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Investigation on slab continuous straightening technology and deformation analysis

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Abstract

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Keywords

deformation, analysis, technology, straightening, investigation, slab, continuous

Disciplines

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Investigation on slab continuous straightening technology and deformation analysis

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Abstract: A new method of setting continuous bending and straightening strain rate according to temperature subzone was brought forward. By making use of the high temperature creep character effectively during the continuous casting slab being straightened, a new model curve of continuous caster was developed. And by using theoretical and finite element method the strain and strain rate of the slab under multi-point straightening and the new continuous

straightening were analysed. The result shows that for continuous straightening the strain rate of the slab is constant and lower than that of the slab under multi-point straightening, and the strain varies linearly. It is verified that the new continuous straightening technology is reasonable and superior.

Keywords: continuous casting; continuous straightening; finite element method; strain; strain rate.

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1 Introduction

Continuous steel casting is an important part in steel production, the technique of slab continuous straightening is the key technology to develop high efficiency continuous casting, of which the connotation is a high casting speed as the core, high-quality, defect free production as the basis to achieve high continuous casting rate, high operating rate. Arc and straight arc continuous casters are the main model in present steel continuous casting production. The slab has to undergo the straightening process in both two models. As for straight arc continuous casters, the slab is also undergoing a bending process. It is easy to generate cracks during the straightening or bending process, which is a major factor affecting the quality of slab. Thus, the crack is directly affected by method of straightening and bending. With the development of modern casting to high-speed casting, slab straightening developed from solid straightening to liquid-core straightening, along with single-point straightening to multi-point straightening, continuous straightening. Cracks may appear at the slab surface and the interface between two phases when being straightened or bended. The generation of the crack is related to the strain and strain rate while bending and straightening. The higher the strain and strain rate are, the lower the ultimate strength is, the more prone to generate crack. In order to avoid cracks, strain and strain rate should be minimised.

In the designing process of the straightening, plastic deformation was considered only while creep deformation is ignored. Yet the slab shows strong creep characteristics when in high temperature. Many researches have been done in the deformation of straightening and the generation of cracks of the slab. Suzuki et al. (1988) and Boitsov and Danilov (1988) had done research about the creep characteristics of steel under casting temperature, the bulging deformation of slab, the generation of cracks, etc. Pascon et al. (2006) and Pascon and Habraken (2007) had done some research works on the straightening of slab and crack defect. Mintz and Crowther (2010) had done analysis on the thermoplastic along with its relationship with cross crack of the slab. Lagerstedt and Fredriksson (2005) had established a prediction model of cracks in solidifying shell. Sevcika and Sevcikovab (2008) had done research works about the plasticity of low carbon steel above 1,200°C. Calvo and Rezaeian (2007) had done researches about the hot ductility and the mechanism of the generation of crack. Niu et al. (2011) had done the research work on the temperature field of the slab, mechanism of the generation of crack and countering measures. Wang et al. (2003, 2005) had done tests and researches about high temperature properties of continuous casting high carbon steels, internal cracks and stress and strain during solidifying process. Feng et al. (2009) and Cai and Zhu (2011) had done research works on the solidifying of the slab, strain in straightening process. These researches indicated that high temperature creep of the steel has significant influence on the deforming of the slab, which cannot be overlooked in straightening and bending process.

As for continuous straightening, Concast Corporation and voestalpine AG first proposed continuous straightening (bending) method, Concast Corporation proposed a straightening method using floating rollers to deform the slab, which automatically adapts to straightening curves, along with cube curve straightening method. Voestalpine AG proposed executing continuous straightening with fixed rolls. Sheng et al. (1997) proposed three-segment-curve straightening method, which modified Concast continuous straightening method. Zeng et al. (2006) had analysed the limitation of Concast curve and

proposed using convolute curve as continuous straightening curve. Li (1996), Man and Li (2008) and Man et al. (2008) had done researches about using the high temperature character in continuous straightening process, the high temperature creep and the stress relaxation of slab, also proposed a late-model continuous straightening curve with two continuous straightening areas. The researches indicated that during bending or straightening process, slab in high temperature with lower strain and strain rate is less likely to generate cracks.

