

不同参数钢和铝 TIG 焊电弧光谱辐射分析

李志勇¹，王 宝¹，李 桓²，杨立军²

(1. 中北大学 焊接研究中心，太原 030051；2. 天津大学 材料学院，天津 300072)

摘 要：通过调整焊接参数，对不同焊接参数下（弧长、电流、气流量），钢（直流正接）和铝（直流反接）TIG 焊电弧的光谱分布信息进行了采集，研究不同焊接参数下焊接电弧光谱信息的变化规律。结果表明，钢 TIG 焊过程中，不同谱段辐射强度会随弧长增加而增加，但在弧长较长时与较短时变化规律不同；其中线谱较少区域与弧长变化之间的线性度最好；辐射随焊接电流的增加成正比增加；在气流量较大时，随气流量变化不明显，气流量较小时存在明显影响。铝在 TIG 焊中，随弧长变化，光谱辐射强度没有明显变化；辐射随焊接电流的增加成正比增加；在气流量较大时随气流量变化不明显，气流量较小时存在明显影响。

关键词：电弧光谱；焊接参数；TIG 焊；辐射强度

中图分类号：TG422 文献标识码：A 文章编号：0253-360X(2008)05-0049-05



李志勇

0 序 言

随着现代焊接技术的发展，焊接机器人等高效化生产手段得到广泛地应用，研究者对于自动化所带来的焊接质量检测与控制越来越重视。焊接电弧光谱由于其自身信息量大、信噪比高、介入性小、测控精度高的优点，在一些场合得到成功应用，如利用电弧弧光信息测控 TIG 焊电弧的弧长，精度可达到 0.2 mm，与传统的弧压测控方法相比具有明显的优势^[1-2]。电弧光谱的其它主要应用领域包括：电弧防护、用光谱法测定电弧的温度场、应用于图像传感和焊缝跟踪方面、气体成分及浓度测定与控制、在 MIG 焊中控制熔滴过渡等特定领域^[3-7]。

上述领域研究与电弧光谱自身辐射特点具有密切联系，而焊接参数是焊接过程中影响电弧光谱辐射的主要因素之一，因此对于不同焊接参数下电弧光谱辐射及其变化特点的研究非常重要。研究者就特定应用领域焊接参数变化与电弧辐射的关系进行了相关研究，如在 TIG 焊弧长测控方面，研究 1~5 mm 弧长变化对应的电弧光谱变化^[1]。但很少有系统地分析焊接参数变化与电弧光谱辐射特征的关系，而且研究的参数基本在正常焊接参数内，变化范围相对较小。在实际焊接过程中，各种干扰因素的

存在会造成焊接参数异常，而焊接过程质量往往受到异常参数的影响，有必要对焊接参数在较大范围变化时的光谱辐射特征进行研究，为焊接质量在线检测提供理论基础。

1 试验方法

焊接光谱信息的采集和分析系统如图 1 所示。系统使用荷兰 Advantes 公司的 Avaspec 2048FT 2 光纤式数字光谱仪采集光谱信息，光纤双通道输入，可以对 200~1 100 nm 波段范围的光谱进行采集，分辨率达 0.3 nm，蓝甲包装的 Y 字形光纤保证了光谱信号的同步同点采集；除可以实现光谱谱段

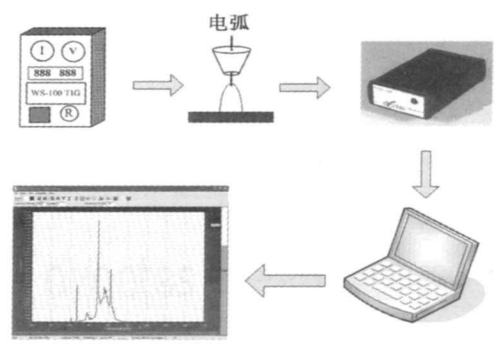


图 1 光谱采集系统示意图

Fig. 1 Sketch of spectrum collecting system

收稿日期：2007-06-08
基金项目：国家自然科学基金资助项目(50505048)；山西省青年科学基金资助项目(2006021027)

