

搅拌摩擦焊在镁合金焊接中的应用与进展

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摘要 近年来, 镁合金在航空航天、汽车电子、轨道交通等领域的需求日益增长, 焊接是保障镁合金工业化应用的重要手段。搅拌摩擦焊(FSW)因其绿色环保、焊接效率高、接头性能好等优势在镁合金焊接中得到了一定的应用。本文从工艺参数与性能、镁合金FSW辅助技术与异种镁合金FSW研究等对国内外镁合金FSW进行了归纳, 并对镁合金FSW未来的发展进行了展望。

关键词 镁合金; 搅拌摩擦焊; 研究现状; 异种材料

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Application and progress of friction stir welding in magnesium alloy welding

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Abstract In recent years, magnesium alloy in aerospace, automotive electronics, rail transportation and other fields of increasing demand, welding is to ensure the industrial application of magnesium alloy is an important technical means. Friction Stir Welding (FSW) has been used in magnesium alloy welding due to its advantages of green, high welding efficiency and good joint performance. This paper summarises the domestic and foreign magnesium alloy FSW from the process parameters and performance, magnesium alloy FSW auxiliary technology and dissimilar magnesium alloy FSW research, and looks forward to the future development of magnesium alloy FSW.

Keywords Mg alloy; friction stir welding; research status; dissimilar materials

作为工程应用中最轻的金属材料, 镁合金的比强度与比刚度高、阻燃性能好、易加工、易回收, 在工业低碳绿色化转型中扮演着重要的角色。焊接是保障镁合金工业化应用的重要手段, 传统的熔焊应用于镁合金材料时容易造成焊缝晶粒粗大, 产生氧化、气孔、裂纹等缺陷, 降低了接头性能, 这些也成了目前镁合金焊接时应该注意的问题, 推动着镁合金焊接技术的发展^[1-2]。

搅拌摩擦焊(friction stir welding, FSW)自发明以来, 因其绿色环保、焊接效率高、接头性能好等优势在有色金属焊接中得到广泛地应用, 尤其是近年来用于镁合金焊接可有效解决常规熔焊所带来问题^[3-4], 在航空航天、船舶制造与汽车工业等领域的镁合金焊接中有着巨大的应用前景, 如应用于新能源汽车的副车架、轮毂等镁合金零件的焊接, 可推动汽车的轻量化发展。本文作者针对近年来搅拌摩擦焊在镁合金中的应用, 从显微组织、接头性能、辅助技术与异种镁合金焊接等方面进行了阐述, 并对未来镁合金搅拌摩擦焊的发展

进行了展望。

1 镁合金FSW工艺参数

1.1 镁合金FSW接头组织

AZ231镁合金FSW接头形貌如图1所示^[5]。根据所受到热力的不同, 可分为焊核区(nugget zone, NZ)、热机影响区(thermal-mechanical affected zone, TMAZ)、热影响区(heat affected zone, HAZ)与母材区(base materials, BM)。

FSW过程中, 通过改变旋转与焊接速度等工艺参数可以改变热输入、材料的塑性变形与流动, 从而影响焊缝的显微组织。一般而言, 低旋转速度或者高焊接速度更易获得细小晶粒。李亚杰等^[6]研究了旋转与焊

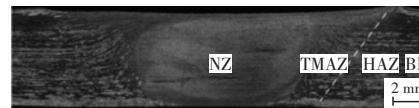


图1 AZ31 镁合金 FSW 接头形貌^[5]

Fig.1 Macroscopic image of AZ31 Mg alloy FSW joint^[5]

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接速度对AZ31镁合金显微组织的影响,研究显示,提高焊接速度可以使焊核区晶粒细化、组织均匀;提高旋转速度会造成晶粒长大。苑晨晨等^[7]对LZ91镁锂合金FSW接头显微组织分析中发现,焊核区由细小的等轴晶粒组成,且随焊接速度的增加,焊核区晶粒由于热输入的降低而细化。LI等^[8]研究了焊接速度对ZK60镁合金FSW接头显微组织的影响。结果显示,在搅拌区由

