Hutnické listy č. 1/2026, roč. LXXIX
ISSN Online: 3029-8350

Evaluation of Thermal Analysis Parameters in Relation to Shrinkage Formation in Castings Made of Ferrous Alloys

Vyhodnocení parametrů tepelné analýzy ve vztahu ke vzniku staženin v odlitcích ze slitin železa

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Abstract

The paper deals with the evaluation of thermal analysis parameters in relation to the formation of shrinkage cavities during the casting of cast iron castings with EN-GJS-500-7 spheroidal graphite. The evaluation was performed on eight melts using single-cup thermal analysis with OCC equipment. The graphitic eutectic temperature, cementite eutectic temperature, and eutectic graphitization ability (EGS) were calculated from the chemical composition. At the same time, the parameter θ, expressing the change in the dynamics of the eutectic reaction, was determined from the first derivative of the cooling curve.

The results showed that no clear correlation was confirmed between the EGS value and the occurrence of shrinkage. On the contrary, the parameter θ showed higher sensitivity, with higher angle values recorded for melts with shrinkage. The findings point to the importance of dynamic analysis of the solidification process in assessing the risk of volume defects and may contribute to the validation of numerical solidification models within digital twin concepts applied in controlled mould systems.

Key words: *Thermal analysis; Ductile cast iron; Shrinkage porosity; Cooling curve; Eutectic reaction; θ parameter*

Abstrakt

Článek se zabývá vyhodnocením parametrů termické analýzy ve vztahu k tvorbě smršťovacích dutin při odlévání litinových odlitků s kuličkovým grafitem EN-GJS-500-7. Vyhodnocení bylo provedeno na osmi taveninách pomocí termické analýzy s využitím jednoho kelímku se zařízením OCC. Z chemického složení byla vypočtena eutektická teplota grafitu, eutektická teplota cementitu a eutektická grafitizační schopnost (EGS). Zároveň byl z první derivace křivky ochlazování stanoven parametr θ, vyjadřující změnu dynamiky eutektické reakce.

Výsledky ukázaly, že mezi hodnotou EGS a výskytem smršťování nebyla potvrzena žádná jasná korelace. Naopak parametr θ vykazoval vyšší citlivost, přičemž vyšší hodnoty úhlu byly zaznamenány u tavenin se smršťováním. Zjištění poukazují na význam dynamické analýzy průběhu tuhnutí při hodnocení rizika vzniku objemových vad a mohou přispět k validaci numerických modelů tuhnutí v rámci konceptů digitálních dvojčat aplikovaných na řízené systémy krystalizátorů.

Klíčová slova*: termická analýza; litinový odlitek; porozita; křivka ochlazování, eutektická reakce, parametr θ*

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1. Introduction

Quality control of molten metal prior to casting is a crucial step in the production of ductile cast iron (DCI), particularly in terms of minimizing shrinkage and ensuring the required number of graphite spheres. Traditional methods of metal quality assessment, such as chill tests or cone sample tests, are time-consuming and their results show significant variability depending on the casting conditions.

Thermal analysis (TA) based on cooling curve recording allows real-time evaluation of eutectic crystallization. In the case of gray cast iron (GCI), a three-tellurium method has been developed that allows the eutectic graphitization ability (EGA) to be determined and the tendency to chilling to be reliably predicted [1].

However, the application of the three-taper method to DCI is problematic, mainly due to the binding of magnesium and modifiers to elements affecting the eutectic temperature, which makes it impossible to directly identify the graphitic and cementite eutectic temperatures by measurement [1].

Thermal analysis based on the evaluation of the cooling curve has been one of the standard tools for assessing the quality of liquid metal since the 1960s. Correlations have been demonstrated between the recrystallization process, the degree of undercooling, and the resulting microstructure of castings, particularly in terms of graphite type and cementite formation tendency [2]. Later work confirmed that parameters derived from the cooling curve allow the nucleation potential of the melt to be quantified and the mechanical properties of castings to be predicted [3].

In the case of DCI, the course of eutectic crystallization is more complex due to the presence of magnesium and modifiers that affect the thermodynamic conditions of graphitic and cementite reactions. It has been shown that the maximum eutectic temperature during solidification does not reach the graphitic eutectic temperature determined by the three-glue method, which complicates its direct use [1]. Analysis of the solidification process of Si-alloyed DCI also showed a significant influence of chemical composition on the stability of the eutectic reaction and graphite morphology [4].

