and it is shown that variation of geometrical parameters of the casting wall is the most important among these factors.

- Increase of wall thickness of the casting “Track link” by 3 mm has diminished the value of shrinkage stresses by 27.62 % (it was established via calculations); in its turn, it leads to decrease of possibility of forming of metal rejects caused by hot cracks.

REFERENCES

1. Hojny M. Multiscale modelling of mechanical properties of steel deformed in semi-solid state — experimental background. *Key Engineering Materials*. 2014. Vol. 622–623. pp. 642–650.
2. Brian G. Thomas Issues in thermal-mechanical modeling of casting processes. *Iron and Steel Institute of Japan International*. 1995. Vol. 35. No. 6. pp.737–743.
3. Morinaga T., Minegishi T., Watanaba H. Examination of crack forming in the castings made from light alloys. *International Congress of Foundrymen*. Amsterdam, 1964. M., Mashinostroenie. 1967. pp. 88–93.
4. Hall H. F. *Iron and steel inst. report*. 1938. Vol. 23. p.73.
5. Fredriksson H., Haddad-Sabzevar M., Hansson K., Kron J. Theory of hot crack formation. *Materials Science and Technology*. 2005. Vol. 21. Iss. 5. pp. 521–530.
6. Davidson C., Viano D., Lu L., St John D. Observation of crack initiation during hot tearing. *International Journal of Cast Metals Research*. 2006. Vol. 19. Iss. 1. pp. 59–65.
7. Choi H. J. Thermal stresses due to a uniform heat flow disturbed by a pair of offset parallel cracks in an infinite plane with orthotropy. *European Journal of Mechanics. A/Solids*. 2017. pp. 1–13.
8. Konstantinov L. S., Trukhov A. P. Stresses, strains and cracks in castings. M., Mashinostroenie. 1981. 199 p.
9. Shvetsov V. I., Kulakov B. A., Ivanov M. A. Features of steel castings fabrication: a monograph. Chelyabinsk. Izdatelskiy tsentr YuUrGY. 2014. 240 p.
10. Savinov A. S., Sinitskiy E. V., Tuboltseva A. S. Research of deformation ability of sand-loam mixtures. *Vestnik Magnitogorskogo gosudarstvennogo tekhnicheskogo universiteta im. G. I. Nosova*. 2011. No. 1 (33). pp. 29–32.
11. Savinov A. S., Tuboltseva A. S., Sinitskiy E. V. Analysis of interaction between cast component and mould. *Izvestiya Samarskogo nauchnogo tsentra Rossiyskoy akademii nauk*. 2011. pp. 623–626.
12. Kachanov L. M. Grounds of the theory of plasticity. M., Nauka. 1969. 420 p.
13. Madhukar V. Mechanics of Materials. Michigan Technological University. Second Edition. 2014. 595 p.
14. Savinov A. S. Kolokoltsev V. M., Vdovin K. N., Feoktistov N. A. Determination of internal forces in the cooled walls of the casting in the implementation of asymmetric elements difficulties. European Conference on Innovations in Technical and Natural Sciences. *Proceedings of the 5th International scientific conference of «East West» Association for Advanced Studies and Higher Education*. Vienna. 2014. pp. 106–112.

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LARGE INGOT. MAIN ACHIEVEMENTS, MOST IMPORTANT SCIENTIFIC AND TECHNICAL PROBLEMS, PERSPECTIVE DEVELOPMENT DIRECTIONS*

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Key words:

large ingot, chemical heterogeneity, structural heterogeneity, crystallization, thermal-physical parameters, critical transition brittleness temperature.

ABSTRACT

The paper describes qualitative variation of thermal-physical parameters of solidifying large ingot and the following consequences of this variation. The chemical elements presented in the ingots, their classification and effect on operating parameters of finished products are described as well. The tendency to rise of ingot metal purity and positive influence of this tendency on the value of brittle-tough transition in steel is presented.

Today we can speak about several general fundamental relationships that allow to consider a large ingot as an object of management and to solve the problems of engineering and control at the most responsible stages of its forming in IT terms.

