激光-短路 MAG复合热源焊接过程稳定性的影响因素

王旭友，王 威，林尚扬，雷 振
(哈尔滨焊接研究所，哈尔滨 150080)

摘 要：以低碳钢为研究对象，通过焊接电弧分析仪，对比研究了激光-短路 MAG电弧复合热源焊接过程中焊接速度、激光与电弧的相对位置对焊接过程稳定性的影响规律。结果表明，随着焊接速度增加，MAG和激光-短路 MAG复合热源焊接过程稳定性都会降低，但由于激光的引入，复合热源在高速焊接过程更稳定。与 MAG相比，复合热源可以提高极限焊接速度 1倍以上；复合热源焊接过程中，与激光在前引导焊接相比，电弧在前引导焊接过程稳定性更高。

关键词：熔化极气体保护焊接；激光焊接；复合热源焊接；焊接过程稳定性
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王旭友

0 序 言

一般而言，激光焊接由于其价格比较高和焊接方面上的特点，更适用于要求比较高的精密构件，而电弧焊接因其对焊前准备要求相对较低和一次性投资较小，比较适合于焊接常规结构件。然而，随着新材料的不断出现和新产品的不断开发，对焊接技术的要求越来越高，要求焊接技术具有生产效率高、生产成本低，而且对新材料有较高的适应能力。为满足上述要求，Steen[1]的课题组（英国）于 20世纪 70年代末，首先开始进行激光-电弧复合热源焊接方面的研究。随后，国内外研究人员研究发现，由于该焊接工艺结合了激光焊接和常规电弧焊接的优点，具有更高的焊接速度和更强的适应能力。但是由于该焊接方法结合了激光焊接和常规电弧焊接两种焊接方法，因此焊接工艺相对比较复杂，影响焊接过程稳定性的因素也较多[2-6]。但是在激光-短路 MAG复合热源焊接方面的研究相对较少。通过焊接电弧分析仪提取的焊接电流和电弧电压等信息，针对焊接速度和焊接方向两个影响过程稳定性的因素展开研究，明确了激光-短路 MAG电弧复合热源焊接过程中，焊接速度和焊接方向对焊接过程稳定性的影响规律。

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1 试验条件

激光器为德国 HAAS公司生产的 HL2006D型大功率连续输出 Nd:YAG固体激光器，激光器最大输出功率 2.6 kW，波长 1.06 μm，当使用焦距为 200 mm的焊枪时，光束聚焦最小直径 0.6 mm。MAG焊机为松下 Pana-Auto new K200熔化极气体保护焊机。焊接过程中的电弧信息通过德国汉诺威大学 AHXV焊接电弧分析仪采集到计算机。试验材料为低碳钢 Q235，试验板材的尺寸为 300 mm×100 mm，板厚为 8 mm，激光垂直入射到工件表面，MAG焊枪与工件表面有 53°的夹角，这样保证激光光斑和 MAG电弧能够共同作用到同一区域中，激光和 MAG采用旁轴复合方式。焊接时的保护气体采用 CO_2/Ar=80/20的混合气体，气体流量 15～20 L/min，焊丝材料为 H08Mn2Si，焊丝直径为 1.0 mm，焊丝伸出长度 12 mm。

