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高熔点材料的搅拌摩擦焊接技术

刘会杰， 周 利
(哈尔滨工业大学 现代焊接生产技术国家重点实验室，哈尔滨 150001)

刘会杰

摘 要：通过焊具设计、接头微观组织与性能、焊接温度场和残余应力、热源辅助的搅拌摩擦焊(FSW)几个方面，全面介绍了高熔点材料搅拌摩擦焊技术的研究现状。结果表明，合适的搅拌头材料为钨铼(W - Re)合金和多晶立方氮化硼(PCBN)；采用合适的焊具设计和工艺参数，可以得到具有良好微观组织、高强度的FSW接头；在模拟搅拌摩擦焊温度场和接头残余应力时，应依据焊接过程实际进一步完善物理模型；引入辅助热源有利于高熔点材料焊缝成形并提高焊具使用寿命。

关键词：高熔点材料；搅拌摩擦焊；焊具设计；微观组织；残余应力；辅助热源
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0 序 言

作为一种新型固相连接技术的搅拌摩擦焊[1]，自问世以来就受到人们的关注，并已成功应用于铝、镁等低熔点材料的焊接，引发了航空、航天、铁路、汽车、造船等装备制造领域生产技术的变革，取得了显著的经济效益和社会效益。为进一步发挥搅拌摩擦焊的优点，扩大其应用范围，近年来开始探索钢、钛等高熔点材料的搅拌摩擦焊技术[2,3]，并取得了一定的研究成果。

文中将从搅拌摩擦焊具设计、接头微观组织和性能、焊接温度场和残余应力、热源辅助的搅拌摩擦焊几个方面，对高熔点材料的搅拌摩擦焊技术进行介绍和分析，以使中国焊接工作者能够及时了解和掌握国际新技术发展的步伐。

1 搅拌摩擦焊具的设计

焊具设计是搅拌摩擦焊技术的关键，它决定焊接过程能否顺利进行并直接影响接头质量。对于铝、镁等低熔点材料而言，目前已设计出多种形式的焊具并用于实际生产。钢、钛等高熔点材料由于具有较高的强度和硬度，显著增加了搅拌摩擦焊的难度，因而对焊具设计提出了更高的要求，目前对高熔点材料搅拌摩擦焊用焊具的设计尚处于尝试阶段，还需开展更为深入细致的工作。

1.1 焊具材料

搅拌摩擦焊接过程中焊具(主要是搅拌头)与被焊材料之间发生热机作用，搅拌头在此过程中承受机械力载和摩擦热载，为完成焊接过程要求搅拌头材料具有远高于被焊材料的熔点、强度及硬度。对于钢、钛等高熔点材料来讲，满足要求的搅拌头材料往往是难熔金属合金[4]或结构陶瓷[5-7]。

Ikeda 等人[8]采用镍基合金作为搅拌头材料，借助于水冷等措施对钛合金进行了搅拌摩擦焊接。采用镍基合金制作搅拌头，可显著降低焊具的制造成本，但其可行性有待进一步研究。

1.2 焊具结构

铝、镁等低熔点材料搅拌摩擦焊用焊具通常采用整体式结构，此时焊具即指搅拌头。高熔点材料搅拌摩擦焊时，焊具一般采用分体式结构。图1为Nelson 等人[9]设计的分体式搅拌摩擦焊具，搅拌头材料为PCBN，与搅拌摩擦焊机匹配的刀柄材料为硬质合金(WC)，搅拌头与刀柄用高温合金紧固以传递扭矩。

Lienert 等人[10]的研究表明1018 低碳钢搅拌摩擦焊过程中接头最高温度在1 000 ℃以上，高强钢及钛合金焊接时温度会更高。因此在焊具设计时需要考虑对温度进行检测，Nelson 等人[9]通过在焊具上引入热电偶对焊接过程中搅拌头温度进行实时监测。高熔点材料搅拌摩擦焊过程中工件在高温下会与空气反应而使接头性能变差并影响焊接过程，此外焊具在高温下持续工作可能发生破坏，因此还需

