

不同体积无铅微尺度焊点的蠕变力学性能

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摘 要: 采用基于动态力学分析仪的精密蠕变试验方法, 对比研究了 $5.34 \times 10^7 \mu\text{m}^3$ 与 $7.07 \times 10^6 \mu\text{m}^3$ 两种体积相差近一个数量级的无铅 Sn-3.0Ag-0.5Cu 微尺度焊点的高温蠕变力学行为与蠕变性能。结果表明, 所有微尺度焊点的蠕变曲线均呈现初始蠕变、稳态蠕变和加速蠕变阶段。虽然微尺度焊点的体积存在较大差异, 但是它们的蠕变激活能与蠕变应力指数均非常接近。此外, 在相同的试验温度与拉伸应力作用下, 大体积微尺度焊点的稳态蠕变速率相对小体积焊点更大, 而蠕变寿命则呈现完全相反的趋势。

关键词: 电子封装; 微尺度焊点; 蠕变; 力学性能

中图分类号: TG 113 **文献标识码:** A **文章编号:** 0253-360X(2014)06-0061-04

0 序 言

电子封装微尺度互连焊点在提供电信号传输和散热通道的同时, 更为重要的是提供机械连接与支持, 以确保电子元器件之间的可靠互连互通以及固定在印刷电路板上。微电子封装结构和系统功能的退化、失效在绝大多数情况下是由于焊点的力学失效造成的, 而蠕变变形与破坏是其中最为主要的力学失效形式之一^[1-2]。由于微焊点无论采用传统锡铅钎料还是新型无铅钎料, 即使在室温环境下工作, 它们的同系温度均已超过 0.7 甚至更高。加之微互连焊点钎料、芯片、基板和凸点金属化层(UBM)等电子封装材料的线膨胀系数不同而导致的严重热失配(热应力), 使得微尺度焊点的蠕变被视为电子封装重要的可靠性问题而备受广泛关注^[3-5]。

伴随现代电子产品的持续微小型化, 封装系统和结构中的焊点尺寸也随之越来越小。很多研究表明微尺度焊点的行为和性能与体钎料材料明显不同, 甚至当微尺度焊点的体积相差较大时也将导致其各种性能存在显著差异, 即体积/尺寸效应^[2, 6-8]。虽然目前有一些研究工作针对钎料合金或焊点的高温蠕变性能进行了探讨, 但是大部分研究要么直接采用体钎料, 要么采用的焊点体积太大, 与实际 BGA、FC 微尺度焊点相差甚远, 因而无法说明真实微尺度焊点的实际情况。

文中研究对比分析了两种不同体积的微尺度焊点的蠕变力学性能, 以为微尺度焊点蠕变力学性能研究提供新的试验方法, 为电子封装系统的可靠性研究提供科学的试验数据与参考依据。

1 试验方法

1.1 试验材料

试验用无铅钎料的成分设计为 Sn-3.0Ag-0.5Cu (质量分数, % , 下同), 采用高纯度的锡粒(99.5%)、银颗粒(99.95%)和无氧铜丝(99.95%) 在陶瓷坩埚熔炼炉中制备而成。熔炼钎料时采用 LiCl 和 KCl 熔融共晶盐覆盖保护以减少钎料合金的氧化。熔炼温度控制在 400 ℃ 左右, 熔炼时间为 30 min。熔炼过程中充分搅拌以保证钎料成分均匀, 重熔精炼后浇铸成钎料条, 采用示差扫描量热仪 DSC Q20 测得钎料的熔化温度为 218.0 ~ 220.6 ℃。最后把钎料精细切割成微颗粒待用。

1.2 微尺度焊点制备方法

钎焊前, 将无氧铜导线待焊的一端精细磨平, 随后与微小钎料颗粒一起在超声波清洗器中清洗干净。微尺度焊点制备在传热性很好的自制铝板夹具上进行, 采用放大倍数为 40 ~ 80 倍的体视显微镜精确控制两根待焊 200 μm 直径铜导线之间的钎焊间隙为 225 μm , 而 400 μm 直径铜导线之间的钎焊间隙为 425 μm 。钎焊时, 温度控制在 240 ~ 260 ℃, 采用添加 5% ZnCl_2 活性剂的松香酒精溶液作为钎焊时的钎剂。待钎料熔化后保温 20 s 左右再从加热板上移走, 随后用电吹风加速冷却至室温。焊好后, 在