2 试验结果与分析

2.1 焊接速度对焊接过程稳定性的影响

无论是 MAG焊接还是激光-短路过渡电弧 MAG复合热源焊接过程，焊接速度都是一个重要因素，它直接影响到焊接最终结果。

首先对焊接电流 80 A，平均电压 16 V，激光功率 1 400 W，光-丝间距为 2 mm的条件下，焊接速

度对焊接过程的影响进行分析. 图 1为 MAG和激光一短路过渡电弧 MAG复合热源焊接两种情况下,焊接速度变化对短路时间平均值和短路时间标准偏差的影响. 从图 1中可以看出,随着焊接速度的增加,短路时间平均值和短路时间标准偏差逐渐增加,短路时间平均值增加是造成短路周期增加、短路频率降低的一个主要原因,使得焊接过程趋向于不稳定. 而短路时间标准偏差描述了熔滴短路过渡时,短路时间的均匀性,当短路时间标准偏差越小时,熔滴的短路时间越均匀,熔滴过渡越均匀,焊接过程稳定,当短路时间标准偏差越大时,熔滴的短路时间长短差异越大,熔滴过渡越不均匀,焊接过程趋向于不稳定. 图 1中的 4条曲线的最小值出现在焊接速度为 0.6 m/min和 0.9 m/min附近,说明在该试验条件下,焊接速度为 0.6 m/min和 0.9 m/min时,焊接过程比较稳定. 图 1中还有一点值得注意,在所作过的试验速度的范围内,激光－MAG复合热源焊接的短路时间平均值和短路时间标准偏差几乎总是要低于 MAG焊接,尤其在高速焊接时更为明显,这说明激光的加入使得焊接过程更稳定,激光－MAG复合热源焊接更适合高速度焊接情况. 图 1中 Hybrid为激光－MAG复合热源焊接; t_1为短路时间.

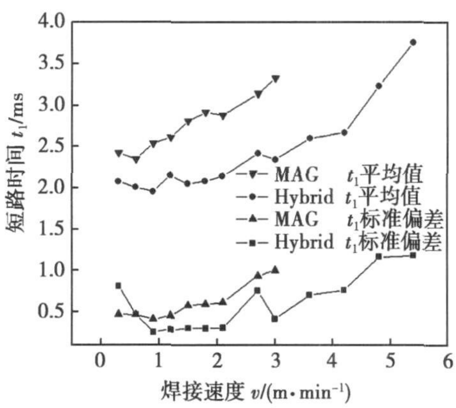

图 1 焊接速度对 t_1平均值和标准偏差的影响

Fig. 1 Effect of welding speed to t_1 mean and t_1 standard deviation

短路过渡电弧的短路周期的倒数为短路频率,而短路频率是评定短路过程稳定性的一个重要指标,短路频率越高则焊接过程越稳定. 图 2为焊接速度的变化对短路周期平均值和短路周期标准偏差的影响. 从图 2中可以看出与图 1同样的规律,在图 2中,MAG焊接和激光一短路过渡电弧 MAG复合热源焊接的短路周期标准偏差两条曲线的最小值也出现在焊接速度为 0.6 m/min和 0.9 m/min附近,可知道在该焊接速度范围附近焊接过程比较稳定,随后,随着焊接速度的增加,两条短路周期标准偏差曲线一路飙升,使得焊接过程越来越不稳定. 当 MAG焊接的焊接速度达到 1.8 m/min以上,激光一短路过渡电弧 MAG复合热源焊接的焊接速度达到 4.8 m/min以上时,它们各自短路周期的标准偏差值已经非常大了,达到了各自最小值的 5倍以上,短路焊接过程极其不稳定,再通过观察焊缝外观形态,发现焊缝已经断断续续的,不能形成连续的焊缝,因此认为,在该焊接条件下,MAG焊接的极限焊接速度为 1.8 m/min,激光一短路过渡电弧 MAG复合热源焊接的极限焊接速度为 4.8 m/min. 另外,从图 2中可以很清楚地看到,在整个焊接试验的速度区间,激光一短路过渡电弧 MAG复合热源焊接的短路周期平均值和短路周期标准偏差值始终低于 MAG焊接的,这说明与 MAG焊接相比,激光一短路过渡电弧 MAG复合热源焊接过程更稳定,更适合于高速度焊接过程. 图 2中 t_c为短路周期.

