核电异种金属焊接材料及方法研究现状

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摘要： 异种金属焊接接头开裂是导致核电事故的主要原因，急需开发新材料新技术，提高焊缝质量。传统电弧焊方法存在效率低、热输入大和变形严重等问题。窄间隙电弧焊的热输入、填充量、变形量等都比传统电弧焊低。与窄间隙电弧焊相比，窄间隙激光填丝焊坡口更窄、热输入更低、变形更小、精度更高。研究表明，窄间隙激光填丝焊可获得满足核电压力容器制造要求的焊缝，有望成为异种金属连接新方法。然而，现有窄间隙激光填丝焊采用常规激光及单焊丝填充，仍存在 3 个主要问题：一是界面容易产生未熔合问题；二是熔融金属粘度大，熔池流动性差，合金元素分布不均匀；三是低熔点共晶相沿晶界析出过多，无法兼顾焊缝抗液化裂纹、应力腐蚀裂纹和高温失塑裂纹能力。研究表明，焊接热源和焊材是解决上述问题的 2 个关键因素。

创新点：（1）系统论述了核电异种金属焊接材料的发展及其趋势。
（2）窄间隙激光焊接有潜力成为核电异种金属连接的新方法。
（3）焊接热源和焊材是解决窄间隙激光填丝焊界面未熔合、熔池流动性差低及低熔点共晶相沿晶界析出过多等问题的 2 个关键因素。

关键词： 核电异种金属；窄间隙激光填丝焊；熔池流动行为；焊接冶金

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Research status of welding materials and methods for dissimilar metals in nuclear power

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Abstract: The cracking of welded joints of dissimilar metals is the main cause of nuclear power accidents. It is urgent to develop new materials and new process to improve the weld quality. Traditional arc welding has some problems, such as low efficiency, large heat input and serious deformation. Heat input, filling and deformation of narrow gap arc welding are lower than those of traditional arc welding. Compared with narrow gap arc welding, narrow gap laser welding with filling wire addition has narrower groove, lower heat input, smaller deformation and higher precision. The previous research indicated that narrow gap laser welding with filler wire addition could meet the requirements of the nuclear pressure vessel manufacture. It was expected to become a new method of the dissimilar metal welding. However, there were still three main problems existing in the available narrow gap laser welding with normal laser and filler single wire addition process. Firstly, the interface was easy to produce incomplete fusion. Secondly, the viscosity of molten metal was high and the fluidity of molten pool was poor resulting in the uneven distribution of alloy elements. Thirdly, the eutectic phase with low melting point precipitated too much along the grain boundary, which couldn't take into account the ability of weld to resist liquefaction crack, stress corrosion crack and high-temperature plastic crack. The applicant believed that the welding heat source and filler materials were the two key factors to solve the above problems.

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Highlights: (1) The development and trend of welding materials for nuclear dissimilar metals were systematically discussed.
(2) The narrow gap laser welding had the potential to become a new method of welding dissimilar metals in a nuclear power.
(3) The welding heat source and welding materials were the two key factors to solve problems such as incomplete fusion of interface, poor fluidity of molten pooland eutectic phase with low melting point precipitated too much along the grain boundary in narrow gap laser welding with filler wire addition.

Key words: nuclear dissimilar metal, narrow gap laser welding with filler wire addition, welding pool flow behavior, welding metallurgy

0 前言

随着全球气候变暖,优化能源消费结构,发展洁净能源成为全球趋势。核电是清洁、低碳、经济能源,受到世界各国的重视和青睐。近年来,中国也大力发展核电,是目前在建核电站最多的国家。因此,核电站的"心脏"——核反应堆的制造技术的重要性日益突出。

核反应堆的主要结构件为核反应堆压力容器、蒸汽发生器和稳压器等压力容器,以及与之相连接的各种管道,其中低合金铁素体钢压力容器与奥氏体不锈钢管道异种金属焊接是其制造难点和关键技术[1]。由于异种金属的成分、熔点、热膨胀系数、强塑性等物理化学性质差异较大,焊缝容易出现 C 元素迁移、未熔合和液化裂纹等问题,是核反应堆最薄弱的部位。而且,焊接接头长期服役在高温高压与腐蚀环境中,极易发生应力腐蚀开裂,导致核电泄露事故。因此,急需开发新材料新工艺新技术,提高核电异种金属焊接接头质量。

