激光焊接对 SPF/DB Ti-6Al-4V 合金疲劳性能的影响

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摘 要: 研究了 SPF/DB Ti-6Al-4V 合金及其激光焊接接头静态拉伸性能和疲劳性能, 并获得 S-N 曲线. 通过观察组织特征和疲劳断口形貌, 分析了激光焊接对 SPF/DB Ti-6Al-4V 合金疲劳性能的影响. 结果表明, SPF/DB Ti-6Al-4V 合金激光焊接接头的抗拉强度略低于母材抗拉强度, 而疲劳强度明显低于母材疲劳强度, 约为其抗拉强度的 40%. SPF/DB Ti-6Al-4V 合金组织为 α+β 等轴细晶组织, 其焊接接头组织为含 α, 针状马氏体 α′和少量 β 相的魏氏组织结构. 焊接接头组织结构的不均匀性, 以及组织的粗大化是导致激光焊接接头疲劳性能下降的重要原因. SPF/DB Ti-6Al-4V 合金疲劳断裂为塑性断裂, 其焊接接头疲劳断裂为准解理断裂, 这显著降低激光焊接接头的疲劳性能. 而焊接气孔等焊缝表层微小几何不连续缺陷的存在往往成为激光焊接接头疲劳断裂的裂纹源.

关键词: 钛合金; 超塑性成形/扩散连接; 激光焊接; 疲劳性能
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0 序 言

钛合金采用超塑性成形/扩散连接(SPF/DB)组合工艺制造结构件与传统方法相比可以提高材料利用率、减小结构重量并降低成本, 为航空航天飞行器大型钛合金薄壁复杂型面结构件的成形制造开辟了广阔的前景. 然而, 由于受钛合金材料尺寸规格的限制, 一个大型 SPF/DB 钛合金结构件往往不能一次制造完成, 而是首先将其分解成若干个小尺寸 SPF/DB 件分别成形, 然后通过焊接将其连成一个整体. 激光焊接作为一种先进的高能束流焊接技术, 焊接热输入低, 焊缝深宽比大, 焊接变形小, 焊接效率高且操作灵活, 特别适合大型 SPF/DB 钛合金薄壁复杂型面结构件的焊接制造.

Ti-6Al-4V 合金是典型的 α+β 两相钛合金, 因其特殊的合金化方式而具有优良的 SPF/DB 性能[1,2]. 焊接是一个非常复杂的热物理化学冶金过程, 焊接接头的存在往往导致焊接结构在几何尺寸、微观组织和力学性能等方面的改变, 并导致焊接结构的疲劳性能下降[3,4], 即使采用激光焊接也同样存在类似问题. 因此, 研究激光焊接对 SPF/DB Ti-6Al-4V 合金疲劳性能的影响具有十分重要的工程应用价值.

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试验研究了 SPF/DB Ti-6Al-4V 合金及其激光焊接接头静态拉伸性能和疲劳性能, 并获得 S-N 曲线. 通过观察组织特征和疲劳断口形貌, 分析了激光焊接对 SPF/DB Ti-6Al-4V 合金疲劳性能的影响.

1 试验方法

试验材料为 Ti-6Al-4V 板材, 其厚度分别为 1.0 mm和 1.2 mm. 首先将这两种板材叠在一起进行 SPF/DB 成形. SPF/DB 工艺: 加热温度为 910 ~ 920 ℃, 压力为 1.5 MPa, 保温时间为 1 h. SPF/DB 成形后的板材厚度为 2.1 mm. 然后对 SPF/DB 板材进行 YAG 激光焊接. 工艺参数分别为离焦量 0 mm, 激光功率 1 800 W, 焊接速度 1.2 m/min.

制取 SPF/DB Ti-6Al-4V 合金及其激光焊接接头试件, 进行静态拉伸和疲劳试验. 试验机为 Instran 液压伺服材料试验机, 试验温度为室温. 疲劳试验采用单轴拉-拉三角波加载, 最大循环应力分别选取为 400, 460, 520 和 640 MPa, 应力比为 0.1, 加载频率为 8 Hz.

