

# Mechanisms and mechanics of porosity formation in ductile iron castings

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## Abstract

Shrinkage defects in ductile iron castings can be of two basic types: shrinkage cavities associated with the liquid contraction prior to the expansion period of the iron as well as the porosity, which may appear even if the liquid shrinkage is fully compensated. In the present paper two possible mechanisms of the porosity are presented and analyzed. The first one is the Karsay's mechanism based on the secondary shrinkage concept. The second one is the mechanism acting during the expansion period of the iron, first suggested by Ohnaka and co-authors and essentially modified by the present authors. The mechanical interactions between casting and mould are determined for the both mechanisms. Their analysis leads to the conclusion, that porosity forms during expansion period of the melt. The direct cause is the negative pressure which appears in the central part of the casting due to the differences in expansion coefficients of the fast cooling surface layer and slow cooling inner region. Observations concerning feeding behavior of ductile iron castings, based on this mechanism, agree well with industrial practice. The secondary shrinkage is not only needless to induce the porosity, but the corresponding mechanism of its occurrence, proposed by Karsay, does not seem to be valid.

**Key words:** Casting defects, Ductile cast iron, Porosity formation, Feeding, Mechanical analysis.

## 1. Introduction

Shrinkage defects in ductile iron castings can be of two basic types. The first one develops due to the liquid contraction prior to the expansion period of the melt. However, for a large variety of castings, particularly made in green sand or shell moulds, the compensation for the liquid contraction by application of feeders which solidify at the onset of the expansion of the casting does not eliminate all shrinkage defects. This second type of defects appears in a form of porosity.

The well known technical publications written by or including the works of Karsay (e.g. [1,2,3]) attribute the appearance of the second type of defects to the so called secondary shrinkage of the

iron, i.e. appearing at the end of solidification. The following mechanism of the porosity formation is assumed. During the expansion period the solidifying casting deforms the mould cavity. If the mould is 'soft' this deformation (mould swelling) is plastic (i.e. excessive yielding takes place) and the mould's spring-back is not large enough to compensate for the secondary shrinkage of the iron. To avoid this, the pressure-relief method of feeding has been elaborated. The pressure development due to expansion of the iron is retarded by usage of risers which solidify later than at the onset of the expansion period and are able to absorb the excessive metal volume. The remaining mould swelling is small and fully reversible during the secondary shrinkage period.

An alternative mechanism of shrinkage porosity formation during the solidification period of the ductile cast iron assumes [4] that the porosity takes place during the expansion. The outer layers of the casting cool and therefore expand faster, thus inducing a tension (negative pressure) in the inner parts of the casting. This negative pressure results in the evolving of the gases from the melt and formation of the porosity defects.

In the following sections the above two mechanisms will be analyzed critically and a modification of the second mechanism will be proposed.

## 2. Porosity formation based on secondary shrinkage mechanism

In Fig.1 the volume changes of the cast iron and mechanical interactions between casting and mould are presented. According Karsay's theory, the spring-back of the mould becomes unsatisfactory as its deformation due to expansion of the casting becomes too large. However, decreasing of the spring-back with increasing deformation during loading can only take place if the material exhibits the so called mechanical instability, i.e. strain-softening, manifesting in the drop on the deformation – load curve. In Fig. 1 the deformation characteristics of the mould, i.e. the deformation – load diagram is assumed as a typical one for compression testing of molding sands. The curve  $p(e_m)$  has a

concave shape, which is related to the strain hardening associated with the volume changes of the granular medium.

Referring to notations in Fig. 1, if the elastic spring-back of the mould  $e_m^{(E)}$  during unloading (due to the pressure drop during secondary contraction of the casting) is smaller than the secondary shrinkage  $s_s$ , then the cavity volume after completing of the solidification is larger than that of the casting and the porosity is likely to form. However, for the different starting points of the pressure development (different sizes of the feeding elements) the following observation can be made. The insufficient spring-back, expressed by positive values of  $s_s - e_m^{(E)}$ , tends to appear for larger feeders (lower temperatures at which the pressure starts), i.e. smaller mold deformations. Only two such points are presented in Fig. 1 for clearness, but they illustrate the general tendency. For the shape of the  $p(e_m)$  curve assumed as in Fig.1 the larger total mold deformation, the larger elastic part of strain is obtained. This tendency obviously disagree with the general principle of the pressure – relief feeding.

