双相钢搭接点焊接头疲劳寿命分析

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摘 要：研究了双相钢焊点特征，对不同匹配双相钢搭接焊点进行了疲劳试验，获得了焊点的载荷寿命曲线。研究了双相钢焊点的疲劳裂纹扩展及失效形式，分析和解释了疲劳过程中的现象，并根据裂纹的实际扩展路径，提出了局部等效张开应力强度因子 k_{eq}，从断裂力学的角度对双相钢焊点的疲劳失效进行了分析。结果表明，k_{eq} 能够有效地关联具有不同厚度，不同熔核直径的搭接焊点试样的疲劳寿命，是反映双相钢焊点疲劳强度的有效参量，能够用来预测焊点疲劳寿命。

关键词：双相钢；点焊；疲劳强度；局部等效应力强度因子
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0 序 言

在汽车工业中，为适应提高油效和减少尾气排放的需要，汽车轻量化已经成为 21 世纪汽车技术的前沿和热点[1]。减少汽车重量的主要途径就是使用轻量化材料。传统的低碳钢以及高强度低碳合金钢(HSLA)现在正越来越多地被双相高强度钢(DP)所取代，双相钢的抗拉强度可以达到 600 MPa 甚至更高，它能够在不降低车身强度和刚度等各项性能指标的前提下，减少车身重量，而它现在也是整个汽车工业以及钢铁工业研究的热点。双相高强钢由低碳钢和低碳低合金钢经临界区处理或控制轧制而得到，主要由铁素体和马氏体组成。具有屈服强度低，初始加工硬化速率高，在加工硬化和屈服强度上表现高应变速率敏感性以及强度和延性配合好等特点[2,3]。不仅如此，双相高强钢还具有极强的吸能作用，从而在车辆发生碰撞或其它事故时更好地保护驾乘者的安全。

近年，虽然汽车白车身部件的连接出现了许多新的方法，比如激光焊接、粘接等等，但是电阻点焊仍然是车身构件连接的最主要方式。一般情况下，一辆轿车的白车身上有大约 3 000 个焊点，焊点周围存在较严重的应力集中，疲劳裂纹易于形成和扩展，车身结构的大部分疲劳失效都发生在焊点或者焊点周围，焊点的局部失效会降低整个车辆的各种功能指标，包括刚度、振动、噪声、以及车辆耐久性等[4]。随着双向高强钢越来越多地应用于汽车车身制造中，双相钢焊点疲劳强度也逐渐成为各大汽车厂商的研究焦点。

在双相钢搭接点焊接头进行疲劳试验的基础上，对双相钢点焊接头疲劳裂纹扩展及失效形式进行了讨论，获得了焊点的载荷寿命曲线，分析和解释了疲劳过程中的现象，并根据裂纹的实际扩展路径，提出了局部等效张开应力强度因子 k_{eq}，它是反映焊点疲劳寿命的有效参量。

1 试验方法

1.1 材料与试样

疲劳试验试样使用了双相高强钢 DP600GI 以及 DP780GI，对应于 DP600GI 有 0.8 mm 以及 1.4 mm 两种厚度钢板，而 DP780GI 则有 1.0 mm 以及 1.6 mm 两种厚度钢板，两种材料化学成分以及力学性能分别列于表 1 和表 2。用于疲劳试验的拉剪试样具体几何尺寸见图 1。为了保证获得焊点的一致性，所有试样的几何尺寸都保持一致，且焊接钢板都是同种厚度的组合，具体焊接参数如表 3。

表 1 DP600GI 和 DP780GI 的化学成分(质量分数，%)

Table 1 Chemical compositions of DP600GI and DP780GI

材料	C	Mn	P	S	Al	Fe
DP600GI	0.11	1.43	0.01	0.001	0.02	余量
DP780GI	0.13	2.01	0.03	0.002	0.049	余量

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表 2 DP600GI 和 DP780GI 的力学性能参数

