切型断裂,如图3b所示. 焊接接头从表面萌生延性裂纹,以韧性方式扩展,说明材料抗腐蚀性能较好.

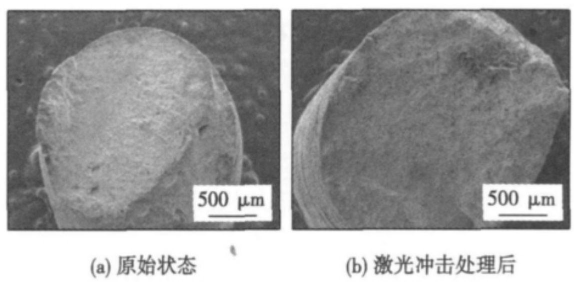


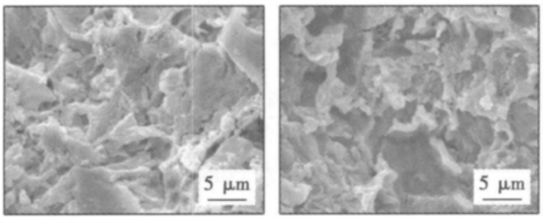
图3 慢拉伸试验断口形式

Fig. 3 Fracture modes of sample for slow strain test

2.3 断口形貌

原始状态的X70管线钢焊接接头在焊接拉应力诱导作用下,当氢浓度很高时,显微缺陷处的氢的压强可以超过材料断裂强度,形成氢致裂纹. 在局部应力作用下微裂纹易解理扩展,在裂纹扩展区断口形式为准解理式,如图4a所示. 经激光冲击处理后试样应力腐蚀断口呈韧性断裂,如图4b所示. 断口处存在大量韧窝,呈现分层状,并且在大的韧窝周

围分布着许多小的韧窝，X70 管线钢焊接接头没有明显的应力腐蚀特征．这是由于激光冲击处理使得焊接接头表面层内形成残余压应力场，表面层材料的亚结构（亚晶粒）尺寸和晶格点阵发生变形，结果塑性形变层内材料密度提高，有利于提高抗应力腐蚀性能[11]．



(a) 原始状态　　(b) 激光冲击处理后

图 4　慢拉伸试验断裂后断口形貌

Fig. 4　Fracture morphologies after slow strain test

2.4　应力腐蚀开裂

对应力腐蚀后试样表面进行 SEM 观察，未发现点蚀现象，表面腐蚀物能谱分析如图 5 所示．其化学成分（质量分数，%）为：C11.43，O6.16，Si 0.66，S2.68，Cl0.50，Fe77.30，Ca1.27．

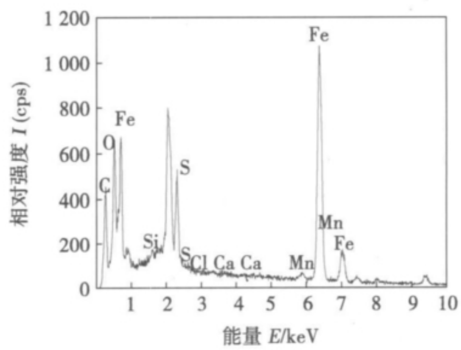


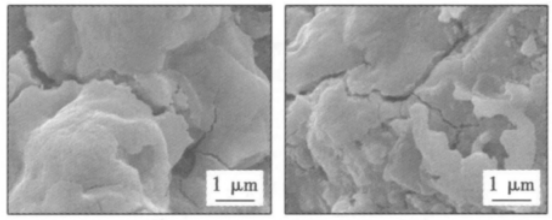
图 5　表面腐蚀物能谱分析

Fig. 5　Energy spectrum analysis of surface corrosion product

图 6 为应力腐蚀开裂后裂纹形貌．原始试样断口裂纹有分叉，微裂纹呈阶梯状，是应力腐蚀开裂和氢致开裂共同作用的结果，如图 6a 所示．经激光冲击处理后断口裂纹其尺寸有所下降，微裂纹的阶梯状比较平缓，如图 6b 所示，这表明激光冲击处理延缓了应力腐蚀裂纹的萌生和发展．