The strain and strain rate of bending and straightening decreased due to continuous straightening, thus the high temperature creep deformation played a large role in the straightening process. The lower the strain and strain rate is, the larger the proportion of creep deformation in the total straightening deformation is. In order to maximise the use of the high temperature creep deformation during the slab straightening and bending process, the model curve of continuous caster was studied in this paper. The new model curve could make the slab bended and straightened in almost the whole second cooling segment before the straightening point. For example, for the straight arc casting machine, the slab is continuously bended just under the straight line segment and continuously straightened right after the bending. The basic arc segment was cancelled so that length of the bending and straightening area can be extended significantly, and bending and straightening strain and strain rate can be substantially reduced. Thus, crack can be avoided effectively and the speed of casting and the productivity of the caster can be increased significantly.

2 Theory of high temperature creep

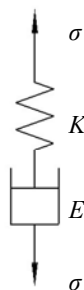
During casting process, the slab temperature ranges from 1,500 to 800 degree. At this temperature, the slab shows strong creep properties. Under the same external force, slab deformation increases with time increasing, which is the high temperature creep.

In the process of continuous casting, the slab corresponds to the steady creep stage of creep curve, the general relationship between the strain rate and the stress is

$$\dot{\epsilon} = K\sigma^n \tag{1}$$

where K and n is material constants.

Figure 1 Maxwell model



According to the material rheological theory, rheological model of high temperature slab can be Maxwell model which is shown in Figure 1 (Wan, 1985). Set the elastic and viscous components were stressed for σ , the strain of elastic and viscous components were ε_1 and ε_2 respectively, the strain rates were $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ respectively, there is

$$\sigma = E\varepsilon_1 \quad (2)$$

$$\sigma = K\dot{\varepsilon}_2 \quad (3)$$

Total pulling strain rate in the system equals to the elastic strain rate plus the viscous strain rate, i.e.,

$$\dot{\varepsilon} = \dot{\varepsilon}_1 + \dot{\varepsilon}_2 \quad (4)$$

From equation (2) and equation (3), there is

$$\frac{\sigma}{K} + \frac{\dot{\sigma}}{E} = \dot{\varepsilon} \quad (5)$$

Equation (5) is the Maxwell rheological equation, and object meeting the equation are known as the Maxwell object. Slab in high temperature can be considered as Maxwell object.

At time t equals 0, load to the slab and keep the stress as constant σ_0 . The solution of the equation (5) can be expressed as

$$\varepsilon = \frac{\sigma_0}{K}t + \frac{\sigma_0}{E} \quad (6)$$

Equation (6) is the Maxwell creep equation, where σ_0 / E is the strain when t equals to 0. The total strain ε increases gradually with increasing of time t . After removing the initial stress σ_0 , the second term is zero in equation (6), and the strain $\varepsilon = (\sigma_0 / K)t$ is preserved permanently which is the creep strain of the slab. Giving full play to the influence of the creep during bending and straightening could effectively avoid bending straightening cracks in the slab.

Among current continuous bending and straightening methods, bending and straightening arcs are comparatively short which have not given full play to the role of the slab high temperature creep deformation during bending and straightening. In this paper, the basic arc of continuous casting machine is cancelled and the length of the bending and straightening areas are increased in which way the strains of bending and straightening have reduced dramatically. This method could give full play to the role of the slab high temperature creep deformation during bending and straightening.

3 New model curve design of continuous casting machine

In this paper, the R9300 straight arc slab casting machine of one steel mill is considered. Its main parameters are shown in Table 1. It uses five-point bending and five-point straightening following the straight section. There is a long basic arc segment between bending and straightening segments. The straightening radius of this casting machine are $R_0 = 9,300$ mm, $R_1 = 11,312.892$ mm, $R_2 = 14,671.987$ mm, $R_3 = 21,396.378$ mm, $R_4 = 41,581.549$ mm and R_5 equals infinity. The bending radius are $R_6 = 49,420.834$ mm,

$R_7 = 24,328.140$ mm, $R_8 = 15,971.287$ mm, $R_9 = 11,797.719$ mm and $R_0 = 9,300$ mm. The mould length is 900 mm, the straight line section length is 1,565 mm, the bending section length is 1,030 mm and the straightening section length is 1,520 mm.