的频域采集外,还可实现 8 个特征谱段积分强度的同步采集,便于信号的融合和特征信号的提取。焊接电源使用时代的 WS 100 TIG 焊机,纯氩气保护,钨极为钍钨极。母材分别为 Q235 钢和工业纯铝板。

焊接过程分别在不同弧长(弧长由 1~8 mm 变化)、电流(焊钢时直流正接 40~100 A,焊铝时直流反接 10~30 A)、气流量(由 10~1 L/min 变化)下进行采集。采集到的光谱信息经过数字化后,传输到计算机中,利用相关软件进行光谱分析。

2 钢在各参数下 TIG 焊电弧光谱

2.1 钢 TIG 焊光谱的基本分布规律

通过图 2 和图 3 钢的 TIG 焊电弧光谱分布,可以看出基本上是连续辐射基础上存在大量线谱,线谱集中区域主要有:在 250~300 nm 段的大量 Fe II 谱线,430~520 nm 段的 Ar II, Fe I, Fe II 谱线,在 700~900 nm 谱段,存在大量的 Ar I 谱线。根据上述谱线分布特征,对于不同焊接参数的变化,选取特征谱段,对特征谱段下的辐射强度积分,获取不同谱段电弧辐射与焊接参数变化的关系。

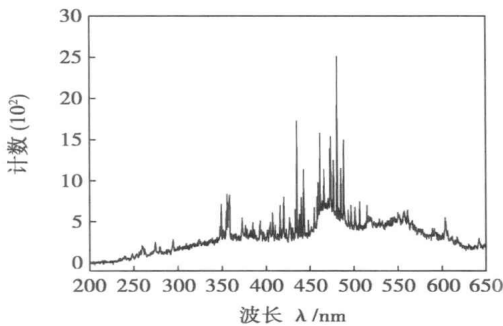


图 2 钢 TIG 焊光谱在 200~650 nm 的分布
Fig.2 Spectral distribution of steel in 200 - 650 nm

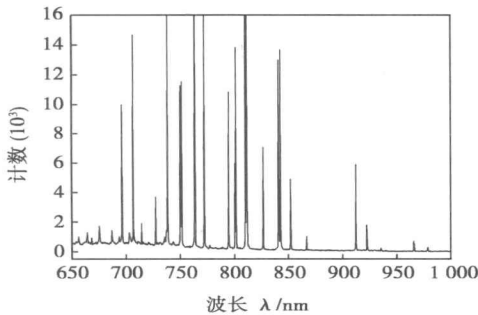


图 3 钢 TIG 焊光谱在 650~1 000 nm 的分布
Fig.3 Spectral distribution of steel in 650 - 1 000 nm

2.2 不同弧长

通过改变弧长,测定弧长由 1~8 mm 时电弧光谱分布的变化。获取 250~400 nm,515~540 nm,670~690 nm,690~700 nm,780~850 nm 和 880~1 000 nm 区段光谱辐射积分强度,研究不同谱段对弧长变化的响应,结果如图 4 所示。由图 4 可知,在 1~5 mm 弧长范围内,不同谱段的电弧辐射随弧长增加而增加,但不同谱段表现的特性不同。在 515~540 nm,670~690 nm,690~700 nm 和 880~1 000 nm 等线谱较少区域,1~3 mm 弧长表现出很好的线性;在 3~5 mm 区段,880~1 000 nm 线性度最好,其它几个谱段表现出指数上升的趋势,但仍可认为具有较好线性度。而在有大量线谱存在的 250~400 nm 和 780~850 nm 区段,其线性度明显不如其它几个谱段。在 250~400 nm 谱段,由于存在大量金属谱线,很容易受到外界干扰因素影响(如试板表面热状态),所以会出现波动,不太适合弧长的传感。在 780~850 nm 存在大量 Ar I 谱线,其辐射明显表现出指数增加趋势,弧长与此谱段辐射的对数成线性关系。对上述弧长的研究与文献[1]的研究基本吻合,但在文献[1]中提出的 696.5 nm 谱段(对应图 4 中的 690~700 nm 谱段),并没有明显表现出优于其它非线谱聚集区的线性特征。与文献[8]的以整体弧光辐射强度为弧长测控基础的研究结果存在较大差异。

