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PRODUCTION OF INGOTS WITH FAVOURABLE LOCATION OF INTERNAL DEFECTS OWING TO VARYING THE FEATURES OF SOLIDIFICATION OF ITS HEAD PART

D. V. Rutskii [1], N. A. Zyuban [1], S. B. Gamanyuk[1]

[1] *Volgograd State Technical University (Volgograd, Russia)*

E-mail: rutskiy79@mail.ru, tecmat49@vstu.ru, gamanuk@mail.ru

AUTHOR'S INFO

D. V. Rutskii, Cand. Eng., Associate Professor, Department "Technology of materials",
N. A. Zyuban, Dr. Eng., Professor, Head of Department "Technology of materials",
S. B. Gamanyuk, Cand. Eng., Associate Professor, Department "Technology of materials"

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ABSTRACT

Solidification of large ingots is accompanied by development of the defects of shrinkage and segregation origination in these ingots. Such defects can reach significant size, remain in forgings after ingot deformation and lead to metal rejects at fabrication stage.

At present time, serious attention is paid to the problems of manufacture of defect-free ingots. Any of such investigations present information about usage of the new technologies providing substantial improvement of ingot quality parameters. These methods make the ingot production process rather more complicated and expensive, especially for the case of fabrication of long hollow forging, what restricts possibility of their wide application. This work proposes the method of ingot production for hollow forgings, allowing to control forming and development of internal axial defects due to local chilling of the ingot head part, and to guarantee their complete removal during forging.

It was established during metallographic examinations as well as physical and mathematical simulation that local chilling of the ingot head part leads to acceleration of solidification process practically in the whole ingot volume. Calculation of thermal work of chilling and hot feeder heads has revealed lowering of heat transferred to the body of chilled ingot. It stipulated increase of solidification rate and decrease of chemical heterogeneity in cast metal. Displacement of a thermal center to the axial part of the middle ingot section finalized in optimal location of a shrinkage, having essential length and small diameter; such location provides its guaranteed removal during fabrication of hollow ingot forging.

Introduction

Increase of capacity of power-generating units, building of superships, rapid development of heavy machinery, search and development of efficient import-replacing technologies stipulate necessity in designing of assemblies and mechanisms with increased operation resource. The components of assemblies and machines used in different industrial branches (nuclear power industry, heavy machinery, shipbuilding) are manufactured from large-size long forgings. It is known that large forged ingot is required for fabrication of such forgings, and its mass can reach several hundred tons. The period of solidification of large ingots can be rather long, and the appearances of shrinkage and segregation developing in solidifying metal support development of physical and chemical heterogeneity in solidified ingot. At present time there are many methods developed for improvement of metal quality of a large ingot. The efficient methods of ladle treatment [1–3] allow to produce metal with minimal contamination by non-metallic inclusions and harmful impurities. However, the achieved effect of quality improvement of metallic melt in a ladle can be substantially decreased owing to development of segregation and shrinkage defects in the process of consequent durable solidification of large ingots.

Different methods of the effect on liquid and solidifying metal are presented in [4, 5]: vibration, ultrasonic effect, electromagnetic stirring, modifying etc. These methods are used both independently and in combination with each other, and they make insufficient positive effect in the case of essential increase of production intensity. Putting into practice of all these technologies requires variation of technological lines in the shop and at the plant in general. It increases amount of capital investments as well as makes technological process more complicated.

Several enterprises [6–9] use remelting processes (electroslag remelting, vacuum arc remelting) that allow to improve metal quality, but they have not been used widely owing to complication of equipment and high level of power and labour expenses.

Evaluation of type and dimension ranges of forgings, manufactured from large ingots, has displayed that up to 80% of these forgings are hollow (rings, thick-wall tubes, rings, casing-type details etc.).

To produce hollow forgings, both feeder-headed ingots with normal length [9] as well as ingots with and without feeder head with increased length [10–12] are used. To produce hollow forgings, it is proposed to use hollow ingots, because their usage allows to decrease forging intensity and respectively to save substantially power and labour expenses during forging.