于剧烈的塑性变形形成了富Zr的颗粒,搅拌区由于Mg-Zn相的溶解造成硬度下降,搅拌区织构在焊接速度为200 mm/min时各向同性最弱,抗拉强度最高。XU等^[9]用WC-Co硬质合金搅拌头连接了Mg-14Li-1Al合金,结果显示,在旋转速度为600 r/min与焊接速度为200 mm/min时获得了平均晶粒尺寸为1.3 μm 的超细晶接头,如图2所示。

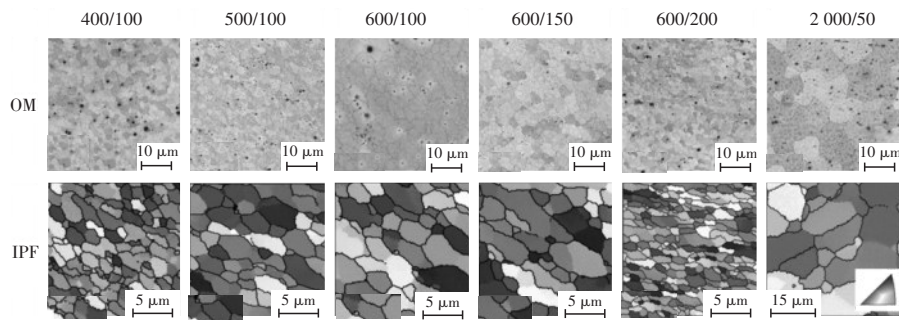


图2 不同焊接条件下搅拌区的OM图与IPF图^[9]

Fig.2 OM and IPF diagrams of stirring zone under different welding conditions^[9]

1.2 镁合金FSW接头性能

FSW工艺参数影响镁合金焊接接头的显微组织,从而使接头表现出不同的性能。一般来说,接头表面平整、内部组织无缺陷、搅拌区形成等轴晶时的性能较好。

目前,研究者对镁合金FSW接头的力学性能进行了大量的研究,镁合金FSW过程中,焊核区材料在搅拌头的剧烈搅拌下发生流动、混合与动态再结晶,从而影响了接头的力学性能。王向杰等^[10]研究了ZK60镁合金FSW接头的弯曲性能与断裂行为,结果显示,焊核区晶粒尺寸约为4 μm ,接头的弯曲性能优于母材,且面弯样品的弯曲强度高于背弯样品,织构突变对弯曲断裂行为为无明显的影响。芦丽莉等^[11]研究了AZ31镁合金FSW接头在质量分数为1%NaCl溶液中的腐蚀疲劳裂纹扩展行为,发现裂纹尖端的阳极溶解和氢脆是焊接接头各区域腐蚀疲劳裂纹扩展的主要机理。LIU等^[12]研究了AZ31镁合金FSW接头的力学性能,结果显示,接头抗拉强度最大值可达母材的88.5%,细晶强化为主要强化机制。XU等^[13]研究了AZ61镁合金FSW接头的力学性能,结果显示,搅拌区为位错密度高、{10-12}孪晶大的超细晶组织,断裂位置位于母材,强化机制为晶界强化、位错强度与析出强化。ZHOU等^[14]研究了LZ91镁锂合金FSW接头的力学性能,结果显示,由于富 α 相晶粒细化,搅拌区的硬度高于母材,热影响区的强度没有下降,搅拌区与母材区试样断裂前应变分别为0.05与0.6,接头的抗拉强度效率为100%。

镁合金接头的耐蚀性是影响其服役寿命的重要

因素之一。雷朱坦等^[15]研究了AZ31镁合金FSW接头的耐蚀性,结果显示,焊接速度对接头的耐蚀性有影响,增加焊接速度,接头的耐蚀性先增强后减弱,最佳的耐蚀性在60 mm/min的焊接速度时获得。董海荣等^[16]研究AZ31镁合金母材与FSW接头的耐蚀性,研究表明,接头的耐蚀性不如母材,浸泡腐蚀后发生全面腐蚀,其中热机影响区的腐蚀最严重,焊核区腐蚀相对较轻。张子阳等^[17]的研究也表明,由于AZ31镁合金FSW焊缝的晶粒细小与 β 相析出使得接头的耐蚀性变差,腐蚀最先从焊缝区开始,但当进入自我保护状态后,焊缝区的腐蚀速率将低于母材。