Table 2 Mechanical properties of DP600GI and DP780GI

材料	屈服强度 R_{eL}/MPa	最大拉应力 R_{max}/MPa	断后伸长率 A(%)
DP600GI	430	620	28
DP780GI	465	835	17

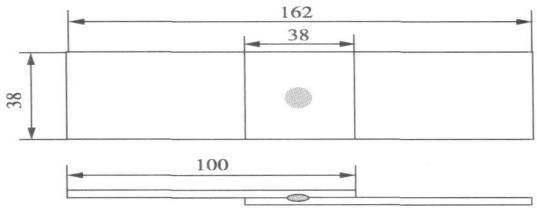


图 1 搭接点焊试样尺寸(mm)

Fig. 1 Dimension of tensile shear specimen

表 3 不同钢板匹配的焊接工艺参数

Table 3 Welding parameters for different specimens

试样	焊接电流 I/kA	电极力 F/kN	焊接时间 t(周波)	熔核直径 d/mm
0.8 mm DP600GI	9.0	2.2	10	4.5
1.4 mm DP600GI	12.0	4.3	18	6.2
1.0 mm DP780GI	11.0	3.5	15	5.1
1.6 mm DP780GI	11.0	4.3	21	6.5

1.2 疲劳试验系统

在 5 t 的岛津疲劳试验机上进行单点搭接点焊接头的疲劳试验。整个焊点疲劳测试系统主要包括试样、拉伸夹具和疲劳试验机三个部分。整个试验过程中，施加的是恒幅三角波载荷，载荷比 R 为 0.1，加载频率 10 Hz。

2 试验结果及讨论

2.1 双相钢焊点特征

图 2 是一未经测试的 DP600GI 1.4 mm 焊点横截面形貌，从图上可以清晰地看到焊点三个区域的分布，即熔核(SN)、热影响区(HAZ)和母材(BM)。熔核边缘的缺口尖端同时具有有限大小的缺口半径。通过扫描电镜观察可知，焊点熔核微观组织形式已经与母材大不相同，主要成分是柱状马氏体。按照图 2 中对角线对焊点进行硬度测试，获得焊点硬度分布如图 3 所示。从图中可知，双相钢焊点热影响区及熔核硬度基本一致，但两者相对母材硬度升高了 1 倍，达到 350 HV，材质变得硬而脆。

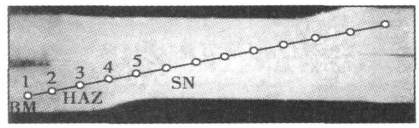


图 2 焊点横截面形貌

Fig. 2 Photomicrograph of spot welded dual phase steels

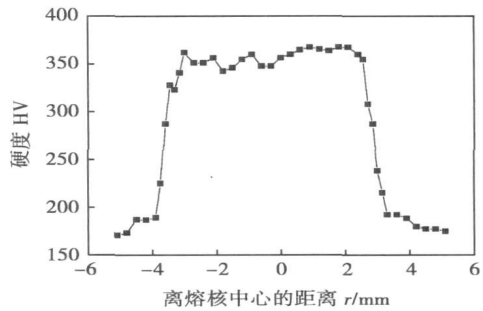
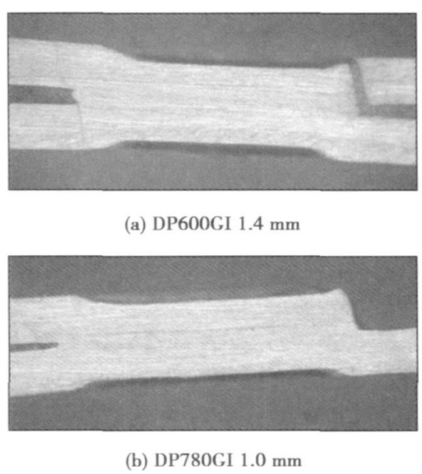