In addition to evaluating the nucleation potential, attention is also focused on the possibility of predicting volume defects. It has been shown that parameters derived from the differentiation of the cooling curve correlate with the tendency to form shrinkage cavities, whereby thermal analysis can replace classic cone tests [5].

To overcome these limitations, a one-cup thermal analysis method has been developed, which allows the graphitic eutectic temperature (TEG) and cementite eutectic temperature (TEC) to be determined by calculating the chemical composition of the melt.

Subsequently, the minimum eutectic temperature at recrystallization (TSC) is determined from the cooling curve and the eutectic graphitization ability (EGA) is calculated according to equation (1):

$$EGA = \Delta T1 \times 100 / \Delta TE \qquad (1)$$

where $\Delta TE = TEG - TEC$; $\Delta T1 = TSC - TEC$ [1].

For DCI, a strong correlation between EGA and the number of graphite balls N (r = 0.97) has been experimentally demonstrated, with equation (1) applying [1]:

$$N = 6.13 \times (\Delta T1 \times 100 / \Delta TE) - 126 \tag{2}$$

In addition to evaluating the nucleation ability, the differentiation of the cooling curve also allows the determination of the parameter of the tendency to form shrinkage cracks θ, which is based on the analysis of the cooling rate during eutectic crystallization. It has been shown that the parameter θ correlates with the volume of shrinkage in a conical test sample and that at values of θ approximately 55 ± 10°, no shrinkage occurs in the test specimen [1].

The aim of the work was to verify the possibility of using single-cup thermal analysis to evaluate the tendency to form shrinkage cavities in DCI EN-GJS-500-7 under operating production conditions. Eight samples were analyzed experimentally, for which characteristic temperatures were determined from cooling curves, eutectic graphitization ability (EGS) was calculated, the estimated number of graphite balls N was determined, and the parameter θ expressing the tendency to form shrinkage cavities was determined.

In recent years, monitoring of the solidification process has gained importance in the context of developing digital models (twins) of metallurgical processes. Experimentally determined parameters derived from thermal analysis can serve as validation inputs for numerical simulations and digital twin concepts of controlled solidification systems. This approach is particularly relevant for the optimization of mould systems and impact plates, where local thermal conditions directly influence solidification behaviour. Accurate characterization of solidification dynamics is therefore essential not only for quality control, but also for model calibration and process optimization.

The parameters obtained were compared with the actual occurrence of shrinkage in the evaluated castings to assess the suitability of the monitored variables for practical melt quality control.

2. Material and methodology

The experimental evaluation was performed on castings made of DCI EN-GJS-500-7. The melts produced under foundry operating conditions were evaluated. The chemical composition of individual samples was determined by spectral analysis and served as an input parameter for calculating the graphitic and cementite eutectic temperatures.

A total of eight samples were evaluated, in which the relationship between the parameters obtained from thermal analysis and the occurrence of shrinkage in the castings was monitored.

The chemical composition of the individual melts evaluated was determined by spectral analysis. The element contents were used as input parameters for calculating the graphitic eutectic temperature (TES) and cementite eutectic temperature (TEM). An overview of the chemical composition is given in **tab 1**. The type of casting used to assess shrinkage is shown in **fig. 1**.

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Tab. 1 Chemical composition of evaluated melts (wt. %)
Tab. 1 Chemické složení hodnocených tavenin (hm. %)

Sample	Si	Mn	P	Cu	Cr	Ni	Mo	Sn	Al	Sb	B	W	V	Nb
K1	2,246	0.288	0.025	0.324	0.019	0.013	0.004	0.004	0.022	0.001	0.0001	0.001	0.003	0.003
K2	2.225	0.286	0.024	0.32	0.019	0.012	0.004	0.004	0.02	0.001	0.0001	0.001	0.004	0.003
K3	2.206	0.274	0.025	0.323	0.019	0.013	0.004	0.004	0.02	0.001	0.0001	0.001	0.003	0.003
K4	2.273	0.276	0.025	0.319	0.019	0.012	0.004	0.004	0.022	0.001	0.0001	0.001	0.004	0.003
K5	2.227	0.273	0.025	0.322	0.018	0.011	0.003	0.004	0.017	0.001	0.0001	0.002	0.004	0.003
K6	2.258	0.272	0.025	0.321	0.018	0.011	0.003	0.004	0.018	0.001	0.0001	0.001	0.003	0.003
K7	2.258	0.286	0.027	0.33	0.02	0.012	0.003	0.004	0.013	0.001	0.0002	0.001	0.003	0.004
K8	2.247	0.277	0.029	0.331	0.02	0.012	0.003	0.004	0.015	0.001	0.0002	0.001	0.003	0.003

Fig. 1 Type of casting used to assess the occurrence of shrinkage
Obr. 1 Typ odlitku používaný k posouzení výskytu smrštění

A single-cup thermal analysis performed using an OCC PhaseLab device with a sand crucible was used to evaluate the solidification process. The temperature was recorded during the solidification of the sample and a cooling curve was subsequently processed.

