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超声波的传播特性及其对钎料润湿行为的影响

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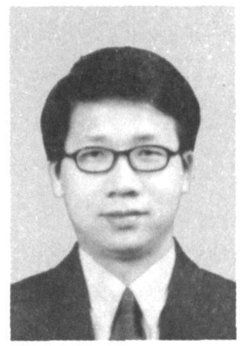

许志武

摘 要: 通过 ANSYS有限元数值模拟和试验相结合, 研究了超声波在固态试件及钎料液滴中的传播特性. 结果表明, 试件表面的声振动分布不均匀, 沿传播方向振幅先增大后减小, 再增大, 各个峰值位置的间隔约为 10 mm. 当加载振幅增大时, 试件表面上同一位置的振幅也随之变大, 且大于所加载的超声波的振幅, 但位移场的分布规律不变, 表面质点保持着与超声频率相近的振动. 钎料液滴内部的声压值随着试件表面振动的增大而增大, 当加载振幅超过 7.5 μm后, 钎料液滴内部的声负压值均可达到数万帕. 试验观察结果较好地验证了有限元模拟的结果.

关键词: 超声波; 数值模拟; 位移场; 声压; 润湿
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0 序 言

超声波钎焊最早出现于 20世纪 50年代. 早期的超声波钎焊工艺, 如超声波波峰焊, 通常是从钎料槽的底部将超声波导入到钎料池中, 焊接时将待焊部位浸入到钎料池内. 研究发现, 这种条件下接头的质量与其在钎料池中放置的深度很敏感, 如果放置的深度不够, 则超声波的空化效应太弱, 起不到去除表面氧化膜的作用[1,2]. 随着研究的不断发展, 超声波钎焊新工艺不断出现, 如超声波电烙铁以及超声频调制激光无钎剂软钎焊等[3,4], 这些方法的特点是将钎料池缩小为钎料液滴, 超声波能量集中施加到其中, 操作方式灵活、节能. 21世纪初, Faridi等人[5]将超声波通过固体夹具传播到铝与不锈钢的钎焊部位实现了焊接. 相继, Nagaoka, Wielage等人[6,7]将超声波直接耦合在母材表面, 实现了铝合金及其复合材料的钎焊. 从这些结果来看, 将超声波能量从固态母材导入到连接部位也是一种非常有效的方式. 与早期的超声波钎焊工艺相比, 超声波能量从固相材料传导至润湿界面, 损耗更小, 施加部位更灵活且针对性更强, 较小的超声功率就可实现焊接. 另外, 超声波工具头还可以远离加热部位, 避免压电振子过热而产生失振的问题[8].

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文中以母材导入超声波的润湿体系为研究对象, 通过 ANSYS有限元数值模拟与润湿试验相结合, 研究了超声波在固体母材和液态钎料中的传播特性及其对润湿行为的影响, 主要分析了试件表面位移场的分布特征、钎料液滴内部的声压变化及可能的声空化效应. 该研究工作可为从母材导入超声波的钎焊过程提供借鉴.

1 模型的建立及试验过程

ANSYS有限元模拟采用其自身包含的声学模块, 建立的几何模型由实际试验过程抽象而成, 如图 1所示. 该模型为二维模型, 其中加载区域为 10 mm. 模拟过程分两个阶段, 一是超声波在固态试件中的传播过程; 二是超声波在液态钎料中的传播过程. 固态试件表面主要考虑质点振动幅值的变化, 而液态钎料中主要考虑声压值的变化.

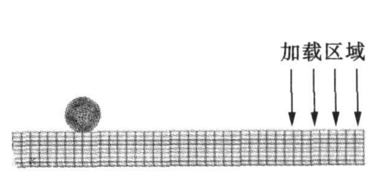

图 1 超声波传播特性计算的几何模型
Fig. 1 Geometrical model for calculation of ultrasonic propagation

初始条件为假设 t=0时, 质点处于平衡位置,

即 $s=0$. 在计算过程中所施加的边界条件为试件左端面、右端面无约束;底面的位移为零;上表面加载部位受到超声波产生的交变压力;钎料球底部与母材接触部位出现一小平台,其源载荷从结构分析中读取位移. 超声波载荷为焊头预压力形成的位移载荷和超声波振动交变压力形成的位移载荷之和,即 $\xi=\xi_1+\xi_2\cdot\sin(2\pi ft)$. 焊接预压力由气缸的压力以及工具头自重计算得到,该研究条件下 $\xi_1=3\ \mu m$.