In Fig. 2 another, generally convex, shape of the  $p(e_m)$  curve is assumed. The expected tendency towards too small spring-backs of the mould with increasing mould deformation (smaller feeders) can be observed for this case. However, it is true only if the above mentioned strain-softening of the molding sand is assumed, which is very unlikely for molding sands subjected to compression. This type of loading curve was presented in [3], however, the upper limit of stress should be specified differently - it is simply equal to the maximum stress. In the earlier Karsay's publication [2], the stress-strain curve was assumed as elastic-plastic (convex) without the pressure drop.

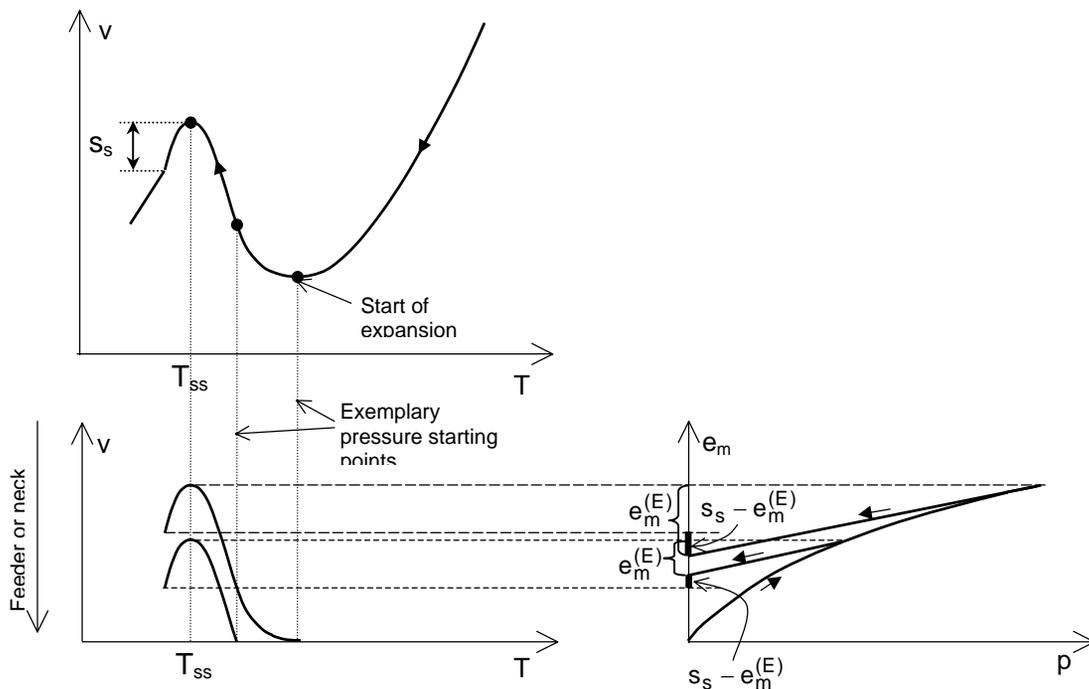


Fig.1. Possible volume changes of the ductile cast iron and interactions between casting and sand mould for typical mechanical characteristics of the sand mould;  $v$  - iron volume,  $T$  - temperature of casting,  $s_s$  - secondary shrinkage,  $T_{ss}$  - temperature at the onset of the secondary shrinkage (end of expansion),  $p$  - pressure at the casting – mould interface,  $e_m$ ,  $e_m^{(E)}$  - total and elastic deformations of the mould; the horizontal broken lines indicate the secondary shrinkage limits.

