ANALYSIS OF FOUNDRY STRESSES IN IRON ALLOY CASTINGS

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Abstract

The paper analyses the magnitude of foundry stresses in cast iron and steel castings. For the analysis of foundry stresses, a new methodology for measuring the level of residua! stresses on modified test bodies was proposed to test the propensity of iron alloys to hot-cracks and cold-cracks. The magnitude of the residua! stresses is determined based on the measured values of the relative shrinkage between the different bar diameters of the test body. To verify the proposed relative shrinkage measurement methodology, the hot-cracks and cold-cracks test body was compared with its modified version. Relative shrinkage (RS) is defined as the difference of lengths ∆l = RS of bars of different diameter-modules on the modified version of the standard test body. Based on the measured RS values, the magnitude of residua! stress in the test castings was calculated. According to the relative shrinkage rate and the known elastic moduli of the cast alloys, the potential residua! stress in the test castings was calculated. The magnitude of the stresses on castings of graphitic cast irons, non-alloy and alloy steels were evaluated.

Keywords: Iron alloys; relative shrinkage; stress

1. INTRODUCTION

Foundry stresses arising during solidification significantly affect the final properties and quality of the castings. The stresses are the result of their volumetric and linear changes during solidification and cooling. Increasing stresses during solidification, exceeding the strength limit of the alloys, can be the cause of internal and surface defects in castings. The degree of stress due to volumetric and linear shrinkage in iron alloy castings depends on:

(a) The C content in the form of graphite or Fe_3C, the Si content and the alloy content.

(b) The homogeneity of the temperature field-differences in the wall thicknesses of the casting-modules.

(c) Cooling rate, temperature of onset of solidification of the alloy, microstructure.

The course of changes in specific volume during equilibrium solidification of iron alloys as a function of temperature can be described on the basis of chemical composition and the temperature of the beginning of solidification in the mould (pouring) to solidification. The volumetric shrinkage of the liquid phase of iron alloys becomes linear on cooling below the solvent temperature [1]. The magnitude of stress depends on the degree of volumetric and linear shrinkage of the casting from the onset of solidification to ambient temperature. The progression of specific volume changes during shrinkage of iron alloys from the onset of solidification to the solvent temperature can be described by equation (1) according to Kochaisen [2]. The equation is valid for equilibrium conditions of solidification of iron alloys. It does not consider the cooling rate or the modulus of the casting. The stress increases already in the first stages of solidification below the liquid temperature and continues to increase until the casting is completely cooled in the mould. The tensile strength and modulus of elasticity increase with decreasing temperature, depending on the chemical composition of the alloy. Phase and thermal stresses may also occur in the castings during further cooling after solidification. Stresses may also increase early in the solidification process due to mechanical stresses on the casting by the resistance of the mould and core [3,4]. The cause of internal stresses and subsequent failures are foundry designs of castings with different module sizes and wall thicknesses. Endogenous stresses are caused by internal forces arising from complex thermo-physical phenomena due to uneven cooling. Internal stresses are due to volumetric changes in the solidification process. The magnitude is the product of the elastic modulus (E) of the alloy, the coefficient of thermal expansion (a) and the solidification temperature gradient (ΔT) [4].

Stresses I. Order - macroscopic stress (macro-stress) acts (equalizes) in the entire volume of the casting or its part. It is the most dangerous for castings. It can add to the external operating stress. It is released over time by plastic deformations during ageing, annealing and machining.

Stresses II. Order - microscopic stresses (micro-stresses) act in the volume of individual crystals and equilibrate in micro-volumes.

Stresses III. Order - submicroscopic stress. It acts and equilibrates in the volume of one or more elementary lattices. The source of stress is atomic lattice disturbances (foreign atoms and dislocations).