收稿日期: 2013-12-20

基金项目: 重庆市教委科学技术研究项目(KJ131415); 重庆科技学院校内科研基金资助项目(CK2010B23, CK2013Z12)

* 参加此项研究工作的还有刘华文

乙醇的帮助下从铝夹具上小心取出焊点试样,最后精细打磨抛光至所需尺寸。大、小两种微尺度焊点的体积分别为 $5.34 \times 10^7 \mu\text{m}^3$ 与 $7.07 \times 10^6 \mu\text{m}^3$ 。

1.3 基于 DMA 的精密蠕变试验方法

动态力学分析仪(DMA Q800,TA-Instruments)的最大动态力为 18 N,最小动态力为 0.000 1 N,力解析度为 0.1 mN,应变解析度为 1 nm,DMA 非常适合于电子封装微尺度焊点的精密力学性能试验。

文中所有蠕变试验均在 DMA 上进行,其中试验夹具选用薄膜或纤维拉伸夹具,试验模式采用控制力模式,试验温度选定为微尺度焊点常见的服役温度 100 ~ 145 °C,拉伸应力载荷设定为 8 ~ 20 MPa。另外,每种不同温度与应力匹配参数的蠕变试验样品数为 3 个,取它们的平均值作为最终试验结果。

2 试验结果与分析

2.1 恒应力不同温度下的蠕变行为与蠕变激活能

为了获得无铅 Sn-3.0Ag-0.5Cu 微尺度焊点的蠕变激活能,试验中保持拉伸应力载荷 20 MPa 恒定不变,同时选定四个不同的试验温度为 100、125、135 和 145 °C。图 1 为两种大小不同体积微尺度焊点在上述试验条件下的应变—时间蠕变曲线。从图 1 中可以看出,所有微尺度焊点的蠕变曲线均呈现出典型的蠕变特征,即出现了明显的蠕变三个阶段:初始蠕变阶段、稳态蠕变阶段和加速蠕变阶段。同时,无论微尺度焊点的体积大小如何,在相同应力载荷作用下,随着温度的升高,稳态蠕变阶段的蠕变速率增大,而蠕变寿命显著降低。

根据图 1 的蠕变曲线可以得到 $5.34 \times 10^7 \mu\text{m}^3$ 大体积微尺度焊点在 100、125、135 和 145 °C 温度下的稳态蠕变速率分别为 5.7×10^{-7} 、 5.6×10^{-6} 、 1.2×10^{-5} 和 $3.3 \times 10^{-5} \% / \text{s}$,蠕变寿命分别为 1 428.5、198.8、95.1 和 34.4 min; 而 $7.07 \times 10^6 \mu\text{m}^3$ 小体积微尺度焊点在 100、125、135 和 145 °C 温度下的稳态蠕变速率分别为 4.3×10^{-7} 、 3.2×10^{-6} 、 1.0×10^{-5} 和 $2.0 \times 10^{-5} \% / \text{s}$,蠕变寿命分别为 1 458.7、479.6、115.3 和 80.0 min。显然,当应力与温度相同时,大体积微焊点的稳态蠕变速率比小体积微焊点更大,而蠕变寿命则更短一些,这是由于蠕变过程中温度造成焊点内部的显微组织粗化程度不同,同时微尺度焊点的体积越大,内部缺陷可能也越多等原因造成的。

