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KINDS OF SHRINKAGE DURING MELTING AND SOLIDIFICATION OF A METAL

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Abstract: Shrinkage is a pretty important property after the metal is being melted and solidificated, for obtaining the desired dimension(s) of the projected castings. Shrinkage is just an oposite physical property to the elongation, i.e. dilataion. For all known metals from the nature or used in the technique, the dilatation or shrinkage properties could not be considered as one constant value from the crystallization periode troughout the solid state, it means up to the room temperature. If the metal/alloy shows the phase transition phenomenon than the problem of representing those values by one number may becomes more complex, even unsusstainable.
On the shrinking behavior during solidification of a metal, as in casting, a lot of factors may have affect, pretty more than at laboratory conditions. Such changes in dimensions are of importance for almost products made by using different technologies, as welding or brazing.

Key words: dilatation, shrinkage, melting, solidification, porosity

INTRODUCTION

It is a habit that dilatation or shrinkage are determined just at an temperature interval, begining from the room temperature up to the desired temperature, if is needed near to the melting [1-5]. In special cases the negative temperatures, i.e. to -80^{0}C, even lower should be is applied. In such pretty wide temperature interval sometimes is needed to diversify the kinds of shrinkage, it means after melting, just in the periode of solidification, i.e. crystallization and down to the room temperature.
Dilatation/elongation or contraction are the fundamental physical properties when any metal is undergoing to heating or cooling. In fact, contraction is just the oposite property to thermal expansion. The dilatation is expressed as function of temperature, multiplied by linear coefficient (α_t). However, the dilatation or contraction always is a volumetric property, but for the simplicity is rather expressed as one value, known as a linear expansion or dilatation. Shrinkage in casting technology shows more complex property than pure dilatation, because during solidification of molten metal inside the narrow cavity into the pattern, the great influence may have the surface tension(s). As a measure for the surface tension or wettability, commonly is used an angle between drop of the molten metal and the solid wall. So, this angle gives an explanation for good or poor fullfilling the thin walls at castings. The value of surface tension of a metal depends both from the kind of molten metal and mold material. All of those properties affect on a castability, it means for obtaining the proper dimensions and without casting deffects, either at surface or inside the wall.
Its clear that the geometrical dimensions of a body may alter when the temperature is changing. Every change in dimensions may be effectively registered at diagram dilatation - temperature.
The achieved temperature in a particular technological or melting process, may have an important influence on the value of shrinkage. Laser beams are able to heat even melt the impingnedsurface very fast, sometimes the second is a large value. Such laser characteristics find out application in industry for metal heating and melting, including brazing or welding. After reaching the desired temperature follows the cooling periode, when in many materials may be expected a (little) changes in dimensions. From that point of view is needed to know how the

used material is expanded (elongated) or shortened (shrinked). Also, the study of shrinkage and forming the residual stresses always are an important field both in engineering and science.

MATERIAL AND METHODS

1. Dilatation and shrinkage as a physical phenomenon

Dilatation or shrinkage are natural phenomenon, when variations in dimensions are measured during heating or cooling of the specimen. Any phase transformation, generally, leads to the change of crystal lattice type or parameters, which implies on change of other physical and other properties [5-7]. In the metallurgical practice it is happened during melting, solidification and in heat-treating processes (quenching and tempering), including the dissolution or precipitation of a new phase.
The variation of dimensions in fact always are volumetric, but measuring is usually provided in one direction – in length. At this measurement is recorded the (linear) displacement as u function of temperature. Such changes are measured by using an instrument based on mechanical, electrical, magnetic and/or optical principle, which are pretty well explained in broad physical or metallurgical text or handbooks [1-4]. The simpliest example of one thermal dilatation curve for pure iron is given in Fig. 1a), while the values of thermal dilatation for principal structures in steel (also in function of temperature) is given in Fig. 1b).