The company «Sheffield Forgemasters International Ltd.» (United Kingdom) has again introduced hollow ingots in the dimension range of its products after 25 years of interruption. NPO "TsNIITMASh" has conducted active works for development and putting hollow ingots into commercial production [9]. Other authors [13–15] have developed geometry of a hollow ingot manufactured via uphill casting has been developed using computer-aided simulation. Restriction of usage of these developments is connected with complication of directionality organization of solidification process. The author [16] has noted in his work that solidification of a hollow ingot can be

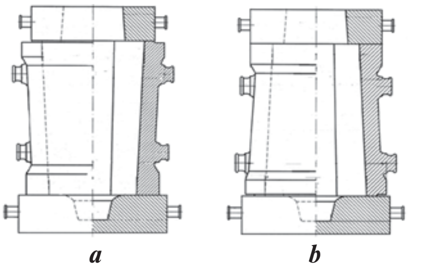

Fig. 1. Ingot scheme with a top cooling part
a — ingot widened in its top [17];
b — ingot widened in its bottom [19]

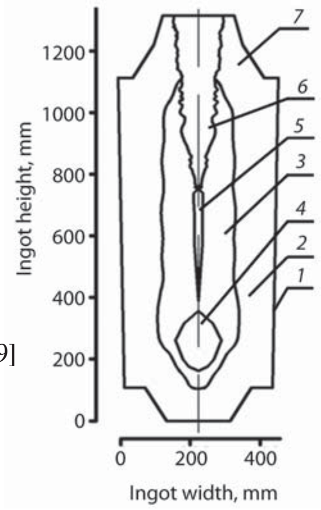

Fig. 2. Ingot structure with chilled head part
1 — crust area; *2* — area of rod-like crystals; *3* — area of equiaxial crystals; *4* — deposition cone; *5* — axial area; *6* — shrink hole; *7* — head part

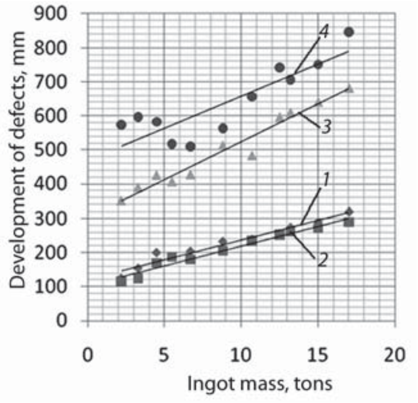

Fig. 3. Influence of mass of the ingot with chilled head part on development of a shrink hole in the ingot:
1 — diameter of a shrink hole (widened to top), mm; *2* — diameter of a shrink hole (widened to bottom), mm; *3* — length of a shrink hole (widened to top), mm; *4* — length of a shrink hole (widened to bottom), mm

resulted in substantial development of shrinkage and segregation and, consequently, in essential development of defects of shrinkage and segregation origination.

Ingots with locally chilled head part seems to be the most prospective meaning providing of qualitative characteristics of products and economical parameters of production [17]. Top cooling part is used instead of "classic" feeder head. Its destination is to compensate shrinkage of solidifying metal until crystallization fronts (moving in horizontal direction from side walls of mould) won't approximate sufficiently, providing obtaining of a narrow shrink hole in the ingot body. At the same time, the metal layer with sufficient thickness has to solidify near the head wall; strength of this layer should be sufficient for reliable ingot fixation via gripping by manipulator during forging.

Experimental methods

The ingots widened in their top and bottom, as well as with chilled head part, have been cast for production of hollow forgings [17–19] (**fig. 1**).

To examine the features of development of internal defects, longitudinal axial plates with 25 mm thickness have been cut of one of the ingots via mechanical shearing, with consequent cutting to metallographic samples. The plane of ingot shearing has been chosen perpendicular to the surface of heat removal, in order to make it possible to determine the structure in peripheral and axial metal layers.

Specimens for chemical analysis have been taken from metallographic samples cut of templates from three ingot levels. Chemical analysis of the samples has been conducted via spectral method on ARC-Met 930 device.

