Modelling the behaviour of ingot axial defects under open die forging

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Abstract. The paper reports findings on mathematical modelling of ingots of different geometry. It is established that V-shaped cracks concentrated in the ingot bottom are gradually removed through upset, while arch-shaped cracks located around the sedimentation cone top open up. A computer simulation made it possible to calculate efficient deformations in the workpiece axial zone. An alteration of the ingot geometry leads to an increase in efficient deformation and, consequently, a better treatment of axial areas and elimination of the axial defects of the ingot metal.

1. Introduction

Nowadays, there is an increasing need in the production of large forgings used to manufacture heavy duty large-sized products for nuclear power engineering, heavy engineering etc. The weight of the ingots required to produce these workpieces can achieve 850 tons. The solidification of a large mass of metal takes an extended period of time (1 to 7 days) and is accompanied with an intensive development of segregation and shrinkage phenomena. The natural shrinkage of the melt is equal to 4% of the solidifying volume, which leads to the development of shrinkage defects inside large ingots. The detailed studies [1-3] demonstrated that after solidification, large ingots have a well-developed heterogeneity of their inner structure. This heterogeneity may be of one of the three types (figure. 1):
- physical heterogeneity (shrinkage cavities, V-shaped cracks, porosity);
- chemical heterogeneity (macrosegregation, microsegregation, ‘A’-segregation);
- structural non-homogeneity.

Currently, there are a number of works [1, 4-6] considering the problems of ingot solidification and the development of internal defects inside them. Computer modeling is the most advanced method which enables us to assess the effects of heating and pouring process parameters on solidification [7-11].

Computer modeling has made it possible to develop methods of improving the quality of the metal in ingots. Somehow, the proposed methods do not always make it possible to fully avoid the development of the aforementioned defects because extensive solidification leads to a considerable development of these defects.

After solidification, ingots undergo metallurgical treatment which includes open die forging, preliminary and final mechanical treatment and heat treatment. Some internal structure defects can be eliminated through these operations.
Open die forging of ingots is one of the major stages of metallurgical treatment when inner defects can be eliminated. Structural heterogeneity is fully eliminated during hot deformation (figure 1c, d). Axial zone defects as well as the “A”-segregation zone noticeably reduce in size and length (figure 1a, 1b).

Somehow, if axial zone defects are well developed, they cannot be removed by forging and remain in the finished product, which is unacceptable. The authors [1, 3, 12] have established that the reason for the rejection of large-sized products is a noticeable concentration of discontinuities in forging axial sections identified by UT (figure 2). Thus, it is an important task to establish the features of ingot internal defect behaviour while forging. Upset is one of the efficient operations of open die forging which helps to eliminate internal axial defects. The paper contains a mathematical modeling of the upset of billets having various geometry.

Figure 1. Defects of a large forging ingot: a – axial zone defects in the form of V–shaped cracks; b – ‘A’ segregation streaks; c – ingot upper part macrostructure; d – ingot bottom part macrostructure.

Figure 2. Defects identified in the axial areas of the forgings produced from large ingots: a – a defect in the axial area of a shaft forging; b – a defect identified while boring the axial channel in a hollow forging.

2. Materials and methods
The authors [1, 2, 9, 12] have carried out a detailed study of a poured structure which enabled to establish the location and extension of axial zone defects (V-shaped cracks, arch-shaped cracks) in ingots with conventional and altered geometry of the bottom part. While modeling the chill, axial zone
defects were specified in the form of cavities with the dimensions and shape similar to real ingot defects identified when studying the ingot internal structure (figure 3).

![Figure 3. Structural zones of a 24.2 ton ingot [1].](image)

9 – shrinkage cavity;
8 – ‘A’ segregation streaks;
7 – ‘A’ segregation zones;
6 – zone of randomly-oriented crystals;
5 – ingot axial zone;
4 – zone of fine randomly-oriented crystals;
3 – zone of arc-shaped cracks;
2 – sedimentation cone;
1 – chill zone;

Mathematical modeling was carried out with the Deform 3D application. Geometry import, symmetry assignment, presetting border conditions and calculation parameters (time interval, stop time etc.) were performed in the ‘Preprocessor’ module. Tool deformation was not considered when modeling the upset operation; besides, only a 90° ingot section was modeled because the problem is fully symmetrical. In addition, steel 38ХН3МФА entry was made in the application in order to make simulation as real as possible. The forging temperature range in the simulation was 1073 K (800 °C) to 1373 K (1100 °C). Heat loss to the tool was calculated through an increased heat loss factor. Ambient temperature was equal to 293 K (30 °C).