Table 1 The main process parameters of continuous caster

Process parameters	Casting speed (m/min)	Slab size (mm × mm)	Basic arc radius (mm)	Casting temperature (degree)	Casting machine length (m)
Parameter values	1.4~1.65	900~1,550 × 230	9,300	1,530	35.8

Figure 2 New continuous bending and straightening curves (see online version for colours)

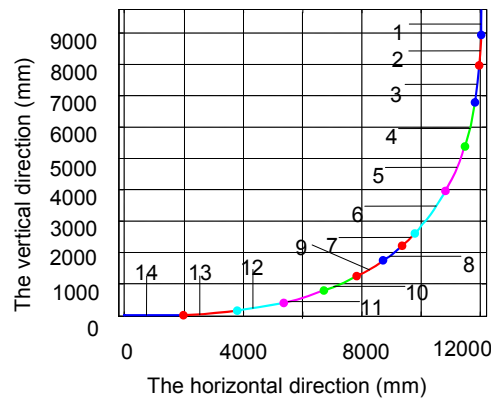


Table 2 The main parameters of continuous bending and straightening curves

		Arc length (mm)	Transition radius (mm)	Transition radius (mm)	Change rate of curvature
Bending curve	Curve 1	800	21,000	Infinity	5.95238E-08
	Curve 2	1,000	14,000	21,000	2.38095E-08
	Curve 3	1,200	10,500	14,000	1.98413E-08
	Curve 4	1,400	8,400	10,500	1.70068E-08
	Curve 5	1,600	7,000	8,400	1.4881E-08
	Curve 6	1,698	6,000	7,000	1.40246E-08
Straightening curve	Curve 7	600	6,000	6,750	3.08642E-08
	Curve 8	800	6,750	7,714	2.31481E-08
	Curve 9	1,000	7,714	9,000	1.85185E-08
	Curve 10	1,200	9,000	10,800	1.54321E-08
	Curve 11	1,400	10,800	13,500	1.32275E-08
	Curve 12	1,600	13,500	18,000	1.15741E-08
	Curve 13	1,800	18,000	27,000	1.02881E-08
	Curve 14	2,000	27,000	Infinity	1.01185E-08

According to this continuous casting machine, combined with the consideration of the high temperature creep deformation characteristics of steel, the new bending and straightening curves of continuous casting machine has been developed by the method of connecting multi-segment curves smoothly, shown in Figure 2. For the new curves, six smoothly connected curves, of which curvatures are changing continuously, are used as bending curve of slab just under the straight segment. At the same time, eight smoothly connected curves, of which curvatures are changing continuously also, are used as straightening curve of slab. The basic arc was cancelled. The bending curve and straightening curve are connected smoothly. Parameters of each curve are shown in Table 2.

4 Straightening strain and strain rate calculation

4.1 Strain rate at the solid-liquid boundary

Because the bending deformation and straightening deformation of slab are similar, the straightening deformation analysis is discussed here only.

The solidified shell thickness can be calculated using equation (7)

$$\delta = k\sqrt{l/v_c} \quad (7)$$

where k is solidification coefficient and equals $26.5 \text{ mm/min}^{1/2}$, l is the distance from the meniscus in m, v_c is casting speed in m/min.

According the theory of multi-point straightening of slab, the strain rate at solid-liquid two phase interface can be calculated using equation (8) with ignoring the gravity of the slab,

$$\dot{\epsilon} = \frac{(D/2 - \delta)(1/R_i - 1/R_{i+1})}{t} \quad (8)$$

where D is slab thickness in mm, R_i and R_{i+1} are the curvature radius of the starting point and the end point of straightening curve in mm, t is deformation time in s.

