Effect of Mold Electromagnetic Stirring Parameters on Segregation Level of a Medium-Carbon Steel

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Oil country tubular goods (OCTG) is a class of steel used for oil and gas exploration in environments where pressure, temperature and acid solutions are frequently present. For this application, a fine-tuned combination of mechanical properties and surface quality are mandatory for the well integrity. One of the ways to reduce surface imperfections on the internal surface of pipes is by reducing solidification segregation. Based on that, this study evaluated the effect of varying the electrical current of mold electromagnetic stirring on segregation level of continuously cast bars of an OCTG steel. Both macro and microstructural characterization were performed to identify the effects of stirring current intensity. Results showed that too-high current levels increase spot segregation and chemical heterogeneity.

Introduction

Segregation is a phenomenon that occurs due to differences in solubility of solute in the liquid and solid phases during solidification. In industrial castings, segregation can be classified into three categories based on the spatial scale at which it occurs. Microsegregation refers to variations in chemical composition on the scale of dendrite arm spacing, while macrosegregation occurs on a much larger scale, typically correlating with the dimensions of the final product.[1] Additionally, a third category, often termed semimacrosegregation[2] or spot segregation,[3] lies between these two length scales.

During the hot rolling of seamless pipes, there is significant contact between the internal surface of the pipe and tooling, such as the piercer plug and mandrel bar. This process induces strong plastic deformation in the steel bar, particularly in the central region of the bar. The steel's ability to flow at elevated temperatures, such as 1,200°C, is influenced by the bar's integrity. High levels of segregation can disrupt material flow, leading to surface imperfections, such as laps.[4] Therefore, minimizing segregation during the solidification process is critical for improving the surface quality of hot-rolled seamless pipes used in the oil and gas industry.

Most alloying elements in steels exhibit a segregation index (k) lower than unity,[5] indicating that their solubility in the liquid phase is higher than in the solid phase. This means that as solidification progresses, the liquid becomes increasingly enriched in solute. Under typical steel casting conditions, the solid growth is dendritic. Solute rejection occurs (in the case of $k<1$) toward the interdendritic region, giving rise to microsegregation.[1]

The two-phase region between the tips of growing dendrites and the fully solidified area is often referred to as the mushy zone. Macrosegregation typically arises from the movement of interdendritic liquid within this zone.[6] Several factors can drive the flow of interdendritic liquid, including: shrinkage during solidification; convection currents due to density differences between the enriched liquid in the mushy zone and the nonenriched liquid in the central region of the ingot; and convection current due to temperature-induced density differences between the liquid in the mushy zone and that in the central region, or movement of the solid shell.[7,8] The interplay of these factors leads to complex macrosegregation patterns, often