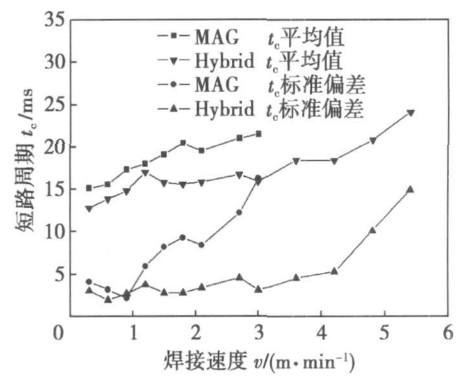

图 2 焊接速度对 t_c平均值和 t_c标准偏差的影响

Fig. 2 Effect of welding speed to t_c mean and t_c standard deviation

以上的试验分析都是针对焊接电流为 80 A时,焊接速度对焊接过程的影响展开分析的,在试验过程中还对焊接电流分别为 60, 100, 120, 140, 160和 180 A进行了相同的焊接速度变化对焊接过程影响的试验,都得到了与焊接电流为 80 A相似的试验结果,即与 MAG焊接相比,激光一短路过渡电弧 MAG复合热源焊接过程更稳定,能够提高极限焊接速度. 图 3是不同焊接电流下,MAG焊接和激光一短路过渡电弧 MAG复合热源焊接的极限焊接速度比较. 从图 3中可以看出,在短路焊接的各个焊接电流下,与 MAG相比,激光一短路过渡电弧 MAG复合热源焊接都能够提高极限焊接速度 1～2倍. 当焊接电流小于 140 A时,两种焊接方法的极限焊接速度随着焊接电流的增加而增加,极限焊接在焊接电流为

140 A时达到最大值，随后极限焊接速度随着焊接电流的增加反而减小．

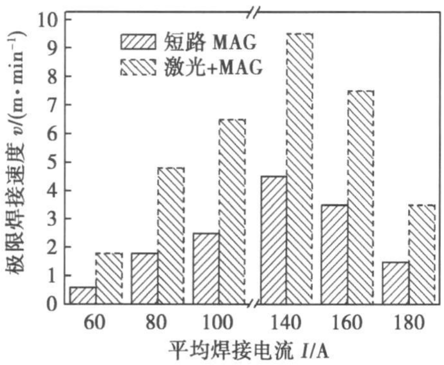

图 3　两种焊接方法的极限焊接速度比较

Fig. 3　Comparation of maximum welding speed

2.2　焊接方向对焊接过程稳定性的影响

对于采取旁轴复合的激光—短路 MAG电弧复合热源焊接过程，焊接方向有两种选择．一种是激光在前电弧在后的焊接方式，该方式的焊接特点是焊缝熔深稍浅，焊缝成形美观，焊缝的铺展性能好，但是焊接飞溅稍大；另一种是电弧在前激光在后的焊接方式．该方式的特点是焊缝熔深相对比较大，焊接过程相对稳定，焊缝成形不好，咬边现象比较严重[7]．

图 4是两种焊接方向的 U—I曲线．试验条件为焊接电流 140 A，平均电弧电压 17 V，焊接速度 0.9 m/min，激光功率 1 800 W，光—丝间距 2 mm，离焦量 −1 mm．图 4a中所标注的 a，b，c，d四个区域分别表示燃弧区、短路开始区、短路区和再引弧区．从图 4可以看出，图 4a和图 4b的 U—I曲线图中四个区域内动态工作点移动轨迹都比较集中，能够形成矩形，表明两种情况下，焊接过程都比较稳定，这里图 4b的矩形曲线 4条边轮廓要略微清晰一些，但这并不一定意味着图 4b的焊接稳定性要高于图 4a．再看图 4b，再引弧区处在较大的电流范围内，而且一部分再引弧电压高达 35 V（e区域），这表明电弧重新引燃时电弧能量较大，容易形成焊接飞溅，影响焊缝成形和焊接稳定性，而图 4a就没有该现象，因此相比较而言，图 4a的焊接过程比较稳定，即 MAG在前，激光在后的激光—短路过渡电弧 MAG复合热源焊接过程比较稳定．通过试验中的仔细观察发现，激光在前时焊接飞溅较大，稳定性略差些，这与以上的分析结果是一致的．

