

熔覆材料对铝合金激光熔覆性能的影响

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摘 要: 通过有效控制固体脉冲式激光器的电流、脉冲宽度、频率、光斑直径、扫描速度等有关工艺参数, 模拟飞机腐蚀损伤的铝合金试样表面激光熔覆 Al-Y 合金、LY12 合金, 充分时效后进行疲劳试验、疲劳断口分析和金相分析。结果表明, 熔覆 Al-Y 合金试样的安全寿命达到了熔覆 LY12 合金试样寿命的 402%, 疲劳断口有明显的疲劳条带, 熔覆层和基体结合得非常紧密, 熔覆层内没有大的气孔和裂纹缺陷, 而熔覆 LY12 熔覆层夹杂等缺陷较多。

关键词: 铝合金; 激光熔覆; 疲劳寿命; 疲劳断口; 金相组织

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0 序 言

航空用铝合金材料工作在含有灰尘、水分甚至含有盐雾的大气环境中, 其表面防护层往往在较短时间内便会失去作用, 从而使铝合金材料产生腐蚀, 降低疲劳性能, 进而减少其使用寿命<sup>[1]</sup>。激光熔覆是近年来新兴的一种材料表面修复技术, 是改善材料其表面性能的有效手段<sup>[2]</sup>。它可以使熔覆层与基体材料之间实现良好的冶金结合, 提高材料的耐磨、耐蚀、耐冲击等性能<sup>[3-5]</sup>。试验以常用航空材料 LY12CZ 为基材, 模拟飞机腐蚀损伤, 在其表面熔覆 LY12、Al-Y 两种不同的合金粉末, 根据所受疲劳载荷的特点, 研究其抗疲劳性能。

1 试 验

1.1 试样的制备

用 LY12CZ 板材为原始材料, 包覆纯铝层, 热处理状态为淬火加自然时效, 其结构尺寸按国家标准 GB/T228-87 执行。试验共制试样 10 件, 分为两组。其中一组熔覆 LY12 合金, 另外一组熔覆 Al-Y 合金。在试样的中心用铣削的方法加工出一小坑, 直径为  $\phi 10$  mm, 坑深为  $1.5\text{ mm} \pm 0.1\text{ mm}$ , 见图 1。其作用是模拟飞机结构件上的腐蚀或损伤小坑, 通过熔覆修补研究激光熔覆修理后铝合金结构件的性

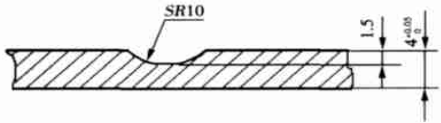


图 1 LY12CZ 熔覆前断面 (mm)  
Fig. 1 Fracture of specimen before cladding

1.2 激光熔覆的试验条件与方法

1.2.1 试验条件

试验使用的激光器为 JHM-1GX-200B 型 YAG 脉冲式激光器。试验采用激光多层多道扫描。激光处理时试样表面由 Ar 气保护, 光斑直径  $\phi 0.5 \sim 1.2\text{ mm}$ , 激光工作电流  $160 \sim 300\text{ A}$ , 脉冲频率  $2 \sim 4\text{ Hz}$ , 脉冲宽度  $1.5 \sim 3.5\text{ ms}$ , 激光扫描速度  $0.4 \sim 1.2\text{ mm/s}$ 。在这个范围内选取一系列参数值进行正交试验, 并根据其性能, 得到一组优化后的参数值, 即电流  $280\text{ A}$ 、脉冲宽度  $3\text{ ms}$ 、频率  $2\text{ Hz}$ 、光斑直径  $\phi 1\text{ mm}$ 、扫描速度  $0.7\text{ mm/s}$ 。

1.2.2 试验方法

熔覆试验分为两组, 一组是熔覆 Al-Y 合金成分 (质量分数):  $3\% \text{ Y}$ , 其余为 Al。另外一组熔覆 LY12 合金, 成分 (质量分数):  $4.5\% \text{ Cu}$ ,  $1.6\% \text{ Mg}$ ,  $0.5\% \text{ Mn}$ , 其余为 Al。激光熔覆的过程是铺粉, 进行多层多道扫描, 每熔覆一层后进行机械冲击。冲击的工具为钢制小锤, 重  $0.4\text{ kg}$ , 冲击的重叠率为  $100\% \sim 200\%$ 。冲击的目的是释放熔覆层内的拉应力, 抑制裂纹的萌生与扩展。熔覆结束后将表面打

