紫铜厚板的搅拌摩擦焊接

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贺地求

摘　要：采用搅拌摩擦焊接方法对厚度为 25 mm的 T2紫铜厚板进行了单道对接焊试验，并对焊缝的微观组织、力学性能、导电特性及焊缝能谱进行了分析．结果表明，用搅拌摩擦焊方法焊接 25 mm厚的 T2紫铜板，可得到成形美观、内部无缺陷的平板对接接头．在旋转速度为 960 r/min，焊接速度为 70 mm/min时，搅拌摩擦焊的焊接接头的抗拉强度可达到 186.6 MPa，搅拌摩擦焊接头的电阻率与母材基本相当．

关键词：搅拌摩擦焊；T2紫铜；厚板；性能
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0　序　　言

铜是主要的电工材料，其中冷作硬化态的硬铜板可用于制造电线，退火态的软铜线用于制造电机绕组[1]，退火态软铜板用于制造大型电机转子导条与端环．因为紫铜导热快，线膨胀系数大，熔融时易吸氢[2]，采用熔焊工艺难以焊接，特别是大厚度焊接，焊缝的导电率只能按母材的 60%设计[3]．搅拌摩擦焊（FSW）已成为一种无可替代的全新焊接技术．目前在国内外对铝合金的搅拌摩擦焊研究较多[4－6]，对于铜及铜合金的搅拌摩擦焊研究较少，国内试验室单道焊接厚度仅为 2～6 mm[3]．瑞典等国对铜厚板搅拌摩擦焊接技术进行了研发，实现 50 mm紫铜的焊接[7－9]．文中研究了紫铜厚板搅拌摩擦焊技术，针对 25 mm紫铜厚板进行了 FSW工艺试验，并对其焊缝成形、焊缝组织形态及焊接接头的力学性能和导电性能进行了分析．

1　试验方法

试验用材料是厚度为 25 mm的 T2紫铜板，其规格为 250 mm×100 mm，主要化学成分如表 1所示，主要物理性能如表 2所示．

搅拌摩擦焊试验在自行研制的搅拌摩擦焊试验机上进行，焊接形式为单道对接拼焊．试验用搅拌头参数：轴肩直径为 40 mm，搅棒直径为 15 mm，搅棒长度为 25 mm．焊接前，对焊接件的对接面和焊接表面用电动钢丝刷进行去污处理．简单地去除对接面和表面的污垢及灰尘后，将焊接件夹紧在工作台上，以防止焊接件在焊接过程中产生松动．

表 1　紫铜的主要化学成分（质量分数，%）
Table 1　Main chemical composition of T2 copper

牌号	Cu	Sn	Pb	Zn
T2	≥99.9	≤0.002	≤0.005	≤0.005

表 2　紫铜的物理性能
Table 2　Physics property of T2 copper

牌号	抗拉强度 R_m/MPa	断后伸长率 A(%)	电阻率 $\rho/(10^{-6}\Omega\cdot cm)$
T2	205	35	1.78

焊接时，搅拌头高速旋转钻入待焊板材接缝，当搅拌头轴肩压实铜板后，沿接缝前进以完成焊接过程．焊接工艺参数：搅拌头旋转速度为 960 r/min，搅拌头沿焊缝方向的焊接速度为 70 mm/min．焊接的铜板试件如图 1所示，在焊接件上沿焊缝横向分

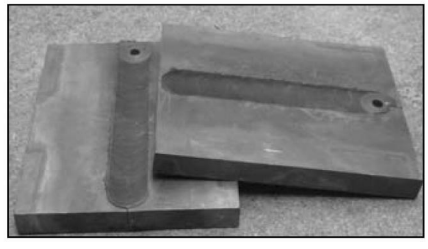

图 1　25 mm紫铜厚板焊接
Fig.1　25 mm-thick T2 copper plate welding

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别取样,制取金相试样、拉伸试样,在焊件接头上截取电阻率测试试样. 在 CSS-44100 电子拉伸机上进行拉伸试验;在 POLYVAR-MET光学金相显微镜上观察焊后各区显微组织;用惠斯通电桥法测试焊接接头的导电性能;使用美国伊达克斯公司的 JSM-6360LV扫描电镜对母材及焊缝进行了能谱分析.

2 试验结果及分析

2.1 紫铜 25 mm厚板 FSW焊缝的力学性能

在上述焊接工艺参数下得到厚度为 25 mm的紫铜厚板焊缝,在没有经过任何焊后热处理时平均抗拉强度已达到 186.6 MPa,断后平均伸长率达到了 28.2%,如表 3所示. 紫铜厚板 R_m=205 MPa,焊缝的焊接强度仍低于母材,但焊缝的平均强度系数已经达到了母材的 91%.