采用德国 Polytec 单点式激光测振仪测量试件表面的振动,其分辨率为 0.76×10^{-8} m,最高响应频率为 500 kHz,最小测量振幅为 0.01 μm. 该仪器可实时观察试件表面某一点的振动速度随时间的变化曲线,也可通过 A/D 采集卡将测振仪输出数据采集到计算机中,利用振动软件计算得到该点的位移. 润湿试验所用的材料和钎料的特性如表 1 所示[1,2],母材试件的尺寸为 40 mm×10 mm×3 mm.

表 1 铝基复合材料和 Zn-Al 钎料的材料特性

Table 1 Physical properties of aluminum-based composite and Zn-Al filler metal

材料名称	弹性模量 E/GPa	密度 ρ/(kg·m^{-3})	泊松比 ν	粘度 η/(Pa·s)
铝基复合材料	110~120	3 000	0.3~0.4	—
Zn-Al 钎料	0.013	6 700	0.3	3.84×10^{-3}

2 试验结果与讨论

2.1 固态试件表面声场分布的模拟结果

图 2 为超声波加载振幅 $A_m=7.5\ \mu m$, 频率 $f=21.774$ kHz 时 20 个周期内试件表面振动特性的计算结果. 特征点 A, B, C, D 分别是从右向左每隔 10 mm 依次取 4 点, A 点是加载区域的边缘, D 点则是试件的最末端. 由图 2 可见,试件上各点保持着与加载频率相近的振动,加载边缘区域 A 点的位移—时间曲线呈典型的正弦态,除此以外的各点振动的曲线都发生了不同程度的畸变,周期重复性及正、负半波对称性变差,其中以 C 点最为明显.

图 3 为不同加载振幅条件下 $t=1\ 000\ \mu s$ 时试件表面位移场的特征. 试件表面的振幅并不均匀,沿试件长度方向变化的趋势为增加—减少—增加,出现两次峰值的位置分别是在 B 点和 D 点区域,振幅的最小值出现在 C 点附近. 随着加载振幅的增加,试件表面沿超声传播方向的位移场的分布形态和峰值位置基本一致. 由图 3 明显还可见,虽然试件表面质点的振幅差别较大,但所有的振幅值都大

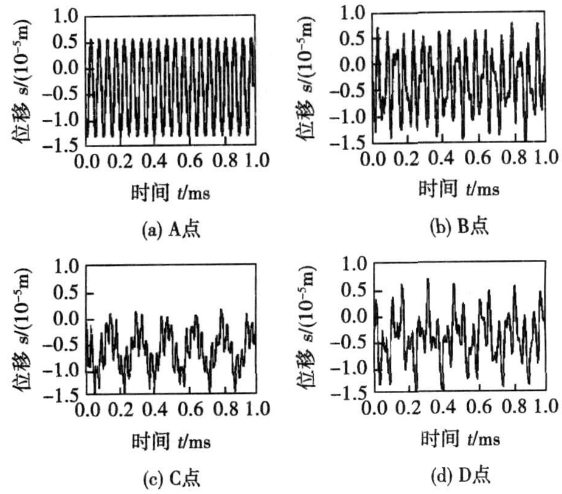

图 2 固态试件表面的振动特性

Fig. 2 Vibration characteristic of substrate surface

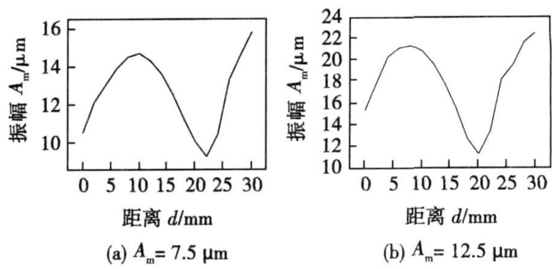

图 3 不同振幅条件下试件表面位移场的特征

Fig. 3 Displacement field of specimen for different loading amplitudes

于加载幅值. 以加载振幅 7.5 μm 为例,在振幅极大值出现的 B 点, D 点,分别达到了 14.8 μm 和 16.0 μm,即使在出现极低值的 C 点,振幅也达到了 9.2 μm.

2.2 钎料液滴声场分布的模拟结果

由试件中位移场的计算结果可见,不同位置、不同加载条件下试件表面的振动不相同,因此考虑钎料液滴放置的位置及加载振幅这两个参数进行计算. 图 4 为 $A_m=7.5\ \mu m$ 钎料液滴放置在 D 点位置时其内部声压随时间的变化. 图 4a 为 $t=2\ \mu s$ 时钎料液滴的声压分布. 此时超声振动刚从试件传入钎料液滴,压力梯度为正,声波逐渐向钎料液滴内部传播. 图 4b~d 显示了液体钎料内部声压的变化过程. 随着时间的推移,钎料内部出现负压区,且面积逐渐变大,负压位置不断上移,压力值也不断增加. 当 $t\geqslant50\ \mu s$ 后钎料液滴内部的声压变化不明显.

