MODERN COMBINE METHODS FOR ESTIMATION CRITICAL BENDING AND UNBENDING PARAMETERS CCM

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Abstract

The conduct conditions peculiarities of solid skin of the cast ingot in conditions of its bending and unbending are considered. Are offered the mathematical models and computation algorithm, allowing to optimize a state of stress of cast ingot and optimize a roller geometry of technological line CCM.

Last decade there was a sharp conceptions change about of modern slab CCM. It has resulted that the majority of CCM in Europe, Japan and USA countries expose to serious reconstruction and modernization \cite{1}. New CCM have productivity in 1,5-1,8 times above, than analogous CCM, which had built 10 and more years ago. It allows them to look most competitive in the market of the metallurgical equipment.

1. Modern design for slab CCM

One of development directions slab CCM are the satisfaction the increasing demands of higher quality products of the clients. For these purposes in practice often applied the improved rectilinear molds. The molds of such design can also be used on already working machines after the conforming renovation. At present for new slab (middle and thick slab 180-300 mm) CCM is possible to pick out the following basic trends of their constructive design:

- application of vertical CCM mold by length 0,8-1,0 m (in dependence on cross-section of cast ingot);
- application of mold CCM with a capability of change of width of a slab during casting;
  - presence of vertical segment under the mold by length 1,5-1,7 m and more;
  - presence a multipoint unbending section;
  - decrease of base radius up to 7-8 m;
  - presence a multipoint (4-5 and more) bending section;
  - presence of "soft" reduction section, the increasing of higher quality internal zone of a slab providing.

As shows the analysis, it is necessary to distinguish two conceptual constructions, which are observed on modern CCM. First construction consists of
creation new CCM without hard connection to old equipment (for example, new CCM at NLMK, c.Lipetsk, Russia), and second construction is characterized by reconstruction already having radial CCM, that foresees maximum "entering" in already the existing parameters (for example, CCM of the company "Sollac Fos"). Unconditionally, second construction has the specific features and can not be used for definition of base parameters by modern CCM. In any case construction of technological line CCM and accordingly calculation of optimum bending and unbending parameters of cast ingot is represented key of construction element modern CCM.

2. Critical literature review

It is known, that a bending and unbending of continuous casting ingot takes place in temperature range from temperature solidus to temperatures of hot rolling. In this range plastic properties of steel began considerably oscillate. Because of cast ingot simultaneously cooling and moves through working space CCM, exists a high probability of cracking zone by reason of stretching strains near to boundary surface between a shell and liquid core.

Some researchers thinks that so far as dendrits near the boundary surface of a solidification act by undesirable mode only in conditions of stretching strains, then a cast ingot can be consider in quality "sensor of stretching strains", i.e. she is sensible to any kind of stretching strain. Usually as the indicator of cracking zone, called by stretching strain, are received a strip, which are observed in appearance of darkenings on macro etching sections of cast and rolled continuous casting ingot.

It is accepted to consider, that this strip are the result of destructions of borders grains in the solidification time, oriented perpendicularly to applied stretching efforts. Because of low plasticity steel at the temperature of near to a solidus the border of a grain near to boundary surface of a solidification can be destroyed, when the stresses will exceed some threshold value. The melt between dendrites, enriched with alloying elements and phases (specially by phosphorus and sulphides) from close-fitting liquid core, then is retracted and is accumulates in destruction zone. A threshold level of formation of strips strongly depends on content of carbon in steel. The generally accepted «safe» strains levels and those, which frequently are quote in the literature, is equal to 1,25 % for surface strains and 0,20-0,25% for interphase strains. Maximum relative lengthening at temperatures 1470-1430°C makes 0,3-0,4% [2,3].

Considering a dynamics of cast ingot solidification, it is necessary to mark, that in the field of temperature a solidus (front of a solidification), there is a mushy region, where the steel is neither completely solid (dendrites) nor completely liquid (interdendritic space). Only on some spacing interval from front of a solidification there are completely solid metal layers. Between that these metal layers are in a state of stress conditioned by a temperatures difference between external surface and front of a solidification. Therefore, in calculations of critical bending and unbending radiuses of cast ingot with liquid core should be considered critical relative lengthening not on border of solidification front, and on some ablation from him (13-15 mm).

To definition of coefficient of relative lengthening of steel in the field of solidification temperatures is dedicated enough of papers [4-8]. As a whole practically all of these data testify that the plasticity of steel at temperatures range 1300-1400°C is much lower 1%. The oscillations of values of a plasticity of steel depend on from researches (methods of obtaining of pattern, strain speed, the sizes of pattern, pattern temperature measuring method, content of carbon in steel and etc.). Therefore, the
reputed literary data in relation to steel plasticity can be used only with account for that they have approximate enough nature.