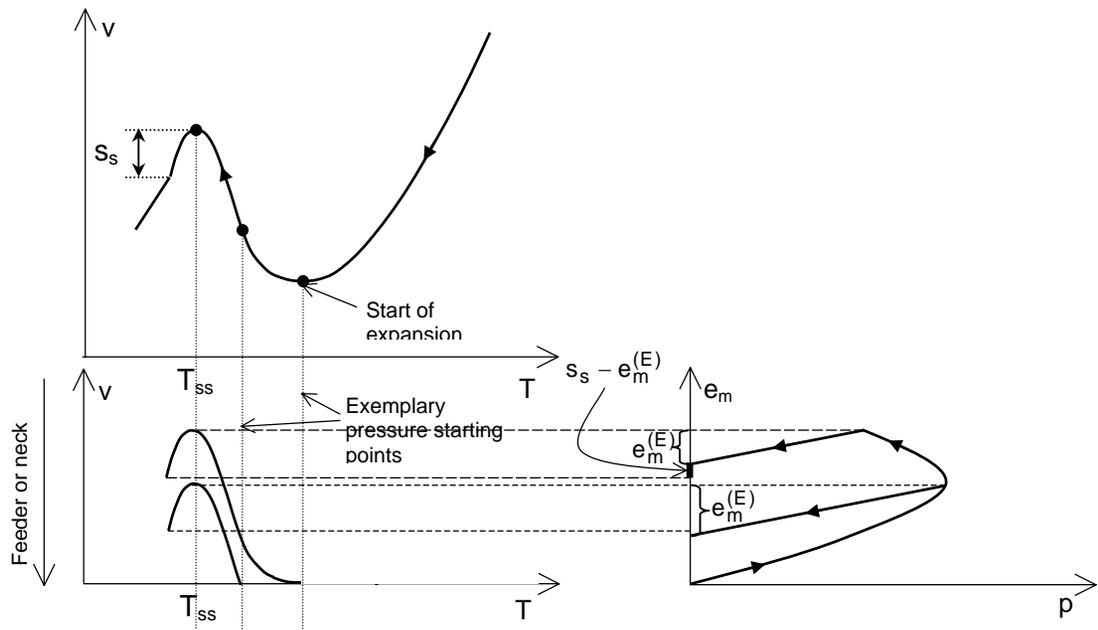


Fig.2. Possible volume changes of the ductile iron and interactions between casting and sand mould for an alternative mold characteristics (notations as in Fig. 1).

The above analysis leads to the conclusion, that the mechanism of porosity formation based on the secondary shrinkage effects may be not justified. It is also worth noticing that the experimentally measured values of the secondary shrinkage themselves are very small and sometimes not detected at all (see, e.g. [4]).

### 3. Porosity formation due to expansion of casting

An alternative approach to the porosity development was recently proposed by Ohnaka and co-authors [5]. Their mechanism of the porosity formation is based on the larger expansion in the surface region of casting due to temperature difference between outer and inner parts of the casting, causing tensile stress (negative pressure) in the inner region. However, in opinion of the present authors, there is an essential shortcoming of this theory, related to the temperature difference as the source of porosity. The inner part, in which the negative pressure develops due to tension induced by the faster cooling and expanding outer region, will obviously further expand when the outer layer completes its expansion and starts to contract. This will neutralize the effect of the initial negative pressure and eliminate the porosity.

The actual cause of the porosity developed during expansion period can be the difference in the expansion coefficients of the inner and outer parts of the castings. The practical observations [1,2,3] show large differences of total expansion values between

massive and thin-walled castings, which is related to the difference in the average cooling rates (thin walled castings exhibit much higher expansion). Obviously, this same dependency of the apparent expansion coefficients on the cooling rate will take place in a single casting, where the outer layer is cooling much faster compared to its inner part. Although the cooling rate increases continuously along the distance from the casting centre, for a qualitative analysis we assume two casting regions, inner and outer, with two different cooling rates and corresponding apparent expansion coefficients  $\alpha_i$  and  $\alpha_o$ , respectively (Fig. 3).