Figure 3 The strain rate at solid-liquid boundary of straightening area (see online version for colours)

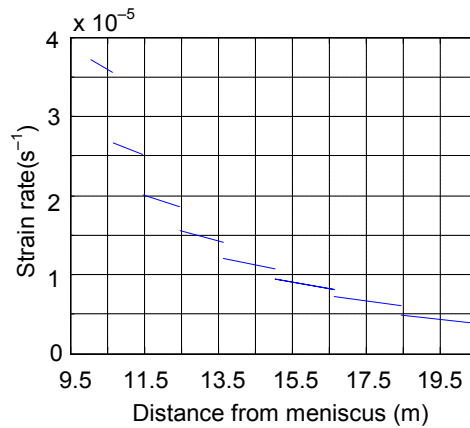
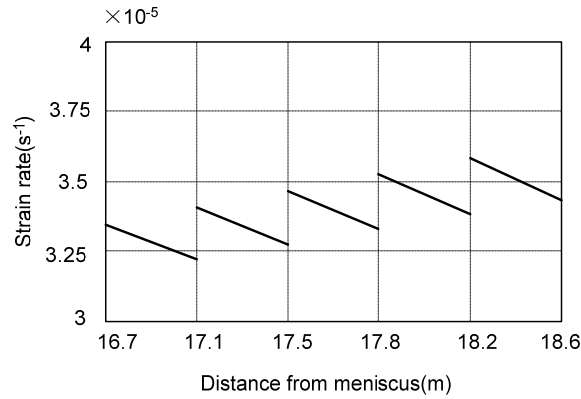


Figure 4 The strain rate at solid-liquid boundary for five-point straightening section



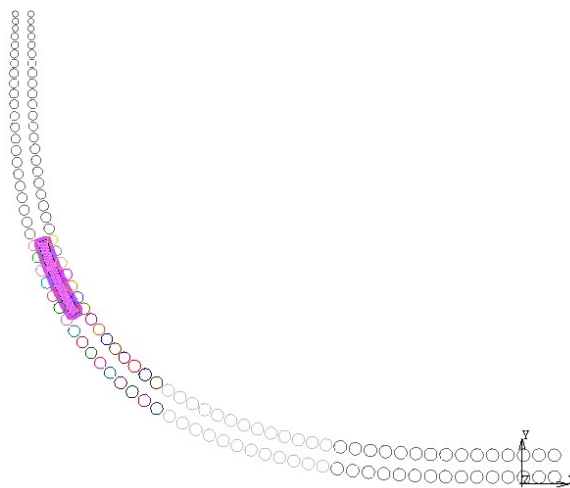
For the continuous straightening, the strain rate at solid-liquid two phase interface of each straightening segment can be calculated using equation (8) approximately. At the casting speed of 1.5 m/min, the straightening strain rates at the solid-liquid two phase interface of the continuous straightening and the original five-point straightening are calculated using equation (8), and the result are shown in Figure 3 and Figure 4.

It can be seen from Figure 3 and Figure 4 that the straightening equivalent strain rate of continuous straightening is smaller than that of the original multi-point straightening. The deformation rate of bending segment has the same characteristic.

4.2 Strain and strain rate at the surface of slab

This section is mainly about the variation law of surface strain and surface strain rate of the multi-point straightening and the new continuous straightening. Through the comparison, the superiority of the new continuous straightening technology has been verified.

Figure 5 The finite element model (see online version for colours)



In order to analyse the straightening strain and strain rate of the slab surface, the finite element model was build which is shown in Figure 5. In this model, the rollers are set along the new continuous bending and straightening curves and the original multi-point bending and straightening curves separately. The size of the slab model is $2,000 \text{ mm} \times 500 \text{ mm} \times 230 \text{ mm}$. During finite calculation, the gravity of slab is neglected. So the strains caused by gravity and misplacement of rollers are ignored.

Figure 6 Straightening strain on the surface of slab (see online version for colours)

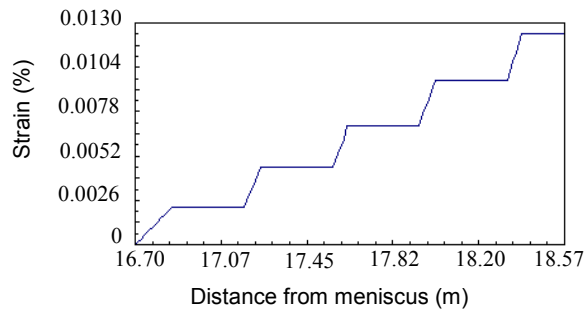


Figure 7 Straightening strain rate on the surface of slab (see online version for colours)