截取 SPF/DB Ti-6Al-4V 合金及其激光焊接接头横截面金相试样, 采用光学金相显微镜观察其组织特征. 截取疲劳试验断口, 经超声波清洗后, 采用扫

描电镜观察其疲劳断口形貌.

2 试验结果与分析

2.1 静态拉伸性能

对SPF/DB Ti-6Al-4V 合金及其激光焊接接头进行静态拉伸试验. 静态拉伸试验中, 母材拉伸试件均断于试件中部最小截面处, 而焊接拉伸试件首先在紧邻焊接热影响区的母材处出现颈缩现象, 而后在此处发生断裂.

表1 为 SPF/ DB Ti-6Al-4V 合金及其激光焊接接头静态拉伸试验结果. 从表 1 可以看出, SPF/ DB Ti-6Al-4V 合金激光焊接接头的抗拉强度略低于母材抗拉强度, 表明激光焊接对试件静态抗拉强度的影响很小.

表 1 SPF/ DB Ti-6Al-4V 合金及其激光焊接接头静态拉伸试验结果

Table 1 Tensile results of SPF/ DB Ti-6Al-4V alloy and its laser welded joints

试件	编号	抗拉强度 R_m/MPa	平均值 R_m/MPa
母材	B01	1 036.4	1 075.35
	B02	1 114.3	
焊接接头	W01	954.8	951.20
	W02	947.6	

2.2 疲劳性能

对SPF/DB Ti-6Al-4V 合金及其激光焊接接头进行疲劳试验. 疲劳试验中, 母材疲劳试件均断于试件中部最小截面处, 而焊接疲劳试件近 80%在焊缝处断裂.

表2 为 SPF/ DB Ti-6Al-4V 合金及其激光焊接接头疲劳试验结果. 可以看出, 最大循环应力为 640 MPa 时, 母材与焊接试件的疲劳寿命分散性较小且相差不大, 中值疲劳寿命分别为 101 096 和 50 070 次载荷循环. 由此可见, 激光焊接试件的疲劳性能明显低于母材试件.

图1 为 SPF/ DB Ti-6Al-4V 合金及其激光焊接接头S-N 曲线. 从 S-N 拟合曲线变化趋势上看, 焊接试件疲劳寿命极限应与试验中试件 100 万次载荷循环未断的最大循环应力 400 MPa 相近, 或高于 400 MPa. 与静态抗拉试验结果相比, 焊接试件的疲劳强度约为其静态拉伸强度的 40%, 表明其疲劳性能能够满足一般结构设计要求.

2.3 组织特征

SPF/DB Ti-6Al-4V 合金显微组织为 α+β 等轴细晶组织, 如图 2 所示.

表 2 SPF/ DB Ti-6Al-4V 合金及其激光焊接接头疲劳试验结果

Table 2 Fatigue results of SPF/ DB Ti-6Al-4V alloy and its laser welded joints

	试件编号	最大循环应力 σ_{max}/ MPa	循环次数 N	中值疲劳寿命 N_{50}(周次)
母材	B03, B04, B05	520	1 000 000(未断)	1 000 000
	B06	640	153 879	101 096
	B07	640	67 533	101 096
	B08	640	99 429	101 096
焊接接头	W03, W04, W05	400	1 000 000(未断)	1 000 000
	W06	460	231 616	426 334
	W07	460	241 493	426 334
	W08	460	134 070	426 334
	W09	460	800 755	426 334
	W10, W11	460	1 000 000(未断)	426 334
	W12	520	179 185	337 122
	W13	520	191 762	337 122
	W14	520	188 168	337 122
	W15	520	227 047	337 122
	W16, W17	520	1 000 000(未断)	337 122
	W18	640	86 832	50 070
	W19	640	27 606	50 070
	W20	640	52 366	50 070