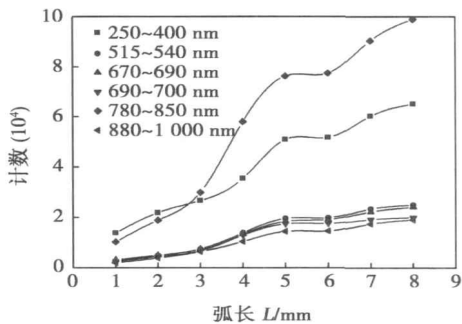


图 4 不同弧长下钢 TIG 焊光谱在各谱段的辐射强度
Fig.4 Spectral intensity of steel with different arc length

而在 5 mm 以上研究者过去较少涉及的弧长区域,却发现光谱辐射随弧长的变化规律发生较明显改变。在 5~6 mm 弧长变化阶段,辐射强度没有明显增加,在不同试验条件下的试验表明,在弧长变化过程中存在一个这样的阶段(虽然变化对应的弧长不完全一致,但一般集中在弧长 6 mm 左右),辐射强度没有随弧长变化明显改变,对电弧的观察表明,

短弧长时的蝶形电弧逐渐变化为钟罩形,电弧的挺度会在一定弧长发生跳变,从而导致在光谱辐射特征上的反应。随着弧长的继续增长,在6~8 mm 间,电弧辐射的增加与弧长变化又表现出线性关系,但在此阶段的斜率明显小于1~5 mm 阶段的变化特征。

2.3 不同电流

通过改变电流,测定在不同电流下电弧辐射分布特征,将特征谱段(250~300 nm,400~500 nm,620~680 nm,740~780 nm,790~850 nm 和 880~1 000 nm)辐射强度的变化表示在图5中。从图5中可以看出,随焊接电流增加,电弧辐射强度呈现增加趋势,在不同谱段的表现存在明显差异。在880~1 000 nm谱段,随焊接电流的增加,辐射强度增加表现出很好的线性;在620~680 nm,740~780 nm,790~850 nm 谱段,线性度不如880~1 000 nm 谱段好,电流增大到一定值,辐射强度的增加幅度减少,这可能与散热损失增大造成电弧辐射无法线性增加有关。在250~300 nm,400~500 nm 区段,由于金属谱线的影响,谱线波动幅度较大,很容易受干扰因素的影响,所以没有表现出很好的线性。

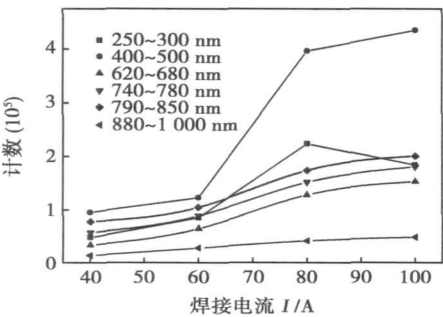


图5 不同电流下钢 TIG 焊光谱在各谱段的辐射强度
Fig.5 Spectral intensity of steel with different current

2.4 不同气流量

试验采用了气流量由10~1 L/min 变化,每次向下调节2 L/min 测量光谱分布的变化。同样将不同气流量下的光谱信息分布进行对比分析,分析对应特征谱段(250~300 nm,300~340 nm,440~500 nm,520~560 nm,762~765 nm 和 880~1 000 nm)辐射强度。辐射强度的变化如图6所示。

由图6可知,在气流量较大时,能够满足 TIG 焊保护的需要,光谱谱线差别不大,仅在700~900 nm 谱段氩气对应的谱线位置。可以通过谱线看出随气流量减小,谱线逐渐降低,因此特别选择Ar I谱线

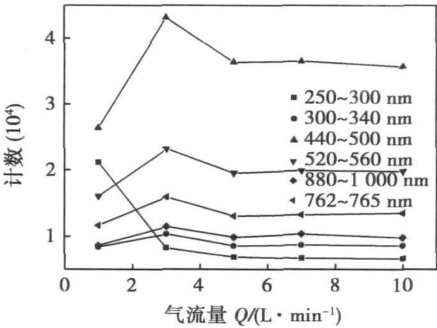


图6 不同气流量下钢 TIG 焊光谱在各谱段的辐射强度
Fig.6 Spectral intensity of steel with different gas flow rate

