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# 时效对铜铝钎焊接头界面化合物和性能的影响

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**摘　要：** 采用Zn-22Al钎料对铜铝异种合金进行了火焰钎焊，并用加速老化试验模拟了其服役环境. 研究了时效过程中铜铝钎焊接头界面化合物的形貌变化及其对铜铝钎焊接头电阻率和抗剪强度的影响，并对其生长规律进行了初步计算. 结果表明，铜侧界面化合物在250 ℃恒温时效过程中不断变厚，其生长规律呈抛物线状，且其生长系数约为$6.1\times10^{-13}$ $cm^2/s$；当界面化合物的厚度为4.2 μm和18.1 μm时，铜铝接头的电阻分别为120.3 μΩ和132.9 μΩ，该界面化合物厚度对电阻率的影响系数为0.25；铜铝接头抗剪强度在时效过程中先有3%的上升，随后逐渐降低至接头初始值的85%.

**关键词：** 铜铝钎焊接头；时效；电阻率；抗剪强度
**中图分类号：** TG454　　**文献标识码：** A　　**文章编号：** 0253-360X(2012)05-0021-04

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## 0　序　言

纯铝因其优异的导电性、导热性以及良好的力学性能，已经广泛应用于电力、制冷等领域. 而随着近年来电解铜价格的增长，在电力、五金和变压器行业，用铝代替铜被认为是降低成本的有效途径，因此铜铝复合接头已经越来越多的应用于电力行业产品的制造过程中[1,2]. 但铝和铜有较大的物理和化学性能差异，如熔点、熔化潜热、线膨胀系数、电阻率等，这使实现铜铝可靠焊接并形成合格的焊接接头存在较大困难. 特别是铝和铜有很高的化学亲和力，当温度超过120 ℃时铜铝之间便会生成金属间化合物，这些化合物的出现会削弱铜铝接头的性能，并使接头电阻增大. 因此，有必要对铜铝接头服役过程中界面化合物的生长规律及其对接头性能的影响进行研究[3,4].

目前在铜铝异种金属焊接的研究过程中，为避免形成大量金属间化合物，研究者往往倾向于使用固相连接方法，因此对铜铝接头的可靠性研究也大多集中于通过固相连接实现的接头. Abbasia等人[5]研究了冷压焊铜铝接头界面金属间化合物的类型和生长规律. Lee等人[6]对铜铝摩擦焊接头的组织和性能进行了详细研究，并计算了其时效时铜铝接头界面化合物的生长系数及激活能. Ouyang等人[7]则研究了紫铜和铝合金搅拌摩擦焊接头的性能和组织演化规律. 试验首次对时效过程中铜铝火焰钎焊接头界面化合物的生长规律进行了分析，并研究了界面化合物厚度对接头性能的影响.

## 1　试验方法

钎焊试验用母材为1060工业纯铝和T2紫铜，钎料采用Zn-22Al合金. 试验采用铜铝搭接方式来评估接头的力学性能，其中搭接长度为3 mm，试验用接头形式及尺寸如图1所示.