The characteristic temperatures of the eutectic reaction were determined from the measured cooling curve. The minimum eutectic temperature during recrystallization (TSC) was determined directly from the curve. The graphitic eutectic temperature (TES) and cementite eutectic temperature (TEM) were calculated from the chemical composition of individual melts according to the methodology published for single-cup thermal analysis [1]. The determination of characteristic points on the cooling curve is based on the principles of DCI differential solidification analysis [3].

The eutectic reaction interval was defined as (3):

$$\Delta TE = TES - TEM \tag{3}$$

The difference between the minimum eutectic temperature during recrystallization and the cementite eutectic temperature was determined as (4):

$$\Delta T1 = TSC - TEM \tag{4}$$

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Based on these values, the eutectic graphitization ability (EGS) was calculated (5):

$$EGS = (\Delta T1 \cdot 100) / \Delta TE \qquad (5)$$

The number of graphite spheres N was estimated from the relationship (6):

$$N = 6.13 \cdot (\Delta T1 \cdot 100 / \Delta TE) - 126 \qquad (6)$$

The relationship between the parameters of the cooling curve and the tendency to form shrinkage has been demonstrated in the literature by several authors [1,2,5]. The diagram for calculating EGS and N is shown in **fig. 2**.

Determination of the parameter θ

In addition to evaluating the eutectic graphitization ability, the parameter θ was determined from the differential cooling curve, which expresses the tendency to form shrinkage during eutectic crystallization. Analysis of the cooling rate curve in the eutectic reaction region allows the stability of the graphitization reaction and the associated volume changes during solidification to be identified [3,5]. The differential curve provides information on the dynamics of latent heat release and the ability of the system to compensate for melt contraction by graphitization expansion [4].

The parameter θ was determined from the section of the differential curve in the eutectic recrystallization region as the angle between the reference axis and the line approximating the relevant part of the cooling rate curve. This parameter was proposed as a quantitative indicator of the tendency to form shrinkage cavities in single-cup thermal analysis [1,2]. Higher values of the parameter θ correspond to a more stable course of the eutectic reaction and a lower risk of volume defects. It has been experimentally proven that the parameter θ correlates with the occurrence of shrinkage in test specimens and in real castings [1,2,5]. The angle θ was determined from equation (7) according to the diagram (**fig. 3**):

$$\theta = 180° - tan^{-1}\left(\frac{\Delta R_1}{\Delta t_1}\right) - tan^{-1}\left(\frac{\Delta R_2}{\Delta t_2}\right) \qquad (7)$$

The determination of the θ parameter provides a measurable experimental quantity characterizing the dynamics of solidification, which can be utilized for calibration of numerical solidification models and digital twins.

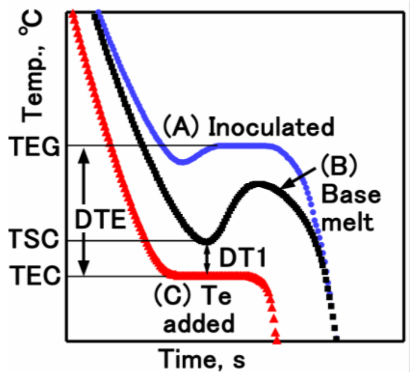

Fig. 2 Diagram for calculating EGS and N [1]
Obr. 2 Diagram pro výpočet EGS a N [1]