The internal thermal stresses act from the beginning of solidification, initially as shrinkage stresses. The shrinkage of the solidified layer is prevented by the mechanical resistance of the mould and core. Subsequently, after solidification of a larger volume of metal, the stresses increase due to differential dilation of the different layers of the inhomogeneous temperature field of the casting [5]. At this stage of solidification, the shrinkage stress induced by the mold resistance is negligible with respect to the strength of the casting relative to the mold. Thermal stresses can be: residual (i.e. permanent, residual) and temporary. Residual stresses increase as the temperature drops throughout the casting volume below the critical temperature T_{kr} into the elastic deformation region at a certain temperature gradient at the time of this transition. It reaches its maximum value when the casting has cooled completely. Temporary stresses occur in the casting at elastic deformation temperatures (below 600 °C) during sudden cooling. After complete cooling and equilibration of temperatures in the casting, the temporary stress disappears. The degree of stress in Fe alloy castings depends on the chemical composition, the cooling rate, i.e. the modulus of the casting, and the metallurgical treatment (number of nuclei, inoculation, desoxidation, melting and casting temperatures). Stresses in Fe alloys increase with decreasing carbon and silicon content as well as with increasing carbide content in the matrix [5].

2. METHODOLOGY OF EXPERIMENTAL MELTS

The melting was carried out on a medium-frequency induction furnace of 30 kg content. The charge for both cast iron and steel was composed of reversible material and additives, which were further treated with added ferroalloys and carburizing. In the first stage of the melting process, low and medium alloy Cr and Ni steels (**Table 1**) with C = 0.27 ÷ 2.04 % were tested. Crack sizes (cracks) on the original body (**Figure 1**) and RS on the modified body (**Figure 2**) were compared. The total shrinkage ($CS = l_{20}$) was also measured on the modified body for the RS percentage. The relative RS shrinkage (Δl) i.e. the difference in lengths of the Ø 20 mm bars and the Ø 40 mm middle bar was measured using standard metal gauges. The magnitude of $RS = \Delta l = l_{20} - l_{40}$ on the modified body was compared with the maximum crack width on the simultaneously cast standard body (**Figure 1**). In the second phase of the melting (**Table 2**), only the relative shrinkage (RS) bodies were cast from low-alloy Cr and Ni combination castings and materials with high Cr = 19.6 %. For comparison, two types of standard EN-GJS-300 flake graphite cast irons No. 6 and 7 (**Table 2**) with the same equivalent carbon but with different combinations of C and Si were also evaluated [6].

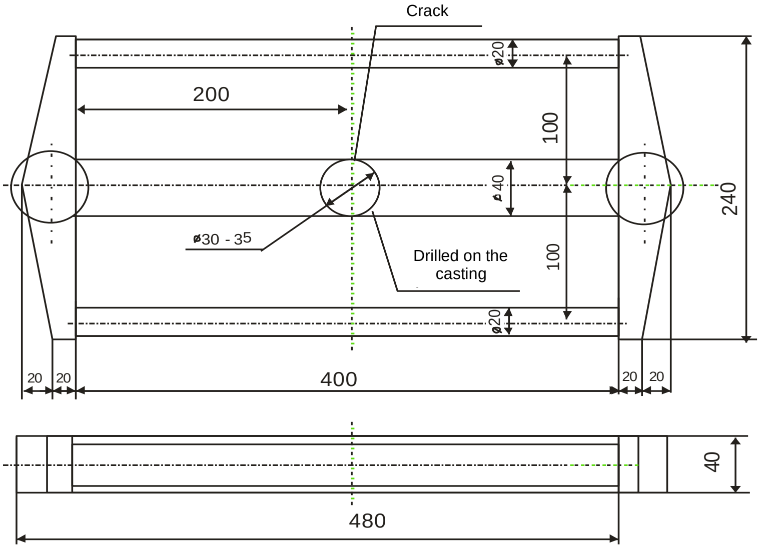


Figure 1 Standard test body-grid for measuring cracks and fissures [7]