超声波振动传播到钎料液滴内部时,液体内的声压产生交替变化,在声压的负压相中,当负压的峰值大到可以克服液体分子之间的结合力时,液体将

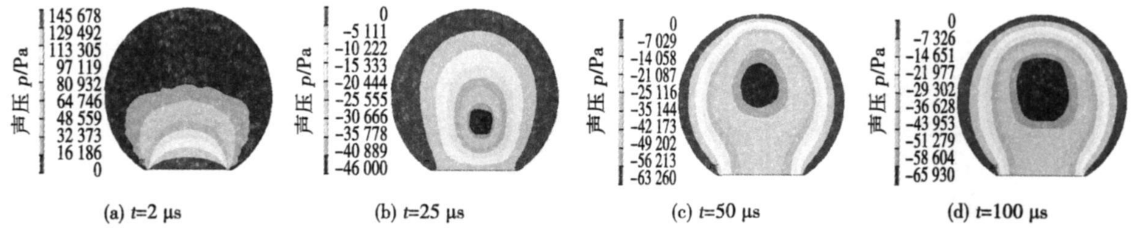

图 4　A_m=7.5 μm时 D点位置钎料液滴内声压变化的计算结果

Fig. 4　Calculation results of acoustic pressure in solder droplet located at point D when A_m=7.5 μm

被拉断而形成空腔,即产生空化气泡,在随后的正压相的压缩力作用下,空化泡急速闭合、破裂,液体间相互碰撞产生强大的冲击波,这就是所谓的空化作用. 从空化作用产生的过程可以看出,声负压值的大小对空化作用的形成至关重要[1].

图 5为 A_m=7.5 μm时试件表面不同位置的润湿界面的声压随时间的变化曲线. 当钎料处于 B点时,如图 5a所示,润湿界面处可以产生 2×10^4 Pa以上的正压和 -1×10^4 Pa以上的负压. 而当钎料处于 C点时,如图 5b所示,润湿界面处的负压值最大仅为 -4×10^3 Pa左右,且出现的几率很小.

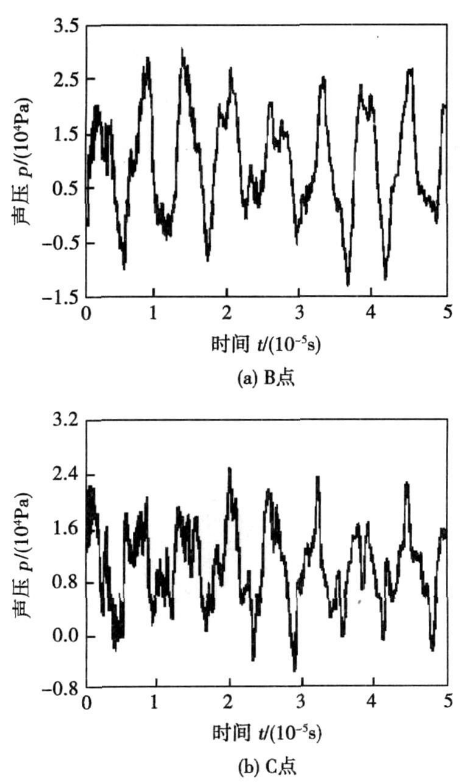

图 5　不同位置的润湿界面的声压随时间的变化曲线

Fig. 5　Variation of acoustic pressure with time at different wetting interfaces

图 6为振幅对钎料润湿界面声压的影响. 当 A_m=5 μm时,润湿界面处虽然能产生较大的正压,达 2×10^4 Pa左右,但负压产生的几率和数值都较小;而当 A_m=10 μm时,润湿界面在很短的时间内产生的负压幅值达到近 -2×10^4 Pa,而且出现的频率很高. 这样强的声负压,通过与声正压的交互作用,应该能产生比较强的空化效应.