磨平整,见图 2。熔覆后室温放置 4 天以上,使试样充分时效。

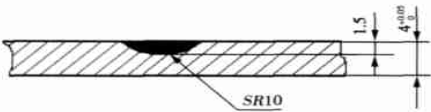


图 2 LY12CZ 熔覆后断面(mm)  
Fig. 2 Fracture of specimen after cladding

2 疲劳性能测试及断口分析

2.1 疲劳性能测试方法

将已完成熔覆并且已经时效的试样,进行疲劳试验,疲劳试验机为立式 INSSTRON—8502型电液伺服疲劳试验机。试验条件为正弦波形,频率 8 Hz,试验最大应力  $R_{\max} = 275\text{ MPa}$ ,最小应力  $R_{\min} = 55\text{ MPa}$ ,负荷控制(其中负荷—100%,变形—50%),拉—拉载荷,疲劳试验结果见表 1。

表 1 疲劳试验结果(周次)  
Table 1 Result of fatigue test

熔覆材料	1	2	3	4	5
熔覆 LY12	12 339	13 317	15 667	15 644	16 132
熔覆 Al-Y	52 320	59 141	55 672	69 013	52 988

2.2 试验结果分析与讨论

通常铝合金材料疲劳性能观测值母体分布规律为正态分布,在此前提下,由于试验采用的应力水平为屈服极限的 60%以上(LY12 的  $R_m = 415\text{ MPa}$ ,  $R_{0.2} = 430\text{ MPa}$ ,  $R_{\max} = 275\text{ MPa}$ ),母体的分散性应较小。因此,试验每组试件数量为 5,属于小子样,可以用小子样数据估计母体参数。

根据表 1 数据及式(1)和式(2),分别计算出子样平均值  $X$  和标准差  $s$  的数值,记入表 2。

$$X = \frac{1}{n} \sum_{i=1}^n \lg Ni = \mu. \tag{1}$$

$$s = \sqrt{\frac{\sum_{i=1}^n X_i^2 - \frac{1}{n} (\sum_{i=1}^n X_i)^2}{n-1}} = R. \tag{2}$$

取可靠度为 99%,查得 99%可靠度的标准正态分布偏量为  $u_p = -2.326$ ,将子样平均值  $X$  和标准差  $s$  的数值代入式(3)和式(4),分别求出对应 99%可靠度的对数安全寿命估计量  $X_p$  和安全寿命估计量  $N_p$ ,再记入表 2。

$$X_p = \mu + u_p R = X + u_p s, \tag{3}$$

$$N_p = 10^{X_p}. \tag{4}$$

表 2 安全寿命估算及对比  
Table 2 Contrast of safety life estimation

熔覆材料	子样平均值 $X$	标准差 $s$	对数安全 寿命估计量 $X_p$	安全寿命 估计量 $N_p$
熔覆 LY12	4.16	0.051 96	4.039	10 940
熔覆 Al-Y	4.76	0.05	4.644	44 025

从表 2 中不难看出,熔覆 Al-Y 试样的安全寿命达到了熔覆 LY12 试样安全寿命的 402%。下面通过疲劳断口和金相组织来分析熔覆 Al-Y 试样安全寿命提高的原因。

