热等静压对钛不锈钢焊接接头组织性能的影响

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摘 要: TA2/316L 爆炸焊接试样在压力 150 MPa, 温度 850 ℃条件下热等静压处理 2 h, 分别对爆炸态和热等静压态焊接接头进行了抗剪强度测试, 重点对比研究了热等静压处理对焊接接头组织形貌、化学成分分布及脆性相的影响。热等静压处理后, 原爆炸态接头附近的缺陷被治愈, Ti, Cr, Fe, Ni 等元素的相互扩散距离明显增加, 但接头中生成的脆性相也增加。结果表明, 爆炸态的剪切试样断裂于 TA2 侧, 热等静压态断裂于金属间化合物相。

关键词: 爆炸焊接; 热等静压; 显微组织; 扩散
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0 序 言

钛/不锈钢的复合构件具有优良的耐腐蚀性和力学性能, 在航空、航天、石油化工、医疗器械等领域具有广阔的应用前景。爆炸焊接作为连接异种金属最重要的固态焊接工艺之一, 虽然已发展成熟, 但由于在焊接过程中, 钛易产生气孔和冷裂纹, 不锈钢易产生热裂纹, 加之两材料的线膨胀系数相差近一倍, 焊接接头往往存在气孔、裂纹等缺陷, 严重影响复合材料的力学性能和耐腐蚀性。热等静压(hot isostatic pressing, HIP)继承和发展了粉末冶金和冷等静压成形的优点, 被广泛用于消除材料中的孔隙, 消除铸、锻件内部的缺陷及异种材料的粘结等。

大多数对爆炸焊接的研究集中在焊接工艺对界面组织性能的影响[1,2]、加中间层的复合板界面形貌和性能研究[3]。然而, 热等静压应用于爆炸焊接接头缺陷治愈方面的报道很少。作者采用 SEM, EDS, XRD 等测试技术, 对比性地研究了热等静压对爆炸焊接接头组织性能的影响。

1 试验方法

试验所用 TA2/316L 复合板由宝鸡有色金属研究院提供。基材 316L 厚 25 mm, 覆材 TA2 厚 5 mm。基覆材化学成分见表 1。

热等静压试样尺寸为 10 mm×10 mm×10 mm。

表 1 试验材料的化学成分(质量分数, %)

Table 1 Chemical compositions of experimental materials

材料	C	N	H	O	P	S	Si	Mn	Mo	Ni	Cr	Fe	Ti
TA2	0.10	0.05	0.01	0.25	—	—	—	—	—	—	—	0.3	余量
316L	0.02	—	—	—	0.03	0.02	0.69	1.05	2.29	12.45	17.61	余量	—

氩气压力为 150 MPa, 温度为 850 ℃, 保温 2 h。上述爆炸态和热等静压态试样经研磨、抛光、侵蚀后, 分别采用带能谱的 LEO 1450 型扫描电镜(SEM)及 MXP21 VAHF 型 X 射线衍射仪分析热等静压前后焊接接头附近组织形貌、化学成分及具体物相的变化。

2 试验结果及分析

2.1 焊接接头的缺陷分析

图 1 为爆炸态和热等静压态 TA2/316L 焊接接头形貌。图 1a, b 分别显示原始焊接接头存在裂纹和气孔, 这些缺陷的形成与爆炸焊接工艺及材料本

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身有关，在焊接过程中，覆板高速冲击基板的瞬间，接触界面聚集了大量的塑性变形功，在微秒级时间内碰撞点温度可以高达上千度[4]，导致基覆材待焊面熔化并形成小熔池，在处于室温的相对庞大的基体金属的冷却作用下，熔池金属快速凝固。由于两材料的线膨胀系数相差近一倍，在焊接过程中产生热应力；另一方面TA2本身在焊接过程中易产生裂纹、气孔，不锈钢也易产生热裂纹，所以TA2/316L焊接接头不可避免地出现裂纹、气孔等缺陷。图1c中出现了明显的组织分层现象，是由化学成分的不均匀造成的层状偏析，可能和熔化的基覆材金属的密度有关，分层组织由里到外依次可区分为中心黑色相、白色相、浅灰色相及最外层颗粒相。对这些相进行能谱分析结果显示，它们都含有Fe，Ti，Cr，Ni等元素，但原子分数有很大差异。这种组织的不均匀性必然造成材料性能的不均一。通过比较可以看出，经热等静压处理后焊接接头附近组织均匀且没有任何缺陷，如图1d所示。