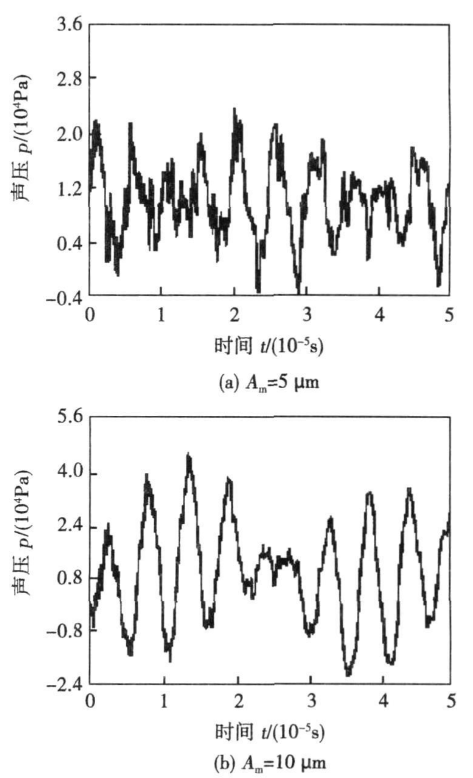

图 6　不同振幅条件下润湿界面的声压随时间的变化

Fig. 6　Variation of acoustic pressure with time at different loading amplitudes

2.3　超声振动的测量及润湿试验

采用 Polytec激光测振仪对试件表面的振动进行了测试,发现从加载边沿起、沿振动传播方向,试件表面的振幅确实是出现增大—减小—增大的变化,每一个极值点的间距约为 10 mm. 图 7为加载振幅为 7.5 μm时,试件表面 D点振动随时间变化

的模拟及检测结果. 从图 7可以看出, 试件表面振动的模拟结果与实际测量的结果随时间的变化规律是一致的, 在幅值的大小方面, 前者比后者略大. 这个误差应是由于试验条件的非理想化状态造成.

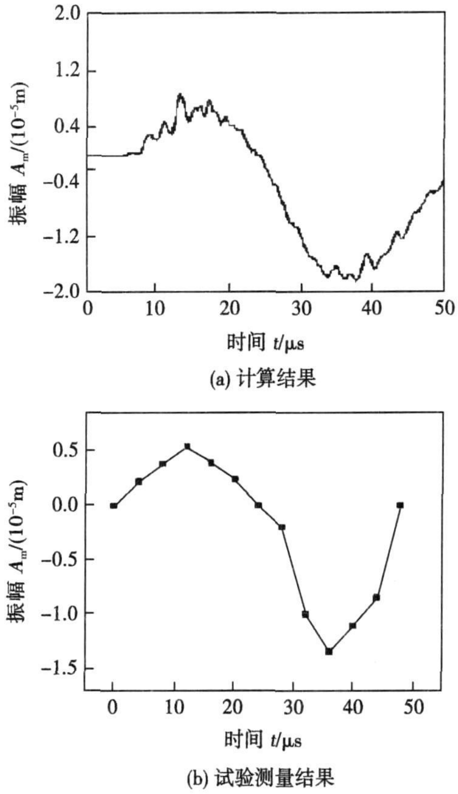

图 7 试件表面质点振动的模拟及测量结果的比较
Fig. 7 Comparison of time-dependent vibration curves between simulation and testing

润湿试验所用的材料与模拟过程所采用的材料一致, 试验结果如图 8所示. 在 $A_m = 7.5\ \mu m (< 10\ \mu m)$条件下试件表面对应 B点和 C点位置上钎料液滴的润湿效果存在明显差别, B点处的钎料液滴的铺展程度显然比较充分, 而 C点处的钎料液滴仍收缩为球形, 如图 8a所示; 而当 A_m大于 10 μm后, 两个位置的钎料液滴都发生了较好的铺展, 差别变得不明显, 如图 8b所示. 这个试验结果与图 3、图 5和图 6所示的计算结果是吻合的. 上述试验结果也表明, 由于试件表面振动的不均匀性, 提高加载振幅是提高钎料在不同区域润湿性的有效途径.

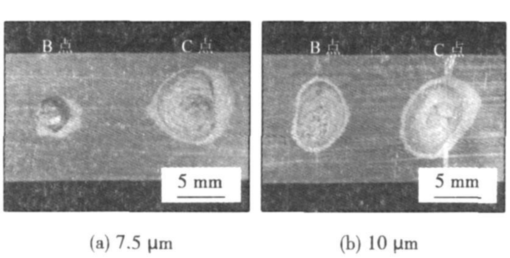

图 8 Zn-Al钎料在铝基复合材料表面的润湿试验
Fig. 8 Wetting of Zn-Al filler droplet on surface of Al-based composite at different locations

3 结 论

(1) 试件表面的超声波振动不均匀, 沿传播方向 (即试件长度方向) 变化的趋势为增加—减少—增加, 峰值位置间的距离约为 10 mm.

