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The Influence of Wall Thickness and Mould Temperature on Structure and Properties of Thin Wall Ductile Iron Castings

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Abstract

The excellent property combination of thin wall ductile iron castings (TWDI), including thin wall alloyed cast iron (e.g. austenitic TWDI) has opened new horizons for cast iron to replace steel castings and forgings in many engineering applications with considerable cost benefits. TWDI is considered as a potential material for the preparation of light castings with good mechanical and utility properties, the cost of which is relatively low. In this study, unalloyed and high Ni-alloyed (25% Ni) spheroidal graphite cast iron, with an austenitic metallic matrix were investigated. The research was conducted for thin-walled iron castings with 2, 3 and 5mm wall thickness, using different mould temperature (20°C, and 160°C) to achieve various cooling rates. The metallographic examinations i.e. characteristic of graphite nodules, metallic matrix, and primary grains of austenite dendrites (in high-nickel NTWDI) and mechanical properties were investigated. The study shows that homogeneity of the casting structure of thin-walled castings varies when changing the wall thickness and mould temperature. Finally, mechanical properties of thin-walled ductile iron castings with ferritic-pearlitic and austenitic metallic matrix have been shown.

Keywords: Metallography, Mechanical properties, Ductile iron, Mould temperature, Thin wall casting, Austenitic ductile iron, High Ni alloying

1. Introduction

The structure of ductile iron is mainly influenced by the following factors: chemical composition, cooling rate, metal treatment, and heat treatment [1-3]. The cooling rate is first of all a function of the casting wall thickness, pouring temperature, and the mould materials. The issue of producing thin-walled castings is not simple, because it is connected with a wide range of cooling rates at the beginning of the solidification process [1,4]. Technical literature provides limited data on the cooling rate-micro and macrostructure relations, which is crucial in the formation of thin walled castings properties.

One of the difficulties in the production process of thin-walled castings is the variable rate of metal cooling in the mould. There is then a high risk of the appearance of chills, heterogeneity of the structure (especially in castings with varying wall thicknesses), and other casting defects. The wall thickness of the casting and the initial temperature of the mould next to its material mould ability to absorb the heat are the parameters that affect to the greatest extent the value of the cooling rate and these changes occur. The combination of excellent properties found in thin-walled ductile iron castings (TWDI), including thin-walled alloyed iron (e.g., with an austenitic metallic matrix), make them highly viable materials to be employed as substitutes for steel castings and forgings in various engineering applications [5-9]. In ductile iron castings, the austenite dendrites and graphite nodule count are quality factors which reflect the physical-chemical state of liquid metal. One of the important factors influencing the austenitic dendrites and graphite nodule count is related to the cooling rate at the beginning of solidification. In this study, ductile iron (TWDI) and a high Ni-alloyed (>18%Ni) cast iron (NTWDI), were investigated. The published literature provides limited data on the formation of the primary structure in thin wall NTWDI [10]. In this present work, an investigation into the changes in primary dendrites, graphite nodules and mechanical properties in TWDI and NTWDI as a result of wall thickness and mould temperature has been carried out.

2. Experimental

The experimental melts were prepared in a 15 kg capacity crucible using an electrical induction furnace of intermediate frequency. The furnace charge consisted of Sorelmetal (High-Purity Pig Iron: 4.46% C, 0.132% Si, 0.01% Mn, 0.006% S, 0.02% P), technically pure silicon, Fe-Mn, steel scrap, copper, and nickel. After melting at 1490°C, the liquid metal was held for 2 min followed by spheroidization and inoculation operations using the bell method. An Fe-Si-Mg (6% Mg) foundry alloy was used for spheroidization, while Fe-Si-Ca-Ba-Al (73-78% Si, 0.75-1.25% Ca, 0.75-1.25% Ba, 0.75-1.25% Al, Fe [balance]) was used for inoculation purposes.

The cast iron was poured at 1400°C into Y block ingots (2, 3, 5 mm) using classic green sand bentonite moulds. The moulds were poured in two variants: casted at ambient temperature (20°C) and at a temperature of 160°C.

The chemical composition tests of the experimental ductile irons were carried out using a SPECTRAMAXx emission spectrometer with spark excitation. The results of the chemical composition are summarized in Table 1.