Physical-chemical and hydrodynamic appearances occurring during crystallization are mainly determined by thermal-physical situation in a solidifying ingot. The appearing dynamic thermal state can be completely described by 3 values: temperature gradient G, linear rate of crystallization V and cooling rate ε. Only two of these values are independent for ideal isotropic medium, consequently

$$\varepsilon = G \times V, \text{°C/c} \quad (1)$$

Variation of the main thermal-physical parameters depending on the average diameter is presented on the

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fig. 1. Analysis of these relationships enables to determine the concept of a large ingot. We can name the object as large ingot if thermal-physical parameters of this object can be hardly varied by the effect on the conditions of external heat transfer. It is evident that such steel ingot will have average diameter larger than 800–900 mm. These data are presented for structural steels with carbon content 0.15 and 0.30% as well as with total content of alloying elements up to 5–7% and impurities (sulfur and phosphorus) about 0.03%. It is clear that modern extra-clean steels (with summarized content of impurities less than 0.01%), carbon steels and high-alloyed steels of austenite or ferrite class are characterized by saving the general view of curves, but numerical characteristics of these curves will differ.

As soon as large ingots have average diameter exceeding 900 mm, variation of ingot thermal work due to intensification of internal heat transfer and management of liquid metal composition owing to reducing of content of technological impurities are evidently the most efficient and technologically suitable ways.

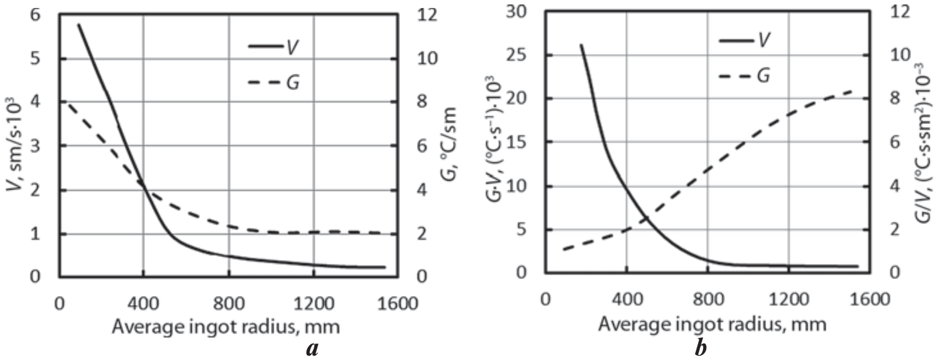
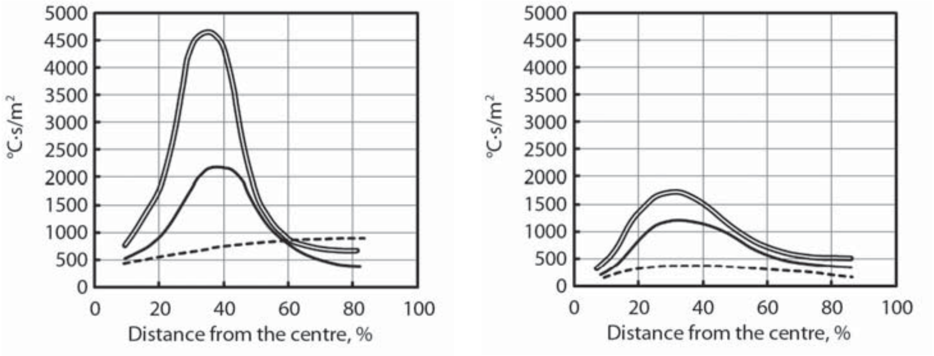
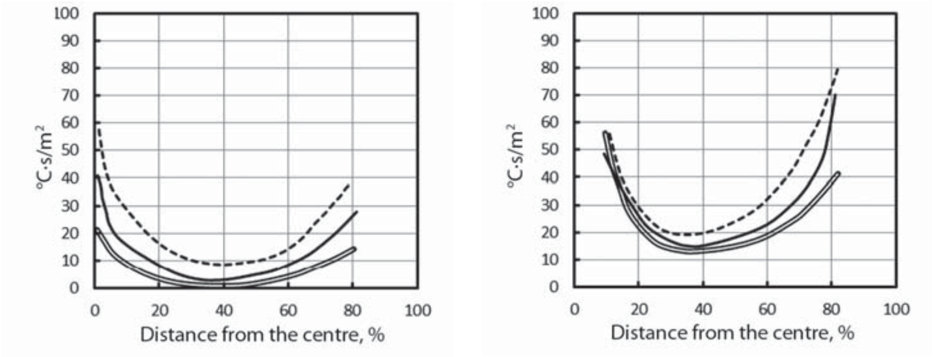


Fig. 1. **Variation of the minimal values of solidification rate (*V*) and temperature gradient (*G*) as well as corresponding values *G–V* and *G/V* depending on ingot size (for rotor steel)**



