$Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ 非晶棒料摩擦焊接

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摘 要: 设计了一种非晶合金摩擦焊装置，以 $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ 非晶棒料为研究对象，进行了摩擦焊试验. 焊接样品经 SEM，XRD，维氏硬度、TEM 等检测，结果显示焊接界面无明显未熔合，样品仍然保持非晶态，接头硬度总体增大，接头处出现了纳米晶. 采用 ANSYS 软件对非晶合金摩擦焊的温度场进行仿真. 结果表明，在摩擦时间 $t=0.25$ s 时摩擦界面中心温度超过非晶棒料玻璃转变温度，接触面全部进入过冷液相区，应进行顶锻. 仿真结果与摩擦焊试验结果基本吻合，有利于指导焊接试验.

关键词: 摩擦焊装置; 非晶合金; 连接; 仿真
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0 序 言

非晶合金是20世纪材料领域的重大发现，其内部原子呈长程无序短程有序排列，没有晶粒与晶界存在. 因此非晶合金具有许多独特的优异性能，如高强度、高硬度、耐磨损、耐腐蚀等[1]. 此外非晶合金在过冷液相区具有良好的超塑性，能够热压成形各种微纳零件[2]，这是传统晶态金属没有的特点. 因此非晶合金在军事、MEMS、体育、光通讯、光集成和输电材料等领域有广泛的应用前景[2].

绝大部分非晶合金材料尺度范围在毫米至厘米之间，且可焊性较差，在焊接过程中容易受热晶化. 因此非晶合金在工程应用上受到很大限制，很难完全发挥实际工程应用价值. 为了增大非晶合金材料的尺寸，研究其可焊性，目前常用的方法有电子束焊、搅拌摩擦焊、扩散焊、激光焊等[3]. 然而这些方法不适合非晶棒料的连接. 摩擦焊属于固相焊接方法，主要优点是环保、接头质量高、适合异种材料连接、可焊接难焊金属材料等. 而且摩擦焊可以焊接棒料，因此采用摩擦焊连接非晶棒料受到密切关注. 2001年 Kawamura 等人[4]采用摩擦焊的方法成功焊接了 $Pd_{40}Ni_{40}P_{20}$. 2003年 Wong 等人[5]采用摩擦焊技术将两块同成分的 $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ 焊接在一起. 目前国内关于摩擦焊设备及其应用的报道较多[6-8]，但对非晶合金摩擦焊研究较少. 而传统摩擦焊装置体积较大，不适合毫米尺度的非晶合金棒料的连接. 为此设计了一种新型的摩擦焊装置，用于连接小尺度的非晶合金棒料. 经过试验，$Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ 非晶棒料焊接成功. 此外采用有限元软件 ANSYS 对非晶合金的摩擦焊温度场进行了仿真，仿真结果有利于指导焊接试验.

1 焊接试验

非晶合金摩擦焊接是利用工件之间的相互摩擦产生热量，使接触面温度到达过冷液相区，在轴向压力作用下非晶材料发生超塑性变形，氧化层被挤出界面，接触面距离达到原子尺度，原子经新鲜表面互相扩散，形成牢固焊接头. 传统摩擦焊装置体积较大，不适合连接小尺寸棒料. 因此设计了一种新型的摩擦焊装置，其结构如图1所示. 该装置配置变

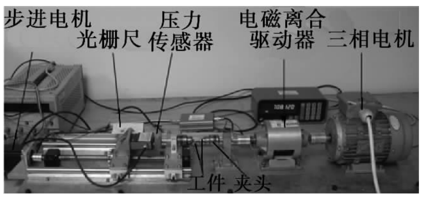

图1 新型摩擦焊装置结构图
Fig. 1 Structure of new friction welding set-up

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频器、光栅尺和压力传感器等部件，能实现焊接过程中摩擦旋转频率、运动行程和压力的精确控制.

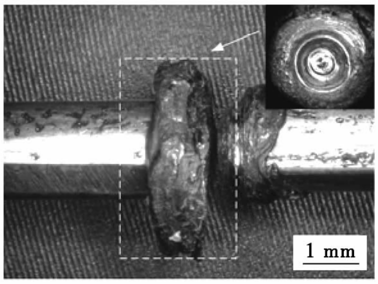
2 试验结果及讨论

试验材料为深圳比亚迪汽车有限公司生产的 $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ 非晶棒料，其直径为 3 mm，玻璃转变温度为 T_g = 360 ℃，晶化开始温度为 T_x = 420 ℃. 摩擦焊过程中电机旋转频率和压力的选取非常重要. 旋转频率过高则惯性较大，装置难以急停. 旋转频率过低会造成摩擦面升温不够. 而压力过大会造成接头膨胀严重，过小则导致热流密度不足. 根据试验经验及文献报道[9]，选取如表 1 所示焊接参数. 不考虑装置本身存在的压力，制动响应延时等误差因素，按照给定条件进行试验，得到了如图 2 所示结果.