图1　铜铝试样搭接接头(mm)
Fig. 1　Sketch brazed specimens for shear testing

将紫铜和纯铝分别切割成25 mm × 3 mm × 3 mm

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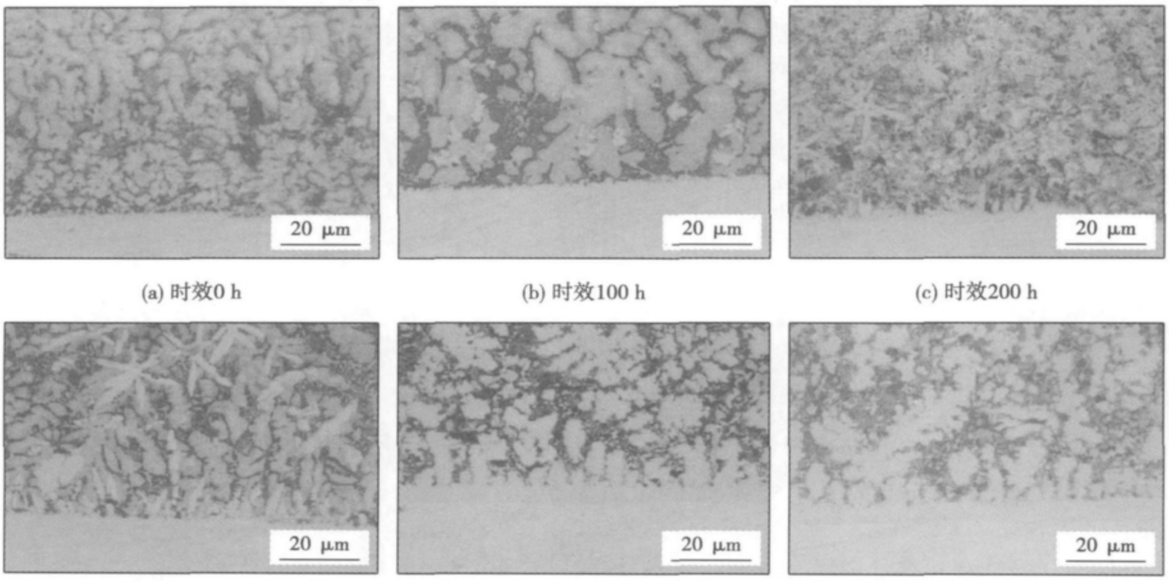
的条状,并钎焊成对接接头用以评估接头的导电性能. 纯铝和紫铜试样分别用 5% NaOH 和 15% $H_2SO_4$ 进行焊前清洗,采用熔化区间与钎剂较匹配的 Zn-22Al 钎料配合自制 $KAlF_4$-$CsAlF_4$ 钎剂对其进行火焰焊接,焊接过程在恒定流量下的氧乙炔火焰中进行. 焊接接头在 250 ℃ ±0.5 ℃的恒温时效箱中进行 0~1 000 h 不等的时效处理. 用万能试样拉伸机和 HIOKI3541 电阻计(精确至 0.1 μΩ) 对时效后的铜铝钎焊接头的抗剪强度和电阻进行了测量,并用光学显微镜观察了不同时间段铜铝接头界面组织的分布和变化.

## 2 试验结果及分析

### 2.1 铜铝接头界面化合物生长速率

在已有的研究中已经指出用 Zn-22Al 钎料钎焊的铜铝接头中铜侧界面化合物主要以 $CuAl_2$ 相的形式存在[4]. 试验主要研究时效过程对该界面层生长行为的影响. 图 2 为铜铝接头在 250 ℃分别恒温时效 0,100,200,500,800,1000 h 后铜侧界面化合物的形貌变化. 可以看出,焊后铜侧界面的化合物主要以较薄的锯齿状出现,其厚度随时效过程的进行




(a) 时效0 h (b) 时效100 h (c) 时效200 h (d) 时效500 h (e) 时效800 h (f) 时效1 000 h

图2 时效过程中界面化合物变化

Fig. 2 Intermetallic compounds of Cu/Al brazing joints during thermal aging

逐渐增加. 通过对图 2a 和图 2f 计算得出,焊后铜侧界面化合物的厚度约为 4.2 μm,而时效 1 000 h 后化合物的厚度可达 18.1 μm.

时效过程中铜侧界面化合物厚度随时间的变化曲线如图 3 所示. 通常由扩散主导的界面生长过程可以表示为

$$W = k\, t^n \tag{1}$$

式中: $W$ 为界面化合物的厚度; $k$ 为生长系数; $t$ 为时间; $n$ 为时间因子. 影响界面化合物的生长过程主要有两方面因素: 原子间反应速率和体积扩散速率. 原子反应速率起主导作用的界面化合物生长形式为线性,体扩散主导的界面化合物生长形式为抛物线形. 从图 2$a$ 可知试验界面化合物的生长情况属于后者,而由体扩散主导的界面化合物生长形式通常把时间因子 $n$ 取为 1/2[6-8]. 图 4 为界面化合物厚度随时间的平方根的变化关系,由拟合结果可得出 $k = 6.1\times10^{-13}\ cm^2/s$. 综上可得,火焰钎焊铜铝接

