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Continuous bending and straightening technology of Q345c slab based on high-temperature creep deformation

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ABSTRACT

A new continuous bending and straightening casting curve with the aim of full using of high-temperature creep deformation was proposed. The curvature of bending and straightening segment varies as sine law with arc length. The basic arc segment is shortened significantly so that the length of bending and straightening area can be extended and the time of creep behavior can be increased. The distance from solidifying front in the slab was calculated at 1200 ℃ by finite element method. The maximum strain rate of new casting curve at different locations inside the slab is 6.39×10^{-5} s^{-1} during the bending segment and it tends to be 3.70×10^{-5} s^{-1} in the straightening segment. The minimum creep strain rate is 7.45×10^{-5} s^{-1} when the stress is 14 MPa at 1200 ℃. The strain rate of new casting machine can be less than the minimum creep strain rate. Thus, there is only creep deformation and no plastic deformation in the bending and straightening process of steel continuous casting. Deformation of slabs depending on creep behavior only comes true. It is helpful for the design of the new casting machine and improvement of old casting machine depending on high temperature creep property.

1. Introduction

Steel continuous casting is the most common way to produce cast steel due to quality and cost advantages[1,2]. Zero defect strategy for the internal quality of continuously cast slabs is a major issue that has drawn much more attention[3]. However, it is easy to generate internal cracks when thick slabs are bent and straightened during continuous casting. These defects will reduce product quality and affect the subsequent rolling process[4]. Kim et al.[5] developed a two-dimensional transient coupled thermo-elastoplastic finite element model to analyze thermomechanical behavior of the solidified shell of beam blank during solidification in the mold. Yamanaka et al.[6] performed some tensile tests on cylindrical ingots with a liquid core in order to evaluate the critical strain for internal cracks in continuous casting. They stated that the internal cracks result from the excessive tensile strains which are produced in the bending and straightening process of steel continuous casting. Li et al.[7] conducted researches on the formation of internal cracks in bearing steels during the soft reduction process in rectangular bloom continuous casting. They assumed that it was closely related to the deformation in the mushy zone, and when the equivalent plastic strain was larger than the critical strain during solidification, internal cracks would appear. Wang et al.[8] analyzed the formation of the internal cracks of medium carbon microalloy steel in continuous casting. They concluded that the formation of internal cracks in continuous casting slabs was mainly attributed to the strain status and micro-segregation near the solidifying front of the slabs. These researches indicated that it was easy to generate internal cracks at the solidification front in the bending and straightening segments, when strain exceeded a critical value. It was necessary to reduce the strain and strain rate of the slab caused by bending and straightening at solid/liquid interface against internal cracks.

With the development of modern casting machine, caster profiles have been improved from simple vertical type to vertical bending after complete solidification to curved mold and solid or liquid core unbending to vertical mold multi-point progressive

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bending and straightening with liquid core[9]. Creep in metals at high temperatures refers to time dependent inelastic deformations that occur when temperature of the material exceeds 0.3-0.4 times of its absolute melting temperature[10]. Therefore, the slab shows strong creep characteristics in present steel continuous casting production. Grill and Schwerdtfeger[11] presented an elastic and creep model for the prediction of bulging owing to creep. Okamura and Kawashima[12] proposed a three-dimensional elastic-plastic and creep finite element model to study the effect of creep on bulging deflection. The maximum value of the bulging by the elasto-plastic analysis is about 1.7 times of the value obtained by the elasto-plastic analysis. Ha et al.[13] calculated the bulging deformation of continuous casting slab by a two-dimensional elasto-plastic and creep finite element model. They concluded that the bulging deflection caused by creep is dominant through comparing the results of experiment and analysis by several creep equations. Li and Thomas[14] developed an elastic-visco-plastic creep constitutive equation to simulate temperature, stress, and shape development during the continuous casting of steel, both in and below the mold. They stated that inelastic strain included both strain-rate independent plasticity and time dependent creep. Creep was significant at the high temperatures of this process and was indistinguishable from plastic strain. Fachinotti and Cardona[15] had done some research works on the great influence of the strain rate on the behavior of steel at elevated temperature. Different material models of steel at high temperature had been analyzed and compared. These researches indicated that high temperature creep of steel had significant influence on the deforming of the slab, which could not be overlooked in straightening and bending process. However, creep deformation is generally considered as harmful deformation and needs to be resisted. There is hardly any literature related to the study of positive effects of high-temperature creep behavior on the deformation of casting steel. High-temperature creep deformation can be fully used in the processing of bending and straightening of steel continuous casting.

As far as is known, the stress within the elastic limit will not lead to material permanent deformation. However, at the high temperature, the permanent deformation of material occurs although the stress is less than yield strength. This is steel creep deformation instead of plastic deformation. Therefore, a new creep straightening curve which made full use of the high-temperature creep deformation during the slab bending and straightening process was proposed in this paper, in order to illustrate the positive effects of high-temperature creep behavior on continuous bending and straightening technology of steel continuous casting.

2. Mathematical Model

Tensile strain ε_h in some fibre of slab caused by bending and straightening can be calculated by Eq. (1)[16,17].

$$\varepsilon_h=(D/2-\delta+h)(k_i-k_{i+1}) \tag{1}$$

where, D is slab thickness; δ is the solidified shell thickness; h is the distance from the solidifying front; and k_i and k_{i+1} are the curvature of the starting point and the end point of bending or straightening curve, respectively. For continuous bending and straightening curves, the strain rate in some distance from the solidifying front can be expressed as Eq. (2).

$$\dot{\varepsilon}_h(t)=v_c\lim_{\Delta s\to 0}(\Delta\varepsilon_h/\Delta s)=v_c(D/2-\delta+h)k'(s) \tag{2}$$

where, $k'(s)$ is the change rate of curvature with arc length; s is the arc length of casting curve; t is the time; and v_c is casting speed which is considered as a constant. From Eqs. (1) and (2), it can be concluded that only when the slab traverses through a path which has a change of radius, the strain caused by bending or straightening exists. For bending and straightening technology of conventional continuous casting machine, the arc length of bending and straightening segments is short comparatively so that the value of strain rate is very high and creep behavior is not fully used. More attention needs to be paid to the relationship of minimum creep strain rate $\dot{\varepsilon}_{cmin}$ and bending or straightening strain rate $\dot{\varepsilon}_h$ of slab.

If $\dot{\varepsilon}_h<\dot{\varepsilon}_{cmin}$, there would be only creep strain without plastic strain in bending and straightening deformation of slab, and the stress of bending and straightening would be less than yield strength.

If $\dot{\varepsilon}_h\geqslant\dot{\varepsilon}_{cmin}$, both of creep strain and plastic strain would exist in the process of bending and straightening deformation and the stress would be above yield strength or equal to it.

It can be concluded that the curvature of bending and straightening segment could change so slowly that strain rate can be reduced substantially. When the strain rate is reduced to be less than $\dot{\varepsilon}_{cmin}$ at the same temperature, the slab can be bent or straightened only by creep deformation.

3. Calculation of New Casting Curve

Concast Corporation and Voestalpine AG firstly proposed continuous bending and straightening method. Sheng and Dong[18] developed a three-segment-curve straightening method based on Concast continuous straightening method. Man and Li[19] studied the high temperature character in continuous straightening