峰值所在谱段762~765 nm 进行采集。但当气流量较低时,如降到5 L/min 以下,保护气流量不能满足电弧稳定的需要,电弧光谱就会出现明显变化,在5~3 L/min 变化区段,电弧辐射强度在不同区段均增加;而在气流量继续减少到1 L/min 时电弧的稳定性受到很大影响,此时除了250~300 nm 对应的Fe II谱线聚集区明显增强外,其它谱段辐射都减小。这与早期研究认为气流量变化对光谱影响不大的结果存在差别^[2]。

3 铝在各参数下 TIG 焊电弧光谱

3.1 铝 TIG 焊光谱的基本分布规律

通过铝的 TIG 焊电弧光谱分布(图7和图8),可以看出其辐射特征与钢 TIG 焊电弧光谱存在较大差别,根据谱线特点,选择以下几个特征谱段为研究区段:250~300 nm,330~440 nm,450~500 nm,520~600 nm,650~720 nm,750~830 nm 和 900~1 000 nm。

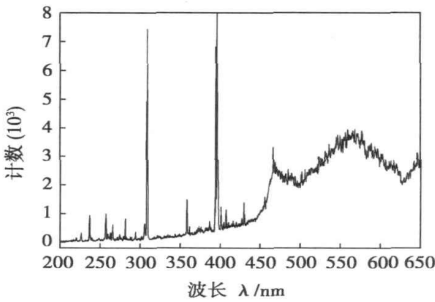


图7 铝 TIG 焊光谱在200~650 nm 的分布
Fig.7 Spectral distribution of aluminum in 200 - 650 nm

3.2 不同弧长

图9给出随弧长变化,不同谱段光谱的变化。

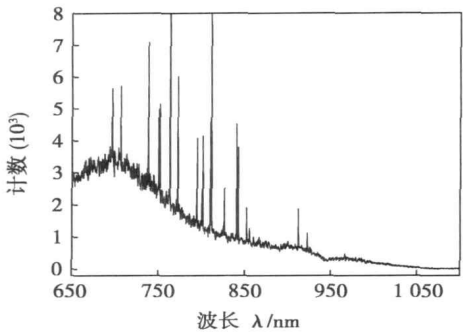


图 8 铝 TIG 焊光谱在 650~1 100 nm 的分布
Fig. 8 Spectral distribution of aluminum in 650 - 1 100 nm

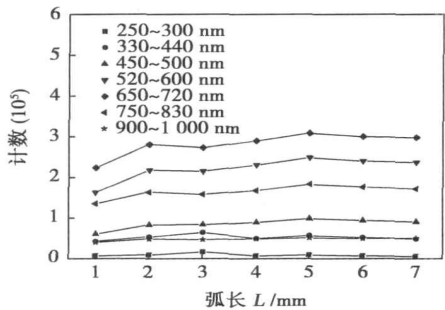


图 9 不同弧长下铝 TIG 焊光谱在各谱段的辐射强度
Fig. 9 Spectral intensity of Al with different arc length

从图 9 中可看出,在直流反接焊铝的情况下,随电弧弧长的增加,不同谱段电弧辐射强度会有所增加,但与钢 TIG 焊相比,变化幅度和规律性明显减少,很难用其弧光辐射强度来进行弧长的测控。

3.3 不同电流

图 10 给出了不同电流下铝 TIG 焊电弧光谱在不同谱段的变化规律。随焊接电流增加,不同谱段的光谱辐射强度均增强,但在不同谱段的表现不一

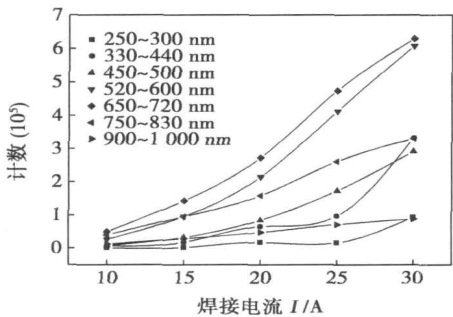


图 10 不同电流下铝 TIG 焊光谱在各谱段的辐射强度
Fig. 10 Spectral intensity of Al with different current

致,在 900~1 000 nm 表现出很好的线性度,在 450~500 nm,520~600 nm,650~720 nm 和 750~830 nm 均表现出指数增加趋势,而在 250~300 nm 和 330~440 nm 存在较多铝金属谱线的区域,辐射表现出波动。