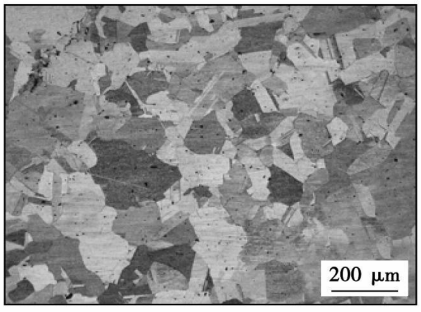
表 3 力学拉伸试验数据

Table 3 Mechanical properties of T2 copper welds

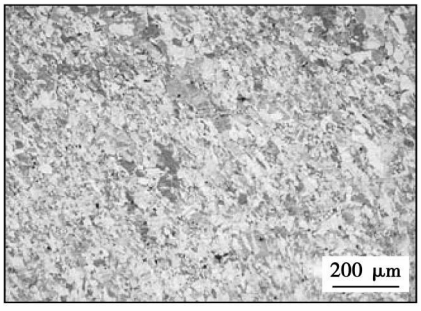
试样编号	最大试验力 F_m/kN	抗拉强度 R_m/MPa	屈服强度 R_{eL}/MPa	断后伸长率 A(%)
1	59	195	56	27.6
2	55	188	53	25.5
3	51	176	57	29.0
4	50	181	59	28.8
5	64	193	61	30.1
平均值	55.8	186.6	57.2	28.2

2.2 紫铜 25 mm厚板 FSW焊缝的显微组织

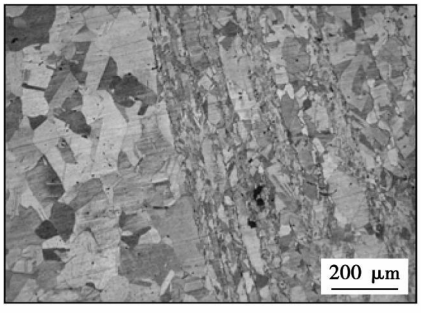
对焊接试件沿接头横向取样制取金相试样. 制作好的金相试样采用氯化高铁盐酸溶液腐蚀后用光学显微镜观察显微组织. 焊缝横截面的金相组织如图 2所示. 图 2a为母材组织,母材呈轧制粗大晶粒,焊核区(WNZ)位于焊缝的中心,焊核区组织见图 2b,可见焊核区的晶粒比原始母材的要细小得多,且晶粒是规则的等轴晶,这些等轴晶是由于受到搅拌头强烈的搅拌作用以及剧烈摩擦产生的局部高温作用,造成大量晶粒破碎,破碎的晶粒发生动态再结晶,杂质相仍然弥散分布于其中,已经看不出孪晶组织. 图 2c,d是焊核区下部两侧的热力影响区组织. 焊缝两侧热力影响区是搅拌摩擦焊焊接过程中在摩擦热和剪切力的压扭共同作用下,母材组织和性能发生变化的区域,呈不对称分布的. 分析认为焊核两侧的金属距离搅拌头不同位置而处于不同的塑性流动状态,材料塑性流动方向与搅拌针侧面旋转方向的切向方向一致. 在前进侧,母材塑性变形方向朝前,即与焊缝金属塑性流动方向相反;在后退侧,母材塑性变形方向朝后,即与焊缝金属塑性流动方向一致. 在焊缝内,由于搅拌头旋转过程中产生的空腔作用,使搅拌区内前进侧的金属沿搅拌头的外表面逆时针地被挤压至搅拌头的后方,而后退侧的金属随搅拌头的外表面顺时针地流向搅拌头的后方. 在前进侧,母材金属与焊缝金属之间存在很大的相对变形差异,因而造成前进侧焊缝与焊缝区有明



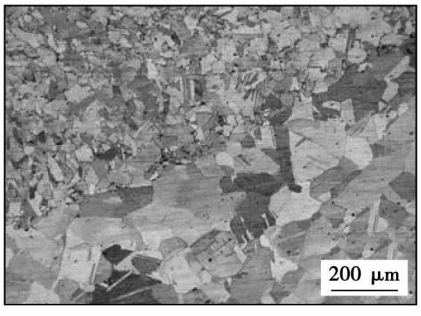
(a) 母材区



(b) 焊核区



(c) 前进侧焊核边界区



(d) 返回侧焊核边界区

图 2 紫铜厚板焊缝的微观组织

Fig. 2 Microstructures of T2 copper joint

显的分界线，如图 2 c所示；而返回侧热力影响区组织向母材区过渡不规则，如图 2 d所示，说明返回侧流变应力大，影响范围宽，流变区域宽且边界具有不确定性.