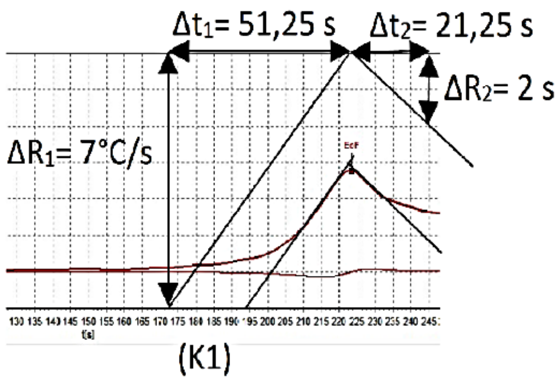

Fig. 3 Diagram for calculating angle θ
Obr. 3 Diagram pro výpočet úhlu θ

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3. Results and discussion

The results obtained (**tab. 2**) confirmed that the eutectic graphitization ability (EGS) alone did not show a clear relationship to the formation of shrinkage cavities. The average EGS values for castings without shrinkage reached 78.232%, while for castings with shrinkage they reached 78.421%. The difference between the groups is minimal and does not show a systematic trend. A similar conclusion can be drawn from a comparison of the estimated number of graphite nuclei N, where the difference between the groups does not exceed 1%.

Tab. 2 Evaluation of TA parameters and shrinkage occurrence
Tab. 2 Vyhodnocení parametrů TA a výskytu smrštění

Castings without shrinkage	Eutectic graphitization ability EGS (%)	Number of graphitic nuclei N	θ (°)
K1	71.93	314.931	66.26
K2	78.858	357.404	47.75
K3	78.885	357.569	47.76
K4	83.253	384.345	31.71
Average	78.232	354.722	48.37
Castings with shrinkage			
K5	69.612	300.724	66.17
K6	81.013	370.61	31.42
K7	76.877	345.261	80.18
K8	86.181	402.291	51.38
Average	78.421	353.562	57.97

It follows from the above that the EGS parameter, which is based on the determination of the eutectic temperatures TES, TEM, and the minimum eutectic temperature TSC, may not be sufficient on its own to assess the predisposition to volume defects. Although EGS expresses the stability of the graphitic eutectic reaction, it does not consider the dynamics of solidification in the final stages of solidification, which are decisive in terms of casting feeding.

On the contrary, the parameter θ showed greater sensitivity to differences between the evaluated melts. The average value of the angle θ for castings without shrinkage was 48.37°, while for castings with shrinkage it was 57.97° (**tab. 2**). The highest value of θ = 80.18° was recorded for melt K7. A representative cooling curve with the first derivative and the marked parameter θ is shown in **fig. 4**.

The angle θ is derived from the change in the slope of the first derivative of the cooling curve in the area where the eutectic reaction ends. This part of solidification is characterized by a gradual decrease in the intensity of latent heat release.

The course of the derivative is closely related to the instantaneous solidification rate and the development of the solid phase fraction in the system. A more pronounced change in slope may indicate a faster transition to a phase in which graphite expansion cannot fully compensate for austenite contraction.