蠕变曲线的第二阶段(即稳态蠕变阶段)占据了整个蠕变变形过程的大部分比例,蠕变寿命也主要由这一阶段所决定。在稳态蠕变阶段,稳态蠕变

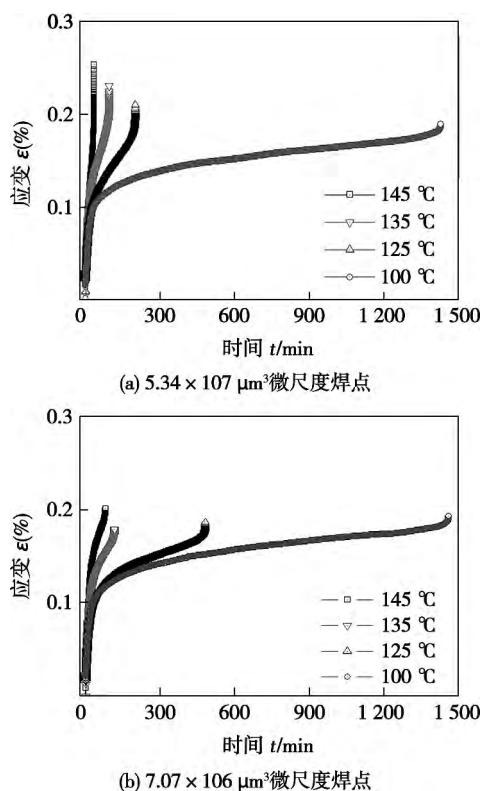


图 1 恒定应力不同温度下微尺度焊点的应变—时间蠕变曲线

Fig. 1 Strain-time creep curves of micro-scale solder joints under constant stress at different temperatures

速率 $\dot{\epsilon}$ 是与应力 σ 和温度 T 相关的函数,通常可采用 Norton 幂律公式 $\dot{\epsilon} = A\sigma^n \exp\left(-\frac{Q}{RT}\right)$ 来表示^[9,10]。

对它两边分别取自然对数后,可以得到 $\ln \dot{\epsilon} = \ln A + n \ln \sigma - \frac{Q}{RT}$,其中 R 代表普通气体常数(下同),再对两端取 $(-1/T)$ 偏导数,可以得到如下蠕变激活能的近似表达式为 $Q = -R \left[\frac{\partial \ln \dot{\epsilon}}{\partial \left(\frac{1}{T}\right)} \right]$ 。因此,蠕变激活

能的数值即为曲线 $\ln \dot{\epsilon} - 1/T$ 的斜率与 $(-R)$ 的乘积。因此,将试验中得到的恒应力(20 MPa)和 4 种不同温度(100、125、135 和 145 °C)条件下的稳态蠕变速率数值及其温度的倒数值绘制于图 2,其中稳态蠕变速率坐标采用自然对数坐标。

这样微尺度焊点在 4 个不同温度下便可得到 4 个坐标点,然后采用最小二乘法对这几个数据点进行线性拟合,得到的直线斜率与 R 乘积的绝对值即为微尺度焊点的蠕变激活能 Q 。按照上述方法得到大、小两种不同体积微焊点的蠕变激活能分别为 114.9、111.5 kJ/mol。可以看出,无论微尺度焊点的体积大小如何,它们的蠕变激活能非常接近。

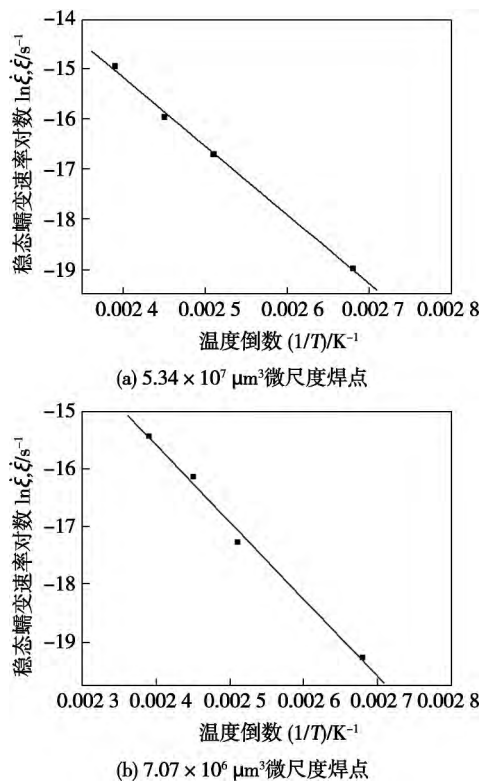


图2 恒应力不同温度下微尺度焊点的 $\ln \dot{\epsilon} - 1/T$ 曲线
Fig. 2 $\ln \dot{\epsilon} - 1/T$ curves of micro-scale solder joints under constant stress at different temperatures