2.5　分析与讨论

X70 焊接接头原始试样表面为 329.5 MPa 残余拉应力，激光冲击处理试样为 −297.6 MPa残余压

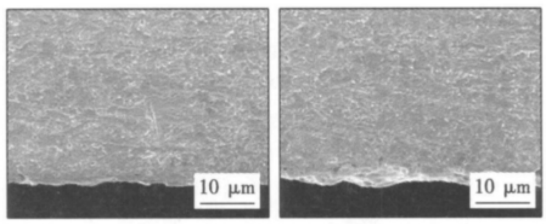


(a) 原始状态　　(b) 激光冲击处理后

图 6　应力腐蚀开裂后裂纹形貌

Fig. 6　Fracture morphologies after stress corrosion cracking

应力．当进行慢拉伸试验时，由于试样表面残余压应力的作用抵消了一定的外加拉伸应力，对裂纹可以产生闭合效果，使得其 SCC 敏感性大大降低．图 7 为 X70 管线钢焊接接头截面形貌．原始状态截面形貌如图 7a 所示，焊接接头处晶粒粗大，由于焊接时热影响区内各点的热循环不同，导致了化学成分以及组织性能的不均匀性．经激光冲击处理后表面产生了微塑性变形，形成明显的形变强化层，平均厚度为 10 μm 左右（图 7b），使焊接接头表面晶粒细化，消除焊接表面缺陷，有利于提高其耐腐蚀等性能．



(a) 原始状态　　(b) 激光冲击处理后

图 7　X70 管线钢焊接接头截面形貌

Fig. 7　Cross-section morphologies of X70 pipeline steel welded joints

3　结　　论

（1）激光冲击处理使 X70 管线钢焊接接头在 NACE 饱和 H_2S 溶液中 SCC 敏感性指数由 48.08% 下降至 19.05%，应力腐蚀倾向不明显，有效地降低了管线钢焊接接头应力腐蚀开裂敏感性．

（2）原始试样在 NACE 饱和 H_2S 溶液中慢拉伸断口形式为脆性断裂，激光冲击处理后焊接接头慢拉伸断口形式发生了变化，由脆性转变为韧性断裂．

（3）激光冲击处理前后 X70 管线钢焊接接头在 NACE 饱和 H_2S 溶液中断裂为应力腐蚀开裂，激光冲击处理使应力腐蚀开裂的敏感性降低，有利于提高其抗 H_2S 应力腐蚀的性能．

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MAIN TOPICS, ABSTRACTS & KEY WORDS

Analysis on microstructure and mechanical properties of aluminum alloy/stainless steel joint made with flux-cored filler metal DONG Honggang[1], YANG Liqun[1], ZHAI Nan[2], DONG Chuang[3] (1. Department of Materials Processing Engineering, Dalian University of Technology, Dalian 116085, China; 2. Shenyang Aircraft Industry Corporation LTD, Shenyang 110034, China; 3. Key Laboratory of Materials Modification, Ministry of Education, Dalian University of Technology, Dalian 116085, China). p 1 – 4

Abstract: Dissimilar metal joining between 5A02 aluminum alloy and AISI 304 stainless steel was conducted by gas tungsten arc welding with ZnAl15 and AlSi12 flux-cored filler metals, and the effect of the filler metal composition on the microstructures and mechanical properties of the joints were investigated. The results revealed that the tensile strength of as-welded joints made with ZnAl15 and AlSi12 flux-cored filler metals was 121 MPa and 162 MPa respectively. After annealed at 280 ℃ for 30 min, the tensile strength of joints made with ZnAl15 flux-cored filler metal reached 180 MPa, while that with AlSi12 flux-cored filler metal was 166 MPa. The interfacial layer in the weld made with ZnAl15 filler metal was comprised of [$FeAl_3$] Zn_x and [Fe_2Al_5] Zn_x, and ternary intermetallic compound $Al_{7.4}Fe_2Si$ was found in the interfacial layer in the joint made with AlSi12 flux-cored filler metal. The thickness of the interfacial layers made with both filler metal was less than 10 μm.