图 3 双相钢焊点硬度分布

Fig. 3 Microhardness of spot welded dual phase steels

2.2 搭接点焊接头疲劳裂纹扩展特性

图 4a，b 是经过高周疲劳(疲劳寿命高于 10^5)测试后失效的 DP600GI 1.4 mm 以及 DP780GI 1.0 mm 焊点的横截面形貌。从图上可以看出，两个焊点的失效均是由于贯穿板厚的裂纹扩展所造成的。而图 5 则是失效焊点裂纹断口处的放大图。从图上可以看到，在循环载荷的作用下，首先在两板搭接面焊点受力方向的边缘萌生出垂直于拉伸方向的细小椭圆形表面裂纹，由于载荷以及试样形状的对称性，裂纹可能出现在焊点左右两端(图4a)，或者裂纹只



(a) DP600GI 1.4 mm

(b) DP780GI 1.0 mm

图 4 失效焊点的横截面形貌

Fig. 4 Cross section appearance of failed specimen

在一端出现(图 4b)，然后裂纹在板厚及板宽方向同时扩展，板厚方向裂纹扩展直到贯穿板厚；接着裂纹在板宽方向快速扩展，直至断裂。如果将原焊点看作具有初始环状裂纹的疲劳试验对象，可以将此扩展裂纹看作曲折裂纹。从图上可以发现，两个试样的曲折裂纹扩展角度基本相同，和原焊点搭接面成 100°左右的交角。

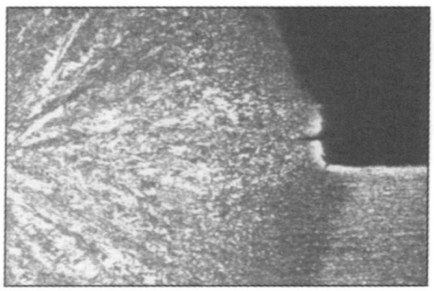


图 5　DP600GI 1.4 mm 失效焊点断口放大图

Fig. 5　Magnification view of notch tip area of failed DP600GI 1.4 mm specimen

2.3　搭接双相钢点焊接头拉剪疲劳试验结果

图 6 是 DP600GI，DP780GI 两种材料以及不同厚度组合的疲劳试验结果。从图上可以看到，随着钢板厚度的增加，焊点疲劳寿命相应增大。但是从图上可以发现，即使相同几何形状的搭接试件，加载条件都一致的情况下，不同焊点的载荷寿命曲线分布范围仍然很宽，无法从已有的疲劳试验结果对其它不同厚度或熔合直径焊点的疲劳寿命进行评价或预测。

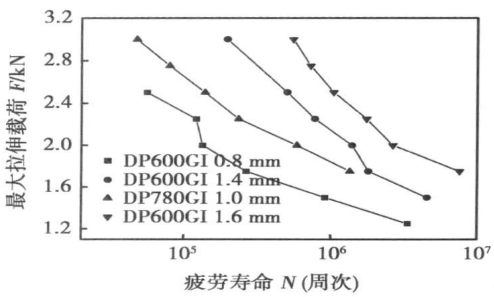


图 6　不同厚度试样的载荷寿命曲线

Fig 6　Fatigue results of different specimens

3　点焊疲劳裂纹扩展断裂力学分析

应力强度因子 K 综合了载荷、焊核直径以及板厚等诸因素的影响，只要材料和焊接条件一定，则各种形状点焊试件的疲劳寿命都可以通过 K 进行统一评价[5]。

考虑薄板搭接焊点的实际受力情况，首先将三维焊点疲劳问题简化为三维裂纹扩展问题[6]，图 7 为搭接试样的上半部分钢板及熔核，熔核直径为 D，作用力 F 离熔核中心距离为 e，且与钢板平面成 θ 角，钢板厚度为 t_s。根据受力平衡原理，下半部分钢板与熔核必须对此部分有反作用力，即垂直于钢板接触面的轴向力 R_a，接触面内的剪切力 F_τ 以及扭矩 M。将点焊接头视为一环状裂纹体，那么反作用力 R_a，F_τ，M 的共同作用必然会引起张开及剪切两种形式的位移，同时可以获得相对于初始环状裂纹熔核边缘的应力强度因子 K_{I}，K_{II} 的表达式[7]，即