1.3 织构对镁合金FSW接头组织与性能的影响

镁合金具有密排六方晶体结构,其塑性变形后会产生较强的织构,而FSW过程中,搅拌针的剧烈搅拌所引起的焊缝区材料的流动与变形会对镁合金的织构分布产生很大的影响,进而影响镁合金焊接接头的显微组织与相关性能^[18]。INOUE等^[19]首次采用FSW技术连接了含有长周期有序堆积相的Mg-Zn-Y-Al-La合金,焊接接头的抗拉强度为248 MPa,稀土织构的形成导致织构弱化,抑制了几何软化,使得材料具有足够的延展性。同时,作者研究了Mg-Al-Ca合金FSW接头的织构演变,结果显示,焊缝主要包括焊核搅拌区(stir zone, SZ)、搅拌影响区外围(stir-affected zone, SAZ)与焊核区上方的扭转影响区(torsion-affected zone, TAZ)织构区,如图3所示^[20]。SZ与SAZ的织构演化是由于基面 $\langle a \rangle$ 与柱状 $\langle a \rangle$ 滑移同时激活,TAZ织构演化源于轴肩旋转激活了锥面 $\langle c+a \rangle$ 滑移,接头的强

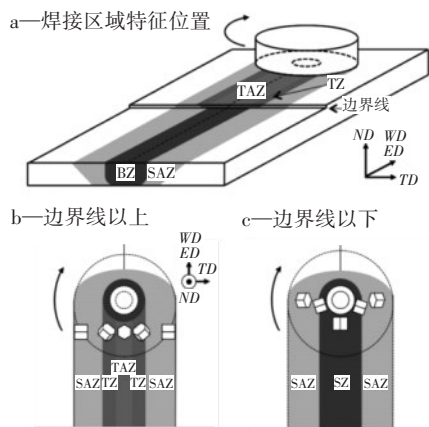


图3 特征区域位置及各区域晶体取向示意图^[20]

Fig.3 Schematic illustrations of characteristic zones positions and crystallographic orientations of individual zones^[20]

度低于母材,其断裂行为主要受区域内的几何软化支配。LI等^[21]研究了Mg-Zn-Zr合金FSW显微组织演变,结果显示,在晶粒结构演变过程中,除了起决定作用的连续动态再结晶之外,还包括应变与{10-12}孪晶的几何软化效应,越靠近焊核区,初始的<0001>||ND结构逐渐向<0001>||TD方向转变,最终转变为接近<0001>||WD的织构。XIE等^[22]研究了Mg-4.6Al-1.2Sn-0.7Zn合金FSW过程中的B纤维织构的演变,研究表明,在轴肩与搅拌针的共同作用下,织构{0001}基面与有效几何剪切面对齐,轴肩影响区织构强度相对于焊缝中心线呈对称分布,搅拌针影响区织构强度从后退侧到前进侧逐渐增大,焊接接头织构的不均匀分布源自不均匀的剪切塑性变形与材料传递。同时,XIE等^[23]研究了Mg-4.6Al-1.2Sn-0.7Zn与ZK60异种镁合金FSW接头的织构演变与力学性能。结果显示,当将塑性变形能力较好的ZK60镁合金放置在前进侧时,在焊核区产生的相对较高的流动变形造成了较高的织构强度,从而导致接头的抗拉强度较低。

2 镁合金FSW辅助技术

除常规FSW外,双轴肩、超声振动、加热/冷却、热处理等被用于镁合金FSW中,这些技术可以满足镁合金焊接接头在不同场合的使用要求,进一步改善接头的显微组织和相关性能,但同时也带来了一些技术难题,如双轴肩的装配精度、超声和加热/冷却增加了焊接过程的复杂性等。

2.1 镁合金双轴肩FSW研究

双轴肩FSW原理图如图4所示^[24]。焊接过程中,利用下轴肩代替垫板,简化了工装要求,避免了根部缺陷,除了使工件受热与组织均匀外,在中空结构型材的焊接中有广泛的应用。