目前,电弧焊是核电异种金属连接的主要方法,奥氏体不锈钢和镍基合金焊丝是主要焊材[2]。与传统电弧焊相比,激光焊具有速度快、热输入低、变形小等优点。相关研究表明,窄间隙激光填丝焊可获得满足核电压力容器制造要求的焊缝,有望成为核电异种金属连接的新方法。然而,现有窄间隙激光填丝焊采用常规激光及单焊丝填充,仍存在以下三个主要问题:①界面容易产生未熔合问题;②熔融金属粘度大,熔池流动性差,合金元素分布不均匀;③低熔点共晶相沿晶界析出过多,无法兼顾焊缝抗液化裂纹、应力腐蚀裂纹(SCC)和高温失塑裂纹(DDC)能力[3-5]。

1 核电异种金属焊接材料

奥氏体不锈钢和镍基合金是核电异种金属焊接的主要焊材,两者各有千秋。

中科院沈阳金属研究所[6]采用 309L 和 308L 奥氏体不锈钢焊丝作为焊材,电弧焊焊接低合金铁素体钢 SA508 与 316L 奥氏体不锈钢,研究表明,焊缝裂纹敏感性较低,308L/316L 界面结合良好,晶粒外延生长,原因是两者的成分、熔点和晶体结构等物理化学性质十分接近。然而,对于 309L/SA508、308L/SA508 界面,因焊材与母材性质差异较大,界面出现未熔合。此外,因浓度梯度的缘故,C 元素从 SA508 母材向 308L、309L 焊缝迁移,导致在界面近 SA508 母材一侧形成贫碳区,也称为软化区,而在界面近 308L 或 309L 焊缝一侧形成脆硬马氏体组织,称为低塑性区。C 元素迁移现象,降低了接头的高温持久强度和塑性。

日本的东北大学与核电安全研发中心[7]、上海大学[8]、土耳其阿塔土尔克大学[9]等研究机构采用奥氏体不锈钢焊丝作为焊材连接低合金铁素体钢和奥氏体不锈钢时,也都发现界面 C 元素迁移现象。因此,印度马尼帕尔理工学院[10]和印度国家冶金试验室[11]对比研究了 309L 和镍基合金焊丝 FM82 作为焊材连接 SA508 和 304L 异种金属,研究表明,与 309L 焊丝相比,FM82 焊丝能更好地抑制 C 元素迁移,原因是 C 元素在镍基合金焊缝金属中的溶解度和扩散系数都较低。伊朗沙希德·昌兰大学[12]对比研究了 309L 和镍基合金焊丝(ERNiCrMoCo-1, ERNiCr-3)作为焊材连接低合金钢 A387 和镍基合金 617 异种金属,研究也表明镍基合金焊丝的抗 C 元素迁移能力更强。

英国曼切斯特大学[13]报道 FM82 焊缝的晶间应力腐蚀裂纹敏感性较高,原因是焊缝大量 $Cr_{23}C_6$ 和 Cr_7C_3 等碳化物沿晶界析出而产生贫 Cr 区。在残余应力或热应力以及腐蚀溶液的作用下,晶界贫 Cr 区的出现容易引起焊缝应力腐蚀裂纹的萌生和扩展。美国俄亥俄州立大学[14]指出 FM 82 焊缝的液化裂纹敏感性也较高,系 Ti, Nb 等合金元素的碳化物或氮化物共晶相沿晶界析出所致。因为,低熔点共晶相液态薄膜最后凝固于枝晶间隙,容易受拉而开裂,形成液化裂纹。与 FM82 相比,镍基合金焊丝 FM52 降低了 Ni, C 含量, Cr 含量也由 15% 增至 30%,晶间碳化物低熔点共晶相的减少,减缓了 FM52 焊缝晶间应力腐蚀裂纹和液化裂纹敏感性。然而,FM52 焊缝容易产生固相裂纹——高温