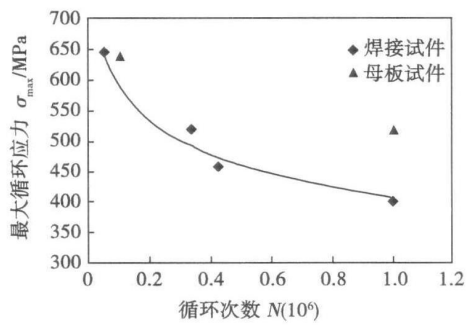


图 1 SPF/ DB Ti-6Al-4V 合金及其激光焊接接头 S-N 曲线

Fig. 1 S-N curve of SPF/ DB Ti-6Al-4V alloy and its laser welded joints

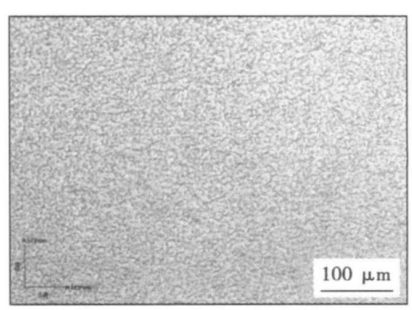
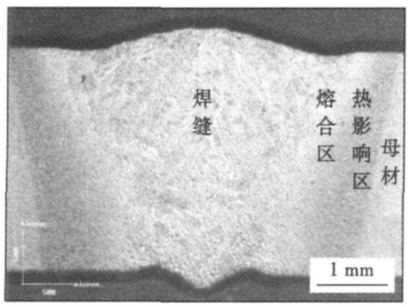


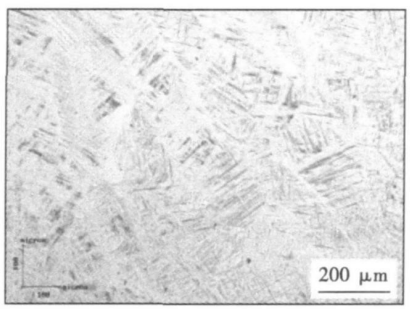
图 2 SPF/ DB Ti-6Al-4V 合金组织特征

Fig. 2 Microstructure of SPF/ DB Ti-6Al-4V alloy

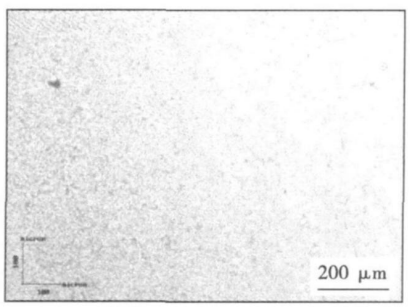
激光焊接接头横截面试样表面经腐蚀后可以清楚地区分为焊缝区、熔合区、热影响区和母材区，如图 3a 所示．由于激光的集中加热和母材自身的传热性能较差，焊缝区晶粒组织粗大．随着距焊缝距离的增大，熔合区和热影响区受热循环影响不同而呈现梯度组织结构．图 3b 为焊缝中魏氏组织结构及其晶内 α 束和针状马氏体 α′ 组织．图 3c 为热影响区中魏氏组织结构及晶内片状 α，针状马氏体 α′ 和少量 β 组织．