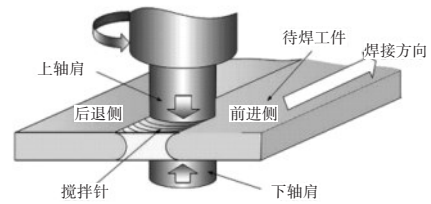


图4 双轴肩FSW原理图^[24]

Fig.4 Diagram of bobbin tool FSW^[24]

吕东泽等^[25]研究了AZ31镁合金双轴肩FSW接头的显微组织与性能,结果显示,后退侧温度高于前进侧,接头的显微硬度呈“W”型分布,抗拉强度可达到母材的92%,断裂方式为韧脆混合断裂。张海峰^[26]建立了ZK60镁合金双轴肩FSW接头材料流动行为的计算模型,研究表明,圆台+铰三平面形搅拌针的产热更高,焊接过程中前进侧搅拌头后方材料流动加强,减薄量更小。李高辉^[27]、LI等^[28-29]研究了ZK60镁合金双轴肩FSW接头的成型机制,不同区域的晶粒演化情况与织构演变规律如图5、6所示。结果显示,热机影响区晶粒取向由<0001>||ND逐渐向<0001>||TD偏转,激

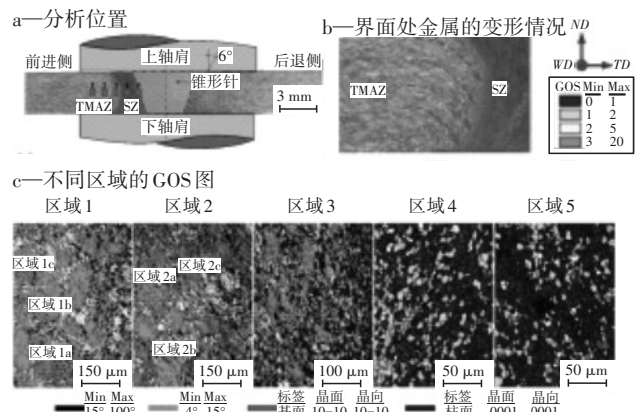


图5 不同区域的晶粒演化情况^[27]

Fig.5 Grain structure evolution in several areas of joint^[27]

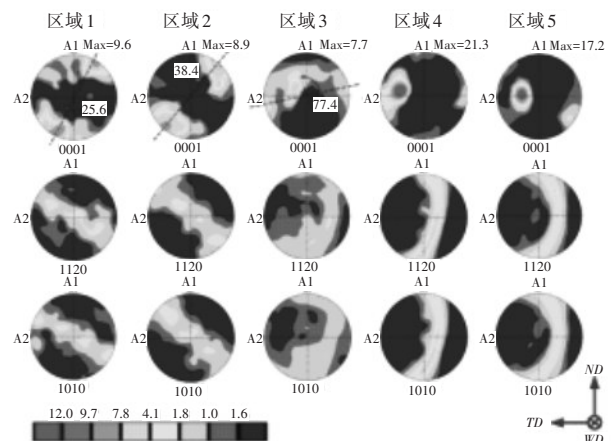


图6 织构演变情况^[27]

Fig.6 Texture evolution in several regions^[27]

活了晶粒内 $\langle 10-12 \rangle$ 和 $\langle 10-11 \rangle$ 的孪生,该区域由于热循环的影响导致 β_1' 和 β_2' 相大量溶解。热机影响区与焊核区的过渡区基面 $\langle a \rangle$ 和锥面 $\langle a+c \rangle$ 位错占比较高,晶粒具有 $\langle 0001 \rangle \parallel TD$ 且 $\langle 11-20 \rangle \parallel WD$ 的择优取向;焊核区由于峰值温度高达460 °C而使得 β_1' 和 β_2' 相全部溶解。罗三峰^[30]研究了ZK60镁合金双轴肩FSW的工艺与机理。研究表明,焊缝区沉淀相在强烈的热机作用下发生不同程度的固溶或破碎,减弱了接头的沉淀强化效果,其中焊核区的沉淀强化效果破坏最严重,硬度最低,接头的抗拉强度为264 MPa,伸长率为9.6%,断裂位置位于前进侧焊核区与热机影响区的交界处。