$\lambda_{eff} = 25$ $\lambda_{eff} = 250$

Fig. 2. ***G/V*** **variation along the 56 t ingot radius (twin line is for sub-feeder cross section, single line is for medium cross section, dotted line is for bottom cross section)**



$\lambda_{eff} = 25$ $\lambda_{eff} = 250$

Fig. 3. G·V (ε) variation along the 56 t ingot radius (twin line is for sub-feeder cross section, single line is for medium cross section, dotted line is for bottom cross section)

It is possible to vary cardinally thermal work of a large ingot via influence on heat transfer in a liquid core of solidifying ingot, as it is displayed on the relationships on the **fig. 2**. This influence was experimentally tested through the effect of electromagnetic field [1] of blowing by inert gas [2, 3]. Such experiments have displayed that heat transfer is activating, but the positive effect on ingot quality was not proved.

The results of influence of variation of the efficient heat transfer coefficient in the liquid core of a solidifying ingot (λ_{eff}) have been analyzed using the mathematical model developed in the State Research Centre JSC SPA "CNIITMASH". This value has been increased by 10 times (from 25 to 250 W/m, °C), simulating mixing of the liquid ingot core. The results of calculation are presented on the **fig. 2 and 3**. They display that increase of λ_{eff} has very substantial effect on variation of thermal-physical conditions in the dual-phase area of a solidifying ingot with mass 56 t.

Variation of the cooling rate (ε), calculated through the equation (1), testifies about essential rise of this parameter more than by two times. It will be accompanied by two appearances.

Firstly, the efficient distribution coefficient in the mixing ingot will be higher than in the ingot with less value of λ_{eff} [4].

Secondly, rise of ε value will lead to decrease of the distance between the first order axes in the whole ingot volume and in all crystal areas.

G/V relationship makes it possible to evaluate numerically the value of variation of the solidification temperature range and the rate of varying of this parameter. Using the data from figures 2 and 3 as well as experimental results [5, 6], we can evaluate possibility of development of out-of-centre segregation cords and essential zonal chemical heterogeneity.

Correct realization of mixing in the liquid ingot core causes significant improvement of homogeneity of distribution of chemical elements along the ingot body, i.e. of the elements with high segregation activity.

Rise of λ_{eff} leads to the situation when large ingots ($D_{av} \geq 900$ mm) with relatively high (according to the modern requirements) total content of sulfur and phosphorus (0.03%) can be manufactured practically without segregation cords.

It should be mentioned especially that lowering of the total content of sulfur and phosphorus down to 0.01% also decreases cardinally possibility of appearance of segregation cords and even zonal chemical heterogeneity in a large ingot.

Chemical heterogeneity of cast metal is considered as very important parameter and its importance rises with increase of ingot mass and size.

All elements presented in liquid metal can be divided by three large groups: impurities, technological elements and composition (alloying) elements.

Influence of each of these elements can be evaluated via its effect on forming of imperfect objects during crystallization, using difference of coefficients of accommodation of Fe and the concrete element ($\Delta A_X^{i-\mathrm{Fe}}$) .

The following elements among those that are practically always presented in liquid steel make the most essential effect:

1) impurities:

- removing — sulfur, phosphorus, oxygen, hydrogen, nitrogen — their content can be varied during melting, ladle treatment and casting;
- non-removing — antimony, tin, lead, arsenic, selenium, zinc, copper, cadmium — their content can be varied during melting preparation, using choice of initial materials;

2) technological elements — silicon, aluminium;

3) alloying elements — carbon.

Accumulation and distribution of alloying elements and impurities depends on thermal-physical and hydrodynamic condition of solidification

$$K_e^i = F(K_0^i, V, [C_0]_L^i), \tag{2}$$

where K_e^i — efficient coefficient of distribution; K_0^i — balanced coefficient of distribution; V — linear rate of crystallization; $[\mathrm{C}_0]_L^i$ – content of ith element in liquid metal before start of crystallization.

This expression explains the most important role of thermal work of ingot (V) and composition of cast metal ($[\mathrm{C}_0]_L^i$).

The State Research Centre JSC SPA "CNIITMASH" has formulated and confirmed the general theory of forming of zonal chemical heterogeneity [5, 10].

In general form, the main regularities of the theory of cord forming (∨-, ∧- shaped) can be presented as the following expression:

$$[C_0]_s^i = F_2\big([H, D], K_0^i, [C_0]_L^i, \lambda\big), \tag{3}$$

where $[C_0]_s^i$ — content of i^{th} element in the concrete ingot point; H, D — geometrical sizes of an ingot; λ — structural parameter of cast metal.