2.3 试样显微硬度分析

紫铜搅拌摩擦焊接头横截面显微硬度分布曲线如图 3所示.

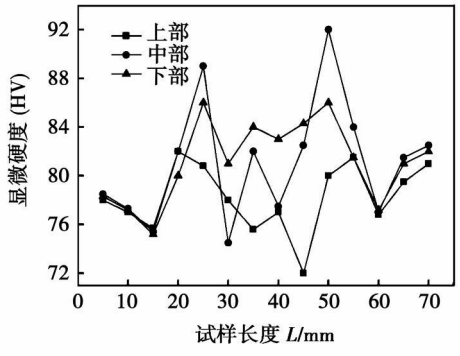


图 3　T2焊缝的显微硬度分布

Fig. 3　Microhardness of T2 welds

25 mm厚的焊缝接头断面显微硬度由上、中、下层依次递减，均呈典型“M”特征分布，峰值均高于母材，到热影响区和焊核区，硬度值降低，说明铜的搅拌摩擦焊焊接接头出现了软化现象. 接头处硬度值的这种分布，是由于受到搅拌头的搅拌挤压及高温作用，接头区主要发生动态再结晶，导致接头处软化速度大于硬化速度，接头整体呈现出硬度值小于母材. 在焊核区，由于晶粒特别细小，其硬度值略有提高. 以上硬度分布符合搅拌摩擦焊焊缝硬度分布规律，说明焊接过程正常.

2.4 焊缝组织电阻率测试

紫铜通常作为导电材料，电阻率也是焊缝组织的重要性能，为探明紫铜搅拌摩擦焊缝电阻率变化规律，特从焊接接头中部截取电阻率测试试样，如图 4所示，试样规格为 50 mm×3 mm×3 mm，在常温下，用惠斯通电桥法测量，测量结果如表 4所示.

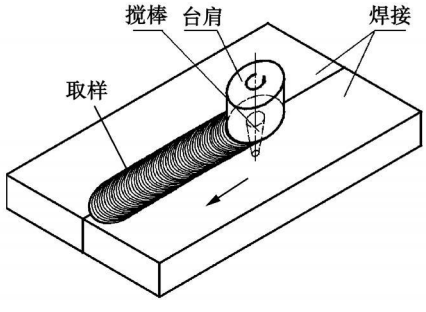


图 4　电阻率取样示意图

Fig. 4　Schematic of sampling conductivity

表 4　电阻率测试数据

Table 4　Conductivity of T2 copper welds

试样编号	1	2	3	4
电阻率 $\rho/(10^{-6}\Omega\cdot cm)$	1.84	1.87	1.86	1.84

从表 4中可看出焊缝部分电阻率比母材略大，增大 3.9%，初步分析认为，FSW焊缝组织为塑性流变形成的近似挤压组织，具有一定变形硬化效应，电阻有微小增大.

2.5 焊缝能谱分析

焊接过程中，搅拌焊头与焊缝组织高温密切接触，是否存在金属原子扩散，形成焊缝合金污染，为探明焊缝与母材在成分上的差异，在美国伊达克斯公司的 JSM-6360LV扫描电镜上，分别对熔深 25 mm焊缝取样，对焊缝和母材的能谱进行了分析，如图 5所示. 结果表明：(1) 两个区域的能谱图中只有 Cu，Si，O元素的谱线，无其它金属元素，说明焊接过程中，搅拌头上的 Fe，W，V，Ni，Cr等元素没有发生显著的原子扩散，焊缝合金污染不显著；(2) 焊缝区与母材区相比，氧含量无明显差异，所测得的氧含量应是表面氧化膜所致，说明焊缝组织无明显氧化，无污染；(3) 出现 2% ~3%硅含量，应是制作