Table 1.
Chemical composition of tested alloys [given in % by mass]

	C	Si	Mn	P	S	Mg	Cu	Ni	CE***
TWDI* (moulds 20°C)	3.58	2.7	0.3	0.02	0.01	0.03	1.06	0.94	4.40
TWDI (moulds 160°C)	3.55	2.8	0.3	0.01	0.007	0.03	1.04	0.91	4.39
NTWDI** (moulds 20°C)	2.51	2.1	0.85	0.02	0.01	0.03	0.03	25.1	4.09
NTWDI (moulds 160°C)	2.62	2.2	0.98	0.001	0.01	0.03	0.02	24.7	4.21

*TWDI – thin wall ductile iron castings,
**NTWDI – high-nickel thin wall ductile iron castings,
***CE – Carbon equivalent: for cast iron CE=C+0.3·Si+0.36·P;
for high-nickel cast iron CE=C+0.33·Si+0.047·Ni-(0.0055·Ni·Si) [11].

An optical microscope (OM) Leica MEF4M equipped with a quantitative analyzer Leica QWin v3.5 were used for the metallographic characterization. Samples for metallographic examinations were taken from the bottom part of the ingots and the microstructure was revealed by using nital reagent whereas the macrostructure was displayed by immersion in a Stead reagent.

Strength testing was carried out on flat samples (in accordance with the ASTM E8M Standard) by means of a Zwick/Roell Z050 device. The strain rate was set to 0.008 s^{-1}.

3. Results and discussion

3.1. Microstructure

Fig. 1 shows the microstructure of ductile iron in castings with a wall thickness of 5 mm for different mould temperatures. Table 2 summarizes the results of these metallographic investigations.

The analysis of the metallographic examination results indicates a significant effect of the wall thickness on the number and size of graphite nodules. Decreasing the wall thickness of the castings increases the cooling rate [3], which leads to an increase in the degree of supercooling at the beginning of eutectic crystallization and to an increase in the number of graphite nodules.

Heating the casting mould caused number of graphite nodules to decrease and there was an increase in structure homogeneity as graphically shown in Fig. 2.

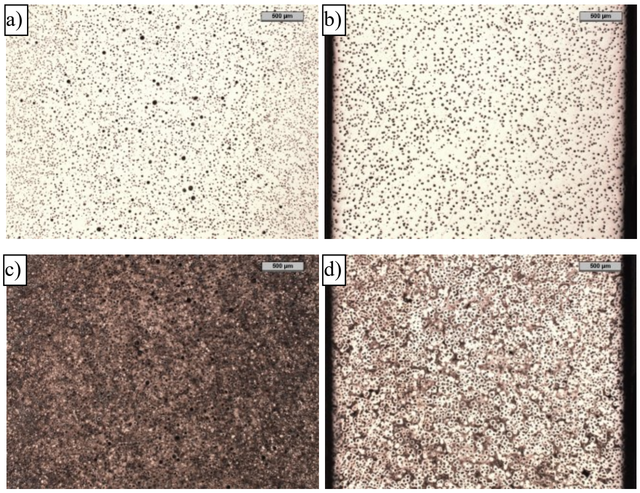

Fig. 1. Microstructure of ductile iron (TWDI) in castings with a wall thickness of 5 mm: a) unetched condition, mould temperature 20°C, b) unetched condition, mould temperature 160°C, c) etched with nital, mould temperature 20°C, d) etched with nital, mould temperature 160°C, mag 25x

Table 2.
A list of basic parameters from the microstructure analysis, g – wall thickness [mm], d_{ek} – mean diameter of graphite nodules [μm], N_A – number of graphite nodules [mm^{-2}], S – shape factor, V_f – ferrite fraction [%], G_f – graphite fraction [%], λ – average distance between graphite nodules [μm]

	g	$d_{śr}$	N_A	S^*	V_f	G_f	λ
TWDI (mould 20°C)	2	8.46	1378	0.81	14.35	8.78	78.25
	3	10.63	772	0.83	14.35	8.08	112.01
	5	13.41	519	0.82	8.57	8.62	131.30
TWDI (mould 160°C)	2	12.35	646	0.83	44.08	8.82	114.29
	3	14.11	569	0.82	54.98	10.31	111.71
	5	18.94	310	0.79	49.71	10.24	152.88
NTWDI (mould 20°C)	2	7.49	1310	0.81	-	6.41	95.38
	3	12.54	533	0.82	-	7.59	138.26
	5	15.38	352	0.79	-	7.57	170.73
NTWDI (mould 160°C)	2	10.66	609	0.80	-	6.35	144.26
	3	12.21	479	0.78	-	6.67	159.58
	5	14.81	312	0.77	-	6.59	202.15

*S – shape factor $S = 4\pi A / P^2$ [12],
A – surface area of graphite particles,
P – perimeter of graphite particles.