I.e. the degree of development of chemical heterogeneity in the each point of solidifying ingot depends first of all on:

– thermal conditions of solidification (size, H/D relation, efficiency of feeder work);

– composition of metal and contents of elements having strong effect on formation of a crystal Fe matrix ($[C_0]_L^i$, K_e);

– dispersion of forming dendrite structure, i.e. distances between the first order axes (λ).

Mathematical simulation is the most modern, efficient, quick and cheap method for optimization of configuration and thermal work of an ingot. The State Research Centre JSC SPA "CNIITMASH" has developed the software [11–14], uniting the advantages of commercial programs (ProCast, Polygon etc.) with the practical experience accumulated in thermographic research of ingots with mass in the range 5 kg – 415 t from different steels. This program allows to examine evolution of thermal-physical parameters, state and configuration of shrinkage defects, chemical heterogeneity, stresses in cooled metal; even hydrodynamics of liquid metal during its casting in moulds can be evaluated.

Achievements in metal refining allow to influence efficiently on chemical heterogeneity, up to complete elimination of the area of out-of-centre segregation cords. At the same time concentration and structural parameters of forming of cords and zonal chemical heterogeneity are varied.

Lowering of Si content in composition as well as adjusting of Al content allows not only to decrease development of chemical heterogeneity, but also to cease essentially segregation of the main composition elements, to improve quality of cast structure, to rise the most important properties (to decrease T_{K_0}, to increase *KCV*, other ductile characteristics) [15].

Knowledge about ingot *structural heterogeneity* is very important, meaning forming of chemical heterogeneity, uniformity of properties and achieving of the required dispersion of grain structure of product after its deformation.

Grain in the product strongly depends on dispersion of cast grain, its size is directly proportional to the distances between the first order axes (λ_1). These distances between the axes and structural areas in an ingot can be predicted on the base of simulation of thermal processes.

At present time the data about distances between axes are used successfully in development of deformation technologies.

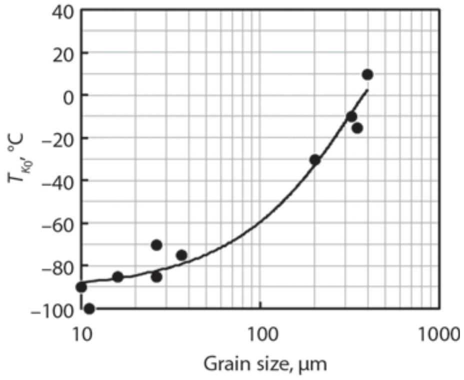


Fig. 4. Dependence between critical brittleness temperature and size of austenite grain (15Х2НМФА (15Kh2NMFA) steel)

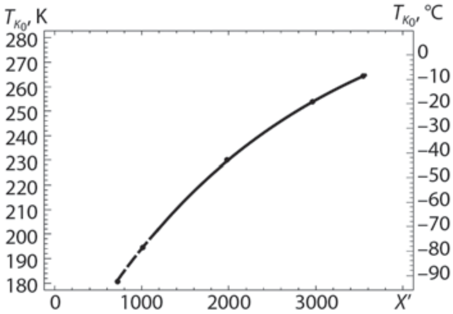


Fig. 5. Influence of 15Х2НМФА (15Kh2NMFA) steel refining on transition brittleness temperature (T_{K_0})

One generalizing example can be presented for demonstration of metallurgical achievements in machine-building. The complex of technological solutions for 15Х2НМФА (15Kh2NMFA) steel that is used for manufacture of the reactor shell of VVER-1000 type, allowed to use ingots with mass up to 420 t, to decrease the temperature of brittle-tough transition by 60 °C, to make this material practically unsusceptible to radiation by neutron flow during 80–100 years, to provide possibility of shortening and cheapening of the cycle and cost of its fabrication, to provide unconditional competitiveness of the Russian nuclear power stations in the global market.

Decrease of grain size improves effectively metal embrittlement strength (T_{K_0}) and cuts expenses for this process (see **fig. 4**).

Content of impurity elements in the 15Х2НМФА (15Kh2NMFA) steel and their influence on its resistance for destruction at low temperatures are analyzed. Regulatory data on maximally allowed content of impurities in the 15Х2НМФА (15Kh2NMFA) steel during total period of its usage and on T_{K_0} level specified by regulatory documents were used for this purpose [16, 17]. The main scientific statements of this article concerning the effect of chemical composition on development of chemical heterogeneity in large ingots have been additionally used. As a result, dependence between the temperature of brittle-tough period (T_{K_0}) in Kelvin grades and the generalized parameter X' expressing summarized steel contamination (i.e. the level of refining that can be achieved by the applied technology) has been established.

