Study of the Effect of Shrinkage Porosity on Strength Low Carbon Cast Steel

E Ol'khovik

1 Admiral Makarov State University of Maritime and Inland Shipping, Saint-Petersburg, Dvinskaya str. 5/7, Russia

e-mail: olhovick@gmail.com

Abstract. Today there are many computer systems for modeling of the casting technology processes. All of them allow calculating the availability and distribution of the shrinkage porosity in the test casting, but this information allows only making changes in existing casting technology. In this paper you obtain the information about changes in the local and structural mechanical properties of the casting in the presence of its volume shrinkage porosity. Article presents the results of direct experimental studies of technological defects (shrinkage and gas porosity) impact on the mechanical properties of low carbon steel castings. Methods of investigation are also disclosed, including the methods for producing of molded samples obtained at different process conditions and the crystallization apparatus which is described for the measuring of the density of the samples. There are the mathematical relationship for the elastic modulus, yield stress, elongation and fatigue characteristics fracture cast steel with low carbon content in the presence of the volumetric shrinkage porosity.

1. Introduction

Shrinkage and porosity are always presented at steel castings which have difficult geometry and form. This known problem leads to uncertainty in the calculations of the structural strength of the cast steel. Porosity is uneven, that affects the overall reliability of the design. Moreover there are no accurate methods for its accounting in the technical strength. As a result, for reliability designers have used the safety factors higher than necessary that leads to heavy steel castings.

The experimental results for the steel plates of the castings are presented at Pellini’s work [1]. Kubo and Pehlk in [2] proposed the mathematical model of the porosity formation process during solidification, based on the solution of the unsteady heat conduction. Paper [3] presents the multi-phase model that predicts melt pressure, feeding flow, and porosity formation and growth in the steel castings during solidification. Niyama, Uchida and Morikawa in [4] examined some castings and confirmed that the feeding gradient could be used to predict the formation of shrinkage porosity. Sigworth and Wang in [5] proposed the simple "geometric" criterion to describe, where there will be shrinkage porosity. Nastac and
Marsden in [6] looked at the solution of the multiphase modeling of macrosegregation and crystallization under various temperature conditions as the cause of the formation of the shrinkage porosity in large steel ingots.

Hardin and Beckermann in [7,8] proposed the methodology to predict the fatigue life of the components made of the cast steel with the shrinkage porosity. They checked data from X-ray tomography measurements of porosity in the castings. They also made combined experimental and computational study to investigate the effect of the central shrinkage porosity on the deformation properties of steel, studied in detail the damage and destruction of the cast steel under tensile tests. More recently Sutaria, Sharma and Ravi in [9] proposed the model that is based on the solution of the Stefan equation for solid and liquid phase with the terms of boundary interface. This solution allows to calculate the mass of the particles by tracking the optimal feed casting and solidification.

In article [10] we proposed the methods and the apparatus for the mechanical testing of the materials under conditions of three dimensional stress state. This procedure gives results better than conventional tensile test of specimens and can be used to assess the strength of porosity. In work [11] we developed the mathematical models to predict the formation of the dendritic structure of the cast steel in various technologic conditions, using the method of the phase field model. These data are also needed to evaluate the strength of the castings by the criterion of austenitic grain size and they are used by us in this work and in the future.

This paper presents the results of the experimental study about effect of the shrinkage porosity on the mechanical properties in the steel castings. There is also offered the analysis of problem of the steel casting parts failure due to the presence of shrinkage or gas porosity in the body casting. A lot of existing literary data show the presence of the characteristic defect in the steel castings under various conditions of their formation: gas or shrinkable porosity. Porosity in the steel casting is the central problem for the most foundries. Most designers are not sure how to account the effect of porosity in the cast steel parts. The casts study using the methods of partial or complete fragmentation on the templet and subsequent separate study do not guarantee the quality of the results [11,12] and they are quite expensive. Various industries use a combination of these strategies to try to establish reliable cost-effective designs. It is produced if there is a lack of liquid metal for the casting feeding during solidification, or as a result the dissolving of gases in the casting. Porosity as systemic phenomenon depends on how the shrinkage process is going. In the case of successful technology management the shrinkage porosity is minimized, on the contrary it becomes chaotic.