2.3 断口分析

试样疲劳断口均出现在熔覆层的位置,见图 3。

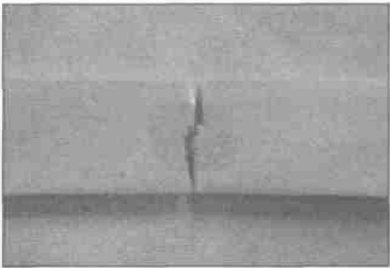


图 3 断口位置  
Fig. 3 Position of crack

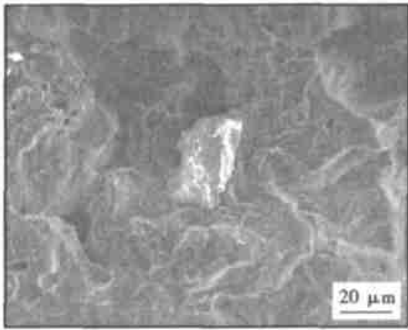
断口分析是在 JXA—8800R 电子探针上对试样断口进行扫描得出的结果。

2.3.1 熔覆 LY12 合金试样的断口分析

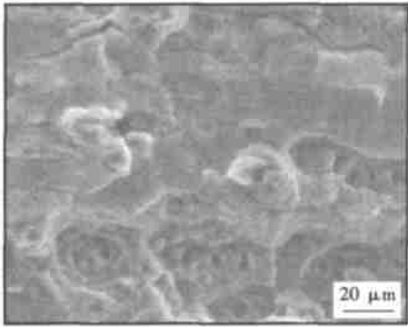
观察熔覆 LY12 合金试样的断口(图 4a),发现在熔覆层靠近熔合区一小颗粒处产生了裂纹源,通过成分测试,这一小颗粒是未熔的锰粉颗粒,在这里产生了较大的应力集中,形成了裂纹源区,在熔合区有少量的气孔。气孔是熔覆过程中产生的,主要来源是保护气体、粉末的粘结剂、金属蒸气等。由于进行了适当的工艺处理措施因而气孔较少。由图 4b 裂纹扩展区看到,在断口中还有少量的“鱼眼”,这是由于熔覆时产生的组织缺陷—夹杂、未熔金属颗粒、孔洞、粗大的晶粒以及影响较大的弱化相等,在它们的周围有许多微小的裂纹。

2.3.2 熔覆 Al-Y 合金试样的断口分析

图 5 是熔覆 Al-Y 合金试样的疲劳断口。熔覆层由于每一层都经过机械冲击处理,因而从图 5a 看



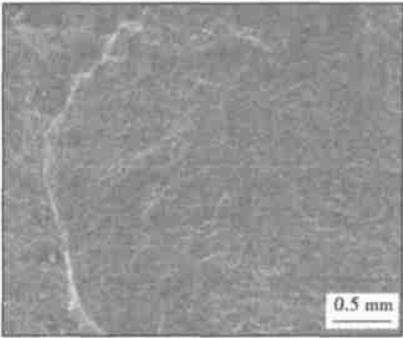
(a) 裂纹源区



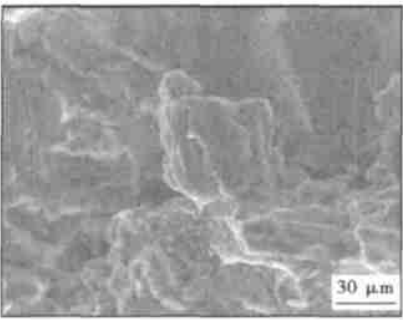
(b) 裂纹扩展区

图 4 熔覆 LY12 合金试样的断口

Fig. 4 Crack of specimens of cladding LY12 alloy



(a) 熔覆层全貌



(b) 次表面裂纹

图 5 熔覆 Al - Y 合金试样的断口

Fig. 5 Fracture of specimens of cladding Al - Y alloy

出裂纹源出现在熔覆层, 熔敷层与基体基本熔为一体, 缺陷很少。图 5b 是基体在次表面下产生的裂

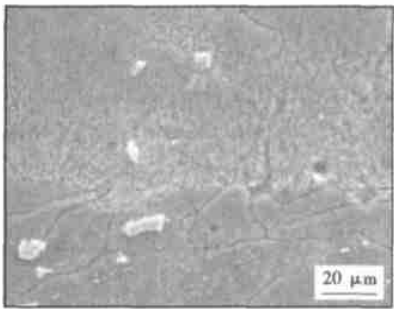
纹, 裂纹较多, 但不是主裂纹, 表现为穿晶断裂。在熔覆层内没有气孔, 这主要是因为稀土元素加入铝合金中, 使铝合金熔铸时增加成分过冷, 细化晶粒, 减少二次枝晶间距, 减少合金中的气体和夹杂, 并使夹杂相趋于球化。还可降低熔体表面张力, 增加流动性, 对工艺性能有明显的影