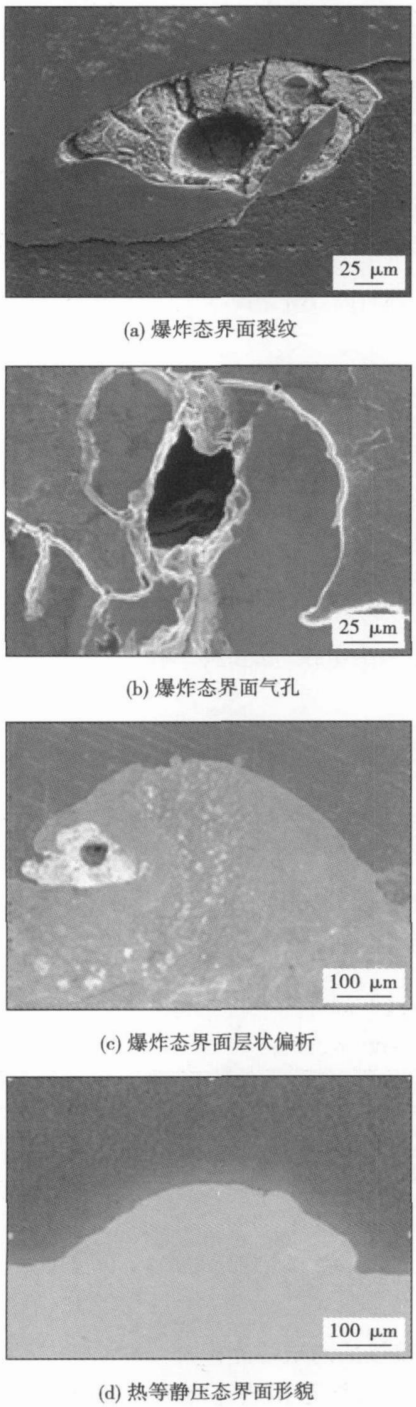

图1 焊接接头内在的缺陷

Fig. 1 Inherent defect of welded joint

2.2 焊接接头组织及化学成分分析

爆炸态和热等静压态TA2/316L复合板的组织形貌如图2所示，其中图2a，b是爆炸态的形貌，图2c，d是热等静压态的形貌，(所有图中TA2都位于焊缝上侧，316L位于下侧)。图2a为爆炸态焊接接头波状界面的一个波，可以明显看到316L侧晶粒沿爆轰方向被拉长呈纤维状，且离界面越近，晶粒变形程度越严重，该形变带在随后的热等静压过程中发生了再结晶，转变为细小的等轴晶。对爆炸态焊接接头分区如图2b所示，在TA2侧A区可以看到呈现明显柱状铸态组织的熔合区，是由爆轰过程中熔化的TA2在随后的快速凝固阶段形成。B区为图中显示的白亮带，含有不同的金属间化和物相[5]，C区是经过熔化再凝固的316L侧熔合区，图中显示为弥散的“云状”组织，一般情况下，焊缝金属若为单相的奥氏体，则具有发达的柱状晶特征，说明316L侧熔合区在焊接凝固过程中有少量奥氏体可能转变为其它相，比如铁素体相。图2c为热等静压后波状界面的一个典型波，对其焊接接头分区如图2d所示，在TA2侧A区对应着魏氏α-βTi组织，此组织由β-Ti向针状α-Ti转变而成。区域C是Fe，Cr，Ni元素在钛基体中的固溶区域，该区约为30 μm，是由Fe，Cr，Ni原子向TA2基体中扩散形成的。呈现白亮色的区域B与图2b中的B区一样，含有不同的金属间化和物相。最下面的区域D是316L不锈钢的奥氏体再结晶细化，该区的晶粒约2 μm。相对于爆炸态接头，热等静压后接头中出现了Fe，Cr，Ni元素在Ti元素中的固溶区，说明热等静压处理促进了元素的扩散。