(2) 当加载的超声波幅值增大时, 试件上同一时刻、同一位置的位移也随之变大, 且大于所加载超声波的振动幅值; 位移场的分布规律不变, 质点保持着与超声频率相近的振动, 但振动的周期重复性有差别.

(3) 激光测振仪对试件表面振动进行测量的结果以及实际润湿试验的结果初步证实了模拟结果的正确性.

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MAIN TOPICS, ABSTRACTS & KEY WORDS

Research on full digitalized automatic tube-plate welding system

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Abstract: The circumferential weld quality of the enormous corner joints between the heat exchange tube and plate in the medium-sized or large scale heat exchangers (condensers) is the key to ensure the manufacturing quality of heat exchangers, which need full position automatic precise welding technology. A full digitalized and low cost tube-plate welding power supply based on ARM (advanced RISC machines) was proposed. The full bridge inverter topology was adopted in the main circuit. The LM3S8971 with 32 bits CortexM3 kernel was used as the core of the process control of welding power source, and the full digitalization control of the welding process was realized. The digital control panel of the welding power source based on ARM & CPLD (complex programmable logic device) was designed to make man-machine interactions really come true. The function test and experimental research on the welding power supply demonstrated the excellent performance of the system and fulfilled the demand of the full position automatic tube-plate welding process of heat exchanger.

Key words: heat exchanger; automatic tube-plate welding; full digitalization; electric welding machine

Propagation characteristic of ultrasonic in Al MMCs and its effect on wetting behavior of liquid filler

XU Zhiwu, YAN Jiuchun, WANG Changsheng, YANG Shiqin (State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p 5—8

Abstract: The propagation characteristic of ultrasonic in the solid substrate and the filler droplet was investigated by using finite element simulation and experimental test. The results show that the ultrasonic vibration of the substrate surface is non-uniform. The ultrasonic vibration amplitude along the spreading direction first increases, and subsequently decreases before a final increase. The space of each peak amplitude location is approximately 10 mm. As the input ultrasonic vibration increases, the particle displacement of the substrate surface increases and is larger than that of the input value. The displacement field remains unchanged and the particle vibrates at a frequency similar to that of the input load. The acoustic pressure in the filler droplet increases with the displacement of substrate surface, which reaches ten thousands of pascals when the input ultrasonic load is higher than 7.5 μm. The finite element simulation results are consistent well with the experimental observations.

Key words: ultrasonic; numerical simulation; displacement field; acoustic pressure; wetting

Application of LS-SVM network in LDF forming process

LU Zhongliang, LI Dichen, LU Bingheng, ZHANG Anfeng (State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an 710049, China). p 9—12

Abstract: The effect of laser power, scanning speed and powder feeding rate on the depositing height of single pass welding is firstly analyzed in laser direct fabrication (LDF), and the result shows that there is the non-linear intrinsic relationship between them. Based on the non-linear characteristic, the least square support vector machine (LS-SVM) network is adopted to predict the building precision. Training and testing samples are collected by using single pass experiments, and non-linear mapping relationship between them is built. Then, the trained LS-SVM network is examined by testing samples, and their training and testing performances are investigated. The result shows that generalization ability, function-approximating ability and real-time of the LS-SVM network are better for the prediction of the building precision in LDF, and high definition thin-walled parts are successfully fabricated.

Key words: laser direct manufacturing; parameters; forming accuracy; least squares support vector machine

Effect of process parameters on torque in friction stir welding

YAN Dongyang, SHI Qingyu¹, WU Aiping, Silvanus Juergen² (1. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China; 2. European Aeronautic Defence and Space Company Innovation Works, Munich 8166, Germany). p 13—16

Abstract: Experiments with stir tool kept rotating at the same position on 6056-T6 aluminium alloy sheet were carried out, and the torque of stir head, down force and welding temperature were all recorded during this process. The experimental results show that the torque will increase with the increasing of down force, the reason for torque increase is that the down force strengthens the material in stir zone. Although the torque will decrease with the increasing of rotation speed, the product of torque and rotation speed which corresponds to the heat generation will increase with the increasing of rotation speed. The rotation speed influences the torque through two ways of welding temperature and strain rate of material in stir zone, and the influence from the former way is more significant.

Key words: friction stir welding; torque; down force; rotation speed; heat generation

Experiment on characteristics of GMAW arc in underwater hyperbaric air condition

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Abstract: GMAW (gas metal arc welding) progress was