失塑裂纹[15-16]。

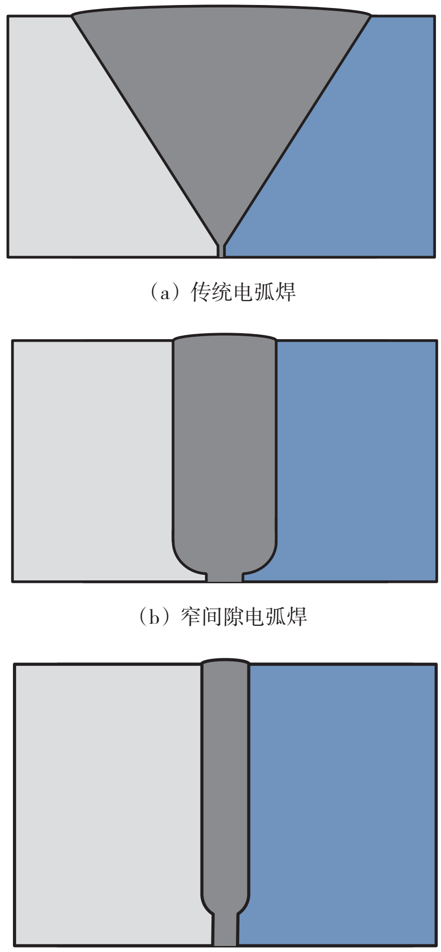
近年来,在 FM52 的基础上,通过添加适量 Nb,Mo 元素,获得了改进型 FM52M 焊丝。虽然,FM52M 并非对高温失塑裂纹完全免疫,但是与 FM 52 焊缝相比,FM52M 焊缝晶界析出较多的富 Nb,Mo 碳化物低熔点共晶相,提高了焊缝抗高温失塑裂纹能力。然而,美国俄亥俄州立大学[17]、韩国东亚大学[18]、华东理工大学[19]的研究表明,Nb,Mo 等元素的作用像一把双刃剑,富 Nb,Mo 碳化物和 Laves 相(富 Nb,Mo,Si 碳化物)等低熔点共晶相可钉扎晶界,防止其滑移为直线,降低焊缝高温失塑裂纹敏感性。但是,过多的低熔点共晶相在晶界聚集,容易引起晶界液化裂纹和应力腐蚀裂纹。因此,美国俄亥俄州立大学[17]探索了用 Hf 替代 Nb 元素的可行性,但研究结果表明,添加适量的 Hf 元素,焊缝高温失塑裂纹敏感性仍较高,原因是 Hf 元素未能像 Nb,Mo 元素一样促使低熔点共晶相生成。最近,美国电力科学研究院[20]采用 2 种不同成分的镍基合金焊丝组合成“双成分焊丝”,以及镍基与铁基合金组合成“异种焊丝”填充电弧焊接,以控制晶界低熔点共晶相的析出行为。此外,美国阿拉巴马州立大学[21]的试验和模拟研究均表明,提高焊接冷却速率至 10 ℃/s 以上,可将低熔点共晶相的含量控制在较低的水平。

以上研究结果表明,奥氏体不锈钢和镍基合金焊丝是核电异种金属焊接的主要焊材,两者的优缺点明显。目前的研究主要从优化焊材和控制焊接热循环两方面入手,调控焊缝低熔点共晶相析出行为,兼顾焊缝抗液化裂纹、应力腐蚀裂纹和高温失塑裂纹能力。

2 核电异种金属焊接方法

目前,传统电弧焊是核电异种金属连接的主要方法。然而,该方法存在效率低、热输入大和变形严重等问题。近年来,窄间隙电弧焊的热输入、填充量、变形量等都比传统电弧焊低,已在实际生产中得到应用[22]。与窄间隙电弧焊相比,窄间隙激光填丝焊坡口更窄、热输入更低、变形更小、精度更高,也有望成为异种金属连接的新方法,如图 1 所示。