This relationship is expressed in the following way:

$$T_{K_0} = 29{,}2 \cdot [X']^{0{,}233}, \quad (4)$$

T_{K_0} — temperature of brittle-tough transition, K;

$$X' = 10P + 3S + 5[Sn + Sb + Bi + As] + + 5[H] + [Cu], \quad (4.1)$$

[P], [S], [Sn, Sb, Bi, As], [Cu], [H] — content of noted elements in liquid steel before casting (ppm).

Graphic interpretation of this relationship is presented on the **fig. 5**. Its analysis displays that the rate of T_{K_0} lowering rises with increase of refining depth. Extrapolation of the obtained results to the level of practically available steel refining shows that it is possible in this case to achieve T_{K_0} equals to minus 90–95 °C (173–178 K), i.e. it is possible to obtain practically safe material for reactor shell with service life more than 100 years.

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REFERENCES

1. Wang J., Fautrelle Y., Nguyen-Thi H., Reinhart G., Liao H., Li X., Zhong Y., Ren Z. Thermoelectric Magnetohydrodynamic Flows and Their Induced Change of Solid–Liquid Interface Shape in Static Magnetic Field-Assisted Directional Solidification. Metallurgical And Materials Transactions A. 2016. March. Vol. 47A. pp. 1169–1179.
2. Efimov V. A., Eldarkhanov A. S. Modern technologies of casting and crystallization of alloys. Moscow : Mashinostroenie. 1998. 360 p.
3. Stupak V. D. Development of the technology and examination of the effect of metal blowing by inert gas in a mould during casting and effect of solidification on quality of a large forged ingot. Dissertation ... of Candidate of Engineering Sciences. Sverdlovsk. 1977. 187 p.
4. Kurz U., Fischer D. Fundamental grounds of solidification. Moscow-Izhevsk : Institut kompyuternykh issledovaniy. 2013. 300 p.
5. Dub V. S. Investigation of out-of-centre segregation and development of the methods for oppression of its development in large ingots. Dissertation ... of Doctor of Engineering Sciences. Moscow : CNIITMASH. 1980. Vol. 1, 2.
6. Khlyamkov N. A. Investigation of influence of impurities on crystallization of large ingots from low-alloyed steel. Dissertation ... of Candidate of Engineering Sciences. Moscow : CNIITMASH. 1982. 194 p.
7. Dub A. V., Makarycheva E. V. Role of micro-processes in forming of macro-properties of the structural chromium-nickel-molybdenum steel. Moscow : *Metally*. 2007. No. 3. pp. 53–63.
8. Makarycheva E. V. Influence of deoxidizers and impurities on cast structure and properties of chromium-nickel-molybdenum steels and choice of the methods for quality management of large ingots for forgings. Dissertation ... of Candidate of Engineering Sciences. Moscow : CNIITMASH. 2003. 186 p.
9. Gamanyuk S. B., Zyuban N. A., Rutskii D. V., Palatkina L. V. Features of the distribution non-metallic inclusions in the structural zones of a 24.2 ton ingot of 38ХН3МФА steel. *CIS*