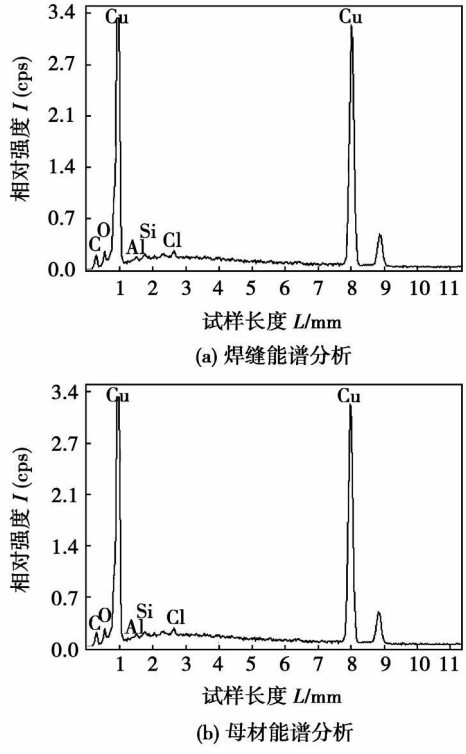


图 5　母材及焊缝 EDS分析

Fig. 5　EDS analysis results of base metal and joint

试样时，砂纸磨料微粒嵌入表面所致.

3 结 论

（1）用搅拌摩擦焊方法成功焊接了 25 mm厚的 T2紫铜厚板，在搅拌头转速为 960 r/min，焊接速度为 70 mm/min时，焊缝的抗拉强度较高，达到了 186.6 MPa，且接头的电学性能和力学性能优良.

（2）能谱分析表明，在焊接过程中没有发生显著的原子扩散，焊缝合金污染不显著.

（3）搅拌摩擦焊接头的电阻率与母材基本相当. 搅拌摩擦焊技术用于电机制造中的紫铜 紫铜接头的焊接，具有很好的应用前景.

参考文献：

[1] 中国焊接学会. 焊接手册：第 2卷 [M]. 北京：机械工业出版社，1992

[2] 王希靖，达朝炳，李 晶，等. 紫铜的搅拌摩擦焊工艺与接头性能分析[J]. 兰州理工大学学报，2006(4)：25—28
Wang Xijing, Da Chaobing, Li Jing, et al. Processing of friction stir welding of copper and analysis of its joint properties[J]. Journal of Lanzhou University of Technology, 2006(4)：25—28

[3] 肖 兵，柯黎明，王伟兰. 紫铜的搅拌摩擦焊接头性能测试与组织分析[J]. 电焊机，2004（增刊）：125—129.
Xiao Bing, Ke Liming, Wang Weilan. Joint properties and microstructure of copper by friction stir welding[J]. Electric Welding Machine, 2004(supplement)：125—129

[4] 周鹏展，钟 掘，贺地求，等. 2519厚板搅拌摩擦焊接工艺及组织分析[J]. 中南大学学报，2006，37(4)：114—118.
Zhou Pengzhan, Zhong Jue, He Dirju. Technique and microstructure of fiection-stir welded 2519 thick plate[J]. Journal of Central South University, 2006, 37(4)：114—118

[5] 周鹏展，钟 掘，贺地求. LC52厚板搅拌摩擦焊组织性能分析[J]. 材料科学与工程学报，2006，24(3)：429—435.
Zhou Pengzhan, Zhong Jue, He Dirju. Microstructure and properties in fiection-stir welds LC52 slab[J]. Journal of Materials Science & Engineering, 2006, 24(3)：429—435

[6] 李慧中，张新明，陈明安. 2519铝合金焊接接头的组织与性能[J]. 中国有色金属学报，2004，14(6)：956—960.
Li Huizhong, Zhang Xinming, Chen Mingan. Microstructure and properties of welded joint of 2519 aluminum alloy[J]. The Chinese Journal of Nonferrous Metals, 2004, 14(6)：956—960.

[7] Fonda R W, Bingert J F, Colligan K J. Development of grain structure during friction stir welding[J]. Scripta Mater, 2004, 51(3)：243—248

[8] Lee Won-bae, Jung Seung-boo. The joint properties of copper by friction stir welding[J]. Materials Letters, 2004(58)：1041—1046

[9] Elrefaeya, Takahashin, Ikeuchik. Preliminary investigation of friction stir welding aluminum/copper lap joint[J]. Proceeding of Pre-Assembly Meeting on FSW in Nagoya, 2004(1)：275—285

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rate environmental noise from arc sound signal. The ICA separating technology provides technical basis for extracting characteristics of arc sound signal and monitoring welding quality via arc sound signal.