通过焊接电弧分析仪提供的焊接电流电压等特征曲线进一步分析两个焊接方向的稳定性．图 5是激光在前和激光在后两个焊接方向的电弧电压概率

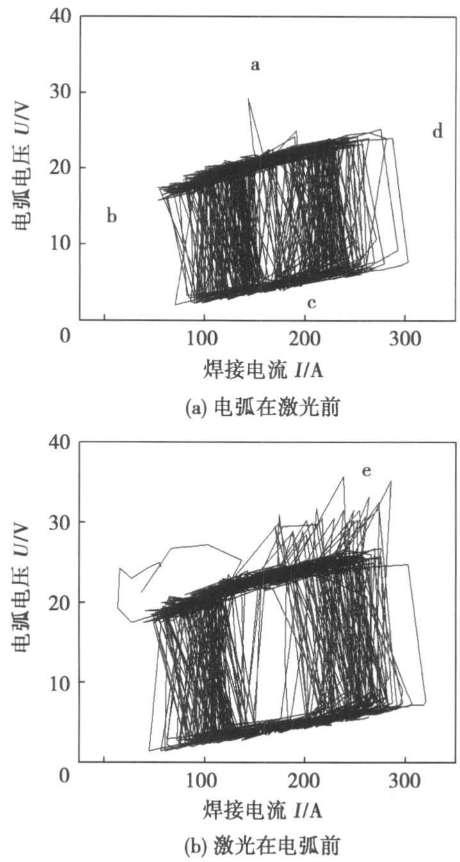

图 4　不同焊接方向的 U—I曲线

Fig. 4　Relation of voltage and current in two welding directions

密度分布曲线，由图 5可见电弧在前焊接时，焊接电流的波动范围比较窄，都集中在 45～320 A之间，而且焊接过程中没有断弧现象．当激光在前焊接时，焊接电流的波动范围大，从 0～350 A都有，最重要的是在 0 A附近有一定的概率密度分布，这说明焊接过程中有断弧现象存在，电弧稳定性稍差．

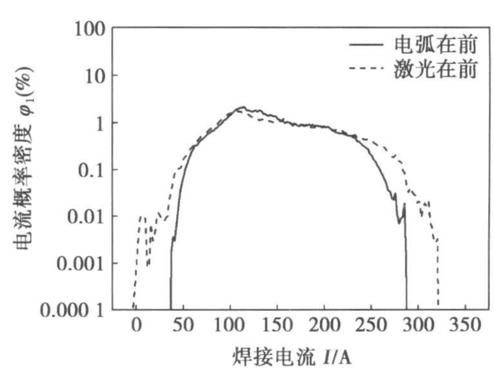

图 5　两个焊接方向上的电流概率密度分布

Fig. 5　Probability density curve of welding current in two directions

图 6是两个方向焊接时的电弧电压概率密度分

布曲线. 图 6中 A区域称之为断弧后再引弧电压区域. 该区域主要提取了再引弧电压、跳弧现象以及空载电压的信息. 当焊接过程不稳定, 熔滴短路过渡后电弧不易重新引燃, 焊接过程中出现较多跳弧现象或存在断弧现象时, 该信息就越显著. 从图 6中很明显地看出 MAG在前焊接时, 电弧电压在 A区几乎没有分布, 而当激光在前焊接时, A区存在一定的电压概率分布, 电弧电压在该区有分布, 就代表焊接过程存在着断弧等导致焊接不稳定的现象, 电弧稳定性下降. 另外, 从图 6中还能看出, 与 MAG在前焊接相比, 激光在前焊接时的燃弧电压值要略高些, 这也使得焊接过程趋向于不稳定.