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图 1 PCBN 焊具示意图

Fig. 1 Schematic illustration of PCBN tool design

设计水冷和气体保护装置以保证焊接过程顺利进行。

高熔点材料搅拌摩擦焊用焊具的研究主要集中在材料选择及结构设计上,研究的成果多以专利形式出现,可供参考的文献资料较少。此外,关于焊具磨损及破坏的报道也很少,应对焊具的磨损及破坏机制进行深入研究,为焊具的优化设计提供依据。

2 接头的微观组织和性能

2.1 微观组织

王文英等人[11]采用钼合金搅拌头对 3 mm 厚 Q235A 低碳钢板进行了 FSW,分析了接头的组成及其微观组织。在整个接头中,明显存在热影响区(HAZ)和焊核区(NZ),而热力影响区(TMAZ)不明显。进一步分析发现,热影响区主要由等轴铁素体和球化珠光体组成,而焊核区在焊接过程中因塑性变形发生动态再结晶,抑制了晶粒长大,冷却后形成了细小的先共析铁素体、铁素体和珠光体组织。

Park 等人[12]研究了 6 mm 厚 304 不锈钢 FSW 接头的微观组织,所用搅拌头采用 PCBN 制成,为防止搅拌头在扎入过程中发生损坏,焊前在工件上加工出引导孔,并采用较小的转速扎入。焊接过程中采用氩气保护,所用焊接速度为 1.3 mm/s,焊具倾角为 3.5°。研究结果表明,焊核区和热力影响区出现再结晶与回复组织,在搅拌区的前进侧形成了具有大量层错的 σ 相,它的形成与焊核区中奥氏体转变为 δ 铁素体有关。

Ramirez 等人[13]研究了 6 mm 厚 Ti-6Al-4V 板材 FSW 过程中的组织演变,被焊材料分为热轧退火(M-A)和 β 态退火(β-A)两种状态,搅拌头采用纯钨制成。试验结果表明,焊核区的组织与其位置有关,焊核区中心的组织与母材相似,而与热力影响区毗邻的焊核区边缘的组织明显不同。热力影响区的组织与母材原始状态有很大关系,M-A 母材的热机影响区中有针状 α 相从 β 基体中析出。

Juhas 等人[14]也研究了 Ti-6Al-4V 的 FSW 接头组织。结果表明,焊核区的微观组织是由等轴 α 相晶粒和层片状($\alpha+\beta$)相晶粒组成,但焊核区上部晶粒比中部晶粒细小,而中部晶粒小于母材晶粒。这是因为,焊核区中部冷速较慢,有更多的时间发生粗化,而在上部会发生局部淬火,但无论中部还是上部都发生了动态再结晶。值得注意的是,在未发生任何变形的热影响区中,由于温度没有超过 β 相转变温度,因而 β 相晶粒并未发生粗化。

2.2 力学性能

Konkol 等人[15]对船舶用 HSLA-65 低合金高强钢进行了 FSW,其中 6.4 mm 厚板材采用单面焊工艺,而 12.7 mm 厚板材采用双面焊工艺,并对不同参数下获得的接头进行了拉伸、弯曲、断裂韧性和硬度等性能测试。结果表明,在合适的焊接工艺参数下,接头能够达到母材的强度,并具有良好的塑性和韧性,可以满足船舶的使用要求。

Sato 等人[6]研究了 SAF2507 双相不锈钢 FSW 接头的组织和性能,搅拌头采用 PCBN 制成。研究结果表明,采用合适的工艺参数可以得到优质的接头。由于焊核区中铁素体和奥氏体晶粒在搅拌摩擦焊接过程中发生了明显的细化,从而提高了焊缝的力学性能,使焊接接头具有与母材相同的抗拉强度与屈服强度。