Ti，Fe，Cr，Ni元素在焊接接头附近的互扩散行为通过EDS的点分析做了研究，且这些元素通过界面的浓度变化已在图3a，b中给出。图3a为爆炸态接头附近各元素分布图，由于爆炸焊接在瞬间完成，所以元素来不及扩散，从图中看到互扩散距离很短。图3b为热等静压态接头附近元素分布图，可以明显

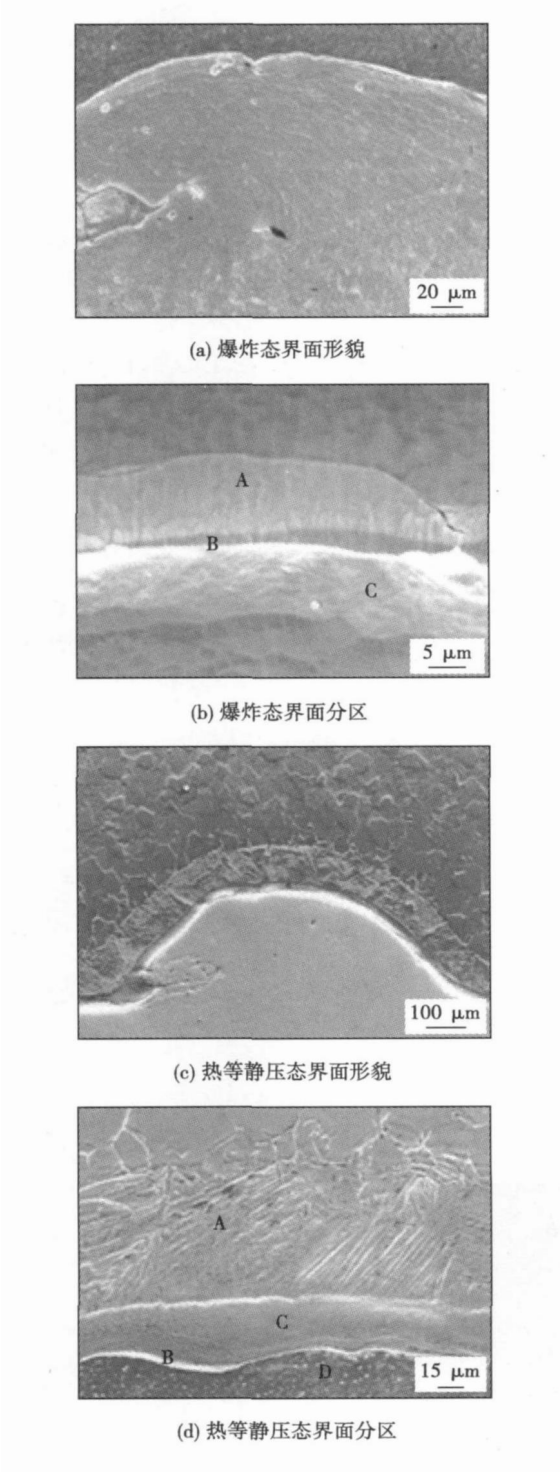

图 2　爆炸态和热等静压态焊接接头形貌

Fig. 2　Morphologies of explosive welded and HIP welded joint

看到 Ti 元素扩散到 316L 不锈钢侧的距离相对于 Fe, Cr, Ni 元素扩散到 TA2 侧的距离小，这是由于 316L 不锈钢的面心立方结构产生了最大的壁垒阻止 Ti 元素向其中的扩散，但是 Fe, Cr, Ni 元素很容易扩散到 Ti 的密排六方结构中。近不锈钢侧，850 ℃热等静压处理后的焊接接头出现了 Cr 元素的富集，如图 3b 所示。这是由于 Ti 元素向不锈钢侧的扩散减小了 Cr 元素的活性，因此观察到了 Cr 元素的上坡扩散且在随后的降温期间此区域转变为 σ 相。