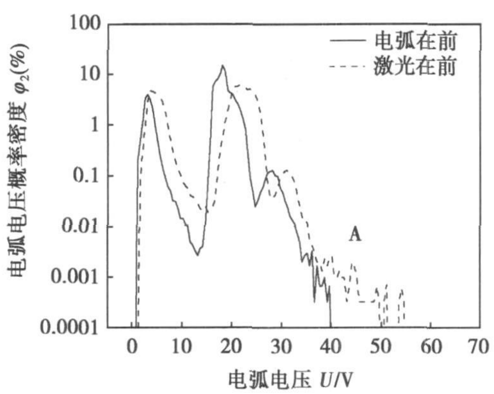

图 6 两个方向焊接时的电压概率密度分布曲线

Fig. 6 Probability density curve of welding voltage in two directions

3 结 论

(1) 随着焊接速度的增加, MAG和激光—短路 MAG复合热源焊接过程稳定性都呈现下降的趋势. 但是由于激光的加入, 激光—短路 MAG复合热源焊接过程更稳定些, 更适合于高速焊接过程. 通过对比不同焊接电流的极限焊接速度发现, 与 MAG相比, 激光—短路 MAG复合热源焊接能提高极限焊接速度 1~2倍.

(2) 对于采取旁轴复合的激光—短路 MAG电弧复合热源焊接过程, MAG在前、激光在后的复合焊接方式焊接过程更稳定.

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作者简介: 王旭友, 男, 1965年出生, 硕士, 研究员, 硕士研究生导师. 主要从事激光加工和激光—电弧复合热源焊接技术方面研究. 发表论文 10余篇.

Email: wang_xuyou@tom.com

MAIN TOPICS, ABSTRACTS & KEY WORDS

Detection of 3D seam position for GTA welding based on mirror of tungsten electrode in pool ZHANG Wenzeng, CHEN Nian, CHEN Qiang, SUN Zhenguo (Key Laboratory for Advanced Manufacturing by Materials Processing Technology, Ministry of Education, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China). p 1—4

Abstract: This paper proposed a novel detection method of seam position for realizing arc length control and seam tracking of GTA welding at the same time. In the method, a developed visual sensor is fixed on a welding torch from the side-front view, captures image, which includes the front of tungsten electrode, pool, seam lines and the mirror of tungsten electrode in pool. An algorithm based on the constraint of real tungsten electrode center line is proposed to calculate the arc length error. Another algorithm by the hypothesis that the pool being considered as a flat plain is proposed to calculate the seam tracking error. Therefore, 3D position of seam relative to tungsten electrode can be obtained as a control input for 3D seam tracking. Experimental results show that the method is valid and the detecting precision reaches ±0.1 mm which meets requirements of precise welding.

Key words: welding automation; GTAW; seam tracking; tungsten electrode error detection; arc length control

An improved phase-shift full-bridge soft-switching welding inverter CHEN Yanming, CAO Qian, CAO Biao, WANG Zhiqiang, HUANG Shisheng (1. College of Electrical Engineering, Guangxi University, Nanning 530004, China; 2. College of Mechanical Engineering, South China University of Technology, Guangzhou 510640, China). p 5—8

Abstract: An improved phase-shift full-bridge zero-voltage zero-current switching (ZVZCS) welding inverter is proposed. By DC block capacitor in series with primary of the transformer and a saturable inductor in series with the lagging-leg switch, the zero-voltage turn-on for the leading-leg could be achieved due to the energy stored in the output inductor and the leakage inductor, the zero-current turn-off for the lagging-leg could be achieved due to the resonant between the DC block capacitor and the leakage inductor, and the reverse current was blocked by the saturable inductor. Thus, the excessive core losses of the saturable inductor in the conventional ZVZCS converter could be overcome, since the inductor was unidirectional saturable. It was especially suitable for high power applications. The principles of operations and the soft-switching operation range were discussed simply. Finally a 3 kW welding inverter was implemented, and the experimental results were also presented to confirm the validity of the proposed inverter.