John 等人[16]对 Ti-6Al-4V 搅拌摩擦焊接接头疲劳性能的研究结果表明,虽然搅拌摩擦焊缝的残余应力较低,但其对焊缝的疲劳性能仍然有很大的影响,而热影响区的残余应力对平行于焊缝方向的裂纹扩展起决定性作用。对于微观组织一定的接头来讲,采用低的应力比率循环时,疲劳极限与试样的几何形态有关,试样的疲劳极限低于或高于母材;而采用高的应力比率循环时,试样的几何形态对疲劳极限没有影响。

目前已对碳钢、低合金高强钢、不锈钢、钛及钛合金等高熔点材料的 FSW 接头组织和性能进行了研究,结果表明采用合适的焊具设计和合理的工艺参数,可以得到具有良好微观组织、高强度的 FSW 接头,但这方面的研究还只是初步的,还需开展更为系统和深入的工作。

3 焊接温度场和残余应力

高熔点材料 FSW 过程中产热是焊具设计中最

为关键的问题之一,同时产热也决定了接头的残余应力分布并直接影响接头性能。因此,有必要对焊接温度场和残余应力进行模拟分析及测试,以便为焊具设计和工艺优化提供依据。

Reynolds 等人[17]对 3.2 mm 厚 304L 不锈钢板进行了搅拌摩擦焊接,采用热电偶测量了焊接温度场的分布,并且采用中子衍射方法分析了接头中的残余应力。结果表明,焊接工艺参数对给定点处的峰值温度及其持续时间有较大影响,接头中的纵向残余应力可达到母材屈服强度。

Zhu 等人[18]采用自行开发的有限元软件 WELDSIM 对 3.2 mm 厚的 304L 不锈钢板搅拌摩擦焊过程的暂稳态温度场和接头残余应力进行了有限元分析,通过测定给定点处的温度,采用逆向分析法分析了产热过程,并采用热机耦合方式获得了接头的残余应力分布。结果表明焊缝中心及其附近区域存在较大的残余拉应力,距焊缝中心越远,残余拉应力越小。

Li 等人[19]对 L80 高强钢进行了搅拌摩擦焊接,分别采用热电偶测量和有限元模拟研究了接头的温度分布,对比结果如图 2 所示。焊缝中心的峰值温度最高,达到 950 ℃以上,而热影响区的峰值温度也达到了 600 ℃,但这并未影响接头的拉伸性能。同时,由图 2 还可以看出,尽管实际测量结果和模拟分析结果反映的温度分布趋势是一致的,但二者在数值上还存在一定的差别。

搅拌摩擦焊接过程中的产热是一个非常复杂的

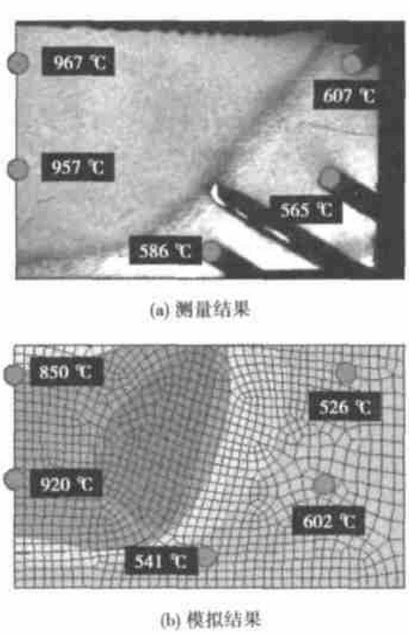

图 2　L80 高强钢 FSW 接头温度分布
Fig. 2　Temperature distribution of L80 FSW joint

问题,使得对焊接温度场和残余应力进行准确分析存在较大难度。目前已提出一些模型和分析方法,对指导焊接工艺起到了一定作用,但还需从搅拌摩擦焊接过程的本质出发,使其更接近实际。