Porosity itself can be harmful for the fatigue durability of the casting, because the act that is manifested as stress concentration and cracks with subsequent formation of «kernel» leads to details destruction. Quantitative influence of porosity on fatigue resistance of the steel castings is not fully studied, and there is no good method for predicting of effect of the mechanical properties reducing in the presence of shrink or gas porosity in the casting.

2. Materials and method
Most of the major body parts have complex geometry or contoured shape and they are made of cast steel. This type of steel has good mechanical properties, including yield strength and elongation (plastic properties) and it is able to provide high resistance to elongation, low-
cycle and cyclic loads, even in excess of the calculated parameters. A lot of the cast parts have a wall thickness which is varied from 15mm to 80 mm. This difference in thickness almost always leads to the formation of local parts of the casting, malnutrition and as a consequence affects the shrinkage porosity. Therefore, there were two objectives: determine the mechanical properties of the presence in the metal shrinkage porosity and explore the speed of the development of fatigue cracks in the different values of local porosity of cast metal. For better study the tests of some castings different geometry (thickness, length, shape) for real castings were conducted. In all cases the steel with low carbon content (C = 0.15 ÷ 0.25%) was studied. This steel crystallizes at the peritectic reaction and has difficulty for most foundries. For the experiments in this work several metal melts were performed, for which the control of the chemical composition was produced by optical emission method and the basic mechanical properties. All data are shown in Table 1.

**Table 1. Chemical composition and mechanical properties of the experimental research of low-carbon steel**

| № (melting) | C, % | Mn, % | Si, % | Al, % | S, % | P, % | YS [MPa] | UTS [MPa] | Elong, % |
|--------------|------|-------|-------|-------|------|------|-----------|-----------|----------|
| 1            | 0.17 | 0.3   | 0.25  | 0.09  | 0.015| 0.025| 196       | 390       | 24       |
| 2            | 0.15 | 0.3   | 0.24  | 0.09  | 0.015| 0.025| 192       | 389       | 24       |
| 3            | 0.18 | 0.32  | 0.25  | 0.08  | 0.014| 0.025| 201       | 390       | 23       |
| 4            | 0.17 | 0.29  | 0.24  | 0.08  | 0.015| 0.024| 203       | 392       | 23       |
| 5            | 0.19 | 0.36  | 0.25  | 0.08  | 0.014| 0.021| 213       | 407       | 20       |
| 6            | 0.20 | 0.33  | 0.25  | 0.08  | 0.014| 0.024| 215       | 408       | 21       |
| 7            | 0.23 | 0.75  | 0.23  | 0.09  | 0.013| 0.023| 231       | 438       | 19       |
| 8            | 0.26 | 0.58  | 0.23  | 0.09  | 0.012| 0.022| 240       | 447       | 18       |
| 9            | 0.28 | 0.83  | 0.27  | 0.09  | 0.015| 0.025| 247       | 452       | 17       |
| 10           | 0.25 | 0.61  | 0.26  | 0.08  | 0.015| 0.025| 242       | 450       | 17       |

All test samples for mechanical properties underwent the pre-heat treatment. Melting was carried out in the open induction furnace using slag. As a charge steel scrap metal and steel with the known chemical composition were used. These mechanical properties of the alloy (Table 1) were obtained by testing samples taken immediately during melting. Thus, all the samples can be divided into two parts on the strength of the group: Group 1 - melting №1,2,3; Group 2 - melting №4, 5.