Key words: welding inverter; phase-shift control; zero-voltage-switch; zero-current switch; saturable inductor

Influence of welding thermal cycle on micro-structural brittleness of T92 steel LI Xiaoquan, TENG Yalan, CHU Yajie, YANG Zonghui (1. School of Material Engineering, Nanjing Institute of Technology, Nanjing 211167, China; 2. Jiangsu University of Science and Technology, Zhenjiang 212003, Jiangsu, China). p 9—12

Abstract: The welding thermal cycles with different peak temperatures for T92 steel were measured with the Gleeble-3800 thermal simulation test machine, and then the specimens were tested with charpy notch in room temperature. Microstructures and its charpy impact fracture morphologies of the thermal simulation specimens were observed using optical microscopy and SEM. The results show that micro-structural brittleness can occurr easily for austenite crystal grain when welding temperature higher than 900 ℃ and quasi-cleavage fracture displays clearly. While the excellent ambient temperature impact toughness could be maintained when welding temperature below 900 ℃ with the fine uniform ductile fracture displaying. The micro-structure brittleness was resulted from high content of strong carbide and nitrogen formation elements which solid dissolved in austenite under high temperature and then the diffusion speed being slower than the speed of grain boundary migration, thus formed room temperature over-saturation micro-structure.

Key words: welding thermal cycle; T92 steel; micro-structure brittleness; thermal simulation test; peak temperature

Influence of heat treatment on residual stress of P92 steel pipe girth weld XU Lianyong[1,2], JING Hongyang[1,2], ZHOU Chunliang[1,2], XU Delu[3], HAN Yu[1] (1. School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China; 2. Tianjin Key Laboratory of Advanced Joining Technology, Tianjin 300072, China; 3. China Electric Power Research Institute, Beijing 100055, China). p 13—16

Abstract: Firstly, the welding temperature field of P92 steel pipe was measured with thermal imaging system, and the thermal cycles were achieved. Secondly, the finite element method (FEM) was utilized to simulate the welding process of P92 pipe girth weld, and to analyze the distribution of welding temperature in the welded joint. It was found that the simulation results had good agreement with the experimental results. Lastly, the simulated welding temperature field was used to calculate the residual stress of P92 steel pipe girth weld, and the emphasis was focused on the influence of the postweld heat treatment on the residual stress. The results showed that the postweld heat treatment could partially release the residual stress, while the comparatively large residual stress still survived in the weld joint. Therefore, the effect of residual stress must be considered in the life evaluation of P92 pipe.

Key words: P92 steel; heat treating; welding temperature field; residual stress; FEM

Two factors influencing welding process stability of Nd:YAG laser-short circuit arc MAG hybrid welding WANG Xuyou, WANG Wei, LIN Shangyang, LEI Zhen (Harbin Welding Institute, Harbin 150080, China). p 17—20

Abstract: The effects of welding speed and welding direction on Nd: YAG laser-short current MAG hybrid welding stability were investigated. The experimental results showed that welding arc stability of MAG and laser+ MAG would decrease with the increasing of welding speed, but the arc of laser+ MAG get more stable comparing with MAG arc. The maximal welding speed of laser+ MAG is more than one time fast comparing with that of MAG. The hybrid welding arc in arc leading direction would get more stable comparing with that of laser leading direction.

Key words: GMAW; laser welding; hybrid welding; welding process stability

Analysis of laser-MAG hybrid welding plasma radiation

LI Zhiyong[1], WANG Wei[2], WANG Xuyou[3], LI Huan[3] (1. Welding Research Center, North University of China, Taiyuan 100081, China; 2. Harbin Welding Institute, Harbin 150080, China; 3. School of Material Science and Engineering, Tianjin University, Tianjin 300072, China). p 21—24, 28

Abstract: Hollow probe is used to detect the plasma radiation of specific point passing the probe for spectrum collecting. The radiation of MAG and laser-MAG hybrid welding are collected with fiber spectrometer. The spatial distribution of the radiation is analyzed to compare the differences between welding process with and without laser hybrid. Furthermore, high speed video is also applied to study the coupling mechanics of laser-MAG hybrid. The result shows that a higher radiation intensity zone will be formed in the arc center. Beside the center zone, there is a somewhat lower radiation intensity zone. An "ionized duct zone" will be formed near the laser focused point. The ionized duct is dominated by Fe fume. The ionized duct makes the welding arc more stable when the laser is applied. The higher radiation intensity zone changes the distribution of plasma energy, thus makes the energy focus on the arc center. The coupling effect of laser-MAG hybrid welding will form weld bead with deeper penetration than MAG welding.