Kinetic features of crystallization and structure forming for ingots with different insulation of a head part have been examined using physical simulation on flat models (moulds with transparent walls) [20, 21]. Sodium thiosulphate (solution of crystalline hyposulphite) $Na_2S_2O_3 \times 5H_2O$ has been used as model melt.

Mathematical simulation of ingot crystallization process has been conducted using the system of computer-aided simulation «Crystal» [22], based on finite-difference method.

Results and discussion

Examination of the features of general ingot structure has displayed that ingots with chilled top part are characterized by the axial porosity area smaller in diameter and shorter in height by 2 times, in comparison with usual ingots. It is explained by smaller length of the area of hindered feed during the final stage of ingot solidification and, consequently, by its better feed with liquid melt. At the same time, segregation processes are characterized by more weak development during accelerated ingot solidification, and it result in decrease of solidification temperature interval and respectively of shrinkage volume.

The shrink hole in an ingot with chilled head part can occupy up to 50% of its height and up to 30% of ingot diameter (fig. 2).

Processing of the data obtained in the system of computer-aided simulation «Crystal» [22] and relating to the effect of conicity of the ingots widened to their top and their bottom and having chilled head part has shown that ingots with reversed conicity are characterized by the shrink hole kess developed in width and more developed in height. Increase of ingot mass leads to stronger development of a shrink hole in ingots widened to their top and their bottom (**fig. 3**).

Location of a shrink hole with small diameter in the ingot with chilled head part, along its axis, provides its elimination in fabrication of a hollow forging.

Chemical heterogeneity of usual ingots is developed rather essentially. It is connected not only with forming of the areas of negative and positive volumetric segregation (respectively in the bottom and top parts of the feeder ingots), but also with zonal segregation appearing as developed cords with increased content of carbon, sulfur and phosphorus. All these elements are

Table 1. **Chemical heterogeneity of ingots**

Parameter	Ingot with mass 1.7 t and with hot top part [23]	Ingot with mass 1.53 t and with top cooling part	Ingot with mass 2.07 t and with top cooling part [17]
Total segregation (%)			
– carbon	18,9	6,0	5,7
– sulfur	25,1	21,4	–
– phosphorus	27,1	11,1	–

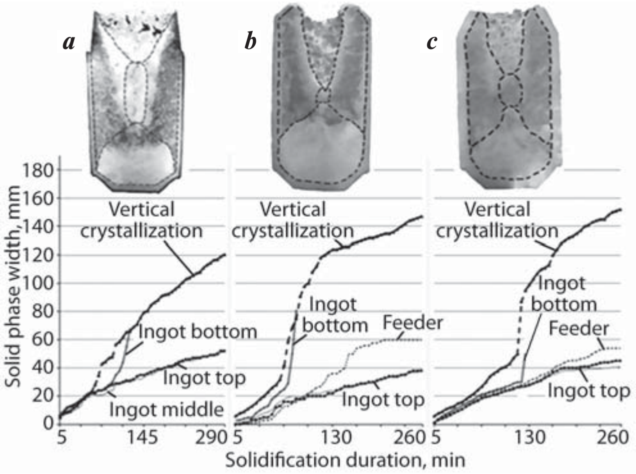

Fig. 4. Enlargement dynamics of the solid phase of model ingots depending on time of their solidification: *a* — ingot with a hot top part; *b* — ingot with a top cooling part (11.6%); *c* — ingot with a top cooling part (21.8%)

distributed more uniformly in the ingots with chilled head part (**table 1**).

The results of physical simulation of model ingots with different volume of a top cooling part are presented on the **fig. 4**.