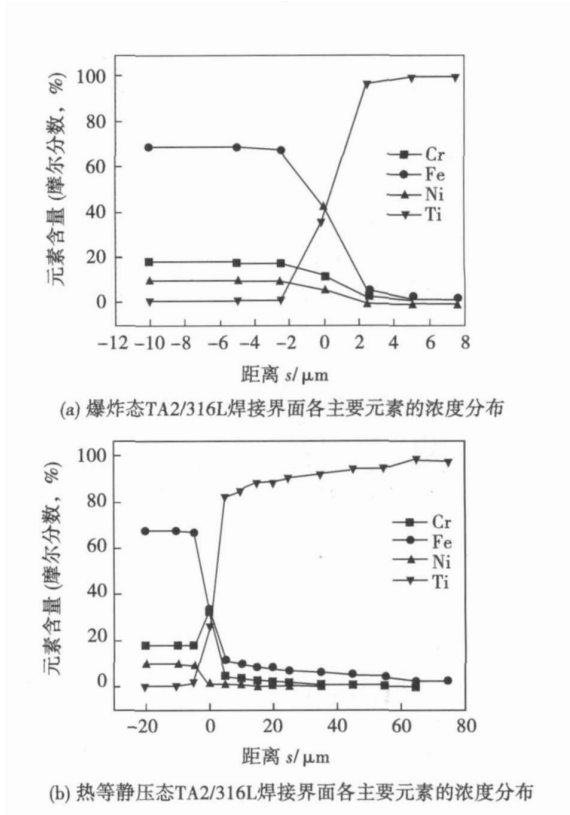

图 3　爆炸态和热等静压态各元素过焊接界面的浓度分布

Fig. 3　Essential elemental distributions across the interfaces of TA2/316L before and after hot isostatic pressing treatment

2.3　剪切断口分析

相对于爆炸态抗剪强度（215 MPa），热等静压态有所降低（161 MPa），这与剪切试样的断裂位置有关。

为了进一步判定剪切试样的断裂位置，并具体鉴定断口上的脆性相，分别对爆炸态和热等静压态的 TA2 侧，316L 侧剪切断口做了 XRD 分析，结果见图 4。图 4a, b 分别为爆炸态 316L, TA2 侧断口的 XRD 图谱，图中显示 316L 侧断口除粘有钛金属还有少量 Cr_2Ti, FeTi, $FeTiO_3$ 等脆性相，而 TA2 侧断口的衍射谱为纯钛，这充分说明爆炸态剪切试样断裂于 TA2 侧。图 4c, d 分别为热等静压态 316L, TA2 侧断口的 XRD 图谱，通过分析 XRD 图谱得出，经850 ℃热等静压处理后，剪切试样在金属间化合物相断裂，这些相主要是 σ, Fe_2Ti, FeTi, Cr-Ni-Ti-Fe 和 NiTi，它们使焊接接头脆化。同时发现热等静压态脆性相数量增多，如NiTi，这是由于热等静压过程中扩散到TA2侧的Ni超出了其在 TA2 中的固溶度，最终析出 NiTi。