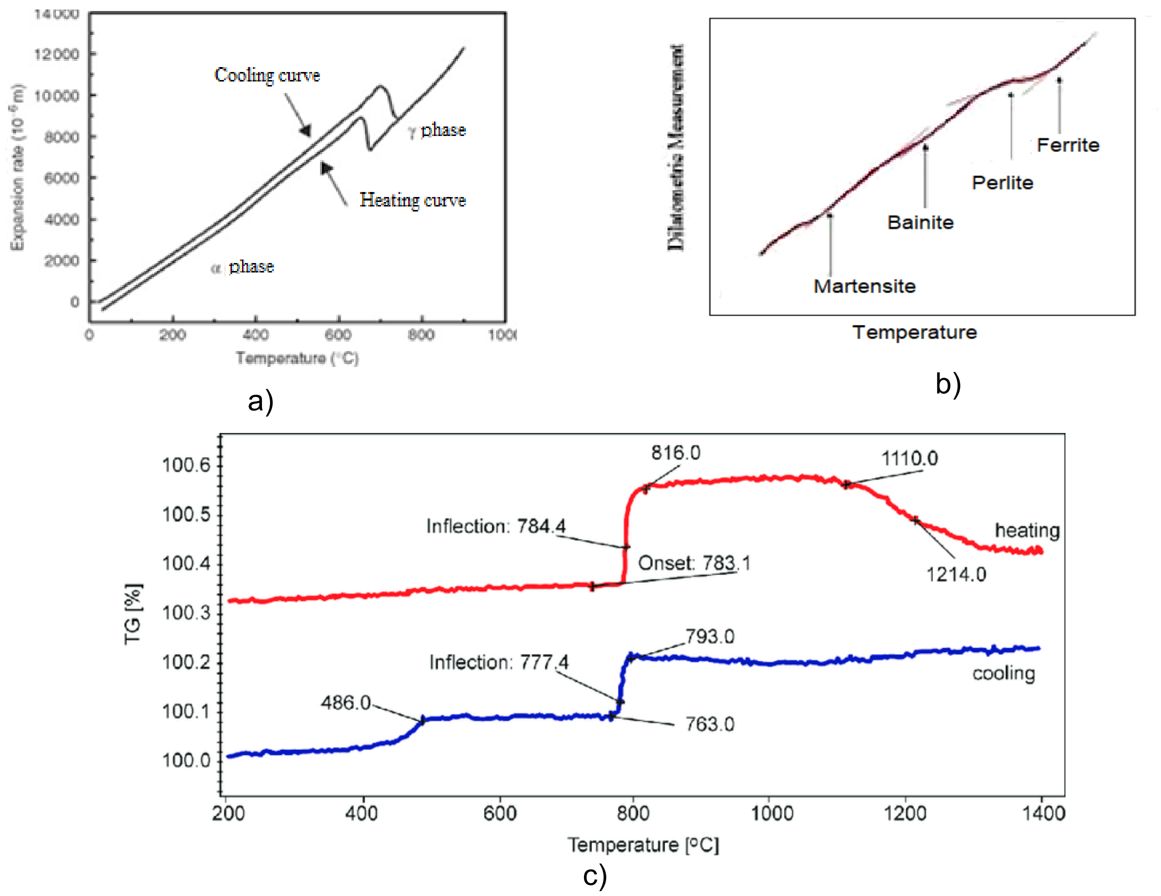


Fig. 1. *Dilatometry curves for pure iron during heating and cooling a), dilatometric values for principal structures at one common steel b) and thermomagnetometry curves for one tool steel c)*

More complex dilatation curves either durin heating or cooling may be found in medium or high alloyed steels, one example for cold work tool steel is given in Fig. 1c), obtained by

thermomagnetometry. This tool steel [8] belongs to the group of ledeburitic structure, which contains (in wt%): 2,47%C; 4,18%Cr; 3,82%Mo: 8,94%V; 1,13%W and 2,02%Co.
The obtained diagrams may serve for furter analysing the phase transformations, as dissolving carbides into matrix or for other processes during solidification, etc.
At one-phase region from Fig. 1a), the temperature influence on dimensional change could be explained by an nearly linear equation, but not at multialloyed steel, see Fig. 1c).
One specific behavior could be found at magnetic materials, when the temperature is constant but geometry of such body may be changed, in small scale, if they are exposed to the magnetic field.