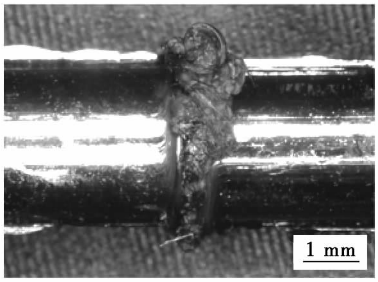
表 1 摩擦焊试验参数

Table 1 Parameters of friction welding experiments

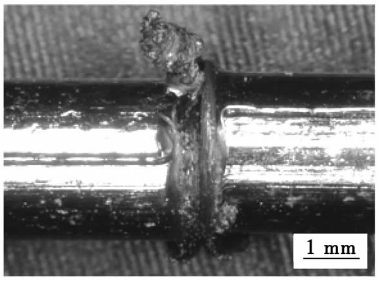
样品序号	旋转频率 n/(r•min^{-1})	摩擦压力 p_0/MPa	顶锻压力 p_1/MPa	摩擦时间 t_0/s	顶锻时间 t_1/s
1	1 500	100	100	0.50	5
2	2 000	80	100	0.30	5
3	2 500	80	100	0.25	5



(a) 摩擦焊样品1



(b) 摩擦焊样品2



(c) 摩擦焊样品3

图 2 摩擦焊样品及其接头外观形貌

Fig. 2 Welded samples and joint appearance

图 2 为焊接样品及其接头外观形貌. 由图 2 可知，样品 1 焊接失败，样品 2，3 连接成功. 所有样品接头处均形成飞边，并包覆在接头周围. 由于样品 1 中心没有进入过冷液相区，顶锻后形成了小突起. 导致这种现象的原因是在焊接过程中，摩擦界面中心区域的摩擦半径小，摩擦产生的热流密度比外围区域低. 当中心温度没有进入过冷液相区即进行顶锻时，则心部和外围区域没有同时发生超塑性变形，界面不能形成原子尺度接触，从而导致连接失败. 这种问题可通过提高电机旋转频率或增大正压力的方式解决. 样品 2，3 因为焊接参数选择得当，整个接触面均进入过冷区间，界面在正压力作用下达到原子尺度的连接，形成牢固接头.

图 3 为样品 2 测试结果. 接头截面 SEM 显示，界面没有出现明显未熔合现象，界面材料产生变形和扩散并最终形成了致密连接. 接头截面上有少量小孔，类似现象在 Wong 等人[5] 的研究中也出现过. 其原因是由于非晶棒料在吸铸过程中形成小孔，或者焊接过程中有杂质进入界面. 图 2b 中样品 XRD 曲线呈典型的非晶漫散射峰，表明样品仍然保持非晶态，未发生明显晶化. 以摩擦界面为对称线沿截面某一直线对称选取 12 个点，其中点 5 ~ 点 8 落在焊接区内. 经检测结果显示焊接区材料的硬度较周围整体上有所增加. 摩擦焊不仅没有明显降低材料的性能，而且适当的焊接工艺对材料性能有一定的增强.

接头 TEM(图 4) 检测显示，母材区材料的电子衍射结果为典型非晶衍射环，表明母材区材料仍然保持非晶结构. 而焊接区内出现了少量 50 nm 左右的纳米晶. 纳米晶通常能增强材料的硬度，这与维氏硬度检测结果相吻合.