The broad analysis conditions of internal cracks formation is executed in [7, 8]. The cracks formation depends on correlation of deformation ability and strength properties of steel. The critical values of relative lengthening can be oscillate in considerable limits depending on carbon content, manganese, sulphur, phosphorus and etc. With that for estimating computations the critical values coefficient of relative lengthening can be within the limits 0,2-0,25%. The critical strain speed within limits $10^{-2} - 10^{-4}$ s$^{-1}$, and a tensile strength of solid shell is equal to 10-20 MPa (or 4-6 MPa for some steel grade).

More exact estimations of strained state of cast ingot during her forming and strain can be executed with the computational methods of the accumulated stresses [9].

It is supposed, that for warning of surface defects it is necessary, that in consequence to shrinkage of steel, temperature strain, mechanical (casting) strains and ferrostatic pressure summary strains, deformation ability and strain speed does not exceed their critical values, at which one there comes destruction of metal. On data [9] for carbon steels enabled summary critical values of cast ingot stretching (unbending-bending, thermal, strain of solidification) should not exceed 0,70%. The reduced recommendations confirmed in practice.

With allowance for above-stated authors design an original modeling methods of a strained state of cast ingot and computation of the optimum technological line CCM in dependence on casting conditions, section of cast ingot, steel grade and etc.

For termal physical processes computations, accompanying a solidification of cast ingot, the dynamic mathematical model permitting to receive following parameters is designed:
- temperatures field (temperature in each cast ingot point);
- heat flow with cast ingot surface at any time point;
- distribution field of solid phase (percent content of solid phase in each point);
- thickness of solid shell in each cast ingot section;
- width of liquid core in each cast ingot section;
- width of a mushy region (solid-liquid) in each cast ingot section;
- depth of liquid core.

The visualization of results, obtained during computations, can implement following ways: the text messages on a screen – values of temperature and parameters of solidifications for the current time moment and in control points (at the mold’s outlet, second cooling zone, cutting zone); the colour charts of temperature distribution and solid fraction range in longitudinal (axial) and cross-sectional sections; the charts of distribution of studied parameters (temperature, heat flow, width of the liquid core, thickness of solid shell, stressed state and relative strains of solid shell) in longitudinal and cross-sectional directions; the tables, which duplicate the information, represented on charts.

3. Mathematical simulation bending and unbending processes

A software allows to vary many technological parameters of process by continuous casting and to study, as influence the selected values on distribution of temperature and formation of cast ingot structure.

For implementation of design computation a technological line slab CCM is breaks up into following sections (fig.1): vertical mold, vertical section under the mold’s outlet, a multipoint bending section, radial section, a multipoint unbending
section, horizontal section.

Fig. 1 Scheme CCM of curvilinear type with vertical caster

By the first stage of designing is the solution of a problem of selection base radius $R$, i.e. radius, on which a back wall of a technological line CCM, including a mold and arc section of zone of second cooling is described. At alteration of the machine on other cast ingot thickness her base radius remains invariable.

One of basic design parameters CCM is a base radius. The minimum value of base radius usually limits by critical values of strain at the straightening. Besides, with decreasing of base radius increase the probability of formation surface defects. Excessive increase of base radius entails increase of height and masses CCM. Also increases pressure from molten steel to cast ingot shell and on backing up rollers, that promotes appearance of internal defects.

On base of theoretical analysis and exploitation experience much CCM of
curvilinear type are produced the recommendations on value limitation of base radiuses within the limits of 25-35-multiple thickness of cast ingot [3,10]. It is necessary to mean, that these values can be corrected with reference to concrete casting conditions.

A computation of full bending section length $L_{zag}$ carry out on original methods, designed by authors. In according to this methods $L_{zag}$ can be defined, knowing a number of bend points and step bending rollers on curvilinear bending section. Besides, bending should be executed so that to provide minimum strain of external or internal layers of case ingot on each section. A least strain speed of external layers can be obtained in that case, if strain would be evenly distributed on all bending section. That is basic factor, determining length of a multipoint bend at a known step, is the condition of unexceeding of relative bending strain on each of bend rollers $\varepsilon_{zag,i}$ with critical value plasticity steel $\varepsilon_{dop}$.