2. Shrinkage effects during casting

After the liquid metal is poured into the mold cavity, Fig. 2a), shrinkage starts an idealized case [8] equaly at all sides as in Fig 2b). In reality, melted metal at a mold solidifies as in Fig. 2c), with unavoidable casting cavities, two examples of them are shown at same figure.

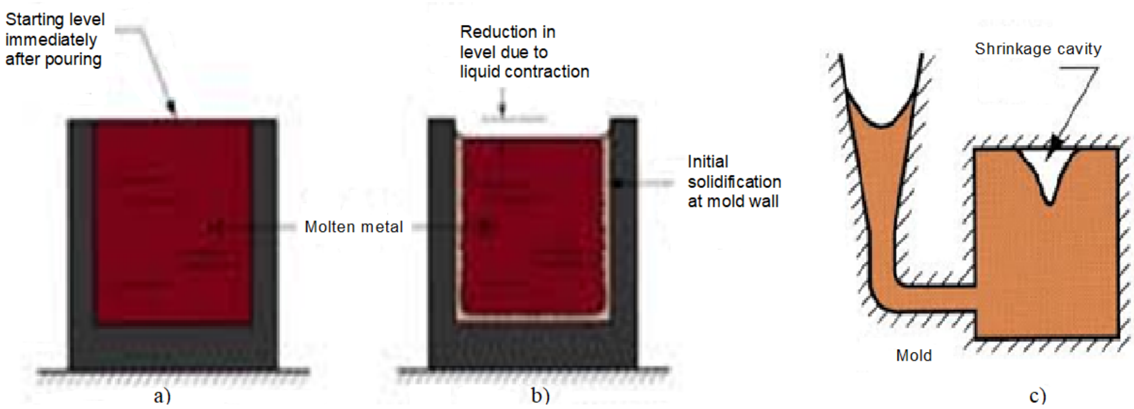


Fig. 2. *Mold cavity fullfilled with molten metal a), shrink begins when temperature is decreasing and solidification starts b) and two common shrinkage cavities formed at one simple castings with its pouring system c)*

In fact, heated metal always shrinks when the temperature is decreasing, see diagram from Fig. 3a). Crystal grains (in dendritic form) growing at an oposite direction from the heat flow, Fig. 3b), in the center of castings wall the shrinkage cavity begins to forms.

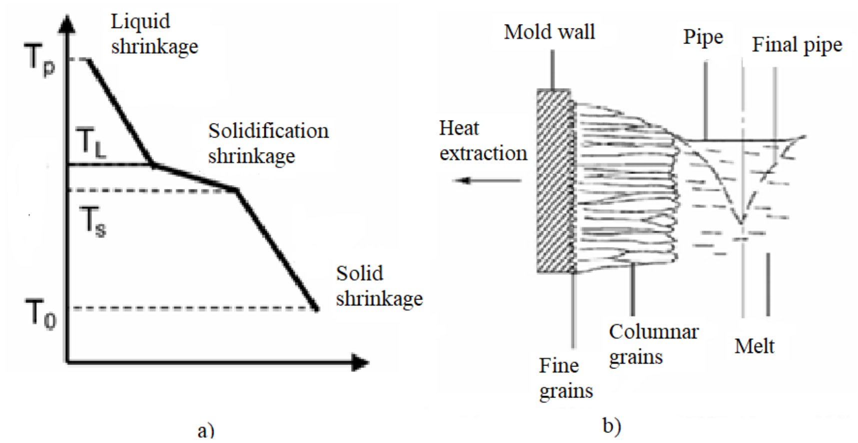


Fig. 3. *Diagram of temperature change in time a) and solidification starts with cavity forming b)*

Between solidified grains may be appeared the shrinkage cavity, Fig. 4a). After solidification is finished, few different types of shrinkage cavities may be formed, Fig. 4b). Other examples of cavities/porosities and distribution of crystal grains and some of the important details after solidification of an angot are shown in Fig. 4c).