2.2 镁合金超声振动FSW研究

FSW过程中引入超声振动可以使得焊缝区晶粒更加细小、均匀、致密,焊缝区位错移动在热效应、体积效应与振动效应的综合作用下加强,从而提高接头的力学性能^[31],近年来在镁合金FSW中得到一定的应用。张丛楠等^[32]研究了超声对AZ31镁合金FSW接头组织与性能的影响,研究显示,超声振动(频率20 kHz)可以改善焊缝区材料的流动,明显细化焊缝中部的晶粒,提高显微硬度,降低焊接缺陷。BARADARANI等^[33]在利用FSW技术焊接AZ31镁合金时引入超声振动。结果表明,最优的FSW参数焊接速度为40 mm/min与旋转速度为1 400 r/min,相同的工艺参数下引入超声振动(振幅15 μm)可使粗大的 β - $\text{Mg}_{17}\text{Al}_{12}$ 枝晶细化且分布均匀,焊缝的显微硬度与抗拉强度分别提升了8HV与30 MPa。ABBASI等^[34]用二维元胞自动机模型分析了振动对AZ91镁合金FSW接头的组织演化。试验结果显示,振动(频率38 Hz)处理的接头中位错密度更高,形核和晶粒长大也更快;模拟结果显示,超声可使焊缝区的位错密度更高,晶粒形核和长大更快,孕育期与再结晶的比例随振动频率的提高而降低。

2.3 镁合金辅助加热/冷却FSW研究

FSW过程中,通过辅助加热可以提升材料的热塑性状态,增强材料的流动性,减少焊接缺陷,提高接头性能。王磊^[35]、CHEN等^[36]在AZ31镁合金FSW焊接过程中引入脉冲电流辅助技术。结果显示,脉冲电流使焊核区与热机影响区的过渡更平滑,焊核区沿厚度方向晶粒尺寸的差异随脉冲电流的增加而减小,焊接界面晶界处出现大量析出强化作用的含Al、Zn的析出相。朱涵文^[37]、臧千昊等^[378]在焊接工件下面添加底部预热工具来改善AZ31镁合金FSW接头的显微组织与性能。研究显示,通过底部辅热可以降低接头的表面粗糙度,弥合焊缝内部孔洞、隧道等缺陷,使接头的显微硬度分布更加均匀,抗拉强度与伸长率更高。章宇盟^[39]通过FSW焊接AZ31时在焊缝区域外侧与内部分

别放置了热管。研究了热管对焊接接头显微组织与力学性能的影响。结果显示,在焊缝区域外侧放置热管可使沿焊接方向焊核区晶粒粗化的趋势减小,且热机影响区与热影响区的再结晶程度显著下降,从而提升接头的抗拉强度,而焊缝区域内部放置热管所产生的效果不明显。

除辅助加热外,FSW过程中施加冷却可以细化晶粒、组织均匀,提高镁合金焊接接头性能。许楠等^[40]、XU等^[41-42]研究了液态 CO_2 对AZ31镁合金FSW接头组织与性能的影响。研究显示,快速冷却可以使焊缝顶部形成高密度位错、 $\langle 10-12 \rangle$ 孪晶与第二相颗粒的细晶结构,拉伸过程中,孪晶面可以协调应变,减小应力集中,提高接头的抗拉强度与伸长率。同时,本研究^[43-44]在Mg-14Li-1Al与Mg-9Al-1Zn-1Ca合金FSW中得到了类似的试验结果。