Key words: arc sound; independent component analysis; fast fixed-point algorithm; signal and noise separation

Simulation of microstructure formation during solidification in weld pool. LI Yubin, MENG Daqiao, LIU Kezhao, XIE Zhiliang (P. O. Box 919, China Academy of Engineering Physics, Mianyang 621900, China). p. 57—60, 64

Abstract: Base on the kinetics of the dendritic tip growth and least energy of grain growth theory, a two-dimension CAMC (Cellularautomata-Monte Carlo) grain growth mathematical model for weld pool which couples macroscopic heat transfer with microscopic solute transfer, nucleation and growth is developped. The skeleton of grain is formed by using CA model, and then the growth of grain is corrected by MC model. In the model, the mechanism and influencing factors of heterogeneous nucleation, which occurs at the boundary of welding zone, are taken into account. The dynamic process of microstructure formation in welding zone is presented. The evolution of amount, dimension and appearance of grains can be described quantitatively by using CAMC model, and the choosing growth of grain and the transition from columnar to equiaxed crystal can be exhibited by model. It is successful to simulate the microstructure evolvement during metal solidification of welding zone by CAMC model.

Key words: weld pool; grain growth; numerical simulation; cellular automata; Cellularautomata-Monte Carlo model

Microstructures and bulging formability of laser welded tailored blanks for high strength steel with unequal thickness. LU Guangda[1,2], LI Yuntao[1,2], ZHANG Jian[1,3], BI Dasen[1,3] (1. School of Materials Science & Engineering, Tianjin University of Technology, Tianjin 300384, China; 2. Tianjin Key Laboratory for Photoelectric Materials & Devices, Tianjin University of Technology, Tianjin 300384, China; 3. Key Laboratory of Display Materials & Photoelectric Devices, Ministry of Education, Tianjin University of Technology, Tianjin 300384, China). p. 61—64

Abstract: Tailor welded blanks (TWB) of laser weld is adopted to weld high strength steel sheets SAPH440 with 1.8 mm thickness and DP600 with 2.2 mm thickness. The microstructures and microhardness of the welded joint for TWB are studied, and the cupping tests are carried out to study the bulging formability of TWB, which is compared with that of the original sheet blanks. The results show that the microstructures of the joint are acicular ferrite and lath martensite, the microhardness of the joint is higher than that of the base metal. And the cupping experimental values of TWB are lower than that of the original sheet blanks. Eventually, the weld location has some influence on the bulging formability of TWB, the bigger the proportion of the thin blank is, the better the bulging formability of TWB is, and the weld will move to the side of the thick blank during bulging formation.

Key words: unequal thickness; high strength steel; tailor weld blanks; bulging formability

Interface deformation and its role of steel 45 in vacuum diffusion welding. PAN Jinzhi, REN Ruiming, QI Zhengfeng (School of Materials Science and Engineering, Dalian Jiaotong University, Dalian 116028, China). p. 65—68, 72

Abstract: The plastic deformation of weld interface under the welding pressure was investigated during the vacuum diffusion welding process of steel 45, and the effects of deformation rate on the welding quality and the process planning was discussed. The results show that the important factor affected on the quality of the vacuum diffusion welding process of steel 45 is the deformation rate under the fixed pressure. The temperature, pressure and holding time have relatively small influence on the welding quality when the deformation rate is beyond a critical value, which the whole welding interface achieves superposition completely by means of plastic deformation. The annealing treatment of post weld can improve the welding strength by changing the microstructures of the interface zone, and the holding time shortens.

Key words: steel 45; diffusion welding; process planning

Automated extraction of spatial locating data for bulk defects in double T joints. SHI Duanhui[1], GANG Tie[2], HUANG Chuanhui[1], YANG Genxi[1] (1. School of Electromechanical Engineering, Xuzhou Institute of Technology, Xuzhou 221008, China; 2. State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p. 69—72

Abstract: The automated extraction algorithm of spatial position data was provided for small defects in double T style weldments. It consists of two parts, one is that automatically extracts projection distance and the distribution of defects along the weld longitudinal direction, and the other is that automatically extracts defect dimension and the distribution of defects along the weld longitudinal direction. Automated corresponding criterion is designed for the defects of left and right turning images in double T joints, and quick extraction of spatial position data for small defects is achieved. Then algorithm verification is carried out by using destructive test of real weldments. The results show that the provided algorithm is feasible in this paper.