(a) 焊接接头形貌



(b) 焊缝



(c) 热影响区

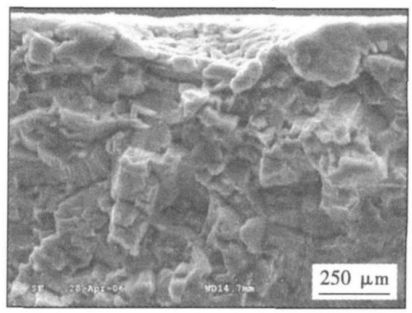
图 3　SPF/DB Ti-6Al-4V 合金激光焊接接头组织特征

Fig. 3　Microstructure of laser welded joints of SPF/DB Ti-6Al-4V alloy

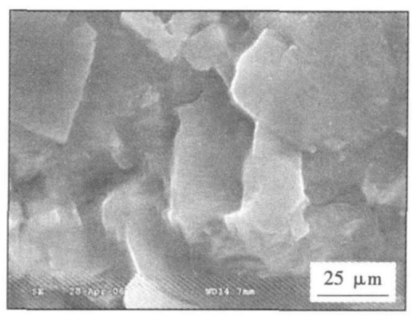
对比 SPF/DB Ti-6Al-4V 合金及其激光焊接接头组织特征可以看出，焊接接头组织结构的不均匀性以及组织的粗大化是导致激光焊接接头疲劳性能下降的重要原因．

2.4　疲劳断口

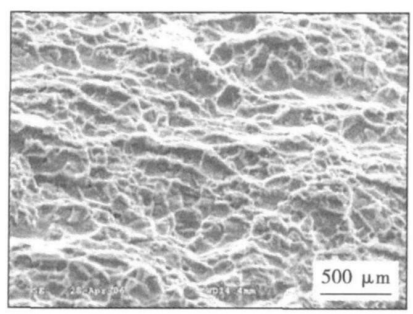
图 4 是最大循环应力为 640 MPa 时母材疲劳断口的典型形貌．母材疲劳试件疲劳源一般位于试件的棱边和表面，是由疲劳过程中滑移的挤出和挤入所形成的．疲劳源区断口除了具有小平面微观特征外，在裂纹源附近的区域内还常看到比较清楚的疲劳纹，如图 4a 所示．裂纹扩展区断口最重要的特征是疲劳纹的存在，如图 4b 所示．裂纹沿等轴晶粒的特定晶面扩展，表现为许多大小不同、高低不等的小断块．在每一断块上，疲劳纹连续而平行，但相邻小断块上的疲劳纹是不平行、不连续的．瞬断区断口主要是等轴韧窝，如图 4c 所示．