3 金相分析

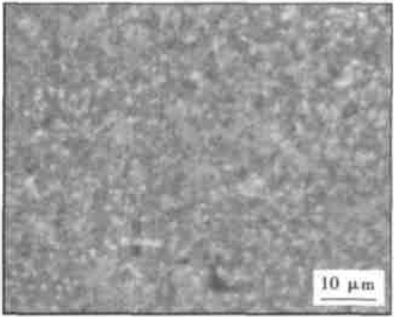
金相分析是在 JXA - 8800R 电子探针上对试样断口进行扫描得出的结果。

3.1 熔覆 LY12 试样的金相分析

图 6 是熔覆 LY12 合金试样断口的金相组织。由图 6a 看出, 熔覆层与基体结合得非常紧密, 可以看到基体较粗大的晶粒组织, 同时弥散分布着一些大的强化相颗粒。而熔覆层组织比较细, 有许多大的未熔颗粒, 是高熔点的锰或者是铜粉末颗粒。从图 6b 中可以清晰地观察到熔覆层的显微组织, 可以看到在熔覆层上有许多微小的析出强化相, 主要是  $Al_2Cu(\theta)$  相,  $Al_2CuMg(S)$  相, 还存在其它杂质相, 如  $Al_7Cu_2Fe$ ,  $Al_6(MnFeSi)$ ,  $Al_6(MnFe)$ ,  $Al_3Fe$ 。这些强化相与基体上的强化相比较, 它们更细小, 弥散分布程度更高, 因而具有更好的强化作用。



(a) 熔覆层与基体过渡区组织



(b) 熔覆层组织

图 6 激光熔覆 LY12 试样断口的金相组织

Fig. 6 Microstructure of fractures of specimens for cladding LY12 alloy

3.2 熔覆 Al-Y 试样的金相分析

图 7 是熔覆 Al-Y 合金试样断口的金相组织。从图 7a 看到, 熔覆层与基体结合非常紧密, 看不到明显的基体和熔覆层分界线, 大的缺陷已经很少, 如气孔、粉末间隙在电子探针下基本观察不到。提高放大倍数, 能够清晰地观察到组织中深颜色的小坑, 见图 7b。这是熔覆层粉末留下的孔隙或者是易浸蚀相在浸蚀试样时被腐蚀出的小坑。熔覆层中的柱

状晶组织具有很强的方向性, 这是激光熔覆后冷速过快及稀土元素的综合作用形成了极其细小的柱状晶。

4 结 论

(1) 在电流为 280 A、脉冲宽度为 3 ms、频率为 2 Hz、光斑直径为  $\phi 1$  mm、扫描速度为 0.7 mm/s 的工艺参数条件下, LY12CZ 铝合金激光熔覆 Al-Y 合金得到了较好的熔覆效果, 而熔覆 LY12 合金在熔覆层内发现了未熔颗粒。

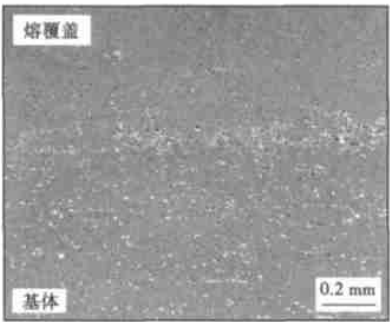
(2) 疲劳试验表明, 熔覆 Al-Y 合金试样的安全寿命达到了熔覆 LY12 合金安全寿命的 402%, 这主要是激光熔覆后冷速过快及稀土元素的综合作用形成了极其细小的柱状晶, 从而起到了细晶强化的作用。表明 LY12CZ 铝合金激光熔覆 Al-Y 合金填补点蚀坑是一种有发展前途的激光应用技术。

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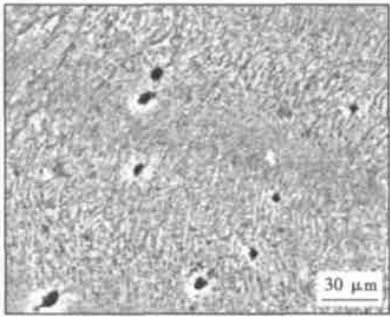
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(a) 熔覆层与基体过渡区组织



(b) 熔覆层组织

图 7 激光熔覆 Al-Y 试样断口的金相组织  
Fig. 7 Microstructure of fractures of specimens for cladding Al-Y alloy

solder. ANSYS finite element analysis tool was used to implement the simulation. In the end, the stress and strain distribution were obtained. The strain range was achieved from the hysteresis loop. The fatigue life of PBGA was predicted using Engelmaier model. The simulation result of the model shows that the position of the critical soldered position of a plastic ball grid array component is right below the edge of its die, but not the outboard solders. This result is helpful to improve the thermal fatigue reliability of plastic ball grid array components.

