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On the damage mechanisms in a continuous casting mold: After-service material characterization and finite element simulation

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ABSTRACT

A mold is a part of a continuous casting plant where the molten steel starts to solidify. The inner surface of the mold undergoes a cyclic thermal load. In fact, service conditions are characterized by a high thermal flux, which vanishes when the plant is switched off. The highest temperatures occur in the area just beneath the free level of liquid steel (meniscus). The same area is typically characterized by thermal fatigue cracks when the mold is inspected after service.

This work presents the characterization of the material of a copper mold after it had been used in the plant. The aim was to understand the damage and cracking mechanism, and our analysis confirmed that a network of cracks was present on the inner mold surface in the meniscus area, which experienced the maximum temperature gradients. Metallurgical examination demonstrated the transgranular characteristics of cracks, thus suggesting that thermal fatigue was the main cause of the damage observed. The location of the thermal fatigue cracks corresponded to the area experiencing the highest levels of plastic strains, as confirmed by the results of a finite element analysis simulating the mold in-service conditions.

1. Introduction

In continuous casting, the molten steel flows from a tundish into a mold, where it starts to solidify. The mold is thus a key component of the overall casting process, as it is subjected to high thermal loads and it also controls the initial shape and quality of semi-finished products (e.g. billets, blooms, slabs), before they enter the rolling mill lines [1–3].

The mold is essentially a water-cooled hollow tube with a rectangular or round cross section. It is usually made of copper alloy which facilitates an optimal combination of thermal and mechanical properties [3–10]. The inner surface of the mold is coated with nickel or chromium-based plating to protect the substrate underneath [11–13].

When the casting plant is operating, a huge thermal flux q is transferred from the molten steel, which is in contact with the inner mold surface, to the water-cooled outer side of the mold (Fig. 1). The values of this flux vary between two conditions: $q = 0$ when the plant is switched off, $q = q_{\max}$ when the plant is switched on and has reached full capacity, (Fig. 2). The mold is exposed, on its inner surface, to a high time-varying temperature combined with a high thermal gradient across the mold wall. This cyclic thermal loading promotes thermal fatigue cracks in the meniscus area, which is the most thermally-stressed and strained region of the mold.

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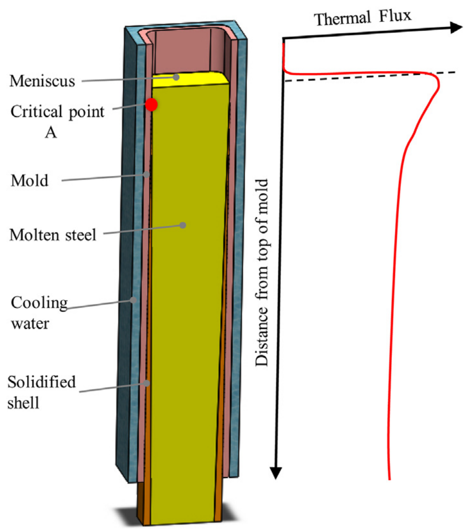

Fig. 1. A mold under working conditions (half section) and axial thermal flux distribution when $q = q_{max}$.

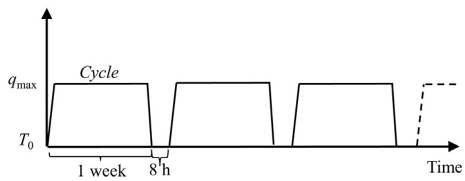

Fig. 2. Variation of the thermal flux during the service life of a mold.

A mold without cracks ensures safety during the working process and guarantees the quality of the final product [1, 3]. On the other hand, through-thickness cracks must be avoided as any contact between cooling water and molten steel would have catastrophic consequences.

Several metallurgical studies [2, 8, 11–13] have been performed to determine the complex damage mechanism that occurs in the mold during its service life. Faries et al. [12] observed crack propagation through the copper substrate with a depth ranging from 0.6 mm to 5 mm. All cracks were found within the area approximately 100 ÷ 140 mm from the top of the mold (i.e. 0 ÷ 40 mm below the meniscus position). The same observations were reported by [2, 8, 11] for square and funnel molds.

The mold in the meniscus zone is damaged because of a detachment of the coating material and mechanical degradation assisted by the chemical attack of low melting point elements on the Cu substrate which thus becomes embrittled [1, 2]. The coatings are used to cover the internal walls of the mold, and they are affected by a thermo-mechanical degradation that reduces the mechanical properties of the deposit [8, 14].

The inner surface of the mold undergoes high fluctuating thermal stresses, which can lead to thermal fatigue. In order to better understand the source of the crack formation and thus to enhance the component service life, we investigated a possible correlation between the metallurgical observations and the stress and strain distribution in the cracked area. This work first presents a metallurgical investigation of a copper mold, and then details the results of a thermo-mechanical analysis performed with numerical techniques.

2. Experimental and numerical procedure

2.1. Sample extraction and microstructural characterization

A copper mold with length 1000 mm, rectangular cross section (172 × 174 mm) and thickness 15 mm (see Fig. 3), internally coated with a thin layer of hard Cr, was investigated at the end of its service life. The copper alloy of the mold had a chemical composition equal to a C14700 alloy, according to ASTM B124B standard [15], see Table 1.

First, the copper mold was visually inspected to locate the most damaged areas, from which samples were subsequently extracted. As illustrated in Fig. 3a, the area near the meniscus is characterized by a wide network of cracks, while the surrounding parts seem to be unaltered.

To characterize the mold microstructure and to determine how cracking takes place, metallurgical investigations (light microscope and SEM) were performed on a total of five samples extracted from different areas of interest. Two metallographic samples (A1 and A01) were taken from the meniscus area (labeled A in Fig. 3b), one from the surface center, and one from the corner,