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F91/ERNiCr-3 堆焊界面真实熔合线识别及冶金分区重构

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 计算和高温原位观察，系统分析了 F91/ERNiCr-3 TIG 堆焊界面的结构特征。结果表明，该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，而电解抛光后观察到的界面可能主要受 Ni 含量及其梯度所控制。两类表观界面均不同于实际熔合线。
结合硬度坑空间标记、EBSD 晶粒分析和 EDS 的 Ni 扩散特征，确认实际熔合线位于传统腐蚀界面更靠近 F91 母材的一侧约 20μm 处。这一结果揭示了 CGHAZ 与 PMZ/TZ 之间存在一层以往容易被忽略的 F91 UMZ。该区域具有与凝固相关的组织特征，可能来源于熔池边界层内液态金属混合不足。上述结果澄清了传统基于腐蚀得到的表观界面并非实际熔合线，完善了 F91/ERNiCr-3 bcc/fcc 异种金属界面的冶金分区认识，并为后续界面碳迁移分析和高温铁素体残留机制解释提供了更准确的冶金分析依据。

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 single geometrical line, but rather as a fusion region or compositional transition zone with a finite spatial extent. The true fusion line represents the boundary of this fusion region closest to the unmelted F91 base metal, and therefore provides an important spatial reference for defining the interfacial thermal history, metallurgical zoning, and carbon-migration behaviour. However, in previous studies, the fusion line has commonly been identified from the apparent interface revealed by metallographic etching or electropolishing, while whether such an apparent interface corresponds to the true 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 systematically investigate the interfacial structure of F91/ERNiCr-3 TIG buttering. The results show that the 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 interface revealed by $FeCl_3$ etching mainly reflects differences in corrosion response, whereas the interface observed after electropolishing may be largely governed by the local Ni content and its compositional gradient. Neither type of apparent interface corresponds to the actual fusion line.
By combining microhardness-indent spatial marking, EBSD grain analysis, and EDS-based characterization of Ni diffusion/enrichment, the actual fusion line was confirmed to be located approximately 20 μm on the F91 base-metal side of the conventionally etched interface. This finding reveals a previously overlooked F91 unmixed zone between the CGHAZ and the PMZ/TZ. This region exhibits solidification-related microstructural features and is likely associated with insufficient mixing of liquid metal within the molten-pool boundary layer. These results clarify that the apparent interface conventionally identified by etching is not the actual fusion line, refine the metallurgical zoning of the F91/ERNiCr-3 bcc/fcc dissimilar metal interface, and provide a

more accurate metallurgical basis for subsequent analyses of interfacial carbon migration and the mechanism of retained high-temperature ferrite.

Keywords

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

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