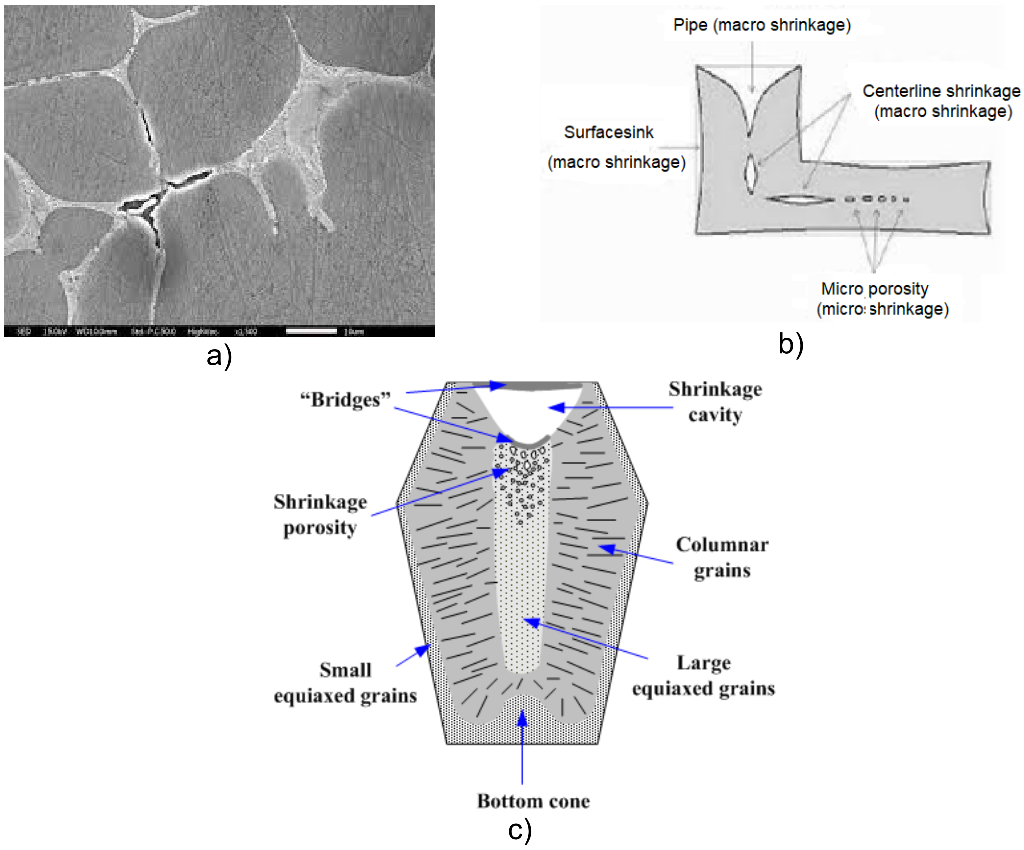


Fig. 4. *Shrinkage microcavities between solidified grains a), one part of casting with possible types of shrinkages after solidification process is finished b) and cavities and different grains at ingot c)*

As well known, the most metals shrink when cooled from the liquid state, while some of them are expanded as suggest data from Table 1.