Physical simulation of head part chilling allowed to reveal features of solidification of the whole ingot as well as of its different parts. In the case of usage of a hot feeder head (see fig. 4, *a*), growth of solid phase in vertical direction is practically directly proportional. It characterizes uniformity of solidification process of a model ingot with conventional form. If the melt with volume 11.6% (see fig. 4, *b*) is chilled, the proportional section of vertical crystallization is reserved during 50 min (i.e. 27% of total solidification time), Then solidification intensity rises (see the vertical section of the curve), what is caused by closing of crystallization vertical front. Increase of chilling volume up to 21.8% (see fig. 4, *c*) leads to enlargement of the proportional section of uniform crystallization up to 110 min. The dynamics of the further crystallization process does not practically differ from the previous case (see fig. 4, *b*). Varying the chilling volumes of the head part has led to variation of general solidification time for all kinds of ingots.

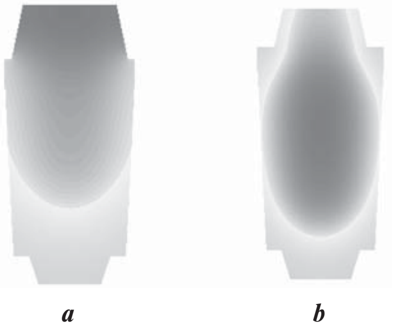

Fig. 6. Temperature fields of the ingots with hot top part (*a*) and top cooling part (*b*)

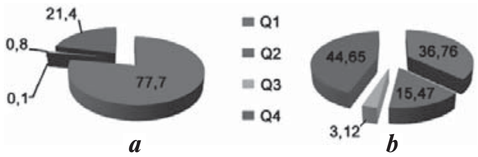

Fig. 5. Heat work balance for chilling and hot top feeder heads *a* — ingot with a chilling feeder head; *b* — ingot with a hot feeder head; Q1 — heat amount consumed for heating of lining materials and shell of a feeder head; Q2 — heat amount radiated from external surface of a mould feeder head; Q3 — heat amount radiated through metal mirror of an ingot feeder head; Q4 — heat amount transferred to an ingot

Calculation of the heat work of hot and chilling feeder heads has been conducted for qualitative estimation of the efficiency of a chilling effect in a head part. The results are presented on the **fig. 5** as a thermal balance. These results testify that usage of the top cooling part results in more than double absorption of molten metal heat by this chilling feeder head (77.7%) in comparison with the ingot having the hot feeder head (36.67%). This result increases intensity of heat transfer in the ingot head part and provides acceleration of metal solidification process.

Mathematical simulation has displayed that the heat center has shifted in the middle part of the ingot height during solidification, owing to the cooling effect of cooling feeder part. At the same time solidification of the upper levels approximate to the mechanisms of formation and growth of the solid phase in the bottom part, with intensively moving crystallization front and restricted possibilities of formation and growth of non-metallic inclusions. Distribution of the temperature fields in the ingot with hot top part and top cooling part (see **fig. 6**) show clearly the difference in location of the heat centers of comparing ingots. In the pilot ingot this center is located lower, due to presence of chilling top part in the ingot top, and it provides intensive heat transfer from the head part. Shifting of the heat center in the narrow axial ingot area leads to forming of long narrow shrink hole. This shifting also results in transfer of segregating impurities to the shrink hole walls. Such location of defects leads to their guaranteed elimination at the following stages of metallurgical processing (such as piercing, drilling of axial channel etc.).

Conclusions

Examination of development features of ingot internal defects, when ingot has been cast with chilling of its head part, testified about favourable location of defects of shrinkage origination. Variation of ingot conicity leads to increase of shrink hole length (up to 50% of ingot height), while shrink hole diameter does not exceed 30%. Such location of physical heterogeneity (shrink hole, axial porosity etc.) is optimal and provides guaranteed elimination of axial defects in metal rejects during forging.

Chilling of the head part leads to quick (twofold) heat absorption of solidifying metal heat by the top cooling part, what stipulates increase of ingot solidification rate along whole its volume, shifting of the heat center to the axial area and, consequently, rise of chemical uniformity of cast metal.

The obtained results allow to make choice of the respective ingot configuration providing manufacture of high-quality hollow forging with minimal development of segregation heterogeneity and controlled location of shrinkage defects. This technology does not require special accessories, variation of the technological process and excludes increase of production expenses in the conditions of strict competition at the metal markets.

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