$$K_{\mathrm{I}} = K_{\mathrm{axial}} + K_{\mathrm{moment}} \tag{1}$$

式中：K_{axial} 为正向拉力引起的张开形应力强度因子分量，$K_{\mathrm{axial}} = \dfrac{R_a}{D\sqrt{\pi \dfrac{D}{2}}}$；$K_{\mathrm{moment}}$ 为扭矩引起的张开形应力强度因子分量，$K_{\mathrm{moment}} = \dfrac{6M}{D^2\sqrt{\pi \dfrac{D}{2}}}$。

$$K_{\mathrm{II}} = K_{\mathrm{shear}} \tag{2}$$

式中：K_{shear} 为扭矩引起的张开形应力强度因子分量，$K_{\mathrm{shear}} = \dfrac{F_\tau}{D\sqrt{\pi \dfrac{D}{2}}}$。

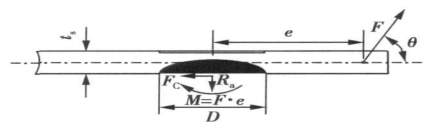


图 7　搭接点焊接头受力分析

Fig. 7　Static equilibrium of spot weld with the applied force

以搭接点焊接头拉剪疲劳试验为例，作用力 F 与钢板平面所成 θ 角为 0，即接触面上的轴向力 R_a 为 0，只存在剪切力 F_τ。但是焊点在实际拉剪载荷作用下的裂纹扩展形式如图 4 所示，裂纹并没有沿着钢板搭接面扩展，而是产生一曲折裂纹，其以原焊点搭接面成 100°左右交角在厚度方向向外扩展，具体可简化为图 8 所示。此处，K_{I}，K_{II} 表示相对原环状裂纹的应力强度因子，而 k_{I}，k_{II} 则是沿厚度方向扩展曲折裂纹的局部应力强度因子。对于曲折裂

纹，当裂纹长度趋于 0 时，局部应力强度因子 k_{I}，k_{II} 可以表示为曲折角 α 以及环状裂纹应力强度因子 K_{I}，K_{II} 的函数[8]，即

$$k_{\mathrm{I}}=\frac{1}{4}\left(3\cos\frac{\alpha}{2}+\cos\frac{3\alpha}{2}\right)K_{\mathrm{I}}+\frac{3}{4}\left(\sin\frac{\alpha}{2}+\sin\frac{3\alpha}{2}\right)K_{\mathrm{II}}$$

$$k_{\mathrm{II}}=-\frac{1}{4}\left(\sin\frac{\alpha}{2}+\sin\frac{3\alpha}{2}\right)K_{\mathrm{I}}+\frac{1}{4}\left(\cos\frac{\alpha}{2}+3\cos\frac{3\alpha}{2}\right)K_{\mathrm{II}} \quad (3)$$

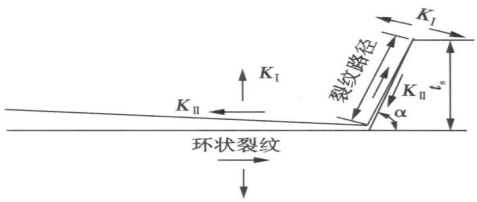


图 8 曲折裂纹扩展路径示意图

Fig. 8 A schematic plot of a kinked crack propagation path

由于焊点失效由贯穿厚度方向的曲折裂纹引起，而曲折裂纹的扩展速度由 k_{I}，k_{II} 两种类型的局部应力强度因子决定；基于以上分析，综合考虑两种类型应力强度因子的作用，建立局部应力强度因子的等效张开应力强度因子 k_{eq}，表达式为