A bending section can be constructed on a curve with permanently decreasing curvature radius from endlessness in bend beginning at transition from a vertical section on curvilinear to value of base radius $R_0$ at transition from bend section on radial section, i.e. in last bend point bend radius $R_{zag,n} = R_0$. Accumulating full relative strain on all bend section $\varepsilon_{zag,\Sigma}$, is determines from expression:

$$\varepsilon_{zag,\Sigma} = \frac{x_0}{2 \left( R_0 - \frac{x_0}{2} \right)}$$  \hspace{1cm} (1)

Then a total number of bending points will be equal: $n_{zag} = \varepsilon_{zag,\Sigma}/\varepsilon_{dop} + 1$. The bending strain on each of rollers $\varepsilon_{zag,i}$ is determined as relation of full relative bending strain on all section $\varepsilon_{zag,\Sigma}$ to total number of bend points $n_{zag}$.

The radius of curvature of bending section on each of rollers $R_{zag,i}$ is determined according to expression (1), if a base radius $R_0$ to substitute by value of current radius $R_i$, and so far as accumulating full relative strain on all bending section is equal to sum of relative bending strains $\varepsilon_{zag,i}$ on each of bending rollers: $\varepsilon_{zag,\Sigma} = \sum\varepsilon_{zag,i} = n_{zag}\varepsilon_{zag,nzag}$ that summary relative bend strain, accumulating to arriving moment by considered section at cast ingot one of bend roller, is equal to $\sum\varepsilon_{zag,i} = i\varepsilon_{zag,i}$. Then after laying of proper replacements and transformations in (1) expression for radius $R_{zag,i}$ on each roller has appearance:

$$R_{zag,i} = \frac{x_0}{2} + \frac{x_0}{2i\varepsilon_{zag,i}}, \hspace{1cm} i=1,\ldots,n_{zag}$$  \hspace{1cm} (2)

A unbending (straightening) section, unlike bending section, must be built on curve with permanently augmentative curvature radius from of base radius $R_0$ attached to transition with arc section on unbended endlessness at close of unbending attached to transition with curvilinear section on horizontal. Originating from this, summary full relative strain on all unbending section determines from expression

$$\varepsilon_{raz,\Sigma} = \frac{x_0}{(R_0 - x_0)}$$  \hspace{1cm} (3)

A total number of unbending points $n_{raz}$ determines as: $n_{raz} = \varepsilon_{raz,\Sigma}/\varepsilon_{dop} + 1$.

A curvature radius crooked of unbending on each of correcting rollers $R_{raz,i}$ determines from expression (4), if a base radius $R_0$ to substitute by value of current radius $R_{raz,i}$ and because full relative strain on all unbending section is equal to $\varepsilon_{raz,\Sigma} = \sum\varepsilon_{raz,i} = n_{raz}\varepsilon_{raz,nraz}$, then summary relative unbending strain, accumulating to arriving moment by considered section at purveyance 1-ro of unbending roller, will be equal
Σε_{raz,i} = iε_{raz,i}. Then expression for radius R_{raz,i} on each roller multipoint of unbending adopts following appearance:

\[ R_{raz,i} = \frac{x_0}{(n_{raz} - (i - 1))ε_{raz,i}} + x_0, \quad i=1, \ldots, n_{raz}. \]  \hspace{1cm} (4)

4. Results

The tested computations, done by authors on given methods for slab by thickness x_0=160-300mm and casting speeds V_m=0.7-2.4 m/min, well will conform to data reputed on literature in relation to construction of technological lines contemporary slab CCM [10].

Like so, worked up methods are a reserved equalizations system, decision of which allows on implementation stage of projects technical and working to calculate on contemporary level the following parameters (Fig. 2, Fig.3):

- regulation of technological axis CCM (dimensions of vertical section and caster, law and bending sections extent and unbending, base radius and length of radial area, length of horizontal section, metallurgical length of CCM, length of liquid phase for each section and each grade of steel);
- casting speed (maximum available and nominal):
- steps and rollers diameters of second cooling with laying out of them on segments.

Fig.2. Process Monitor
Fig. 3. Process Monitor

In all worked up and adapted immediately by authors mathematical models, a solidification process computation algorithm continuous casting ingot a field of real values of technological casting parameters and computer program do not use the data of other elaborators. The methods and calculable programs to effect done on contemporary level with calculation of last science achievements and technique. The computations results mount in graphic and tabular appearance. Besides, in program interface is foreseen use of data base open for addition on diverse steel stamps, containing the deskbook data, necessary for implementation of computation, with direction of their sizes and receipt sources.

5. Conclusions

A computer program worked up in Borland Delphi 6.0 and destined for work in MS Windows. In program work motion the outgoing data at will of user can be represented in graphs appearance or temperatures of-surfaces, fraction of solid phase, thermal efforts and strains; additionally hatch the process data of continuous casting in diverse time moments. In program is foreseen a interact lead-in of elementary data and record of intermediate computations in file. It allows for user-technologist to work efficiently with program attached to laying of computations.