(a) 疲劳源区



(b) 裂纹扩展区



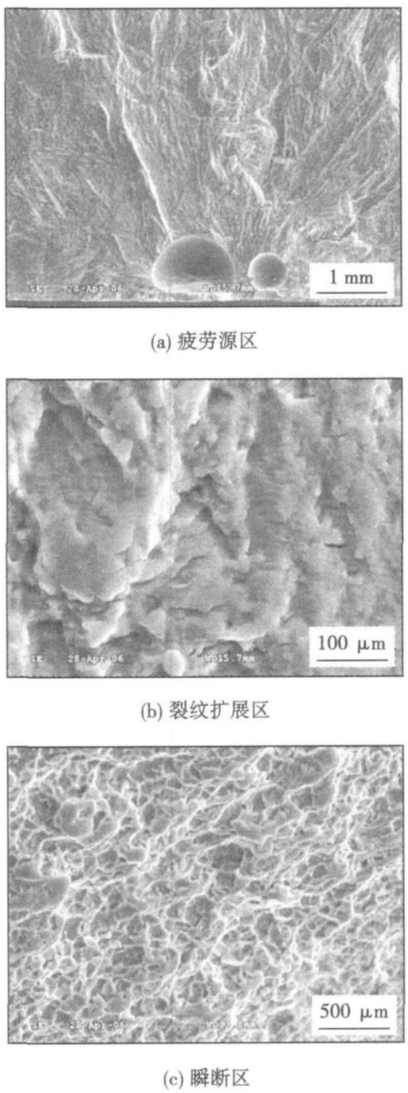
(c) 瞬断区

图 4　SPF/DB Ti-6Al-4V 合金疲劳断口形貌

Fig. 4　Fatigue fracture morphology of SPF/DB Ti-6Al-4V alloy

图 5 是最大循环应力为 640 MPa 时焊接接头疲劳断口的典型形貌．焊接疲劳试件疲劳源一般为以气孔为中心向四周辐射的放射花样，说明焊缝疲劳

裂纹一般起源于焊缝表层的微小几何不连续缺陷. 疲劳源区断口为准解理断裂, 除具有脆性断口的一般特征之外, 还有少量塑性变形的撕裂棱, 如图 5a 所示. 裂纹扩展区断口为疲劳纹, 并伴有大量的二次裂纹, 而瞬断区断口主要是等轴韧窝, 分别如图 5b, c 所示.



(a) 疲劳源区

(b) 裂纹扩展区

(c) 瞬断区

图 5 SPF/DB Ti-6Al-4V 合金激光焊接接头疲劳断口形貌

Fig. 5 Fatigue fracture morphology of laser welded joints of SPF/DB Ti-6Al-4V alloy

对比 SPF/DB Ti-6Al-4V 合金及其激光焊接接头疲劳断口可以看出, 焊接接头的准解理断裂显著降低激光焊接接头的疲劳性能, 而焊接气孔等焊缝表层微小几何不连续缺陷的存在往往成为激光焊接接头疲劳断裂的裂纹源.

3 结 论

(1) SPF/DB Ti-6Al-4V 合金激光焊接接头的抗拉强度略低于母材抗拉强度, 而疲劳强度明显低于母材疲劳强度, 约为其抗拉强度的 40%.

(2) SPF/DB Ti-6Al-4V 合金组织为 α+β 等轴细晶组织, 其焊接接头组织为含 α, 针状马氏体 α′和少量 β 相的魏氏组织结构. 焊接接头组织结构的不均匀性, 以及组织的粗大化是导致激光焊接接头疲劳性能下降的重要原因.

(3) SPF/DB Ti-6Al-4V 合金疲劳断裂为塑性断裂, 其焊接接头疲劳断裂为准解理断裂, 这显著降低激光焊接接头的疲劳性能. 而焊接气孔等焊缝表层微小几何不连续缺陷的存在往往成为激光焊接接头疲劳断裂的裂纹源.

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microstructure; shear strength

Wettability and microstructure of multicomponent Cu-based active filler metal on c-BN WANG Yi[1,2], QIU Xiaoming[1], LU Guanglin[3], YIN Shiqiang[1] (1. College of Materials Science and Engineering, Jilin University, Changchun 130025, China; 2. School of Mechatronics Engineering, Changchun Institute of Technology, Changchun 130012, China; 3. The Key Laboratory for Terrain-Machine Bionics Engineering, The Ministry of Education, Jilin University, Changchun 130025, China). p133—136

Abstract: By using the sessile drop method, the effects of active elements Ti and Zr on the wettability of the multicomponent Cu-based active filler metal on c-BN were studied. With the help of SEM, EDS and XRD, on basis of the key parameters theory, microstructure of the multicomponent Cu-based active filler metal were discussed. It can be found that the filler metal mainly consisted of Cu solid solution, Sn-rich phase as well as a small amount of intermetallic compound. By calculating the relation among the chemical affinity of elements, the influence mechanism of the wettability of the active element Ti, Zr in the multicomponent Cu-based active filler metal on c-BN was further elaborated. The results showed that the wettability of CuNiSnTi active filler metal on c-BN is better than CuNiSnZr.