$$k_{\mathrm{eq}}=\sqrt{k_{\mathrm{I}}^2+k_{\mathrm{II}}^2} \quad (4)$$

该等效应力强度因子表征了该曲折裂纹长度近似为 0 的前提下，裂纹尖端应力场强弱程度。为了检验该等效张开应力强度因子 k_{eq} 与焊点疲劳寿命之间的关系，将疲劳试验中试样失效后的裂纹扩展曲折角 α 以及根据原环形裂纹计算获得的应力强度因子代入上式，从而获得等效应力强度因子 k_{eq} 的值。

图 9 是该等效应力强度因子 k_{eq} 与焊点疲劳寿命之间的对应关系。对图中分布焊点作线形回归分析，从图上可以看到，所有不同厚度匹配的焊点在恒幅载荷下的疲劳寿命都位于拟合直线两边的狭窄区域内，拟合直线的相关度为 −0.96，从而证明该等效应力强度因子能够有效关联焊点疲劳寿命，通过它能够对搭接点焊试件的疲劳寿命进行统一评价。

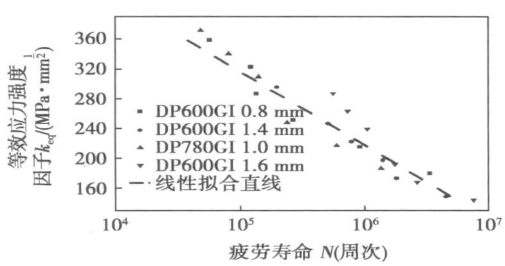


图 9 等效应力强度因子与疲劳寿命关系

Fig. 9 k_{eq} vs fatigue life of dual phase spot weld

4 结 论

（1）金相试验表明，双相高强钢焊点熔核区微观组织与母材大不相同，热影响区及熔核的硬度相对母材增加了 1 倍。

（2）将原焊点看作环状裂纹体，讨论了双相钢焊点高周疲劳裂纹的扩展形式，贯穿厚度方向的曲折裂纹引起焊点失效。

（3）通过疲劳试验，获得了不同厚度双相钢焊点的载荷疲劳寿命曲线。

（4）根据焊点裂纹实际扩展路径，从断裂力学的角度对焊点疲劳进行了分析，提出了厚度方向扩展的曲折裂纹等效应力强度因子 k_{eq}，并将试验结果代入公式进行验证，证明该应力强度因子能够有效关联焊点疲劳寿命。

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factured by electron beam welding is simulated by finite element method, according to the relation between the power and weld depth, the heat input is decreased by change of the power with weld depth to control the welding distortion of blisk. The result of calculations shows that the blisk distortion of the aero-engine can be controlled by decreasing the heat input on the conditions of meeting the demand of weld penetration and guaranteeing the quality of the welding, a theoretical method and numerical data is provided for controlling the welding distortion of the aero-engine.

Key words: heat input; numerical simulation; distortion

Heat input mechanics for spot welding electrode based on FEM LUO Aihui[1], ZHANG Yansong[1], CHEN Guanlong[1], ZHU Wenfeng[2] (1. Mechanical and Power Engineering College, Shanghai Jiaotong University, Shanghai 200240, China; 2. Mechanical Engineering College, Tongji University, Shanghai 200092, China). p41—44

Abstract: In order to study the heat dissipation of electrode during the spot welding process, the heat input mechanics of electrode for spot welding was analyzed in detail firstly. Then, the heat input model for electrode was built based on the finite element method (FEM) and the information of heat input during the welding process was analyzed. Finally, experiment was carried out to validate the conclusion. It's found that the dissipating heat of electrode was made of resistance heat and conduction heat. The resistance heat had the same law with the welding current and the conduction heat was the major part of the dissipating heat. This research is helpful to the further study on heat dissipation of electrode and quality control of spot welding.