Iron and Steel Review. 2016. Vol. 11. pp. 35–40.
10. Kopeliovich D. D. Prediction of parameters of the out-of-centre segregation area in steel ingots. Dissertation ... of Candidate of Engineering Sciences. Moscow : CNIITMASH. 1990. 137 p.
11. Inventor's certificate No. 2013618230. «Simulation of steel melt solidification». Dub A. V., Ivanov I. A., Romashkin A. N., Dub V. S., Makarycheva E. V., Malginov A. N., Shamrov E. V. Registered 04.09.2013.
12. Inventor's certificate No. 2016614040 «Program of computer simulation of forming of physical heterogeneity during metals solidification from the melt «Porosity 3D». Romashkin A. N., Ivanov I. A., Malginov A. N., Dub V. S., Tolstykh D. S. Registered 12.04.2016.
13. Inventor's certificate No. 2016610257 «Program of computer simulation of dynamics of solid phase growth during metals solidification from the melt «Solid 2D». Romashkin A. N., Ivanov I. A., Malginov A. N., Dub V. S., Tolstykh D. S. Registered 11.01.2016.
14. Inventor's certificate No. 2016610506 «Program of computer simulation of forming of structural heterogeneity during metals solidification from the melt «Structure 3D». Romashkin A. N., Ivanov I. A., Malginov A. N., Dub V. S., Tolstykh D. S. Registered 13.01.2016.
15. Dub A. V. Physical-chemical grounds and management on the processes of primary structure forming and on the complex of operating properties for low-alloyed steels. Dissertation ... of Doctor of Engineering Sciences. Moscow : Moscow Institute of Steel and Alloys. 2000. 405 p.
16. Markov S. I. Metal science grounds of billet production for high reliable components of power engineering equipment and pipeline systems. Dissertation ... of Candidate of Engineering Sciences. Moscow : CNIITMASH. 2012. 83 p.
17. Markov S. I., Balikoev A. G., Dub V. S., Lebedev A. G., Gurovich B. A., Krikun E. V., Kuleshova E. A. Shell steels for perspective nuclear power units. *Tyazheloe mashinostroenie*. 2016. No. 7-8. pp. 2–8.

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ARITHMETICAL METHOD OF CALCULATION OF POWER PARAMETERS OF 2N-ROLLER STRAIGHTENING MACHINE UNDER FLATTENING OF STEEL SHEET

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Key words:

steel sheet, multiroll sheet-straightening machines, working and support rollers, curvature of sheet, alternating bending, bending moments of sheet, elastoplastic continuous medium with linear hardening

ABSTRACT

The main task of the technology of the steel sheet flattening is to calculate the optimal reduction of a sheet billet by the working rollers of straightening machines so that the sheet at the outlet from the machine has the minimum residual stress and curvature. In the mathematical and numerical modeling of the flattening process of the steel sheet in the multiroll straightening machines, in the beginning we calculate the curvature and bending moments of the steel sheet at the points of the tangency with the machine's working rollers, and then we calculate the energy-power parameters of the sheet's flattening. The calculation of energy-power parameters of the multiroll sheet-straightening machines is an important technological estimation at the steel sheet's flattening. The basis of energy-power calculation includes the estimation of the support reactions of working rollers and the efforts of the upper and lower rollers' cassettes of straightening machine at the sheet flattening. When there is an insufficient bending moment of steel sheet, it is impossible to eliminate the harmful residual stresses in the sheet wall and the surface defects of the sheet. If the force of the upper cassette rollers is insufficient, then to achieve the required reduction of the sheet for the quality flattening is impossible. The excessive values of the rollers' torque moments and the efforts of rollers' cassettes often lead to the sheet defects, the breakage of the working and supporting rollers and the breakage of whole sheet-straightening machine. The approximate method for the determining of the optimal technological parameters of the cold flattening of the steel sheet on the 2N-roller sheet-straightening machine is proposed in this paper. The calculations allow us to determine the type and curvature of the neutral plane of the steel sheet under the flattening, the residual curvature of the sheet after the flattening, the sheet's bending moments, the support reactions of working rollers, the residual stresses in the wall of the steel sheet, the proportion of plastic deformation on the sheet thickness and the relative deformation of the longitudinal surface fibers of the sheet under the flattening depending on the rollers' radius, the pitch between the straightening machines' working rolls, the magnitude of the sheet reduction by the upper rollers, the sheet thickness, as well as the elastic modulus, the yield stress and the hardening modulus of the sheet metal. The research results can be widely used at the engineering and metallurgical plants.

1. Introduction

The rolling mills and the multi-roller straightening machines are widely used in the manufacture of steel sheet in the Russian and foreign metallurgical industry [1–35]. For example, the five- and nine-roller straightening machines of the company "SMS Siemag" are used at the metallurgical complex mill-5000, and the five-, six-, eleven-, fourteen- and fifteen-roller straightening machines of the company "Fagor Arrasate" are used at the metallurgical lines of transverse cutting of steel sheet.

After the hot rolling [6, 7], the steel sheets are deforming during cooling due to the residual stresses and often have the surface defects in cold condition (for example, buckles, wavy edges, camber, crossbow, coil set and so on). Therefore, the steel sheets are flattened in the multi-roller straightening machines [12–15].

The process of sheet's straightening in the multi-roller flattening machines is mandatory (required) process for the technological processes of metallurgical production. The sheet flattening are widely used at Russian metallurgical plants (for example, in Vyksa, Chelyabinsk, Magnitogorsk, Izhora and so on) and at overseas metal-