**Key words:** plastic ball grid array; soldered joint; thermal fatigue; finite element method

**Effect of cladding material on LY12CZ aluminium alloy by Laser Cladding** SUN Fujuan, HU Fangyou, HUANG Xuren, TANG Yuanheng (Qingdao Branch, Naval Aeronautical Engineering Academy, Qingdao 266041, China). p93—96

**Abstract:** Through controlling process parameters of impulse laser, current, pulse width, frequency, spot diameter and scanning velocity, laser cladding LY12 and Al-Y was used to repair corrosion damage of aluminum alloys. After cladding, fatigue test, fracture and microstructure of the specimens were studied. The result indicated that the life of the specimen cladded by Al-Y was 402% of that by LY12. There was no large pore and crack in the Al-Y layer which joined with the substrate firmly. There was much impurity in the cladding layer of LY12.

**Key words:** aluminum alloys; laser cladding; fatigue life; fatigue fracture; microstructure

**Comparison of stress relief by PWHT and VSR in large dimension straight welded pipe** ZHANG Chao, LU Qinghua, XU Jijin, CHEN Ligong (School of Materials Science and Engineering, Shanghai Jiaotong University, Shanghai 200030, China). p97—100

**Abstract:** Post-weld heat treatment (PWHT) and vibratory stress relieving (VSR) were used to control the residual stress in large-dimension welded pipes. The results show that both PWHT and VSR are able to relieve the residual stress effectively in large-dimension straight welded pipe and make the distribution of residual stress more uniform. Their effect in weld zone is more obvious than these in base metal. The results of stress relieving of VSR of as-cast microstructure are qualified but not acceptable in cold plastic deformation zone. The effect of PWHT on the stress relieving and stress uniform ability is better than that of VSR. However, considered of economy factor and technique convenience, VSR is confirmed as stress relieving technique to control the residual stress in large-dimension straight welded pipe.

**Key words:** vibratory stress relieving; post-weld heat treatment; residual stress

**Progress in friction stir welding of high melting point materials** LIU Huijie, ZHOU Li (State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p101—104

**Abstract:** The research status of friction stir welding (FSW) of high melting point materials was introduced from the aspects of FSW tool design, microstructural characteristics and mechanical

properties of the joints, welding temperature distribution and residual stress and FSW assisted by hybrid heating sources. It indicates that the W-Re alloy and polycrystalline cubic boron nitride are suitable FSW tool materials. The FSW joints with high strength and fine microstructure can be produced when the proper tool geometry and welding parameters were used. For simulation of temperature distribution and residual stress in the FSW joints, physical models should be improved according to the real FSW process. The utilization of hybrid heating source is benefit to weld formation and tool life.

**Key words:** high melting point materials; friction stir welding; tool design; microstructural characteristics; residual stress; hybrid heating source

**Review of X100 pipeline steel and its field weldability** YAN Chunyan<sup>1</sup>, LI Wushen<sup>1</sup>, FENG Lingzhi<sup>1</sup>, XUE Zhenkui<sup>2</sup>, BAI Shiwu<sup>2</sup>, LIU Fangming<sup>2</sup> (1. School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China; 2. Petroleum-Gas Pipeline Research Institute of China, Langfang 065000, Hebei, China). p105—108

**Abstract:** In view of the ever-increasing pipeline length and operating pressure, development of high-strength linepipes has become increasingly attractive and needed. The current knowledge of X100 pipeline steel about research and development status, metallurgical principles, mechanical properties, field weldability, and so on were presented. Production of grade X100 steel requires combination of super-clean refining, thermo-mechanical controlled process, proper metallurgical design and some other advanced techniques. Excellent mechanical properties and satisfying weldability are possessed for grade X100 steel. Yield strength of X100 grade steel generally exceeds 690 MPa. High strength-toughness welded joint can be obtained through proper welding procedures. Further work is required to improve the production of X100 pipeline steel and to establish appropriate material standards.

**Key words:** X100 pipeline steel; microstructure; ductile fracture arrest; girth welding; weldability

**General rules of writing scientific and technical papers** WANG Ya (Harbin Welding Institute, China Academy of Machinery Science and Technology, Harbin 150080, China). p109—112

**Abstract:** In order to help scientific and technical workers to know the basic requirements of writing academic papers, master its general methods and improve their rules, common problems in the submitted original manuscripts were analyzed and the methods to resolve these problems were given, based on the features of academic papers and combined with the experiences of the author on editing academic papers for many years. The basic structures of academic papers, requirements on writing and some problems needing in attention were also stated. According to some national and professional standards, standardized uses of professional terms and phases, symbols of physical quantity and measurement units, the requirements on figures and tables and regulations of references literature in papers were briefly explained.

**Key words:** scientific and technical papers; writing; standardization