Key words: multicomponent Cu-based active filler metal; c-BN; wettability; microstructure

Brazing of IC10 superalloy with Ni-based brazing fillers using Hf and Zr as melting-point depressants YE Lei, LI Xiaohong, MAO Wei, XIE Yonghui (Laboratory of Welding and Forging, Beijing Institute of Aeronautical Materials, Beijing 100095, China). p137—140

Abstract: Three Ni-based brazing fillers were designed using Hf, Zr and Hf+Zr as melting-point depressant respectively with the addition of a certain amount of Cr, Co, and Mo. The liquidus-temperature, hardness and spreadability of three fillers were measured. The results signify that Hf can decrease the hardness and improve the spreadability of filler more effectively than Zr. But as to the capability of depressing the liquidus-temperature, Zr is superior to Hf. The tensile strengths at 900 ℃ of the joints bonded with three fillers were also tested. It shows that the strength of joint brazed with the filler using Hf+Zr as melting-point depressant is higher than the others. In particular, Zr-containing filler presents the lowest joint strength. Furthermore, the high-temperature strength of the joint can be improved by adding a certain amount of Zr to Ni-Hf filler.

Key words: melting-point depressant; brazing filler; superalloy; high temperature tensile strength

Research on dissimilar steel welding via spark plasma sintering ZHANG Guodong, HONG Min, ZHANG Jianqiang, ZHANG Fuju (Welding Institute, Wuhan University, Wuhan 430072, China). p141—144

Abstract: The dissimilar steel weldes by spark plasma sintering (SPS) technology was developed in this paper. The welded joints of 45 steel and 18-8 stainless steel were obtained under different SPS parameters, and the microstructure, chemical composition, fractography and micro-hardness of the joints were examined. The influence of SPS parameters on the microstructure and properties of welding joints was studied, and the SPS welding metallurgy mechanism was also discussed. The result indicated that the new SPS technology could make effective welding in short time, low temperature and pressure, and the influence of the temperature is higher than the holding time and the pressure in the SPS procedure.

Key words: spark plasma sintering; dissimilar metal; welding

TIG-MIG indirect arc welding process WANG Jun[1,2], FENG Jicai[1], HE Peng[1], ZHANG Hongtao[1] (1. State Key of Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China; 2. Jiamusi University, Jiamusi 154007, China). p145—148

Abstract: A TIG-MIG indirect arc welding system was set up by reforming the traditional TIG welding system in which the arc was ignited and burnt steadily between the tungsten and the welding wire. This new process was used to deposit CuSi3 welding wire onto the 30CrMnSi steel plate. The effect of welding current and feeding wire speed on the consistency of the welding process and the effect of the flux, welding current, welding speed and distance between the tungsten and the welding wire were analyzed by changing the welding process parameters. The result shows that by choosing the proper process parameters, low heat input and high deposition ratio joint can be obtained in TIG-MIG indirect arc welding process, at the some time, the deleterious iron picking up can be also retrained for the decreasing of the mutual solution between the deposited metal and the work piece.

Key words: TIG; MIG; indirect arc

Influences of laser welding on fatigue propertis of SPF/DB Ti-6Al-4V alloy YAO Wei, GONG Shuili (National Key Laboratory For High Energy Density Beam Processing Technology, Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China). p149—152

Abstract: Tensile and fatigue properties of SPF/DB titanium alloy and its laser welded joints were investigated experimentally, and S-N curve was obtained. Microstructure and fatigue fracture features were observed, and influences of laser welding on fatigue properties of SPF/DB Ti-6Al-4V alloy were analyzed. It showed that tensile strength of the laser welded joints of SPF/DB Ti-6Al-4V alloy is less than that of the base metal slightly, but fatigue strength of the laser welded joints, about 40% of its tensile strength, is less than that of the base metal obviously. SPF/DB Ti-6Al-4V alloy is composed of equiaxed structure with α and β phases, and its laser welded joints are composed of weave structure with α, acicular martensite α′ and β phases. Uniformal and coarse microstructure is an important factor causing decrease of fatigue properties of laser welded joints. The fracture of SPF/DB Ti-6Al-4V alloy is plastic failure, but the welded joints are quasi-cleavage fracture which decreases fatigue properties obviously. At the same time the minute flaws below the surface of weld are usually the origin of fatigue failure of laser welded joints.

Key words: titanium alloy; SPF/DB; laser welding; fatigue properties