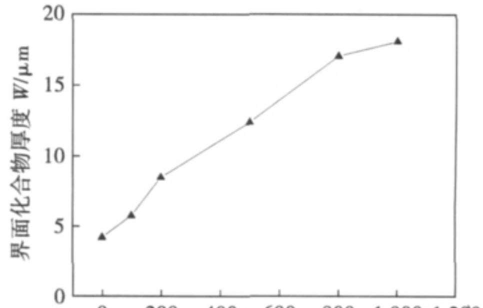



图3 不同时间段界面化合物厚度分布

Fig. 3 Width of intermetallic compounds during thermal aging

头铜侧界面化合物的生长情况可近似表示为

$$W^2 = 6.1 \times 10^{-13}\, t \qquad (2)$$

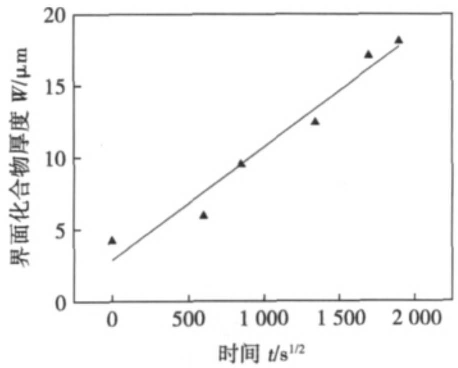



图 4　界面化合物厚度与时间平方根拟合曲线

Fig. 4　Variation of intermetallic thickness with square root of annealing time

## 2.2　时效时铜铝接头电阻率的变化

铜铝接头电阻率随铜侧界面化合物厚度的变化规律如图 5 所示. 随着化合物厚度的增加，铜铝接头的电阻也逐渐提高.

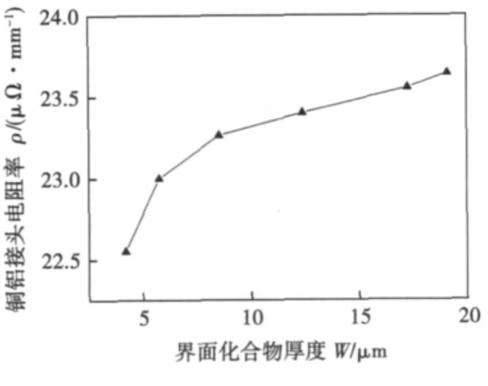



图 5　电阻率随界面化合物厚度变化曲线

Fig. 5　Relationship between resistivity and intermetallic thickness

从试验测量结果看，焊后当铜侧界面化合物厚度为 4.2 μm 时，铜铝钎焊接头的电阻为 120.3 μΩ；而接头时效 1 000 h 后，铜侧界面化合物厚度为 18.1 μm 时，铜铝钎焊接头的电阻增加为 132.9 μΩ. 导致接头电阻升高的主要原因是靠近铜侧界面化合物的生长. 另外，随着界面化合物的生长在化合物和钎料界面还会产生气孔、裂纹等缺陷，还有就是在时效过程中扩散区域的晶粒尺寸和位错密度也会大大增加，这些缺陷的出现会大大增加电流的阻力从而导致铜铝钎焊接头电阻率的增加.

图 6 为电阻相对变化率随界面化合物厚度的变化规律. 通常用以下经验公式来表示界面化合物厚度对铜铝接头电阻率的影响规律，即

$$r = \frac{(R_f - R_r)}{R_r} = C \cdot W \qquad (3)$$

式中：$r$ 为电阻的相对变化率；$R_r$ 为时效前接头电阻值；$R_f$ 为时效后接头电阻值；$C$ 为相关系数. 从图 6 的拟合结果可以计算得出 Zn-22Al 钎料钎焊的铜铝接头 $C$ 值为 0.25，这要小于冷压焊的 0.44 和摩擦焊的 0.48[5]，即铜铝钎焊接头界面化合物厚度对接头电阻率的影响要小于冷压焊和摩擦焊铜铝接头. 这个现象可以从两方面解释. 首先由于选用电阻较大的锌基钎料来钎焊紫铜和纯铝，导致接头本身电阻值要远大于冷压焊和摩擦焊接头. 因此相对于钎缝中大量的锌基钎料，界面化合物对电阻率的影响相对要小；另外就是铜铝冷压焊接头和摩擦焊接头中有大量复杂铜铝化合物形成，如：CuAl，$Cu_3Al_2$，$Cu_4Al_3$ 等，这些混合的复杂化合物对电阻率的影响要远大于单一化合物对电阻率的影响.