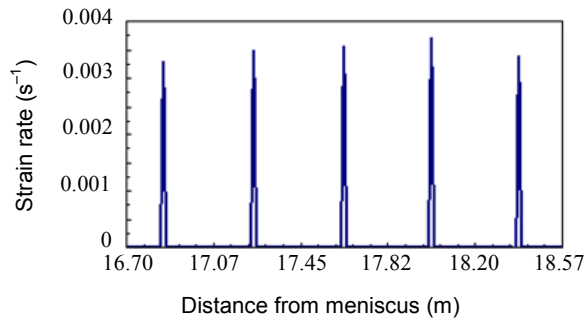


Figure 8 Straightening strain on the surface of slab

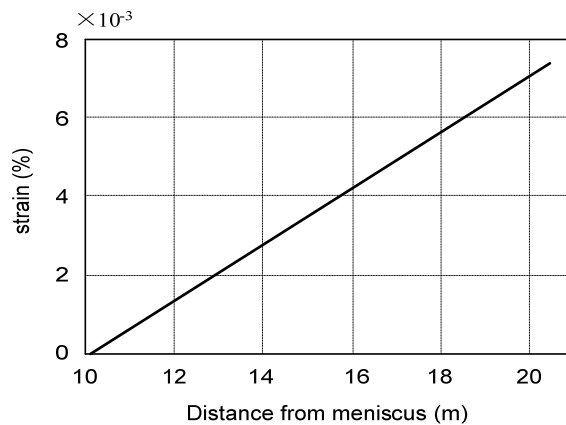
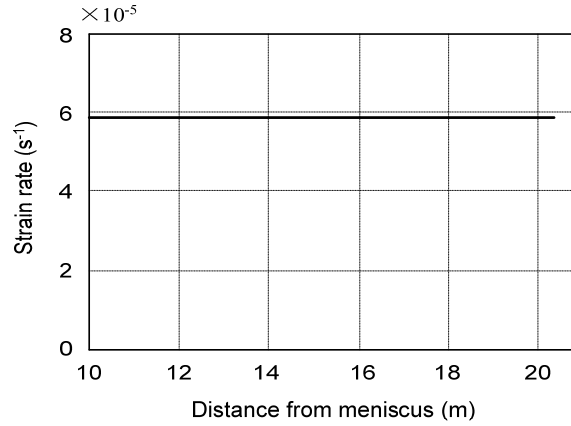


Figure 9 Straightening strain rate on the surface of slab

As the results, the straightening strain and straightening strain rate on the slab surface during continuous straightening and multi-point straightening are shown in Figure 6, Figure 7, Figure 8 and Figure 9. It can be seen that for the multi-point straightening, the straightening strain jumps ladder-like near the straightening point, the straightening strain rate also has large peak values with the maximum strain rate being about $3.75 \times 10^{-4} \text{ s}^{-1}$, and for the continuous straightening the straightening strain changes linearly, the straightening strain rate is constant with the value of $5.88 \times 10^{-5} \text{ s}^{-1}$.

It can be seen by comparing Figure 6 and Figure 8, Figure 7 and Figure 9 that the strain of continuous straightening changes slowly, and the strain rate is far less compared with that of multi-point straightening. So compared with multi-point straightening, the continuous straightening has superiority in preventing the straightening cracks happening.

5 Conclusions

The basic circular arc segment of traditional model was cancelled and the lengths of continuous bending and straightening areas were expanded in the new continuous bending and straightening method. Thus the strain rates of bending and straightening were reduced, the crack caused by bending and straightening could be effectively avoided, and the quality of the slab was improved. At the same time, this new bending and straightening method is adaptable for the high casting speed.

For the design of the new casting machine, by using this continuous bending and straightening technique, the height of the caster could be reduced, and the molten steel static pressure can be reduced, too, then it could result in the decrease of the bulging deformation of the slab. And as for the improvement of the existing continuous caster, the lengths of bending and straightening areas could be increased without changing the height of casting machine to realise continuous bending and straightening of slab.

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