The role of a riser in the second mechanism is possibly a reduction of the expansion of the outer layer, through absorbing the excessive metal. This would explain why feeders having solidification times which fall between start and end of the casting solidification are most often applied (pressure-relief feeding).

Another observation, that can be made basing on the mechanism of porosity formation associated with the expansion period, is also confirmed by the industrial practice: feeding of massive castings is often easier. This is because the fast cooled surface layer, which stretches the inner part, is relatively thinner, i.e.  $(x_c - x_{ci}) \ll x_{ci}$ , and weaker, compared to thin-walled castings.

Due to the mechanical interaction between mould and casting: the reduction of the expansion takes place. For the riserless design the resulting pressure  $p_{cm}$  should compress the casting so that  $p_{cio} = 0$  (to avoid tension of the inner part). This can be achieved if the displacement of the inner surface of the outer part  $d_{co}$  is reduced to the value which is equal to the free expansion of the outer surface of the inner part  $d_{ci}^{(b)}$ , i.e.:

$$d_{ci}^{(f)} = d_{co} = d_{co}^{(f)} + d_{co}^{(p)} \quad (1)$$

where  $d_{co}^{(f)}$  is a free expansion of the outer part and  $d_{co}^{(p)}$  is the mechanical portion of displacement of the inner surface of the outer part, induced by the pressure  $p_{cm}$  resulting from the mould reaction.

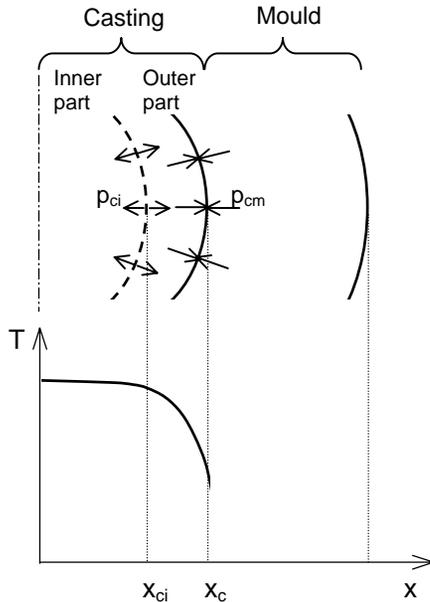


Fig. 3. Schematic of the casting's partition based on the cooling rates and the mechanical interactions between casting and mold.

From the equation (1) the following relationship can be easily obtained:

$$(\alpha_o - \alpha_i) \cdot \Delta T_{\text{expansion}} = p_{cm} \cdot (x_{ci} \cdot k_{co})^{-1} \quad (2)$$

where  $\Delta T_{\text{expansion}}$  is the temperature drop between start and end of the expansion period,  $x_{ci}$  is a half of the thickness of the inner part of the casting and  $k_{co}$  is the stiffness of the outer part of casting.

The pressure developed by the mold mechanical reaction  $p_{cm}$  is proportional to its stiffness  $k_m$  and, from the equality of displacements of the mold and the casting at  $x_c$ , we get:

$$(\alpha_o - \alpha_i) / \alpha_i = (k_m / k_{co}) \cdot (x_c / x_{ci}) \quad (3)$$

The difference between expansion coefficients of the inner and the outer parts of the casting, being a driving force of the porosity formation, can be treated as the alloy characteristics, related to its metallurgical quality. From eq. (3) it results, that the higher the difference (i.e. the lower metallurgical quality), the higher stiffness (rigidity) of the mould is required to prevent porosity formation. This agrees well with the foundry practice.

## 4. Discussion of results and conclusions

The analysis of mechanical interactions between a solidifying ductile iron casting and a sand mold leads to the conclusion that porosity forms during expansion period of the iron. The direct cause is the negative pressure which appears in the central part of the casting due to the differences in apparent expansion coefficients of the fast cooling surface layer and slow cooling inner region.

The secondary shrinkage is not only needless to induce the porosity, but the corresponding mechanism of its occurrence, proposed by Karsay, does not seem to be valid.

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