对比可以发现,辅助加热可减少焊接缺陷与不同焊接区域的晶粒尺寸差异,从而使力学性能得到提升。而辅助冷却可以细化晶粒,增加位错密度,从而提升接头的力学性能。

2.4 镁合金FSW热处理工艺

镁合金为密排六方结构,其滑移系较少,导致其塑性变形能力较差,接头的组织与性能存在一定问题,热处理是改善镁合金FSW接头组织并提高其性能的有效手段。陆寒等^[45]在焊接AZ91镁合金前对其进行400 °C保温12 h的预固溶处理。研究显示,尽管焊前热处理会使焊核区晶粒尺寸有所增长,但是可显著改善焊缝区第二相的分布,显微组织变形更均匀,接头的强度和塑性得到改善。罗畅等^[46]对Mg-6Zn-1Gd合金FSW接头进行430 °C保温0.5/1/2/3/4 h水冷的固溶处理,研究了热处理时间对接头组织与性能的影响。结果显示,焊核区平均晶粒尺寸随固溶时间的增加而增大,4 h后达到46 μm ,第二相由大块状逐渐破碎、溶解为小颗粒,焊核区出现软化现象,固溶2 h后接头的抗拉强度最大。姜超等^[47]研究了焊后拉伸+退火对AZ31镁合金FSW接头耐蚀性的影响。研究显示,焊后拉伸会导致接头的耐蚀性降低,但是拉伸后退火处理可以提高接头的耐蚀性。李锦鹏等^[48]研究了固溶与人工时效对AZ91镁合金FSW接头显微组织与力学性能的影响。结果显示,固溶处理可以使脆性 β 相完全溶解,改善接头的塑性。KUMAR等^[49]对AZ31镁合金FSW接头进行热处理。研究发现,250 °C保温1 h可以细化 α -Mg,使 β - $\text{Mg}_{17}\text{Al}_{12}$ 相溶解到基体中。GAO等^[50]研究了自然时效对双相Mg-9Li-3Al-3Zn合金显微组织的影响。结果表明,自然时效过程中 γ 相析出物含量增加,焊缝的析出强化效应减弱,导致接头强度与耐蚀性下降。

2.5 其他

陈玉华等^[51]利用单轴肩搅拌头实现了AZ31镁合金的双面FSW,结果显示,在焊缝区域出现了双面FSW独有的重叠区,该区域存在超细晶粒与 Al_3Mn_5 沉淀相,使接头的抗拉强度与伸长率分别达到217.7 MPa与14.65%,接头的强度系数达到母材的85.81%。闫志峰等^[52]研究了AZ31镁合金双面FSW接头的疲劳性能。结果显示,双面焊的疲劳极限提高了76%,双面焊可增强镁合金FSW接头抵抗变形的能力。

王大伟等^[53]研究了AZ31镁合金FSW静轴肩技术。结果显示,旋转速度为700 r/min时的焊核区晶粒沿板厚差异最小,接头的强度系数达到90.2%。陈树君等^[54]建立了AZ31镁合金载流FSW静轴肩双热源数值模型。结果显示,温度场分布沿焊缝厚度方向随电流的增加趋于均匀化,应力场峰值从532 MPa降至461 MPa。

LI等^[55]研究了AZ61镁合金自反应FSW。结果显示,在较低焊接速度下的焊缝存在孔隙缺陷,在较高焊接速度下的晶粒更加细小。随焊接速度的增加,接头的抗拉强度逐渐增大。

任大鑫等^[56]为解决FSW过程中板材厚度与搅拌针长度的适应性问题,提出了在焊缝背面添加适当厚度同种材料垫板的新型工艺。这一技术可以降低对搅拌针长度的要求,同时可消除焊接过程中的焊缝减薄问题,该技术成功实现了1.5 mm厚的AZ31镁合金对接。

高辉等^[57]在AZ31镁合金FSW中添加纳米SiC颗粒。研究发现,增加加工道次可使纳米SiC颗粒在焊缝中分布更加均匀。添加纳米SiC颗粒可以增加形核点,细化晶粒,提高接头的抗拉强度与耐腐蚀性。

3 异种镁合金FSW研究

近年来,异种金属材料结构可以发挥单一材料所不具备的性能,从而成为材料焊接领域的研究热点之一^[58-60]。对于异种镁合金搅拌摩擦焊,目前的研究较少,国内外学者针对异种镁合金的焊接性、材料流动等行为进行了初步的研究。