3 ANSYS 温度场仿真

非晶合金摩擦焊过程中，温度过高将导致材料晶化，过低则摩擦界面不能形成连接. 然而在焊接过程中很难直接测量界面的温度场分布，只能通过重复试验获得合适的焊接参数. 这对时间、材料和能源的浪费较大. 为了验证和优化焊接参数，采用

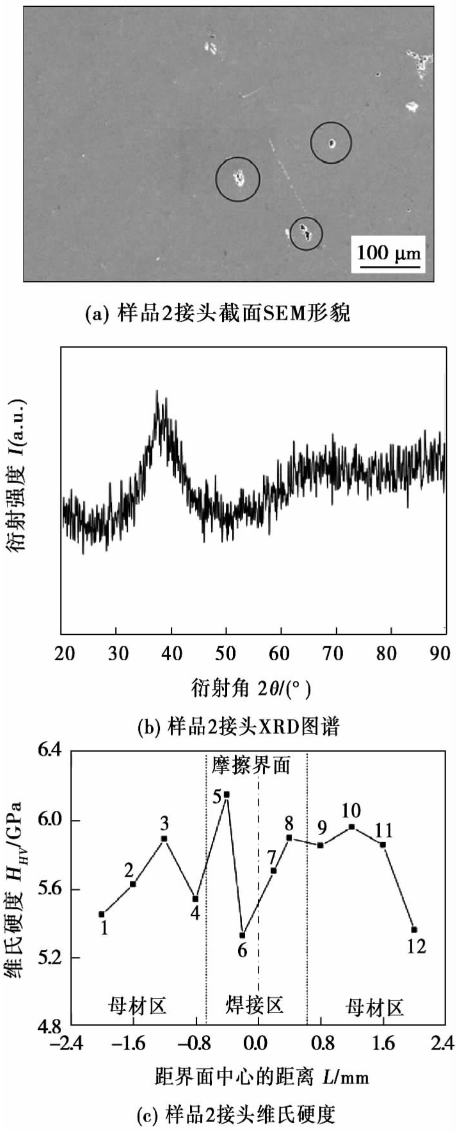


图3　样品 2 接头检测结果

Fig. 3　Examined results of joint taken from sample 2

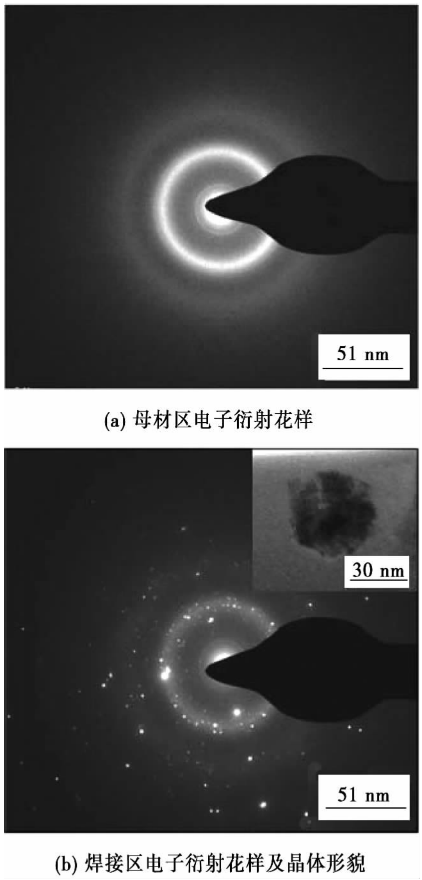


图4　样品 2 接头 TEM 形貌

Fig. 4　TEM images of joint taken from sample 2

界面低温区逐渐缩小，当整个界面温度达到非晶过冷液相区后，进行顶锻．

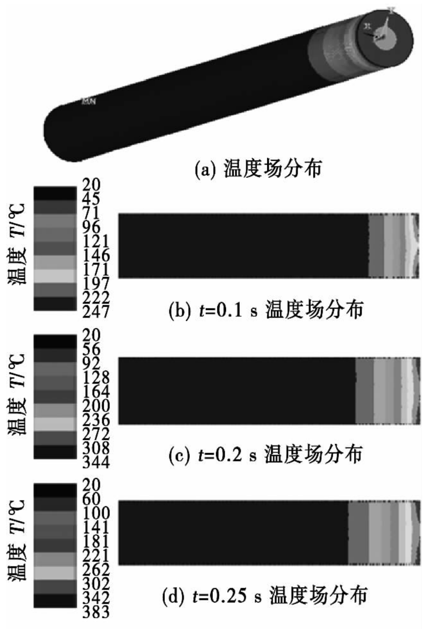


图5　摩擦焊温度场分布

Fig. 5　Distributions of temperature field during friction

ANSYS 模拟摩擦界面的温度场分布，有利于获得好的试验结果．根据摩擦做功，得到方程为

$$f = upA \tag{1}$$

$$\eta = \int_0^r f\omega r \mathrm{d}r = \frac{2}{3}\pi up\omega r^3 \tag{2}$$

$$q = \frac{\eta}{A} \tag{3}$$

式中：f 为摩擦力（变量）；u 为摩擦系数；p 为焊接正压力；A 为摩擦面积；η 为摩擦功率；r 为工件摩擦半径；ω 为工件旋转角频率；q 为热流密度．

由于摩擦时间极短，取 $u = 0.6$ [10]．此外取对流换热系数为 $h = 20$ W/($m^2 \cdot K$)．根据样品 2 摩擦焊参数，加载边界条件，得到如图 5 所示仿真结果．结果显示界面中心区域温度较低，边缘区域温度较高，升温速率可达 1 500 ℃/s 以上．随着摩擦的进行，

图6为轴向和径向所选节点的升温曲线. 由结果可知,摩擦界面径向节点的温度上升很快,在 $t=0.25$ s 时棒料心部即进入过冷液相区. 而轴向靠近接触面的节点升温较快,靠近夹持端的节点温度变化较慢. 最容易出现晶化的位置在摩擦界面及相邻区域.

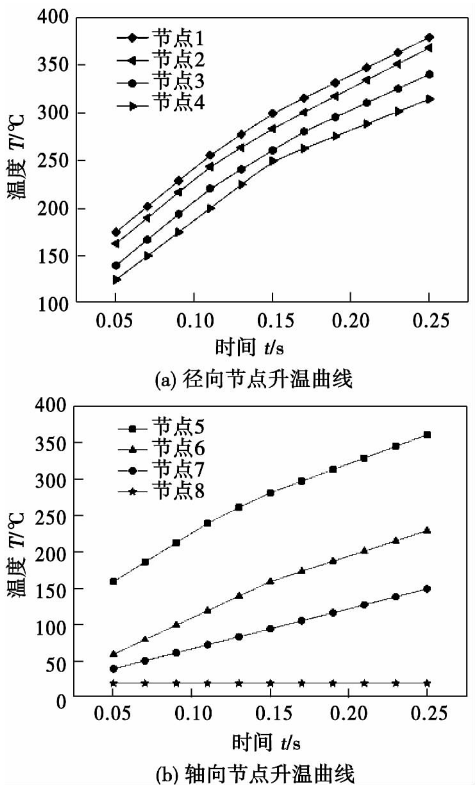


图6 节点升温曲线

Fig. 6 Temperature curves of selected nodes

4 结 论