Key words: double T style; laser weldments; X-ray image; spatial position data; automated extraction

Friction stir welding of thick copper plate. HE Dinglu, YI Xin, LI Zaihua (Key Laboratory of Design for Modern Complex Equipment and Extreme Manufacturing, Ministry of Education, P. R. China, Central South University, Changsha 410083, China). p. 73—76

Abstract: Friction stir welding is a solid-state welding technique, which may offer a new solution for thick copper plate joining. Friction stir welding of T2 copper plate, 25 mm in thickness, was completed successfully by single pass welding, and the microstructure, physical property, electrical property and energy spectrum of the T2 copper joint were analyzed. The ex-

periment results demonstrate that the appearance of the joint is good and the inner in the joint is detect-free under optimum joining conditions. When the rotating speed is 960 r/min and the welding speed is 70 mm/min, the tensile strength of the joint reaches 186.6 MPa, and the conductivity of the joint is approximately equal to that of the base metal.

Key words: friction stir welding; T2 copper; thick plate; mechanical properties

Ultrasonic monitoring of residual stress reduction methods

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Abstract: The ultrasonic system of accurately measuring internal stress of welding structure is established based on acoustoelasticity effect and critically refracted longitudinal wave that is most sensitive to stress in order to shorten the time of the welding residual stress measurement. A new series decreasing residual stress methods, such as trailing rotating extrusion, trailing impactive rolling, electromagnetic impact and pre-stress, are verified by this measurement system. The experiment results show that the decreasing degree of residual stress can validate the effectiveness of technical parameters by those methods. The measurement speed of the nondestructive system is quicker than that of traditional section release methods, which accelerates the research process.

Key words: ultrasonic measurement; control residual stress methods; welding residual stress

Effects of service conditions on properties of in-situ particle-reinforced composite solder joint

TAI Feng, GUO Fu, MA Limin, HAN Mengting (College of Materials Science and Engineering, Beijing University of Technology, Beijing 100124, China). p. 81—84

Abstract: In-situ particle-reinforced composite solder was considered as an effective method to enhance the properties of lead-free solders. In-situ Cu_6Sn_5 particles were added into the eutectic Sn-3.5Ag solder to form in-situ metal particles enhanced SnAg-based composite solder. The microstructure and mechanical properties of the composite solder joint during reflow and isothermal aging were investigated, and the fracture mode of composite solder joint and the role of in-situ Cu_6Sn_5 particles were analyzed. Experimental results show that the microstructure and dimensions of in-situ Cu_6Sn_5 particles in composite solder matrix have changed during reflow and isothermal aging. So the shear strengths of composite solder joints have influenced by the sizes of in-situ Cu_6Sn_5 particles. Besides, the deformation of composite solder joint is dominated by shear bonding mode, and the in-situ Cu_6Sn_5 reinforced particles can retard the fracture path of shear bonds.

Key words: in-situ Cu_6Sn_5; particle; composite solder; reflow; aging; shear strength

Microstructure and mechanical properties of ultrafast-convert VPTIG arc welding of 2219 high strength aluminum alloy

CONG Baoqiang, QI Bojin, ZHOU Xingguo, LUO Jun (School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics, Beijing 100191, China). p. 85—88

Abstract: A novel ultrafast-convert intermediate and high-frequency variable polarity arc welding technology for aluminum alloys was developed. The effect of variable polarity current frequency on the microstructure and mechanical properties of 2219-T87 weld joints was researched based on the variable polarity TIG welding process. The experimental results show that the structure in the weld zone is predominantly columnar in the case of lower variable polarity current frequency. The grain structures in the weld zone become finer and more equiaxed with the increase of current frequency. Tensile strength and percentage elongation of the weld joints also improve predominantly. The type of weld fracture is changed from brittle to the mixture of dimple and brittle. Under the current frequency of 1 kHz, the rates of weld tensile strength and percentage elongation of the joints are 69% and 58% than those of the base metal respectively.

Key words: high strength aluminum alloy; ultrafast convert; variable polarity; grain refinement

Nonlinear multiple regression model of resistance spot welding for galvanized steel sheet

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Abstract: A method of nonlinear multiple orthogonal regression assembling design was applied in the investigation of the resistance spot welding process on galvanized steel sheet. The indexes studied in experiments were nugget geometry and tensile-shear strength of spot welds. Furthermore, four process parameters, namely welding current, electrode force, welding current duration and preheat current, and interactions among them were considered as the factors impacting indexes. The experimental results showed that there was a more accurate prediction on nugget size and mechanical properties of spot welds by the models optimized. Based on these prediction results, the optimization of welding process also was realized by the analysis to the effect of parameters and interactions on the welding quality.

Key words: galvanized steel sheet; spot welding; regression model; nugget diameter; tensile-shear strength

Condenser discharge percussion welding of iron wire to copper sheet

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Abstract: In order to study new jointing technique about