Table 1. *Shrinkage of selected metals, their crystal structures and melting points*

Metal	Crystal structure	Melting point °C	Solidification shrinkage (%)	Total shrinkage (%)
Ag	fcc	962	3.8	10.99
Al	fcc	660	6.0 ÷ 7.14	11.66
Au	fcc	1063	5.1 ÷ 5.47	11.0
Bi	rhomb	271	−3.35 ÷ −3.32	-2.73
Cd	hcp	321	3.8 ÷ 4.7	7.18
Cu	fcc	1083	4.1 ÷ 5.3	10.7
Ga	orthorhombic	30	−3.2	-3.05
In	fct	156	1.98 ÷ 2.0	3.8
Mg	hcp	651	3.1 ÷ 4.1	8.6
Ni	fcc	1453	5.11 ÷ 5.4	10.67
Pb	fcc	327	3.22 ÷ 3.56	8.58
Sb	rhomb	631	−0.9 ÷ 0.8	2.95
Si	diam	1410	−9.6 ÷ −2.9	-6.26
Sn	tetrag	232	2.51 ÷ 2.6	4.1
Zn	hcp	420	4.08 ÷ 4.3	7.9

(https://www.researchgate.net/figure/Shrinkage-of-selected-metals_tbl4_276481998)
Note 1) exact values of % solidification depends from the cleanliness of a metal,
2)sign (-) means that the particular metal does not shrinks but expands during solidification.

Shrinkage shows the influence not only on changing dimension but also on shape, especially in walls with different position and thickness, some pretty simply examples are shown in Fig. 5, either on the surface (when metal sinks) or inside the wall (as voids/porosity). No doubt that both macro- and microcavities lead to the decreasing of mechanical properties of castings.

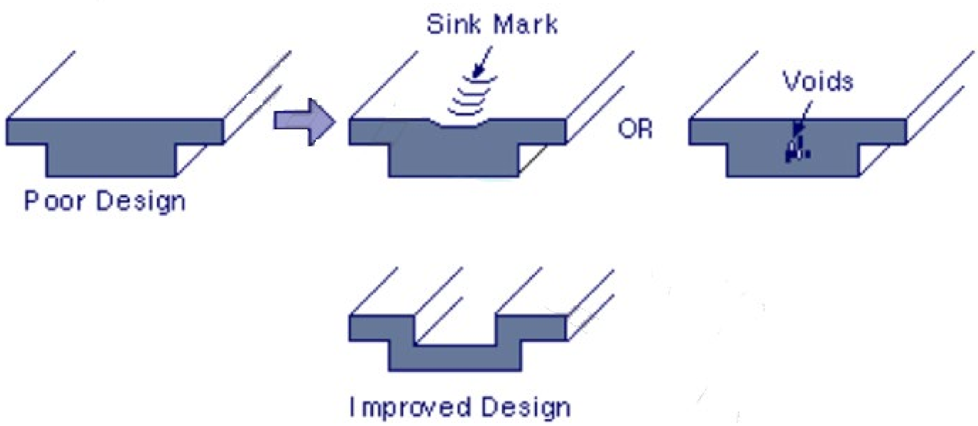


Fig. 5. *One example in designing of walls at casting against shrinkage*

How shrinkage looks-like in many shapes at one wall is shown in Fig. 6.