田菲等^[61]开展了AZ31与ZK60异种镁合金的FSW研究。结果显示,ZK60一侧焊核区的晶粒更细小,焊接接头的屈服强度介于两种基体之间。崔成武等^[62]采用不同FSW工艺参数制备了AZ40M/AZ61A焊接接头。研究表明,焊核区由于动态再结晶形成了细小的等轴晶粒,接头的最大抗拉强度达到235 MPa。雷朱坦等^[63]、张香云等^[64]对AZ31镁合金与LA141镁锂合金的焊接性进行了分析。研究表明,前进侧热机影响区的晶粒比后退侧更加细小,而热影响区呈相反趋势,接头抗拉强度随旋转速度的增加先升高后降低,拉剪力在旋转速度为1 600 r/min时达到最大,为2 313.5 N。XIE等^[65]开展了ZK60与ATZ511异种镁合金双道焊FSW研究。结果显示,双道焊可以提升焊接接头的抗拉强度。LUO等^[66]对AZ91与ZG61异种镁合金FSW进行了研究。结果显示,焊接界面未出现明显的反应层和金属间化合物,接头的力学性能主要受材料位置、晶粒尺寸与结晶取向的影响。LIANG等^[67]讨论了含准晶相的 $Mg_{95.8}Zn_{3.6}Cd_{0.6}$ 与含长周期相的 $Mg_{97}Cu_1Y_2$ 异种镁合金的可焊性。结果显示,在焊核区形成了含不同合金层的洋葱环结构,粗大的准晶相颗粒破碎转变为立方结构的W相,18R-LPSO有序相转变为细小的14H-LPSO板条,新形成的相与基体之间无特定的取向关系,同时,在两侧热机影响区发现,少量的准晶粒子与长周

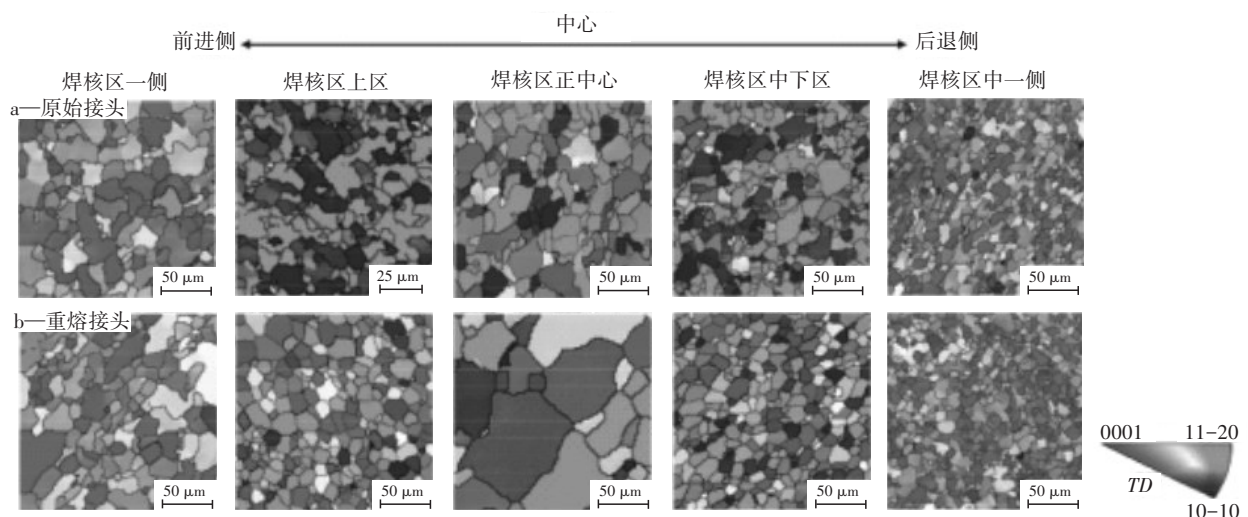


图7 不同AZ31/AM60接头的IPF图^[68]

Fig.7 IPF diagram of different AZ31/AM60 joints^[68]