(1) 设计了一种新型摩擦焊装置,按照给定条件进行摩擦焊接试验,成功连接了 $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ 非晶棒料. 摩擦焊装置设计达到试验要求.

(2) 样品经 SEM、XRD、维氏硬度、TEM 检测,结果显示高旋转频率下接头连接成功,仍然保持非晶态. 接头内出现纳米晶,一定程度上增加了材料的硬度.

(3) ANSYS 模拟结果显示,摩擦界面外围温度较高,较早进入过冷液相区. 当中心区域温度进入过冷液相区方可进行顶锻. 界面径向节点升温速率较轴向节点快,接头最容易晶化的位置在摩擦界面及相邻区域. 温度场仿真可以用来验证焊接参数,包括旋转频率、压力及时间之间的匹配,最终达到优化焊接参数和指导试验的目的.

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Abstract: Based on the Nastac model, a new capture mechanism, named node-based-correction method, was proposed to improve cellular automaton (CA) technique in the simulation of grain growth during solidification process with arbitrary crystallographic orientations. By coupling with the finite volume method (finite volume method, FVM), a FVM-CA simulation model was put forward and applied to the simulation of microstructure evolution of solidification during the arc deposition. The influences of the deposition rate on dendrite arm spacing and the growth direction were also discussed. Experiments were carried out to verify the validity of the numerical model. This research will lay the theoretical foundation of the prediction and control of microstructure in additive manufacturing.