值得指出的是,纯锡晶界扩散的激活能为 $98 \sim 118 \text{ kJ/mol}$ ^[3,11],试验研究得到的锡基无铅钎料 Sn-3.0Ag-0.5Cu 微焊点的蠕变激活能 $111.5 \sim 114.9 \text{ kJ/mol}$ 正好介于其间;并且试验温度为 $100 \sim 145^\circ\text{C}$,是纯锡熔点 232°C 的 $0.74 \sim 0.83$ 倍,而纯锡在此过渡温度区间正好由位错扩散转为晶界扩散。据此可以推断,晶界扩散是 Sn-3.0Ag-0.5Cu 微尺度焊点在 $100 \sim 145^\circ\text{C}$ 蠕变过程中的主要变形机制;并且可以认为,尽管锡基微尺度钎料焊点的体积相差近一个数量级,但是由于制备微焊点的钎料合金相同,同时模拟再流焊工艺也基本一致,故而相同的蠕变变形机制导致了蠕变激活能非常接近。

2.2 恒温不同应力下的蠕变行为与应力指数

为了测试并计算 Sn-3.0Ag-0.5Cu 无铅钎料合金的高温蠕变应力指数,蠕变试验的温度恒定为 145°C 不变,4 种不同拉伸应力载荷分别为 8, 12, 16, 20 MPa。图 3 为两种不同体积大小微尺度焊点在上述条件下的应变—时间蠕变曲线。

从图 3 可以看出,所有蠕变曲线仍然存在明显的典型蠕变变形三阶段。同时,在相同温度条件下,应力水平越高,微尺度焊点的稳态蠕变速率越大,而蠕变寿命越短。在相同的测试条件下,大体积微尺度焊点的稳态蠕变速率更大,而蠕变寿命则明显短

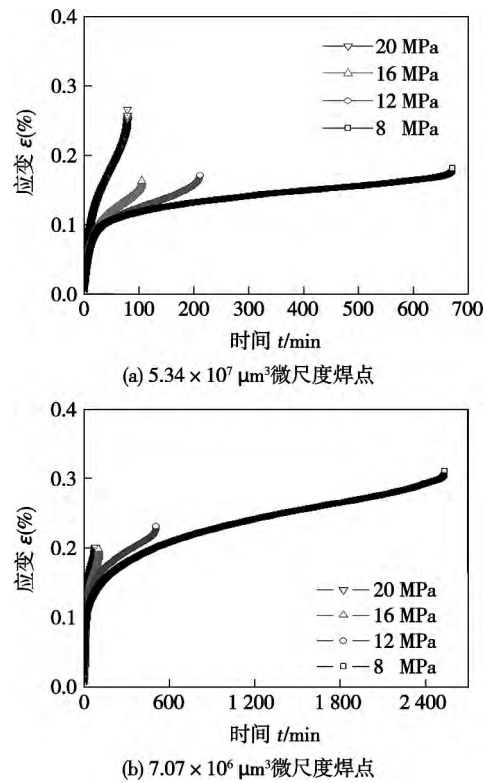


图3 恒温不同应力下微尺度焊点的应变—时间蠕变曲线
Fig. 3 Strain-time creep curves of micro-scale solder joints under different stresses at constant temperature