Key words: laser; MAG; hybrid welding; plasma; spectrum

Feature evaluation and selection of penetration arc sound signal based on neural network

LIU Lijun[1,2], LAN Hu[3], ZHENG Hongyan[3] (1. Ningbo Institute of Technology, Zhejiang University, Ningbo 315100, Zhejiang, China; 2. School of Material Science & Engineering, Harbin University of Science and Technology, Harbin 150080, China; 3. Applied Science College, Harbin University of Science and Technology, Harbin 150080, China). p 25—28

Abstract: In welding processing penetration detection and diagnosis based on arc sound, how to choose its proper parameters is vital to diagnosis. The feature evaluation and selection methods were presented, the results trained by neural network were used to evaluate feature parameters. Because neural network satisfied the nonlinear mapping requirement for high-resolution information compression, the complex classification problem in welding penetration pattern recognition was transferred to feature processing stage, and feature extration was realized by neural network effectively. An illustration validated the effectiveness of the method.

Key words: neural network; penetration; arc sound; feature evaluation; pattern recognition

Influence of welding heat input on microstructure and properties of coarse grain heat-affected zone in X100 pipeline steel

ZHANG Xiaoyong[1,2], GAO Huilin[2], ZHUANG Chuanjing[3], JI Lingkang[3] (1. School of Materials Science and Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China; 2. School of Materials Science and Engineering, Xi'an Shiyou University, Xi'an 710065, China; 3. Tubular Goods Research Center of China National Petroleum Corporation, Xi'an 710065, China). p 29—32

Abstract: The influence of welding heat input on the microstructure characterization and properties of coarse grain heat affected zone (CGHAZ) in a X100 pipeline steel were investigated by means of thermal simulation technique, microscopic analysis method and mechanical property testing. The results showed that the strength and toughness of X100 pipeline steel decreased with the welding heat input increasing. The microstructure of CGHAZ was mainly made up of bainitic ferrit and granular bainitic which could bring excellent strength and toughness when welding heat was about 10 kJ/cm. The quasi-polygonal ferrite and granular bainitic were formed with welding heat input about 20 kJ/cm, which could get fine strength-toughness. When the welding heat input was higher than 30 kJ/cm, the strength and toughness decreased because of the increasing of polygonal ferrite. Therefore, welding heat input at range of 10—20 kJ/cm was recommended in the welding process of X100 pipeline steels.

Key words: X100 pipeline steel; welding heat input; microstructure; properties

Establish of ultrasonic residual stress measurement system based on entire envelope weighting algorithm

WU Zhonghua[1,2], ZHANG Shiping[1], SUN Haoyu[1], ZHU Zheng[3] (1. College of Mechanical and Electronic Engineering, China University of Petroleum, Dongying 257061, Shandong, China; 2. Drilling Technology Research Institute, Shengli Petroleum Administration Bureau, Dongying 257017, Shandong, China; 3. School of Electrical Engineering and Automatic, Harbin Institute of Technology, Harbin 150001, China). p 33—36

Abstract: The entire envelope weighting algorithm is proposed in this paper and realized by virtual instrument to obtain residual stress by ultrasonic measurement. Different weight of reference point is assigned to measure time of echo signal more accurately. Compared with traditional single threshold method, the experiment results show that the algorithm improved the stabilization of repeat measurement at the same point by different conditions. The uncertainty is calculated to validate the accuracy of the ultrasonic measurement.

Key words: ultrasonic measurement; welding residual stress; weighting algorithm

High gradient residual stresses during laser deep penetration welding of titanium alloy

ZHANG Kerong, ZHANG Jianxun (School of Materials Science & Engineering, Xi'an Jiaotong