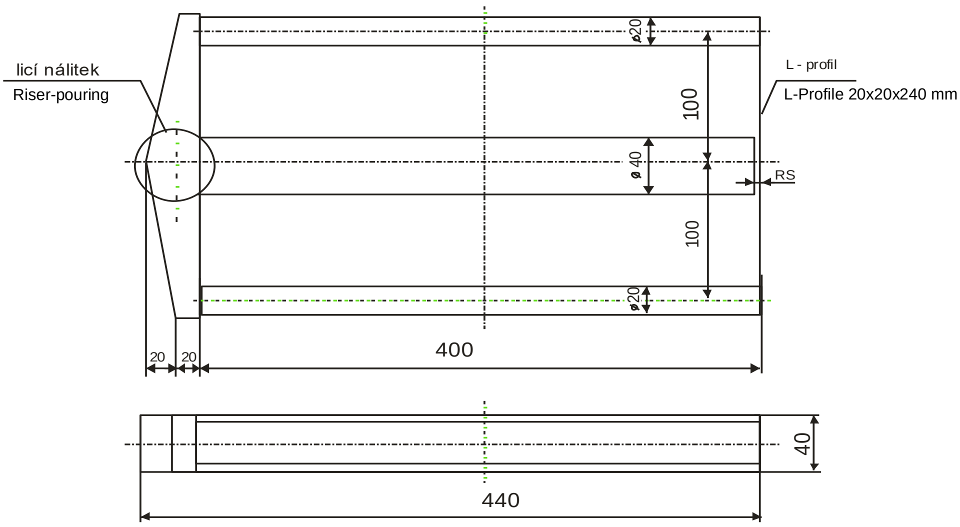


Figure 2 Modified test body for relative shrinkage (RS) measurement

Figure 3 Test body cracked outside the measurable area under the sprue

For stress testing, there are various technological tests for evaluating the tendency of foundry alloys to tear and crack [7]. As a rule, the number and dimensions of cracks and cracks on the test bodies are evaluated. In the case of a casting of a standard crack and fracture test body according to Schneider modified by Bradik (**Figure 1)**, for the evaluation it is necessary to drill or "cut" the casting and then tap it to induce a fracture and measure the width of the resulting crack. These measurements are often difficult to make, especially in the case of castings made of very hard alloys with zero ductility. Another disadvantage is that test casings made of these materials usually fail while still in the mould and their evaluation is not possible. For example, a standard test grid (**Figure 3**) will usually crack in the cross-arm-outside the center bar.

Problems with the evaluation of difficult-to-machine materials led to the design of a modification of the standard crack and fracture body for relative shrinkage measurements (**Figure 2**). The modification consisted of removing one transverse arm [8]. Instead, a 20 mm x 20 mm x 240 mm L-profile was inserted into the mould cavity. After casting, the total shrinkage length of the Ø 20 mm bar (CS = l_{20}) and the relative shrinkage RS (RS = Δl = l_{20} - l_{40}) were measured on this modified casting. The modification allows for free shrinkage of all three bars, unhampered by mould resistance. The shrinkage is measured directly on the casting without further adjustments. The relative shrinkage (**Figure 2**) is measured as the difference in the lengths of the bars (Ø 20 mm and Ø 40 mm), with metal gauges between the attached L-profile through the ends of the Ø 20 mm bars and the middle Ø 40 mm bar. To calculate the 'potential' residual stress бp in the casting according to (1).

$$\sigma_p = \frac{\Delta l \cdot E}{l} \tag{1}$$

where:

$б_p$ - the potential tensile stress (MPa)
Δl - the relative shrinkage RS (mm)
l - the length of bar Ø 20 (mm)
E - the modulus of elasticity of the tested material (MPa)

Table 1 Chemical composition of steels, shrinkage (CS, RS), cracks and hardness of test bodies

Melt no.	C	Si	Mn	Ni	Cr	Total shrinkage (CS)		Relative shrinkage (RS). Modified body		Width of cracks. Standard body	HBW30
	(%)					(%)	(mm)	(%)	(mm)	(mm)	
1-0	2.04	1.23	0.58	0.03	0.70	2.5	10	0.57	2.2	1.6 t	579
1-1	1.94	0.76	0.70	0.35	0.75	2.3	9	0.51	2.0	-	446
1-2	1.94	0.76	0.70	0.35	0.75	-	-	-	-	1.8 t + 1.2 t	446
2-1	1.47	0.61	0.59	0.26	0.55	2.3	9	0.44	1.7	-	460
2-2	1.47	0.61	0.59	0.26	0.55	-	-	-	-	1.6 t + 0.1 p	460
3-1	0.27	0.26	0.80	0.05	1.13	-	-	-	-	1.4 p	272
3-2	0.27	0.26	0.80	0.05	1.13	3.3	13	0.41	1.6	-	272
4-1	0.84	0.23	0.83	0.04	1.14	2.5	10	0.46	1.8	-	351
4-2	0.84	0.23	0.83	0.04	1.14	-	-	-	-	2.0 p	351

t- Cracks in the vicinity of the casting. p- Cracks measured after cutting the bar Ø 40 mm.