Key words: resistance spot welding; heat input; finite element method

Fatigue life analysis of lap-shear spot weld of dual phase steels XU Jun, ZHANG Yansong, ZHU Ping, CHEN Guanlong (Body Manufacturing and Technology Center, Shanghai Jiaotong University, Shanghai 200240, China). p45—48

Abstract: Dual phase steel spot weld characteristic was investigated. And then fatigue strength of dual phase steel lap-shear spot weld was tested, the data for spot weld fatigue curve were obtained. The fatigue crack propagation path and failure modes of specimens were also studied. On the basis of crack propagation path local equivalent stress intensity factor k_{eq} was applied to analyze the fatigue life of dual phase steel spot weld. The test result indicated that k_{eq} was an effective parameter to predict spot weld fatigue strength prediction, which can correlate fatigue life of spot weld specimens with different thickness and weld nugget size.

Key words: dual phase steels; spot welding; fatigue strength; local equivalent stress intensity factor

Analysis on arc spectral radiation of TIG welding process of steel and aluminum with different parameters LI Zhiyong[1], WANG Bao[1], LI Huan[2], YANG Lijun[2] (1. Welding Research Center, North University of China, Taiyuan 030051, China; 2. School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China). p49—52, 56

Abstract: Through adjusting welding parameters such as welding current, arc length and gas flow rate, the spectral distributions of TIG welding arc were collected. In order to explore the variation of arc radiation in different spectral zone, TIG welding processes of steel and aluminum were studied for spectral distribution analysis, respeetively. For TIG welding of steel, the light radiation increases with the arc length in different spectral zone, among which the radiation intensity in spectral zones with less line spectrum increase linearly with the arc length. However, the change law is different for long arc and short arc. The light radiation increases with the growth of welding current. The light radiation is nearly the same when the gas flow rate was in a rather large value. When the gas flow rate was low which can not provide enough protection for the welding arc, the light radiation is affected obviously. For TIG welding of aluminum, the light radiation does not change a lot with the arc length variation. The radiation increases with the growth of welding current. The gas flow rate has great effect on the light radiation of arc when it is low, while has less effect on the light radiation of arc when it is high.

Key word: arc spectrum; welding parameter; TIG welding; intensity of radiation

Thermal cycling of rectangular chip resistor joints soldered with lead-free solder by diode laser HAN Zongjie[1], XUE Songbai[1], WANG Jianxin[1], YU Shenglin[1,2], FEI Xiaojian[1,3], ZHANG Liang[1] (1. College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China; 2. The 14th Research Institute, China Electronics Technology Group Corporation, Nanjing 210013, China; 3. Guangzhou CSSC-Ocean-Gws Marine Engineering Co., Ltd., Guangzhou 510727, China). p53—56

Abstract: Soldering experiments of rectangular chip resistor components were carried out with Sn—Ag—Cu lead-free solder by diode laser soldering system and IR reflow soldering method, respectively, and the thermal cycling test of chip resistor component joints was also carried out. It is found that mechanical properties of chip resistor joints soldered by laser soldering system are better than the ones of chip resistor joints soldered by IR reflow soldering method; shear forces of chip resistor joints decrease gradually with the increasing of thermal cycling times, while at the same time, shear forces of laser soldered joints are larger than that of IR soldered joints. Shear fracture mode of chip resistor joints change from toughness fracture to brittle fracture as thermal cycling times increase.

Key words: rectangular chip resistor; Sn—Ag—Cu lead-free joints; diode laser soldering; thermal cycling

Heating characteristic of constricting arc with flux strips in ultra-narrow gap welding ZHENG Shaoxian, ZHU Liang, ZHANG Xulei, CHEN Jianhong (State Key Laboratory of Gansu Advanced Non-ferrous Metal Materials, Lanzhou University of Technology, Lanzhou 730050, China). p57—60, 64

Abstract: Constricting arc with flux strips is employed in ultra-narrow gap welding, by measuring the cross sectional sizes of welds under different welding parameters, heating characteristic of