很多。由图 3 可以得到的 $5.34 \times 10^7 \mu\text{m}^3$ 大体积微尺度焊点在 8, 12, 16 和 20 MPa 应力下的稳态蠕变速率分别为 1.4×10^{-6} , 8.8×10^{-6} , 3.2×10^{-5} 和 $3.3 \times 10^{-5} \%$ /s, 蠕变寿命分别为 672.0, 210.8, 104.0 和 34.4 min; 而 $7.07 \times 10^6 \mu\text{m}^3$ 小体积微尺度焊点在 8, 12, 16 和 20 MPa 应力下的稳态蠕变速率分别为 5.5×10^{-7} , 4.5×10^{-6} , 1.1×10^{-5} 和 $2.0 \times 10^{-5} \%$ /s, 蠕变寿命分别为 2 535.3, 506.5, 102.1 和 80.0 min。

蠕变应力指数 n 是蠕变变形幂律公式的另外一个非常重要的参数,对 Norton 幂律公式的两边分别取对数后可以得到 $\lg \dot{\epsilon} = \lg A + n \lg \sigma - \frac{Q}{RT}$,再对其两边就 $\lg \sigma$ 求导,可以得到应力指数 n 的近似计算公式为 $n = \left(\frac{\partial \lg \dot{\epsilon}}{\partial \lg \sigma} \right)$ 。因此,将 4 组稳态蠕变速率与 4 种不同应力 (8, 12, 16 与 20 MPa) 数据点绘制于 $\dot{\epsilon} - \sigma$ 图 4 中(其中横坐标和纵坐标均采用对数 \lg 坐标),再将得到的数据点进行最小二乘法线性拟合,最后得到的直线斜率即为蠕变应力指数 n 的数值。

试验得到大小两种不同体积 Sn-3.0Ag-0.5Cu 微尺度焊点在 145°C 温度和 8~20 MPa 条件下的蠕变应力指数 n 值分别为 3.8 与 3.9。同样,这一计算

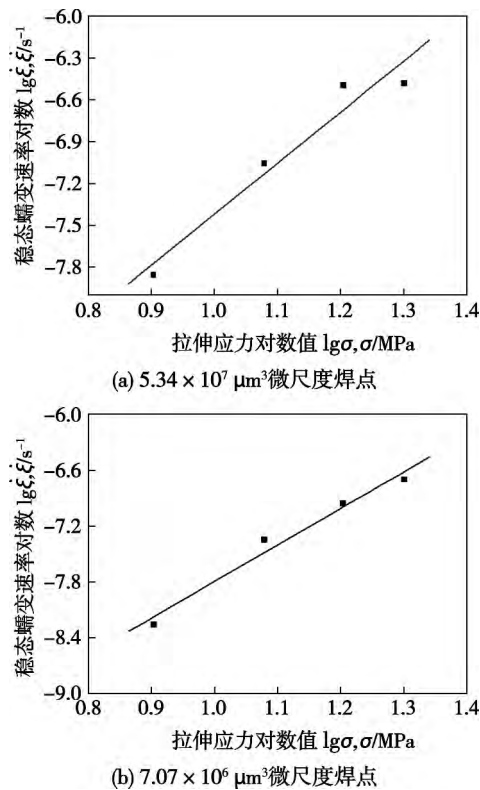


图 4 恒定温度不同应力下微尺度焊点的 $\lg \dot{\epsilon} - \lg \sigma$ 曲线
Fig. 4 $\lg \dot{\epsilon} - \lg \sigma$ curves of micro-scale solder joints under different stress at 145 °C

试验值与理论计算纯锡晶界扩散所得的蠕变应力指数 n 值 3.8 ~ 4.5^[4,12] 非常接近,数据再次表明,锡基无铅钎料 Sn-3.0Ag-0.5Cu 微尺度焊点的蠕变机制以晶界蠕变/扩散机制为主。

3 结 论

(1) 在 100 ~ 145 °C 温度与 8 ~ 20 MPa 应力下,所有不同体积微焊点的蠕变曲线均呈现典型的初始蠕变阶段、稳态蠕变阶段和加速蠕变阶段。

(2) 由于相同的晶界扩散蠕变机制,尽管无铅 Sn-3.0Ag-0.5Cu 微焊点的体积大小明显不同,但是它们的蠕变激活能与蠕变应力指数均非常接近。

(3) 在相同的试验温度与应力下,大体积微焊点的稳态蠕变速率总体明显比小体积焊点的大,而蠕变寿命呈现完全相反的趋势,这主要归因于大体积焊点中可能存在更多的微空洞等缺陷造成的。