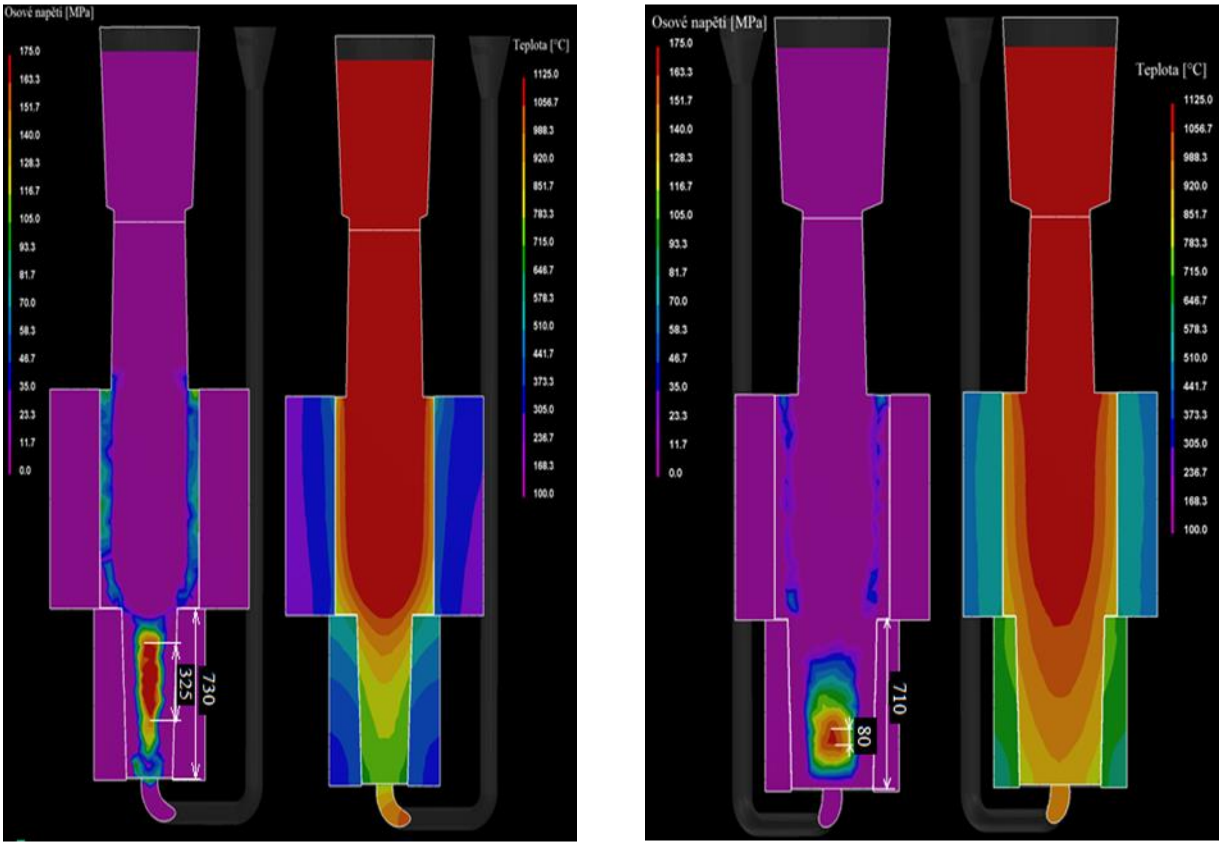
Table 2 Chemical composition of cast irons, RS, $б_p$ and hardness of the treated body

Melt no.	C	Si	Mn	Ni	Cr	Mo	RS-Modified body		$б_p$	HBW 30
	(%)						(mm)	(%)	(MPa)	
5	3.59	2.18	0.59	0.03	0.07	0.27	0.4	0.13	152	210
6	3.0	2.57	0.16	0.01	0.02	0.24	0.3	0.07	114	229
7	3.3	1.03	0.15	0.01	0.02	0.26	0.7	0.18	269	233
8	3.17	1.10	1.26	3.44	1.71	0.25	1.8	0.46	694	503
9	2.56	0.62	0.85	0.18	19.56	0.82	1.7	0.43	656	458
10	2.58	0.63	0.84	0.17	19.60	0.81	1.4	0.35	540	474