期有序堆积相发生了相变。图7中ZHANG等^[68]对异种镁合金FSW接头进行重熔处理。结果显示,电弧加热可使AZ31/AM60异种接头焊核区中部的织构发生变化。同时,作者研究了AZ31/AM60双面FSW工艺^[69],结果显示,织构在焊核区呈对称分布,接头基底滑移的Schmidt因子从焊核区附近到焊核区中心呈减小趋势,接头具有良好的力学性能。SINGH等^[70]开展了AZ91与AZ31异种镁合金FSW研究。结果显示,接头断裂位置位于于前进侧,显微硬度最大值为84.04HV。

4 总结

1) 对镁合金FSW接头的金属间化合物的生成情况进行了研究,分析了有害金属间化合物的产生及预防措施,尤其是异种镁合金FSW。

2) 开展新工艺、新技术来进一步降低镁合金FSW过程中织构对接头性能有害影响。

3) 开发新型镁合金(如稀土镁合金、镁锂合金等)FSW技术,优化焊接工艺参数,提高接头性能,拓展镁合金FSW在工程中的应用范围。

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铝合金搅拌摩擦焊接头疲劳性能研究进展

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摘要 铝合金因优异的性能被广泛用于航空航天、交通运输等领域,但其连接工艺仍制约着铝合金的使用。固相焊接——搅拌摩擦焊解决了铝合金铆接的增重和熔化焊连接时易产生焊接缺陷的问题,在一定程度上解决了铝合金的连接问题。与其他焊接工艺相同,铝合金的搅拌摩擦焊接头是焊件的薄弱环节,影响焊件的安全性及寿命。故铝合金搅拌摩擦焊接头疲劳性能的优劣是决定构件耐久性和安全性的关键因素。因此,系统而深入的掌握铝合金搅拌摩擦焊接头疲劳性能至关重要。本文详细介绍了铝合金搅拌摩擦焊接头的组织及疲劳断裂特征,分析了工艺参数、显微组织、外加载荷、腐蚀环境等因素对铝合金搅拌摩擦焊接头疲劳性能的影响,总结了表面强化技术、外加辅助技术、热处理等提升铝合金搅拌摩擦焊接头疲劳性能的方法,最后对铝合金搅拌摩擦焊接头疲劳性能的研究进行了展望。

关键词 搅拌摩擦焊;铝合金;研究进展;疲劳性能;强化方法

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Research progress on fatigue performance of aluminum alloy friction stir welded joints

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Abstract Aluminum alloy is widely used in aerospace, transportation and other fields because of its excellent performance, but its connection process still restricts the use of aluminum alloy. Solid phase welding-friction stir welding solves the problem of weight gain in aluminum alloy riveting and the problem of welding defects in fusion welding connection, and solves the connection problem of aluminum alloy to a certain extent. As with other welding processes, the friction stir welding joint of aluminum alloy is a weak link in the weldment, affecting the safety and life of the weldment. Therefore, the fatigue performance of aluminum alloy friction stir welding joint is the key factor to determine the durability and safety of the component. Therefore, it is very important to systematically and deeply grasp the fatigue performance of aluminum alloy friction stir welding joints. This paper introduces the microstructure and fatigue fracture characteristics of aluminum alloy friction stir welding joints in detail, analyzes the effects of process parameters, microstructure, applied load, corrosion environment and other factors on the fatigue performance of aluminum alloy friction stir welding joints, and summarizes the surface strengthening technology, external auxiliary technology, heat treatment and other methods to improve the fatigue performance of aluminum alloy friction stir welding joints. Finally, the research on fatigue performance of aluminum alloy friction stir welding joints is prospected.

Keywords friction stir welding; aluminum alloy; research progress; fatigue performance; strengthening methods

铝合金具有密度低、比强度高、耐腐蚀性好、加工性能优异、导电导热性好等优点,被广泛用于航空航天、交通运输等领域^[1]。但铝合金的连接仍是工程上关注最多的重要问题之一。铝合金铆接是一种较常见的连

接工艺,虽能增加构件的安全性但也会增加了构件质量;而常规的铝合金熔焊会出现气孔、变形等缺陷,降低焊件质量,严重影响焊件的强度及性能,限制铝合金的使用范围。当搅拌摩擦焊(FSW)技术被提出后,铝

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