4　热源辅助的搅拌摩擦焊

对高熔点材料的搅拌摩擦焊而言,为使待焊部位发生塑性软化并实现连接,需要较高的摩擦产热。若能够通过外加热源补充焊接所需的热量,则可以降低焊接所需的摩擦热,同时也能降低焊接过程中的作用力,减少焊具磨损,提高焊接生产效率。因此,研究人员相继开发了一些热源辅助的搅拌摩擦焊方法,并获得了初步应用。

从外加热源的种类来看,主要包括电阻热[20]、高频感应热[21]、电弧[22]和激光[23]等。当然,这些热源辅助的搅拌摩擦焊方法也可以用于铝、镁等低熔点材料的连接中。例如,Liu 等人[22]在硬铝的搅拌摩擦焊接中采用了微束等离子弧作为辅助热源,不但提高了焊接效率,而且提高了焊接质量。再如,Gabriel 等人[23]在铝合金薄板的搅拌摩擦焊接中采用了激光作为辅助热源,降低了焊接过程中焊具所承受的机械载荷,提高了焊接速度。

正是基于辅助热源在铝合金搅拌摩擦焊中应用所取得的较好结果,一些研究人员提出在高熔点材料搅拌摩擦焊中引入辅助热源的构想。这样不但有利于焊缝成形,而且能显著降低焊具的磨损,提高焊具的使用寿命。可以预见,随着研究的不断深入,热源辅助的搅拌摩擦焊接技术必将在高熔点材料的连接中获得应用。

5　结　论

(1) 高熔点材料搅拌摩擦焊用焊具的研究主要集中在材料选择及结构设计上,合适的焊具材料主要有 W-Re 合金和 PCBN,焊具结构以分体式为主。对焊具的磨损及破坏机制应进行深入研究,以期优化焊具结构及尺寸,提高焊具使用寿命。

(2) 针对碳钢、低合金钢、不锈钢、钛及钛合金等高熔点材料进行 FSW 接头组织和性能的研究表明,采用合适的焊具和合理的工艺参数,可以得到具有良好微观组织的、高强度的 FSW 接头。但在这方面的研究还只是初步的,尚需开展更为系统和深入的研究工作。

(3) 为确定搅拌摩擦焊接温度场和接头的残余应力,一些学者从不同的角度提出了有益的模型和

分析方法,对指导焊接工艺起到了重要作用,但尚需从搅拌摩擦焊接过程的本质出发,进一步完善模型,使其更接近于实际。

(4) 在高熔点材料搅拌摩擦焊中引入辅助热源,不但有利于焊缝成形,而且能降低焊具磨损,提高焊具使用寿命。可以预见,随着研究的不断深入,热源辅助的搅拌摩擦焊接技术必将在高熔点材料的连接中获得应用。

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作者简介: 刘会杰,男,1962 年出生,博士,教授,博士研究生导师。主要从事特种连接技术研究。发表论文 100 余篇。

Email: liuhj@hope.hit.edu.cn

solder. ANSYS finite element analysis tool was used to implement the simulation. In the end, the stress and strain distribution were obtained. The strain range was achieved from the hysteresis loop. The fatigue life of PBGA was predicted using Engelmaier model. The simulation result of the model shows that the position of the critical soldered position of a plastic ball grid array component is right below the edge of its die, but not the outboard solders. This result is helpful to improve the thermal fatigue reliability of plastic ball grid array components.

Key words: plastic ball grid array; solded joint; thermal fatigue; finite element method

Effect of cladding material on LY12CZ aluminium alloy by Laser Cladding SUN Fujuan, HU Fangyou, HUANG Xuren, TANG Yuanheng (Qingdao Branch, Naval Aeronautical Engineering Academy, Qingdao 266041, China). p93 - 96

Abstract: Through controlling process parameters of impulse laser, current, pulse width, frequency, spot diameter and scanning velocity, laser cladding LY12 and Al-Y was used to repair corrosion damage of aluminum alloys. After cladding, fatigue test, fracture and microstructure of the specimens were studied. The result indicated that the life of the specimen cladded by Al-Y was 402 % of that by LY12. There was no large pore and crack in the Al-Y layer which joined with the substrate firmly. There was much impurity in the cladding layer of LY12.