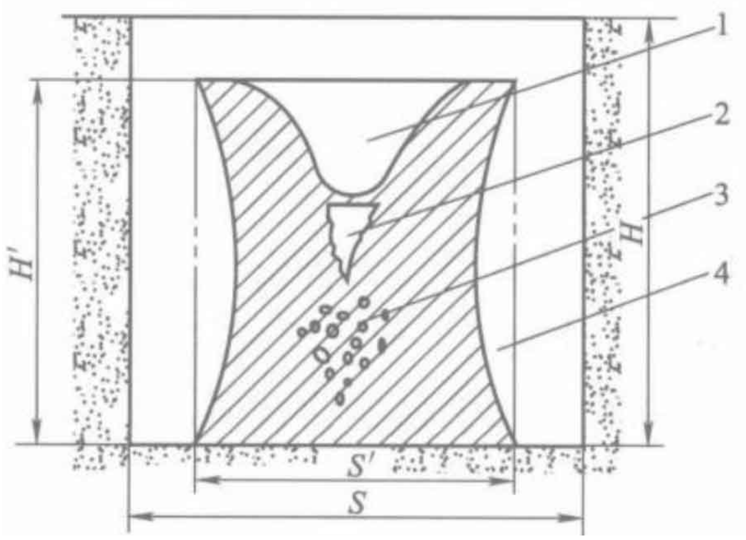
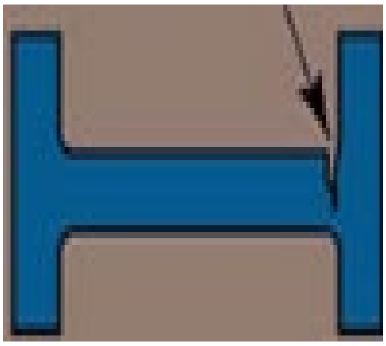
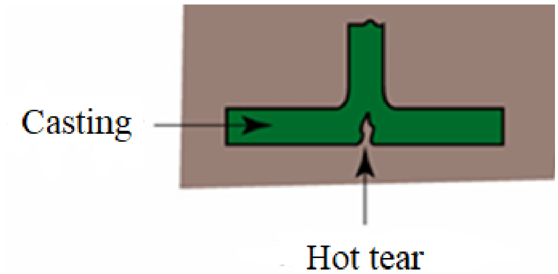


Fig. 6. *Ilustration of shrinkage types at casting wall*
1-open cavity, 2-closed cavity,. 3-porosity and 4-shrinkage/sinking of the wall

If shrinkage remains uncontrolled than it´s undesirable not only for designers but also for usage. Sinking the surface may have the influence on general appearance of the object, and farther similar behavior (or problems) may be found not only during casting but also after welding or brazing.

The appearance of residual stresses at castings also is influenced by the shrinkage, so sometimes those residual stresses are the main reason for cracking. Such cracking may be monitored as their appearing, i.e. as semisolid cracking. Two examples of how the shrinkage during solidification periode may affect on the cracking, also called hot tear, into the casted material are shown in Fig. 7.





b)

a)

Fig. 7. *Solidification as a reason for forming*
a) crack at casting with crossed walls and b) hot tear

From the foundry technology, cracks commonly are forming when thin and thick sections are crossed. as shown in Fig. 7a), and similar explanation is for the case from Fig. 7b). It is frequently considered that stresses at castings are in elastic region, but it was not always thrue. In fact, cracks were formed when stress overcome the elastic limit. The uncontrolled residual , however, may have the harmful effects on the operation periode of such element, also for the etnire equipment. These phenomena usually appeared when the solid fraction reaches the 85-95% of the total volume.
The position of shrinkage from Fig. 7b) may be similar to the cases in welding or brazing, when affecting on the visual appearance.
The values of dilatation in wires may be concerned also at quite different applications than casting, as in temperature measuring based on thermoelectric principles, when may be used various materials at interval from -260 up to 2500^{0}C [9-11].

CONCLUSION

Sometimes, the shrinkage is considered as a kind of casting defect. The shrinkage effects are the largest just at a solidification periode, but should be considered at the entire periode of cooling, it means that begun from the liquid state, than during crystalization and finely at a solid state – to the room temperature. It seems that the last one periode is the most studied, even to subzero treatment.
Shrinkage and produced thermal stresses are the main contributors to the hot cracking, at castings as well at welded joints, rarely after brazing, but frequently during heat.treatment operations. So, the shrinkage phenomenon could not be considered as behaviour only at a short periode of material cooling.
However, the forming of residual stresses is pretty complex from various aspects, including a shrinkage, no matter where they are appeared: at casting, forgings or welded components.

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