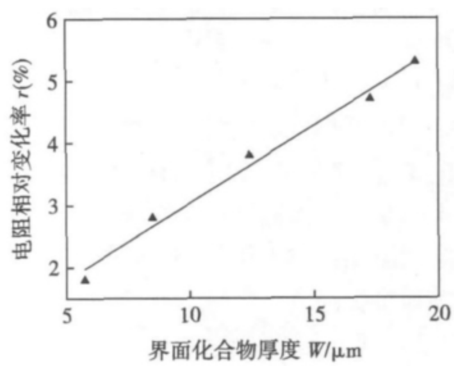



图 6　电阻相对变化率随界面化合物厚度变化曲线

Fig. 6　Variation of resistance changing with intermetallic thickness

## 2.3　时效时铜铝接头强度的变化

铜铝钎焊接头中铜侧界面化合物厚度对接头强度的影响如图 7 所示，可以看出，接头抗剪强度随时效过程进行先有 3% 左右的小幅上升，随后便急剧下降. 250 ℃恒温时效 1 000 h 后，接头的抗剪强度较初始值已有 15% 的下降. 从图 2a 可以看出，焊后界面处化合物先呈锯齿状分布，随时效过程进行锯齿状化合物不断长大并从界面处断裂，而后界面化合物逐渐转变为向垂直钎缝方向平行推进. 因此，当时效时间较短时，界面化合物锯齿会略微长大，此时这些锯齿状的化合物会进一步抑制接头的形变从而略微提高接头的抗剪强度. 随着时效过程的进行，界面化合物的厚度不断增加，同时钎缝中化合物也由原来的颗粒状逐渐长大为粗大的条块状，这直

接导致了铜铝钎焊接头抗剪强度的持续下降.

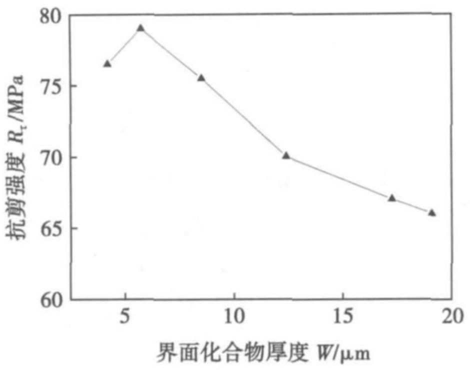



图7 接头抗剪强度随界面化合物厚度变化曲线

Fig. 7 Shear strength variation with various annealing time

## 3 结 论

(1) 铜铝钎焊接头铜侧界面化合物厚度随时效过程进行不断增加,其生长过程符合抛物线生长规律. 经计算得,250 ℃时铜铝接头界面化合物的生长系数为 $6.1\times10^{-13}$ $cm^2/s$.

(2) 铜铝钎焊接头电阻率随界面化合物厚度的增加不断增加,接头于 250 ℃时效 1 000 h 后,电阻值达到 132.9 μΩ. 铜铝钎焊接头界面化合物厚度对接头电阻的影响系数为 0.25,该系数小于铜铝冷压焊和摩擦焊接头的值.

(3) 250 ℃恒温时效过程中,铜铝钎焊接头的抗剪强度先有3%左右的上升,然后持续下降. 时效 1 000 h 后,降幅达到初始强度的15%.

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ing strength; CuCrZr alloy

**Efficient numerical simulation and experimental study on residual stress induced by GMAW with cable-type wire**

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**Abstract:** Gas metal arc welding (GMAW) with cable-type wire is an innovative welding method which provided prominent advantages of high efficiency and low power consumption. Untill now, it has rare report on the welding residual stress of the new welding method. In the present study, the heat source model based on the welding seam profile is adopted to efficiently simulate the weding tempature field, and it is validated by comparison of simulated temperature field and experimental welding seam profile of bead-on-plate welding through GMAW with single wire. In addition, the simulated residual stress results are compared with the experimental ones on the top surface obtained by the hole drilling method. The investigated results show that the heat source model based on the weld seam profile is suitable for efficient temperature field simulation of GMAW with cable-type wire; on the top surface within the welding line and adjacent region, the residual stress distribution and magnitude of GMAW with cable-type wire are almost identical to those of submerged arc welding (SAW) under the same welding specifications, however, in the region far from the welding line, the amplitude of longitudinal compressive residual stress induced by GMAW with cable-type wire is larger than that induced by SAW.