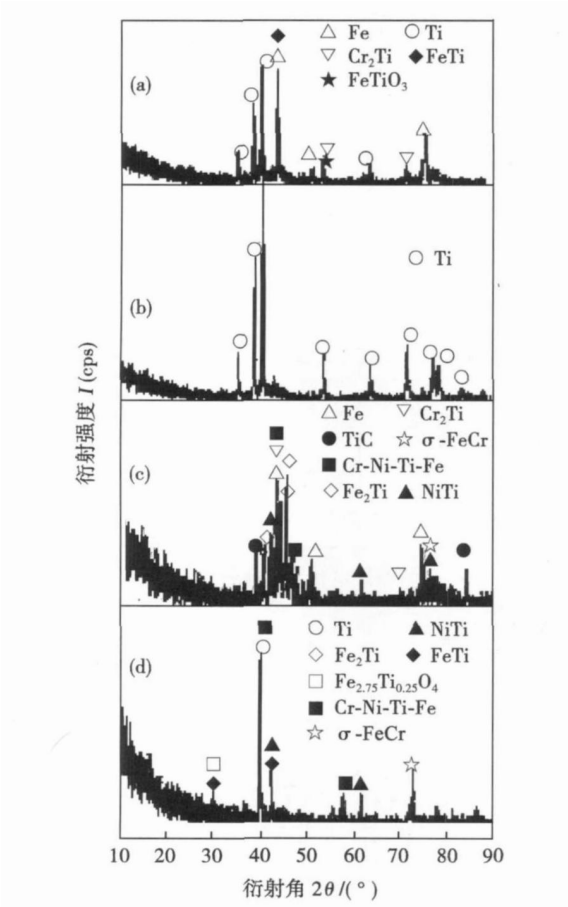

图 4 爆炸态和热等静压态剪切断口 XRD 衍射图谱

Fig. 4 X-ray diffraction patterns of shear fracture surfaces of joints before and after treatment

3 结 论

(1) 热等静压后焊接接头的裂纹, 气孔等缺陷被治愈。

(2) 原 316L 侧被拉长呈纤维状的组织在热等静压过程中发生再结晶, 出现等轴的细晶区。相对于爆炸态, 热等静压后 TA2 侧出现了 α-βTi 魏氏组织区和 Fe, Cr, Ni 元素在 TA2 中的固溶区, 这和元素的扩散有关。

(3) 相对于爆炸态, 热等静压态 Ti, Cr, Fe, Ni 等元素的扩散距离更远, 生成了更多的脆性相, 如 Fe_2Ti, Cr-Ni-Ti-Fe 和 NiTi。

(4) 爆炸态的剪切试样在 TA2 侧断裂, 而热等静压态的剪切试样在金属间化合物相断裂, 且抗剪强度有所降低, 有待于进一步试验研究。

参考文献:

[1] Nizamettin Kahraman, Behcet Gulenc, Fehim Findik. Corrosion and mechanical-microstructural aspects of dissimilar joints of Ti-6Al-4V and Al plates[J]. International Journal of Impact Engineering, 2007, 34(8): 1423—1432.

[2] Mustafa Acarer, Behcet Gülenc, Fehim Findik. Investigation of explosive welding parameters and their effects on microhardness and shear strength[J]. Materials and Design, 2003, 24(8): 659—664.

[3] Kamachi Mudali U, Ananda Rao B M, Shanmugan K, *et al*. Corrosion and microstructural aspects of dissimilar joints of titanium and type 304L stainless steel[J]. Journal of Nuclear Materials, 2003, 321(1): 40—48.

[4] 史长根, 王耀华. 爆炸焊接界面的结合机理[J]. 焊接学报, 2002, 23(2): 55—58.

[5] Crossland B. Explosive welding of metals and its application[M]. Oxford: Clarendon Press, 1982.

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sized yttria partially stabilized zirconia powder. FESEM and XRD were applied to analyze the microstructure and phase composition of as-sprayed coatings. The results showed that the nanostructured TBCs exhibit a unique complex microstructure including non-molten nanosized particle and columnar grains. XRD analysis indicated that the nanostructured TBCs mainly consists of metastable tetragonal phase. The results of the high temperature stability property of nanostructured TBCs demonstrated that the grain size of the coating increases with the increases of temperature and time, but the grain size was still less than 100 nm and the phase composition of the coating didn't change with the different temperature and time. So the nanostructured coating possesses better high temperature stability.