The forging press speed was assumed to be unchanged and was equal to 0.5 mm/s. Calculation was stopped at the distance between the tools equal to 1200 mm. Estimated forging time was equal to 40 minutes which fully corresponds to a real production process.

3. Results and discussion
Temperature field calculation throughout the ingot under upset shows that upon upset completion, the temperature of the billet center was not lower than 1263 K (990 °C), which complies with forging temperatures for this grade of steel. The temperature throughout the axial zone is equal and it leads to equal plastic properties of steel throughout the billet and prevents crack formation when forging the ingot.

The application makes it possible to monitor deformation process (figure 5) thus enabling to establish the time of the complete removal of defects thus avoiding additional loading and, consequently, additional costs.
The calculation results provided in figure 7 demonstrate that axial zone cracks are gradually removed through upset.

Figure 4. Temperature distribution field in the conventional shape ingot: a – before upset; b – after upset.

Figure 5. Shape and strain changes throughout the ingot during hot working: a – the conventional geometry ingot; b – the altered geometry ingot.
During minute 15 of upset, the geometry of cracks starts to change intensively; as this takes place, V-shaped cracks are gradually removed by forging while arch-shaped cracks around the sedimentation cone top open up by minute 23 (figure 5). This behaviour of cracks is typical for both ingots.

A mathematical calculation of efficient deformations in the axial zone of the workpiece manufactured from the altered geometry ingot demonstrates that cracks are eliminated more efficiently in the ingot due to their advantageous orientation in the original ingot and a difference in dendrite structure density.

**Figure 6.** Distribution of total strains after the hot working of ingots: a – the conventional geometry ingot; b – the altered geometry ingot; deformed metal section with crack remnants in the axial zone; deformed metal section with defect remnants of the arch-shaped crack zone.

**Figure 7.** Efficient deformation behavior in the course of time in the ingot axial zone: a – the conventional geometry ingot; b – the altered geometry ingot.
Somehow, even an alteration of the ingot geometry does not allow one to get rid of crack development in the central section of the forging. Moreover, some cracks develop to a great extent (figure 6) because the direction of working coincides with the crack inclination angle thus favoring the crack growth.

We can clearly see from figure 7 that efficient working along the axis of the altered geometry ingot is notably higher than that in the conventional geometry ingot. It can be explained by a higher density of metal in the axial zone; this higher density was obtained during pouring and teeming. An increased density improves the degree of deformation of the axial areas throughout the workpiece thus contributing to the removal of defects.

4. Conclusion
A computer modeling of ingot upset demonstrates that axial zone cracks behave differently during upset: V-shaped cracks are removed by forging while arch-shaped cracks open up. Cracks are not completely removed by the end of upset.

The computer modeling of hot working also proves that during the upset of the conventional geometry ingot, most axial zone defects are not removed as it was believed before, but continue to develop.

Axial zone defects do not develop so rapidly in the altered geometry ingot, cracks are eliminated in the course of hot working (upset) and efficient deformation is twice as high as that in the conventional shape ingot.

Acknowledgments
The reported study was funded by the RFBR, research project No. HK 15-08-08098/15

References
[1] Zyuban N, Rutskii D, Konovalov S and Gamanyuk S 2014 *Metallurgical and Mat. Transactions A: Phys. Metallurgy and Mat. Sci.* 45 6200-6206
[2] Poslomovskaya Yu A and Zhul'ev S I 2008 *Metallurgist* 52 253-258
[3] Shamrei V A and Zhul'ev, S I 2007 *Metallurgist* 51 617-623
[4] Romashkin A, Dub V, Tolstykh D, Ivanov I and Ekhvaya G 2016 *Metallurgist* 56 1163-1172
[5] Liu H, Fu P, Kang X and Ma X 2014 *China Foundry* 11 46-51
[6] Dub A V, Dub V S, Makarycheva E V and Ivanov I *Russian Metallurgy* 7 560-564
[7] By Sang-Hun OH, Jung Namkung, Seog-Ou, Cho, and Dong-Hee Lee 2011 18th Int. Forgemasters Market and Technical Proc. p 179-182
[8] Tu W, Zhang X and Shen H 2014 *China Foundry* 11 52-58
[9] Jiaqi W, Paixian F, Hogwei L, Dianzhong L and Yiyi L 2012 *Materials and Design* 35 446-456
[10] Lan P and Zhang J 2014 *Ironmaking & Steelmaking* 41 598-606
[11] Liu D, Sang B, Kang X, Li D, Oh J, Yun E, Golkovski M and Lee S 2009 *Acta Phisica Sinica* 58 104-111
[12] Rutskii D V, Zyuban N A and Titov K E 2009 *Metallurgist* 53 585-591