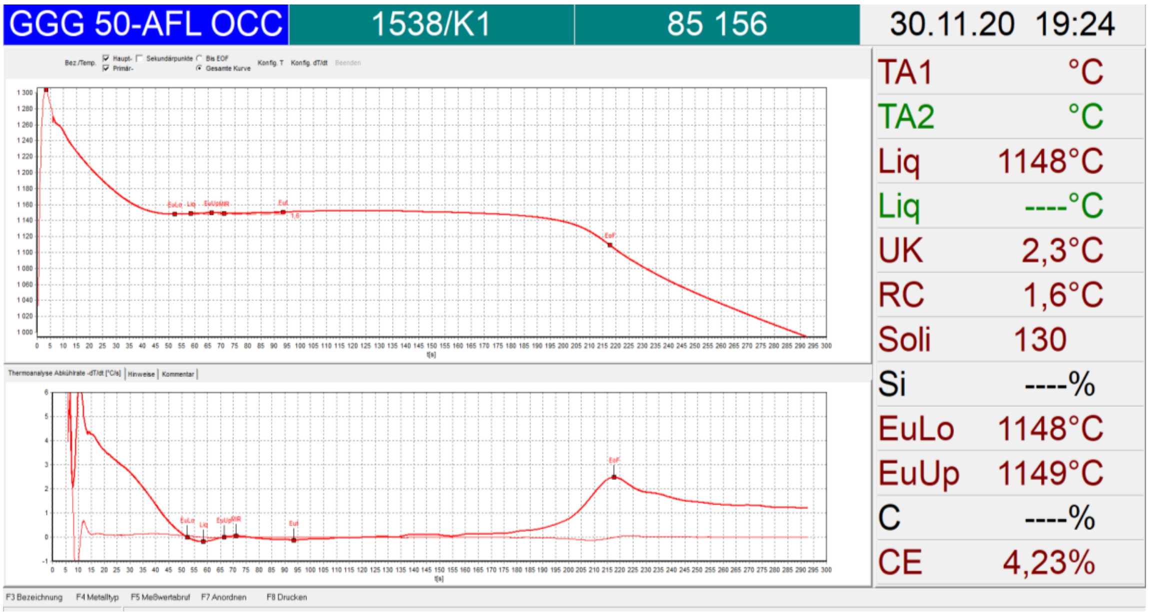

Fig. 4 Representative cooling curve with first derivative and parameter θ
Obr. 4 Reprezentativní chladicí křivka s první derivací a označeným parametrem θ

According to the theoretical principles of differential thermal analysis, the first derivative of the cooling curve is a sensitive indicator of the solidification mechanism and the dynamics of latent heat release [6]. A change in the derivative curve may therefore reflect deteriorated feeding conditions, which will subsequently manifest itself in the formation of shrinkage cavities. Long-term applications of thermal analysis in foundry practice point to the importance of dynamic evaluation of the solidification process beyond the chemical composition itself [6].

The macroscopic manifestation of shrinkage on the monitored casting is shown in **fig. 5**. The location of the defect corresponds to the area of highest risk of insufficient feeding, which supports the interpretation based on the analysis of the θ parameter. The evaluation was performed on a limited set of melts, which requires further experimental verification of the conclusions obtained.

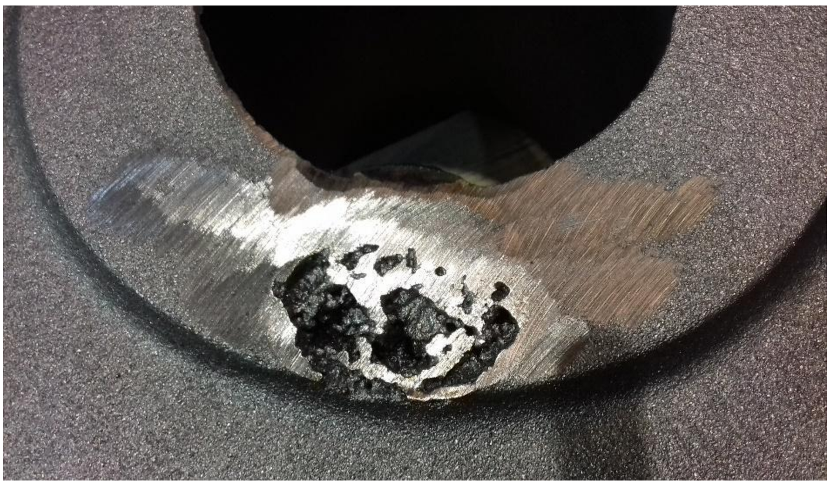

Fig. 5 Detail of internal shrinkage on the casting under examination
Obr. 5 Detail vnitřního smrštění na zkoumaném odlitku

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ISSN Online: 3029-8350

4. Conclusion

The aim of this work was to evaluate selected parameters of thermal analysis in relation to the formation of shrinkage cavities during DCI casting. Based on experimental evaluation, no clear correlation was confirmed between eutectic graphitization ability (EGS) and the occurrence of shrinkage, as the average EGS values in both groups studied were practically identical.

The parameter θ, determined from the course of the first derivative of the cooling curve, showed greater sensitivity to differences between melts. Higher values of θ were recorded in castings with shrinkage cavities, with an extreme value of 80.18° corresponding to the confirmed occurrence of a defect. The results suggest that dynamic evaluation of the eutectic reaction curve can provide more accurate information about solidification conditions than the determination of eutectic temperatures alone.

From a broader technological perspective, the characterization of solidification dynamics is also relevant for the development and optimization of impact plates and cooling elements in continuous casting mould systems. Experimental parameters derived from thermal analysis may contribute to the validation of numerical models used in digital twin concepts of controlled solidification processes.

The findings point to the potential use of the θ parameter as a supplementary indicator in the technological control of melt quality.

Acknowledgements

This research was funded by VEGA project No. 1/0199/24 „Development of mathematical control models and digital twins for individual steel production processes based on machine learning with the aim of increasing the competitiveness of the sector and reducing the carbon footprint" and project APVV-21-0396 The development of a spherical impact pads in ladles and tundishes for high-quality steel grades.

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