3.4 不同气流量

不同气流量下电弧光谱的变化规律与钢 TIG 焊基本类似(图 11),但在 450~500 nm 和 520~600 nm Ar II 聚集的谱段,电弧光谱的分布表现出不同的变化规律,可能气流量过大时,由于气流的“冷却”作用,不利于 Ar II 谱线的生成。在其它谱段辐射基本保持不变,气流量小于 4 L/min 时,不能满足保护要求,不同谱段电弧的辐射强度出现增强;气流量为 1 L/min 没有出现明显的电弧不稳定现象,不存在钢 TIG 焊时的电弧辐射明显下降区段。

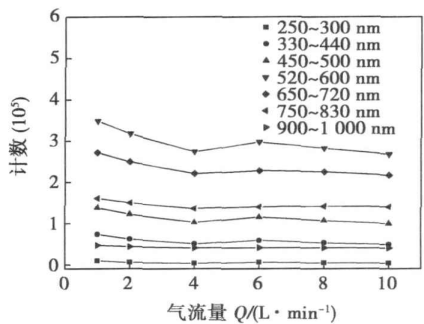


图 11 不同气流量下铝 TIG 焊光谱在各谱段的辐射强度
Fig. 11 Spectral intensity of Al with different gas flow rate

4 结 论

- (1) 钢 TIG 焊电弧光谱随弧长变化在各谱段响应不同,在 1~5 mm 弧长变化时,线谱较少的区段线性反映弧长的变化,在 Ar I 线谱聚集区,弧长与辐射的对数成线性关系;在 250~400 nm 谱段,无法保证线性关系。在 5 mm 弧长以上,会出现辐射强度没有明显增加的小区段,随后电弧辐射与弧长变化又表现出线性关系。
- (2) 随弧长的增加,铝 TIG 焊电弧光谱不同谱段辐射强度会有所增加,但规律性较差,不适合用来进行弧长测控。
- (3) 钢和铝的 TIG 焊电弧光谱辐射随电流的增加而增加;在波长较短的谱段,规律性不明显。880~1 000 nm 谱段表现出线性关系,其它特征谱段表现出指数增加趋势。

3 结 论

(1) 激光软钎焊矩形片式电阻焊点的力学性能优于传统红外再流焊工艺所获得的电阻焊点的力学性能,激光软钎焊技术在提高元器件焊点力学性能方面可完全替代传统的红外再流焊工艺。

(2) 对于片式电阻的热循环试验,焊点剪切力随热循环次数的增加呈现下降趋势,且在 120 次循环之后焊点剪切力大幅降低。在热循环次数相同的情况下,激光软钎焊焊点的力学性能均优于红外再流焊焊点。

(3) 随着热循环次数的增加,片式电阻剪切断裂的方式由明显的韧性断裂逐渐向脆性断裂转变,当热循环超过 160 次时,焊点断裂曲线无塑性变形阶段存在。

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(4) 随气流量的变化,在气流量较大时影响不大,但气流量较小时(约 4 L/min 以下),影响到对电弧的保护时,不同谱段的辐射特征发生明显变化。

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作者简介: 韩宗杰,男,1981 年出生,博士研究生。研究方向为无铅钎料及微电子焊接技术。发表论文 5 篇。

Email: hanzongjie113@nuaa.edu.cn

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作者简介: 李志勇,男,1972 年出生,博士,副教授。主要从事焊接电弧物理、焊接过程控制和焊接材料方面的研究。发表论文 18 篇。

Email: lzhy - 2002@126.com

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 aeroengine 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 aeroengine.

Key words: heat input; numerical simulation; distortion

Heat input mechanics for spot welding electrode based on FEM
LUO Aihui¹, ZHANG Yansong¹, CHEN Guanlong¹, ZHU Wenfeng² (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 Zhiyong¹, WANG Bao¹, LI Huan², YANG Lijun² (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, respectively. 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 Zongjie¹, XUE Songbrui¹, WANG Jianxin¹, YU Shenglin^{1,2}, FEI Xiaojian^{1,3}, ZHANG Liang¹ (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 Nonferrous 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