上海交通大学和南京理工大学[23]课题组采用窄间隙激光填充 FM52M 焊丝的方法,成功实现了低合金钢 18MND5 与 316L 异种金属的可靠连接,该研究还表明,富 Nb 碳化物和 Laves 相等低熔点共晶相优先沉淀于晶界,焊缝应力腐蚀裂纹和液化裂纹敏感性较高,且该低熔点共晶相含量与焊接热输入成正比。同时,FM52M



(a) 传统电弧焊

(b) 窄间隙电弧焊

(c) 窄间隙激光焊

图 1 核电异种金属不同焊接方法对比示意图

熔融金属流动性差,容易产生界面未熔合问题,界面反应化合物主要是呈絮状和链状的富 Cr,Mo 化合物,降低了焊接接头拉伸性能。

大连理工大学[24]从成分角度研究了镍基合金 C-276 与 304 奥氏体不锈钢异种金属激光焊焊缝裂纹敏感性问题,研究表明,当 304 的稀释率在 73% ~ 85% 时,即 Fe 元素含量较高时,Mo 元素偏析系数较低,对应低熔点共晶相非常少,降低了晶间应力腐蚀裂纹和液化裂纹敏感性。美国宾夕法尼亚州立大学[25]利用激光增材技术制备 Ni,Cr,Fe 元素梯度过渡的异种金属接头,与传统接头相比,成分梯度过渡接头抑制 C 元素迁移能力提高了 20 倍,应力腐蚀裂纹敏感性也较低。

哈尔滨工业大学课题组[26]则从焊接热源角度改善镍基合金与铜基合金异种金属焊缝合金元素分布不均与低熔点共晶相析出过多问题,研究表明,摆动激光焊接异种金属,界面结合不良区域以及共晶相含量明显

减少,合金元素分布均匀。该课题组[27]采用摆动激光焊接304奥氏体不锈钢时,熔池前部形成涡流和一些湍流,焊接冷却速率增加,焊缝晶粒尺寸明显减小,提高了接头力学性能。

华中科技大学[28-29]课题组采用高速摄像系统监控窄间隙激光焊接过程,成功实现了异种金属的连接,研究表明,窄间隙条件下,焊丝熔化形成的熔融金属未能过渡至熔池,而是过渡到侧壁上,产生未熔合等缺陷。哈尔滨工业大学[30-32]也采用高速摄像系统获取了焊丝熔滴的过渡行为及其对激光焊接过程稳定性的影响规律,同时,亦研究了厚板激光焊接组织演变及裂纹扩展特性[33]。英国曼切斯特大学[34]则采用实验与模拟相结合的方法研究了窄间隙激光填丝焊熔池动力学与焊缝熔合区的形成过程,获得了焊接温度场分布与熔池流动行为。此外,英国焊接研究所[35]、新加坡万度力公司[36]、印度安纳马莱大学[37]等机构亦开展了核电异种金属窄间隙激光焊接工艺与性能方面的研究。

英国曼切斯特大学参与了英国新一代核电制造项目,开展了窄间隙激光填丝焊接SA508的可行性研究[38-40],主要获得以下成果:①获得了满足关键核电部件制造要求的焊缝,阐明了焊缝组织演变机制与连接机理;②裂纹、未熔合和气孔是窄间隙激光焊的主要缺陷,通过控制焊接热输入,可以抑制裂纹产生;合理匹配激光-焊丝的能量与空间关系,可以消除未熔合;优化保护气流量和输送位置,可以减少焊缝气孔;③焊缝裂纹择优向屈服强度低的母材扩展。

3 结束语

(1)界面容易产生未熔合问题。

(2)熔融金属粘度大,熔池流动性差,合金元素分布不均匀。

(3)低熔点共晶相沿晶界析出过多,无法兼顾焊缝抗液化裂纹、应力腐蚀裂纹和高温失塑裂纹能力。焊接热源和焊材是解决上述问题的两个关键因素。

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