**Key words:** cable-type welding wire; gas metal arc welding; residual stress; efficient numerical simulation

**Effects of thermal aging on intermetallic compounds and properties of Cu/Al brazing joint**

JI Feng[1], XUE Songbai[1], ZHANG Man[1], LOW Jiyuan[2], WANG Shuiqing[2] (1. College of Materials Science and Technology, Naijing University of Aeronautics and Astronautics, Nanjing 210016, China; 2. Zhejiang Xinrui Welding Material Co. Ltd, Shaoxing 312400, China). pp 21 – 24

**Abstract:** Cu/Al dissimilar metals were joined with Zn-22Al filler metal by torch-brazing technology and heat treated at constant temperature of 250 ℃ for 0 to 1000 h. To guarantee the reliability of the Cu/Al torch-brazing joints in service requirement, the growth rate of intermetallic compounds on Cu side was calculated and the effects of the intermetallic compound layer on the electrical and mechanical properties have been investigated under various annealing time. It was observed that the width of intermetallic compound increased as the thermal aging proceeded, and the growth rate of the intermetallic compound was $6.1 \times 10^{13}$ $cm^2/s$ when the aging temperature was 250 ℃. A thicker intermetallic compound layers could degrade the resistivity and shear strength of Cu/Al joints. When the thickness of intermetallic compound was 4.2 μm and 18.1 μm, the electric resistance was 120.3 μΩ and 132.9 μΩ, respectively. Moreover, the shear strength of Cu/Al brazing joint increased by 3% when the aging time was 100 h while the strength decreased by 15% when the Cu/Al joints endured 1000 h thermal aging.

**Key words:** Cu/Al brazed joints; thermal aging; resistivity; shear strength

**Numerical simulation on dynamic performance of assistant gas during laser cutting process**

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**Abstract:** The dynamic performance of assistant gas plays an important role on cutting kerf forming in laser cutting process. The VOF method and depth adaptive laser heat source were used to set up a multiphase flow model which can simulate the interaction between assistant gas and cutting kerf. Cutting experiments were carried out to verify this model. The cut kerf morphology, dynamic performance of assistant gas and temperature distribution were investigated from holing to stable cutting in the total cutting process. The calculation results show that the dynamic performance of assistant gas changes constantly during laser holing, which is affected by cutting frontier shape and cutting depth, etc. Assistant gas flow, cutting kerf morphology and temperature are no longer changing during stable cutting stage. The model can effectively reflect the cutting depth and width which are influenced by dynamic performance of assistant gas.

**Key words:** laser cutting; assistant gas flow field; numerical simulation; depth adaptive heat source

**Quantitative evaluation on metal transfer process stability of arc welding based on autocorrelation analysis**

GAO Liwen[1,2], XUE Jiaxiang[1], CHEN Hui[1], ZHANG Xue[1], Wang Ruichao[1] (1. School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, China; 2. College of Information Technology, Guangzhou University of Chinese Medicine, Guangzhou 510006, China). pp 29 – 32

**Abstract:** This paper proposed a quantitative evaluation method based on autocorrelation analysis, to extract the coefficient of variation of intervals between autocorrelation function peaks from arc welding voltage and current signals, which were then used as the quantitative values to evaluate the metal transfer process stability in arc welding. Experiments showed that results obtained through this method were consistent with those from manual analysis. Besides, the combination of the quantitative values obtained through this method and other quantitative values has preferably realized the automatic evaluation evaluation of dynamic characteristics of power supply for $CO_2$ arc welding. The recognition accuracy reached 97.4359%, which was quite close to the standard of practical use.

**Key words:** metal transfer; stability; autocorrelation; quantitative

**Microstructure and properties of Sn-Zn-Ga-xPr lead-free solder**

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