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Key words: intersecting pipe; opening; welding mating surface; rapid prototyping

Performance of shock processing on aluminum alloy welded joint

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Abstract: In order to improve the mechanical properties of aluminum alloy welded joints, this paper respectively applied ultrasonic and Q-switch YAG laser shock processing on the weld toe of A6061-T6 aluminum alloy welded joints to study the performances of aluminum alloy welded joints after shock processing. Under two shock processing modes, the near surface on weld toe of aluminum alloy welded joints generated shock strengthening effect, and greater compressive residual stress was produced. The maximum compressive residual stresses generated by ultrasonic and laser shock processing were about -158 MPa and -145 MPa, respectively. The fatigue life of aluminum alloy welded joints after ultrasonic and laser shock processing was similar, increased more than one time compared to that of the welded specimen without shock processing. All specimens during fatigue test fractured in the base metal, and no fatigue crack occurred near the weld toe.

Key words: laser shock processing; ultrasonic shock processing; aluminum alloy welded joint; mechanical property

Creep properties of microscale lead-free solder joints with different volumes

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Abstract: Adopting accurate creep testing method based on dynamic mechanical analyzer (DMA Q800, TA-Instruments), high temperature creep mechanical behaviors and properties of lead-free Sn-3.0Ag-0.5Cu microscale solder joints with volumes of $5.34 \times 10^7 \mu\text{m}^3$ and $7.07 \times 10^6 \mu\text{m}^3$ were investigated under two different service conditions. One condition was keeping the tensile stress (20 MPa) constant at four different temperatures (100, 125, 135, and 145 °C), and the other was keeping the temperature (145 °C) constant under four different tensile stresses (8, 12, 16, and 20 MPa). The experimental results show that all strain-time creep curves of microscale solder joints included three typical stages-primary creep, secondary creep (steady creep) and tertiary creep. Also, the creep activation energy and creep stress exponent value were very close to each other, though the volumes of the Sn-based solder joints were

obviously different, this was mainly because the lattice diffusion was thought as the creep mechanism during the high temperature creep process. In addition, under the same testing temperature and same loading stress, the steady creep rate of the Sn-3.0Ag-0.5Cu microscale solder joints with large volume was much higher than that of the smaller ones, however, the creep lifetime had totally opposite trends due to more defects in the larger solder joints.

Key words: electronic packaging; microscale solder joint; creep; mechanical property

Molybdenum coating prepared on inner surface of tube by wire electrical explosion spraying

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Abstract: A continuously wire electrical explosion spraying device was developed to prepare Mo coating on the inner surface of stainless steel tube with variation of energy density. The surface morphology of coating and the bonding with the substrate were analyzed. The results show that the formation of coating was mainly caused by impact of liquid metal of explosion products. With increasing of energy density, the accumulated liquid coating changed to liquid spraying coating. When the energy density was greater than 350 J/mm^3 , the size of liquid drop reduced but the temperature and velocity of liquid drop increased. In this case, the smooth spraying coating with larger bonding strength was formed, but the coating deposition rate decreased due to more vapor particles produced.

Key words: wire electrical explosion spraying; inner surface of tube; Mo coating

Experimental study of electron beam welded pure aluminum to Q235 steel joint with beam deflection

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Abstract: Electron beam welding of pure aluminum to steel with beam deflection was carried out. The microstructure and phase constitution of the joint was examined by optical microscopy, scanning electron microscopy, EDS and XRD. The tensile strength of the joint was also tested. The results show that the alloying process and thermal distribution was improved. The interface between the weld and steel was well bonded with uniform microstructure. The fusion zone on aluminum side was characterized by a transition layer with inner intermetallic compounds. The tensile strength of the joint could be increased with appropriate beam deflection. In this paper, the highest tensile