Key words: finite volume method; cellular automaton; solidification simulation; macro-micro coupling; grain growth

Joint characteristics of refill friction spot welding of magnesium/aluminium dissimilar metals FENG Xiaosong[1], GUO Lijie[1], MIAO Yugang[2], HAN Duanfeng[2] (1. Shanghai Aerospace Equipments Manufacturer, Shanghai 200245, China; 2. College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China). pp 41 – 44

Abstract: Experiments of refill friction spot welding of Mg/Al dissimilar metals were carried out. The mechanical properties and microstructure of the joints were tested and analyzed. The results showed that the weld spots had smooth appearance and high shear strength, and the shear stress could reach 1 865 kN at the proper welding parameters if the lap joints were properly designed. Little cavity and microcracks are found on the nugget/Mg vertical interface, where is the fracture zone. At the horizontal nugget/Al interface with certain thickness, where the microhardness is obviously higher than that of two-side materials, which has some relation with the formation of brittle and hard intermetallics.

Key words: refill friction spot welding; dissimilar metals; mechanical properties; microstructure

Friction welding of $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ bulk metallic glass bar CHEN Biao[1,2], SHI Tielin[1], LIAO Guanglan[1], ZHANG Shuaimou[3] (1. State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, China; 2. Department of Mechanical and Electrical Engineering, Hubei University of Education, Wuhan 430205, China; 3. Department of Mechanical Engineering, Anhui Technical College of Mechanical and Electrical Engineering, Wuhu 241000, China). pp 45 – 48

Abstract: A new friction welding system was developed to join the bulk metallic glass. The $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ bulk metallic glass bars were joined by this welding system. The welded sample was tested by scanning electron microscope, X-ray diffraction, Vickers hardness and transmission electron microscope. The results show that no incomplete fusion or obvious defects are found, and the welded joint maintains the amorphous structure. The hardness is enhanced because a few nanocrystallines occur in the joint. Subsequently, the friction welding temperature field was simulated using finite element software ANSYS. The simulation results indicate that the friction time can not exceed 0.25 s and the upset forging should be carried out. The temperature on center interface exceeds the glass transition temperature of $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$, and the superplastic deformation occurs. It is concluded that the new friction welding system can be used to join the bulk metallic glass bars. The simulation results of temperature field accords well with that of the experiment, which is beneficial to optimize the welding parameters and guide the experiment.

Key words: friction welding system; bulk metallic glass; joining; simulation

Impact of addition of Sn on resistivity and solderability of Zn4Al3Cu solder ZHAO Kuaile[1], DU Ning[2], YAN Yanfu[3], LI Chenyang[1] (1. Zhengzhou Coal Mining Machinery Group Co., Ltd., Zhengzhou 450013, China; 2. Zhengzhou Linda Compressor Co., Ltd., Zhengzhou 450000, China; 3. College of Materials Science & Engineering, Henan University of Science & Technology, Luoyang 471003, China). pp 49 – 52

Abstract: The resistivity and solder abilities of Zn4Al3Cu*x*Sn solder alloy were investigated by adding Sn (0 – 15%) into Zn4Al3Cu alloy through alloying principle. Results show that the resistivity of the Zn4Al3Cu*x*Sn solders is reduced with the increasing of the addition of Sn. The resistivity of the Zn4Al3Cu15Sn solder is 7.9×10^{-7} Ω·m which is approximately 47.0% lower than that of the matrix solder. When the content of Sn is lower than 10%, the spreading area of the Zn4Al3Cu*x*Sn solder alloy is increased linearly. The spreading area of Zn4Al3Cu10Sn reaches to the maximum value of 98.3 mm^2, which is about 59.1% larger than that of the matrix solder. It is mainly related to the formation of the new SnZn eutectic phase and the metal intermetallic compounds between the solder and the substrate. Therefore, for the consideration of resistivity and spreading property of the novel solders, the proper addition of Sn is about 10%.

Key words: Zn4Al3Cu solder; resistivity; spreading area

Microstructure of Al-Si-Zn filler metal and brazed seam modified with Cu-P DAI Wei[1], XUE Songbai[1], SUN Bo[2], LOU Jiang[2], WANG Shuiqing[2] (1. College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China; 2. Zhejiang Xinrui Welding Material Co., Ltd., Shengzhou 312452, China). pp 53 – 56

Abstract: The effect of Cu-P modification on the microstructure of Al-Si-Zn filler metal and 6061 aluminum brazed joints were investigated. Experimental results showed that the tensile strength of 6061 aluminum brazed joints were improved by Cu-P addition, and the highest value was achieved at 144 MPa when the content of Cu-P was 1.5%. A small amount of P addition can modify the primary Si and refine α-Al in the filler metal. Primary Si growth based on the finely AlP phases were induced by Cu-P addition, and the size of primary Si was much smaller than that without P. Meanwhile, after P addition, the eutectic