There are many methods to determine the volume of porosity in the samples, each of them has certain advantages and disadvantages. The most commonly used method is x-rays, it is well-suited for determining the local zones affected by porosity, but it cannot give the accurate information about the volume of porosity. Porosity detection through non-destructive testing is a common method. Unfortunately, often the amount of porosity in the critical section can be so slight that it cannot be detected. Now there are no standards defining the critical values of porosity, but even if there is a quality system in a separate company, which determines the critical volume of porosity in casting body, it is likely that this approach will be subjective.
In experiments, it was important to limit impact force action on the part of sand mold. During solidification shrinkage also creates a force field in the casting – [12, 13]. We used the sand mold with minimal sealing that ensures its high ductility after the start of crystallization and during this process. Thus, solidification and shrinkage of the steel samples were conducted without force influence of foundry mold.

3. Experimental methods
In this paper, the method of hydrostatic weighing was used to determine the density of the cast steel samples and amount of shrinkage or gas porosity in the samples, thus, in the future, these samples will be used to determine the mechanical properties.

![Figure 1](image1.png)

**Figure 1.** The casted cone samples for studying of the mechanical properties of the metal (a); The scheme for the tenderloin of the samples to determine the density and strength (b)

For testing of research methods, on the first stage there was cast special steel cone sample (Fig.1(a)) of sufficient length without profits which scheme is shown in (Fig.1(b)). Two samples were cut for further study of determination of the mechanical properties and the density of the metal. The advantage of this scheme is the region where the upper sample feeds the lower one by liquid metal. Thus it can be initially assumed that lower molten metal sample has higher density, while the upper sample is struck by the shrinkage pores. The experimental castings were tapered samples and they had sufficient length and different cross-sectional area. To perform this work the series of the experimental castings, various lengths and diameters were casted. The general characteristics of the casting of cone geometry are represented in detail in Table 2, where L - length; \(d_1\) - smallest diameter (bottom); \(d_2\) - largest diameter (top).
Using a thermocouple the time of full curing was recorded in seconds ($\tau$ [sec]) for each sample. The total time of crystallization was the time of achievement of the solidus temperature at the top of the casting. About 40 different cast steel samples were made. All data about experimental castings are shown in Table 2. Additional samples for research were obtained from actual castings with a wall thickness from 15 to 50mm and the test block (ISO 4990:2003, par. 6.2.2.2) was casted from the casting and feeding. It is necessary to compare the overall results obtained from the sample of the cone’s alloy and the test block. These results have approximately the same mode of solidification, which is made in the real castings.

Table 2. Geometric characteristics of experimental castings and time of their complete solidification

| N  | L[mm] | d₁[mm] | d₂[mm] | Volume $[\text{mm}^3] \times 10^3$ | Square Lateral surface $[\text{mm}^2] \times 10^3$ | $\tau_{\text{sol}}$[sec] |
|----|-------|--------|--------|---------------------------------|---------------------------------|------------------|
| 1  | 100   | 60     | 80     | 387.3                           | 22                              | 310              |
| 2  | 150   | 45     | 60     | 326.7                           | 24.7                            | 265              |
| 3  | 180   | 35     | 50     | 257.8                           | 24                              | 190              |
| 4  | 200   | 30     | 40     | 193.6                           | 22                              | 160              |
| 5  | 250   | 20     | 30     | 124.3                           | 19.6                            | 45               |
| 6  | 290   | 30     | 45     | 324.4                           | 34.1                            | 95               |
| 7  | 320   | 15     | 70     | 517                             | 42.7                            | 150              |
| 8  | 320   | 40     | 60     | 636.3                           | 50.2                            | 320              |
| 9  | 320   | 25     | 60     | 479.3                           | 42.8                            | 200              |
| 10 | 350   | 50     | 65     | 913.5                           | 63.1                            | 515              |
| 11 | 380   | 10     | 100    | 1103.7                          | 65.6                            | 610              |

The samples were cut from the experimental castings by machining, with the great control of geometrical accuracy. To perform hydrostatic weighing it is required more precise measurements and therefore specially designed installation shown in Figure 2 was created. To measure the strain gage specially made bar with four strain gauges is used which is connected to the Wheatstone bridge to maximize accuracy. In the processing of signal from the Wheatstone bridge 14-bit analog-to-digital converter (ADC) is used, which provides the measurement accuracy at least 0.025% from the sample weight. During the preparation the samples were heat treated at the temperature of 150-200°C for 10-15 minutes to eliminate the effect of factors associated with the possible fluid or other substances accumulation in the sample body.
Each sample was analyzed sequentially: initially the sample is weighed into the open air and then in the distilled water. Previously, the geometric dimensions of the sample were measured and its volume was calculated precisely. Using the difference in the results of the sample weighing in the air and in the water the density was calculated. The density changing during sample immersion in the liquid indicates the presence of voids (porosity) in the sample, which have buoyancy force.

