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从表观熔合线到真实熔合区：**F91/ERNiCr-3** 堆焊界面分区及 **PMZ** 高温风险

摘要

F91/ERNiCr-3 异种金属堆焊界面存在显著的成分、组织、相结构及热物理性能梯度，是接头高温服役过程中的潜在薄弱区域。从微观尺度看，该界面并非单一几何线，而是具有一定空间尺度的熔合区或成分过渡区。其中，真实熔合线代表熔合区最靠近未熔化 F91 母材一侧的边界，是界定界面热历史、冶金分区及碳迁移行为的重要空间基准。然而，现有研究通常依据金相腐蚀或电解抛光后观察到的表观界面标定熔合线，其是否等同于真实熔化边界仍缺乏验证。
本研究结合 $FeCl_3$ 腐蚀、电解抛光、硬度坑空间标记、EDS、EBSD、JMatPro 计算和高温原位实验，分析了 F91/ERNiCr-3 堆焊界面的宏观偏析特征、真实熔合线位置及 PMZ 高温相稳定性。结果表明，TIG 堆焊界面并非均匀单一结构，而主要由无 PMZ 的普通界面和含 PMZ 的宏观偏析界面组成，二者沿界面长度占比分别约为 24.2% 和 75.8%。$FeCl_3$ 腐蚀界面主要反映腐蚀响应差异，电解抛光界面主要对应 bcc/fcc 相界，二者均不应直接等同于真实熔合线。
通过硬度坑定位、EBSD 晶粒形貌和 EDS 的 Ni 分布的联合分析发现，真实熔合线位于传统腐蚀界面更靠近 F91 母材的一侧，并揭示了 CGHAZ 与 PMZ/TZ 之间常被忽略的 F91 UMZ。该区域具有凝固组织特征，其形成源于熔池边界层混合不足。进一步研究表明，PMZ 虽在室温下保持 bcc 结构，但因 Ni 渗入导致 Ac1 降低至约 300–400 ℃，低于典型服役温度 541℃，并在高温原位实验中观察到疑似固态相变行为。该研究澄清了表观腐蚀界面、相界和真实熔合边界之间的差异，为 F91/镍基焊材异种金属接头界面组织识别、碳迁移分析、高温铁素体残留机制解释及服役风险评估提供了更准确的冶金依据。

关键词

异种金属焊接、熔合线、界面宏观偏析、部分混合区

Abstract

F91/ERNiCr-3 dissimilar metal buttering interfaces exhibit pronounced gradients in composition, microstructure, phase constitution, and thermophysical properties, making them potential weak regions during high-temperature service. At the microscale, such an interface should not be regarded as a geometrically sharp line, but rather as a fusion region or compositional transition zone with a finite spatial extent. The true fusion line, defined as the boundary of this region closest to the unmelted F91 base metal, provides an essential spatial reference for interpreting the interfacial thermal history, metallurgical zoning, and carbon-migration behaviour. However, in previous studies, the fusion line has commonly been identified from the apparent boundary revealed by metallographic etching or electropolishing, although whether this boundary truly corresponds to the actual melting boundary remains insufficiently verified.
In this study, $FeCl_3$ etching, electropolishing, microhardness-indent spatial marking, EDS, EBSD, JMatPro calculations, and in-situ high-temperature observation were combined to investigate interfacial macrosegregation, the location of the true fusion line, and the high-temperature phase stability of the partially mixed zone (PMZ) in F91/ERNiCr-3 TIG buttering. The results show that the TIG-buttered interface is not a uniform single structure, but mainly consists of PMZ-free ordinary interface segments and PMZ-containing macrosegregated interface segments, which account for approximately 24.2% and 75.8% of the interfacial length, respectively. The boundary revealed by $FeCl_3$ etching mainly reflects differences in corrosion response, whereas the boundary observed after electropolishing primarily corresponds to the bcc/fcc phase boundary. Therefore, neither boundary should be directly equated with the true fusion line.
By correlating microhardness-indent markers with EBSD grain morphology and EDS Ni distributions, the true fusion boundary was found to lie on the F91 base-metal side of the conventionally etched boundary. This finding further reveals a previously overlooked F91 unmixed zone (UMZ) between the CGHAZ and the PMZ/TZ. This zone exhibits solidification-related microstructural features, and its formation can be attributed to insufficient mixing within the molten-pool boundary layer. Further analysis indicates that, although the

PMZ retains a bcc structure at room temperature, local Ni enrichment lowers its Ac1 temperature to approximately 300–400 ℃, below the typical service temperature of 541 ℃. In-situ high-temperature observation also revealed microstructural changes indicative of possible solid-state transformation. This study clarifies the differences among the apparent etched boundary, the phase boundary, and the true fusion line, providing a more accurate metallurgical basis for interfacial microstructure identification, carbon-migration analysis, interpretation of retained high-temperature ferrite, and service-risk assessment of F91/Ni-filler dissimilar metal joints.

Keywords

Dissimilar metal welding，Fusion line，Interfacial macrosegregation，Partially mixed zone (PMZ)

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