Key words: nanostructured thermal barrier coating; microstructure; phase composition; high temperature stability

Influence of hot isostatic pressing on structure and properties of titanium/stainless steel joint by explosive welding HAN Liqing[1], LIN Guobiao[1], WANG Zidong[1], LI Feng[1], BAI Xingguo[2] (1. School of Materials Science and Engineering, Beijing University of Science and Technology, Beijing 100083, China; 2. Tianjin Steel Tube(Group)Co., Ltd, Tianjin 300301, China). p41—44

Abstract: TA2/316L joints acquired by explosive welding were treated by hot isostatic pressing treatment at the pressure of 150 MPa and at 850 ℃ for 2 hours. The effects of the treatment on the shear strengths, microstructure and chemical composition distribution of the joints were investigated. The treatment made the defects in the joints heal and inter-diffusion space of Ti, Cr, Fe and Ni be longer and also the embrittlement phases increase. The treated samples breaks along embrittlement phase during shear tests, which is different from the samples before treatment, and it generally fails at TA2 alloy sides of the joints.

Key words: explosive welding; hot isostatic pressing; microstructure; diffusion

Stud welding with hybrid heating resource WANG Kehong, ZHANG Deku, XUE Pengfei, GU Mingle (Department of Materials Science and Engineering, Nanjing University of Science and Technology, Nanjing 210094, China). p45—48

Abstract: Stud welding experiments of thick steel plate and large diameter stud were carried out based the induction heating and stud arc welding, and the effects of welding process and parameters on joint performance were researched. Results show that for medium carbon heat treated high strength steel with thickness of 30—80 mm and stud with 16—27 mm in diameter, the stable welding process and the joint with good appearance and high strength and without defection can be acquired with the proper welding parameters. Microstructure of the joint shows that heating and melting of both the base metal and stud is homogeneous and there are no defects such as incomplete fusion and porosity on the joint interface. The microstructure is lath martensite and bainite and the structure performance is good. The EDAX analyses on the joints show that the transition of Cr exists from base metal to stud zone and the joint quality has been effectively improved.

Key words: stud welding; induction heating; hybrid heating resource; automatic welding

Multifunction electrode for all position and vertical down welding HU Lianhai[1,2], HUANG Jian[1], REN Deliang[2], SUN Jiyou[3], WU Yixiong[1] (1. Shanghai Key Laboratory of Materials Laser Processing and Modification, Shanghai Jiaotong University, shanghai 200240, China; 2. Department of Materials Science and Engineering, Shijiazhuang Railway Institute, Shijiazhuang 050043, China; 3. CSR Shijiazhuang Rolling Stock Works Co. Ltd., Shijiazhuang 050000, China). p49—52

Abstract: A new kind of covered electrode for all position and vertical down welding was developed. The composition of the electrode coating has been optimized using the uniform design method. Melting properties of the electrode coating were studied using test instrument of the GX-III high-temperature physics properties. Experiments results show that the developed electrode has excellent operating characteristics such as arc stability, slag detachment, bead shape, welding spatter and so on. The mechanical tests show that the weld metal obtained in SMAW with this electrode exhibits high tensile strength, yield strength and toughness at low temperature. Through fracture micrograph, weld microstructure, weld composition and hardness distribution of welded joints the weld has high mechanical properties. The electrode can be widely used for the welding of important structures. This new method of developed the electrodes can shorten the development cycle, reduce costs and improve quality of the electrode.

Key words: all position and vertical down welding; uniform design; melting properties; welding operating characteristics; mechanical properties

Optimization on welding procedure of high temperature pipeline based on orthogonal test design ZHANG Guodong, XUE Jilin, ZHOU Chang Yu (School of Mechanical and Power Engineering, Nanjing University of Technology, Nanjing 210009, China). p53—56

Abstract: The welded joint of heat-resistant steel P91 is used widely at high temperature in power palnt. The distribution of welding residual stress of thick wall pipeline is more complicated, and the welding residual stress has great effect on the creep at high temperature environment. The welding parameters of P91 were optimized by the method of orthogonal experiment design, which uses welding residual stress as the index of evaluation and then the welding residual stress under the optimum welding procedure was simulated by the finite element analysis codes ABAQUS. The distribution of welding residual stress for P91 thick wall pipeline was obtained. The research results show that the effect of welding speed on welding residual stress is the most remarkable. Then the effect of arc voltage, welding current and groove gap on welding residual stress is reduced sequen-