RS measured on the modified test specimen is substituted into the formula after Δl. The potential stress ($б_p$) is the same stress that would be developed in a standard solid (**Figure 1**).Comparison of two types of cast irons with flake graphite according to EN-GJL-300 (**Table 2** no. 6 and 7), with almost identical carbon equivalents (CE = 3.56 and 3.59) and tensile strengths (R_m = 303 MPa and 305 MPa), show that LLG with low C = 3.0 % and higher Si = 2.57 % has a significantly lower RS = 0.3 mm compared to RS = 0.7 mm of cast iron with C = 3.3 % and Si = 1.03 %. From the measured RS values and the known modulus of elasticity for these cast irons of E = 150,000 MPa, the magnitude of the potential tensile stress that would act in the central bar of the standard body can be calculated. In a cast iron with flake graphite according to EN-GJL-300 with C = 3.0 and Si = 2.57 % (RS = 0.3 mm), the magnitude of the residual stress is $б_p$ = 114 MPa. In the LLG casting with C = 3.3 % and Si = 1.03 % (RS = 0.7 mm) the residual stress is significantly higher $б_p$ = 269 MPa. The residual stress close to the ultimate strength of LLG, significantly increases the risk of casting destruction with minimal external stress. It follows that LLG castings with higher silicon content have a significantly lower propensity for residual stress and stress failure. The highest calculated potential residual stress $б_p$, ranging from 540 MPa to 694 MPa, was exhibited by castings made from medium and high alloy Fe alloys (E = 150,000 MPa) [9]. A typical case of the influence of different moduli (and shrinkage magnitudes) on stress development is castings of metallurgical cylinders. Differences in the degree of shrinkage and the solidification time of the cylinder body and pin are the cause of the tensile stresses, which are concentrated in the transition of the cylinder body and pin (**Figure 4**). A larger diameter cylinder body takes up to five times longer to solidify than a smaller diameter pin, depending on the difference in the diameters (modules) of the body and pin. If the solidification rates and shrinkage rates of the two modules are not equal, the tensile stress ($б_a$ = 325 MPa) increases to a level that can cause the casting to destroy (**Figures 4** and **5**).

Figure 4 Breakage of the body and pin of the metallurgical cylinder

Optimizing the temperature field gradients, while minimizing the differences in shrinkage between the body and pin of the cylinder, can reduce the stress to a level that will not break the casting. The stress in the critical region of the cylinder was reduced to a quarter of the original value of σ_b = 80 MPa (**Figure 5 b**) [10].



a) b)

Figure 5 Simulation of stress and temperature field in the critical region of the metallurgical cylinder-original a) and optimized technology b)

3. CONCLUSION

It is clear from the analyses performed that the standard test bodies cast from high hardness alloys could not be evaluated using the recommended measurement procedure (**Figure 3**). Comparison of defect dimensions on the standard body and relative shrinkage (RS) on the modified body shows that their dimensions were almost identical. Also, the measurement of the cracks after cutting the middle member of the "elastic" steel body confirmed that the RS dimensions on the modified body can be used as a relevant value for the calculation of the potential residua! stress. Therefore, only the RS on the modified solids was measured in further tests. From the RS magnitude, the potential residua! stress that would be generated in the original test body and in castings with similar modulus ratios was calculated. The advantage of the proposed methodology is the simple and accurate measurement of RS and the subsequent calculation of the stress value. The test can be used to test the manufacturing conditions of castings with a known module ratio, read from the module diagram of the casting. The test conditions can be adapted to different casting temperatures, metallurgical processing and solidification rates. The test conditions may vary depending on the alloy being cast and the complexity of the casting with different wall thicknesses. The measurements confirmed that the RS measurement methodology is applicable to predict stresses in real castings. The stresses calculated by RS include both material and process parameters of the tested castings that can be applied to a given production technology. The described method can be used to determine the relative volumetric and linear shrinkage of iron alloys. The test castings can also be used to verify heat treatment (HT) procedures to remove residua! stresses. After HT, the reduction in RS and thus the degree of reduction in residua! stresses in the castings can be easily measured.

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