4. Results

The value of the porosity volume for all received (tested) samples was ranged from 0% to 10% from mass, however, the samples with the volume of shrinkage porosity more than 5% were found faulty and they have been excluded because for the real castings, such porosity volume is not valid. The study of mechanical properties of cast steel was performed for all samples in order to identify the change of deformation and strength characteristics depending on the amount of porosity.

The mechanical tests of all samples were carried out in accordance with ISO 6892, the preparation of the samples was carried out in accordance with ISO 377. The geometric dimensions of the samples were different, but the ratio of the length to the size of the working part of the samples cross-section was compiled in respect from 1/10 to 1/5. The mechanical tests were performed on the cylindrical fivefold and tenfold samples on the testing machines that provide the sufficient accuracy. According to the results of the mechanical tests the standard mechanical properties of the samples were determined, such as - the elastic modulus, yield strength, tensile strength and elongation.

The figure 3 presents the test results as a function of elasticity modulus from the volume of shrinkage porosity for the samples obtained from our melts №1 ÷ 5, and for the additional samples which were cut from various castings operating under load for 5-10 years. For more accurate analysis, the samples were divided into two groups according to the strength category.

It can be concluded that the porosity does not have serious influence on the modulus of elasticity, while in the case of excess amount of the porosity (more than 3%) the reduction of the elastic properties occurs steadily. It should be understood that the elastic modulus has an integral property, which has the total dependence for a large group of steel. Nevertheless, these data are necessary in the
case of calculation the overall structural strength of the cast parts. This relationship (Fig.3) can be applied in the calculations where the finite element method is being used.

![Figure 3. Experimental relationship of modulus of elasticity from the volume of shrinkage porosity](image)

- • Samples from melting № 1,2,3;
- ♦ Samples from melting № 4,5;
- ○, ◇ Samples of castings which are operated under load for 5-10 years.

To calculate the local changes in the strength the mathematical relationship for the yield stress (YS) was developed – fig.4. Thus it is possible to construct the distribution of such important parameter as the yield stress for all castings, in case of shrinkage porosity.

![Figure 4. Experimental relationship of yield strength from volume shrinkage porosity](image)

- • Samples from melting №1-5

The greatest interest is the change in the plastic properties of the cast steel in the presence of porosity, because the steel castings are working in harsh conditions and cyclically varying loads that require high plastic properties - yield strength and elongation.
5. Conclusion
Currently castings designers don’t have quantitative information about change of the mechanical properties of the cast steel directly into the casting. The elaboration of engineering principles for improving of the casting quality allows selecting the assurance factor using methods proposed in this paper. Most foundries conduct such experiments, but don’t systematize the data influencing on the strength of the cast steel.

The proposed method for the structural analysis of the shrinkage porosity impact on the quality of steel castings has sufficient capacity and the qualitative methodology. Moreover, all obtained data can be used in the computer analysis of the casting technology and they allow determining the possible reduction in the structural strength of castings in the most loaded areas.

All developed techniques are being applied for production the steel castings of high strength and quality, for example, for the production of the shafting blanks [15], which surface will be processed in the future and for the bodies of ship's pipe fittings [16] or railway bogie[17,18], including some of its highly stressed parts.