Key words: aluminum alloys; laser cladding; fatigue life; fatigue fracture; microstrcture

Comparison of stress relief by PWHT and VSR in large-dimension straight welded pipe ZHANG Chao, LU Qinghua, XU Jijin, CHEN Ligong (School of Materials Science and Engineering, Shanghai Jiaotong University, Shanghai 200030, China). p97 - 100

Abstract: Post-weld heat treatment (PWHT) and vibratory stress relieving (VSR) were used to control the residual stress in large-dimension welded pipes. The results show that both PWHT and VSR are able to relieve the residual stress effectively in large-dimension straight welded pipe and make the distribution of residual stress more uniform. Their effect in weld zone is more obvious than these in base metal. The results of stress relieving of VSR of as-cast microstracture are qualified but not acceptable in cold plastic deformation zone. The effect of PWHT on the stress relieving and stress uniform ability is better than that of VSR. However, considered of economy factor and technique convenience, VSR is confirmed as stress relieving technique to control the residual stress in large-dimension straight welded pipe.

Key words: vibratory stress relieving; post-weld heat treatment; residual stress

Progress in friction stir welding of high melting point materials LIU Huijie, ZHOU Li (State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p101 - 104

Abstract: The research status of friction stir welding (FSW) of high melting point materials was introduced from the aspects of FSW tool design, microstructural characteristics and mechanical properties of the joints, welding temperature distribution and residual stress and FSW assisted by hybrid heating sources. It indicates that the W-Re alloy and polycrystalline cubic boron nitride are suitable FSW tool materials. The FSW joints with high strength and fine microstructure can be produced when the proper tool geometry and welding parameters were used. For simulation of temperature distribution and residual stress in the FSW joints, physical models should be improved according to the real FSW process. The utilization of hybrid heating source is benefit to weld formation and tool life.

Key words: high melting point materials; friction stir welding; tool design; microstructural characteristics; residual stress; hybrid heating source

Review of X100 pipeline steel and its field weldability YAN Chunyan[1], LI Wushen[1], FENG Lingzhi[1], XUE Zhenkui[2], BAI Shiwu[2], LIU Fangming[2] (1. School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China; 2. Petroleum-Gas Pipeline Research Institute of China, Langfang 065000, Hebei, China). p105 - 108

Abstract: In view of the ever-increasing pipeline length and operating pressure, development of high-strength linepipes has become increasingly attractive and needed. The current knowledge of X100 pipeline steel about research and development status, metallurgical principles, mechanical properties, field weldability, and so on were presented. Production of grade X100 steel requires combination of super-clean refining, thermo-mechanical controlled process, proper metallurgical design and some other advanced techniques. Excellent mechanical properties and satisfying weldability are possessed for grade X100 steel. Yield strength of X100 grade steel generally exceeds 690 MPa. High strength-toughness welded joint can be obtained through proper welding procedures. Further work is required to improve the production of X100 pipeline steel and to establish appropriate material standards.

Key words: X100 pipeline steel; microstructure; ductile fracture arrest; girth welding; weldability

General rules of writing scientific and technical papers WANG Ya (Harbin Welding Institute, China Academy of Machinery Science and Technology, Harbin 150080, China). p109 - 112

Abstract: In order to help scientific and technical workers to know the basic requirements of writing academic papers, master its general methods and improve their rules, common problems in the submitted original manuscripts were analyzed and the methods to resolve these problems were given, based on the features of academic papers and combined with the experiences of the author on editing academic papers for many years. The basic structures of academic papers, requirements on writing and some problems needing in attention were also stated. According to some national and professional standards, standardized uses of professional terms and phases, symbols of physical quantity and measurement units, the requirements on figures and tables and regulations of references literature in papers were briefly explained.

Key words: scientific and technical papers; writing; standardization