Key words: aluminum alloy; stainless steel; flux-cored filler metal; microstructure; mechanical properties

Analysis on electromagnetic heat strengthening of welded joint with embedding crack and mechanical performance testing ZHENG Lijuan, CHAI Xuan, HAN Xiaojuan, FU Yuming (School of Mechanical Engineering, Yanshan University, Qinhuangdao 066004, China). p 5 – 8

Abstract: Numerical simulation on welded joint of 45 steel using electromagnetic heating was made by ANSYS. The temperature and residual stress field were analysed. The result showed that the crack tip in the welded joint melted and dulled after discharge, the stress concentration also was reduced, in addition, the three residual compressive stress field around welded crack tip was appeared. The tensile properities were tested to compare the mechanical performance before and after pulsed current discharges. The result indicated that tensile strength and elongation were improved. Numerical analysis and experimental research confirmed the feasibility of applying electromagnetic heat strengthening technology into welding field.

Key words: welded joint; embedding crack; electromagnetic heat strengthening; numerical analysis; mechanical properties

Numerical simulation and experimental test of DP590 dual-phase steel welding LI Huiqin, LIU Yixuan, HAN Qiang, MA Yonglin (School of Material and Metallurgy, Inner Mongolia University of Science & Technology, Baotou 014010, China). p 9 – 12

Abstract: DP590 dual-phase steel weld temperature field was analyzed by using ANSYS softwere. A program was developed with APDL language supported by the ANSYS, combining the body heat rate and element birth and death technology to simulate the welding filling process and heat input. A butt welding experiment with the DP590 dual-phase steel (3.8 mm thickness) was done in order to verify the accuracy of the simulation calculation. It is verified that numerical simulation is feasible.

Key words: DP590 dual-phase steel; numerical simulation; temperature field

Effects of laser shock processing on H_2S stress corrosion fractures of X70 pipeline steel welded joints KONG Dejun, WU Yongzhong, LONG Dan (College of Mechanical & Energy Engineering, Jiangsu Polytechnic University, Changzhou 213016, China). p 13 – 16

Abstract: The surfaces of X70 pipeline steel welded joints were processed with laser shock and its stress corrosion sensitivity was investigated in NACE saturated H_2S solutions by slow strain rate testing (SSRT). The fracture surfaces were analyzed with scanning electric microscope (SEM). The results show that the X70 pipeline steel welded joints in primitive state is brittle fracture. The cracks of tensile fracture is stress corrosion cracking. The mechanical properties of the X70 pipeline steel welded joints after laser shock processing is enhanced, its dimple dimension and depth becomes smaller, and the fracture mode is ductile fracture. SCC is the main mechanism of X70 pipeline steel welded joint stress corrosion cracking. Laser shock processing reduces the tendency of SCC and improves stress corrosion resistance H_2S of the welded joint.

Key words: X70 pipeline steel; welded joint; laser shock processing; stress corrosion

Analysis on corrosion behavior of welded joint of A7N01S-T5 aluminum alloy for high-speed train GOU Guoqing[1], HUANG Nan[1], CHEN Hui[1], LI Da[1], MENG Lichun[2] (1. College of Materials Science and Technology, Southwest Jiaotong University, Chengdu 610031, China; 2. CSR Qingdao Sifang Co., Ltd., Qingdao 266111, China). p 17 – 20

Abstract: Salt fog corrosion tests were employed to observe the corrosion behavior of welded joint of A7N01S-T5 aluminum alloy for high-speed train. The results showed that many corrosion products and pits distributed on the surface of the wel-