6. Highlights
- The methods for obtaining of the cast steel samples (casting cone) that replicate the wide range of conditions of solidification process
- Experimental relationship of changing of mechanical properties of cast steel with low content of carbon with technologic defects as gas porosity and shrinkage
- All obtained data can be used to simulate the casting technology in order to prevent the formation of defects such as shrinkage porosity
- All obtained data can be used in the future to assess the structural strength of the steel castings in their long-term operation

References
[1] Pellini W S Trans Amer Foundrymen’s Soc 61 (1953) p 61–80
[2] Kubo K Pehlke R D Mathematical modeling of porosity formation in solidification Metallurgical Transactions B 16 2 (1985) p 359-366
[3] Carlson K D Lin Z Hardin R Beckermann C Mazurkevich G & Schneider M (2003) Modeling of porosity formation and feeding flow in steel casting In Proceedings of the 56 SFSA Technical and Operating Conference Paper (No 4 4)
[4] Niyama E Uchida T Morikawa M Predicting shrinkage in large steel castings from temperature gradient calculations Int Cast Met J 6 2 (1981) p 16-22
[5] Sigworth G K Wang C Mechanisms of porosity formation during solidificationp A theoretical analysis Metallurgical Transactions B 24 2(1993) p 349-364
[6] Nastac L Marsden K Numerical modelling of macrosegregation and shrinkage in large diameter steel roll castingsp A mould study International Journal of Cast Metals Research 26 6 (2013) p 374-382
[7] Hardin R A Beckermann C Prediction of the fatigue life of cast steel containing shrinkage porosity Metallurgical and Materials Transactions A 40 3 (2009) p 581-597
[8] Hardin R A Beckermann C Effect of porosity on deformation damage and fracture of cast steel Metallurgical and Materials Transactions Ap Physical Metallurgy and Materials Science 44 12 (2013) p 5316-5332
[9] Mayur Sutaria Vinesh H Gada Atul Sharma B Ravi Computation of feed-paths for casting solidification using level-set-method Journal of Materials Processing Technology 212 6 (2012) p 1236-1249

[10] Ol'khovik O E and Ol'khovik E O Endurance of structural materials in the triaxial stress state Industrial Laboratory 63 7 (1997) p 423-428 (http://www.scopus.com/inward/record.url?eid=2-s2.0-33748894154&partnerID=FN8TOARS)

[11] Ol'khovik E O Desnitskaya L V Prediction of structures of castings Izvestiya Vysshikh Uchebnykh Zavedenij Chernaya Metallurgiya 11 (2004) p 49-53 (http://www.scopus.com/inward/record.url?eid=2-s2.0-10144260026&partnerID=FN8TOARS)

[12] Ol'khovik E O Desnitskii V V Molchanyuk R A Interaction between casting and mold during solidification Steel in Translation 37 5 (2007)p 422 – 424 (doi10.3103/S0967091207050051)

[13] Desnitskii V V Ol'khovik E O Molchanyuk R A Investigations of deformativ-strength properties of the molds materials during metal crystallization Blanking productions in mechanical engineering (Forging and stamping foundry and other productions) 1 (2007) p 16-19

[14] Ol'khovik E O Desnitskii V V Development of methods aided design foundry technology steel castings fitting oil and gas Izvestiya Vysshikh Uchebnykh Zavedenij Chernaya Metallurgiya 12 (2006) p 40-43

[15] Khmelevskaya V B Moseyko Y S Ol'khovik E O Research of hardening of ship propeller shaft by plasma spraying coverage with ultrasonic treatment Vestnik gosudarstvennogo universiteta morskogo i rechnogo flota imeni admiral S O Makarova 19 3 (2013) p 81-87

[16] Ol'khovik E O Reznik U A Development of laser welding technology of bellows assemblies for ship pipeline valves Vestnik gosudarstvennogo universiteta morskogo i rechnogo flota imeni admiral S O Makarova 25 3 (2014) p 119-122

[17] Ol'khovik E O Desnitskiy V V Research of influence of dimensional accuracy of casting of bogie sidebar of rail freight car on its strength Vestnik Mashinostroeniya 10 (2014) p 47-49

[18] Ol'khovik E O Development process design with effects of technology quality Applied Mechanics and Materials Applied Mechanics and Materials 770 (2015) p 419-423 (doi10.4028/www.scientific.net/AMM.770.419)