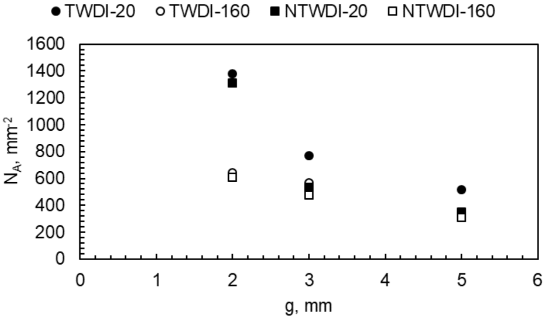

Fig. 2. The effect of wall thickness and mould temperature on the number of graphite nodules

For castings with a wall thickness of 2, 3 and 5 mm, in the case of castings attained in heated moulds the difference in the number of graphite nodules was about 300 mm^{-2} to over 700 mm^{-2} for those received in the classic way. Analysis of data in Fig. 1 also indicates a much greater heterogeneity of the microstructure from the point of view of graphite in thin-walled castings obtained in the classic way (ie. without heating the mould).

This is manifested by the fact that cross-sections of castings tend to increase the size of graphite particles along with the distance from the mould wall. This can be seen in Figure 1, where larger graphite nodules are visible (primary graphite) around half of the cast section. This phenomenon is generally disadvantageous and may constitute a local reduction of the mechanical strength of a given element. Castings attained in heated moulds do not show such features.

Structure homogeneity is a desirable feature, because it eliminates the anisotropy of properties and provides similar strength parameters throughout the casting section. In the case of a casting with a wall thickness of 2 mm, the average size of graphite particles increased by about 50% in relation to the casting obtained in a non-heated mould. A similar change occurred in terms of the number of graphite nodules, which is almost two times less in the castings received in heated moulds. The shape factor of graphite particles in non-heated moulds is practically in the same range. An analysis of the microstructure does not show local graphite assemblies, nor occurrence of flake graphite at the surface, i.e. frequent defects occurring in ductile iron castings. The structure is relatively homogeneous, and the graphite nodules have a high shape factor. In each of the discussed cases, castings produced from unheated moulds were characterized by smaller sizes of graphite nodules.

The metallic matrix of unalloyed ductile iron consists of ferrite and pearlite. The high cooling rate promotes the formation of pearlite, which is noticeable in castings from unheated moulds. In castings obtained from non-heated moulds, the ferrite fraction is at the level of 8-15%, whereas in castings from pre-heated moulds at the level of 44-55%. Thus there is a significantly noticeable difference between the castings obtained from moulds having different temperatures. The wall thickness does not affect the microstructure as much as the mould temperature. The results of metallographic tests indicate that castings with a higher wall thickness (5 mm), i.e. those with a lower cooling rate, contain less ferrite than thinner castings. This phenomenon is caused by the absorption of carbon by graphite nodules during eutectoid transformation. The large number of graphite nodules contributes to increasing the fraction of ferrite, which is deficient in carbon in the matrix, at the cost of pearlite.

3.2. Macrostructure

High-nickel ductile iron, due to the high content of alloy additives, is characterized by an austenitic metallic matrix. Nickel stabilizes austenite at lower temperatures, which eliminates the allotropic transformation and does not lead to pearlite and ferrite formation. Thanks to this phenomenon, it is possible to assess the crystallization of the primary structure, which is created directly from liquid metal. Fig. 3 shows examples of the macrostructure of ductile iron, whereas in Table 3 the results of the metallographic analysis of a primary structure is shown.

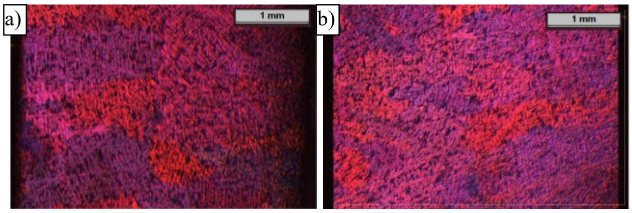

Fig. 3. Macrostructure of high nickel ductile iron (NTWDI) in castings with a wall thickness of 5 mm: a), mould temperature 20°C, b) mould temperature 160°C, etched with Stead reagent, mag. 20x

Table 3.
Results of metallographic tests of NTWDI: g – wall thickness, N_L – number of primary grains per unit length, SDAS – secondary dendritic arm spacing

	g, mm	N_L, 1/mm	SDAS, µm
NTWDI (moulds 20°C)	2	2.94	21
	3	2.60	29
	5	2.39	32
NTWDI (moulds 160°C)	2	2.40	23
	3	2.40	26
	5	1.60	32

Castings obtained from pre-heated moulds are characterized by a smaller number of primary grains per unit length (NL), which is also caused by a lower rate of heat dissipation from the crystallized casting. The size of the primary grains of the casting with a wall thickness of 5 mm from the unheated mould is similar to the castings with a wall thickness of 2 and 3 mm from pre-heated moulds. Secondary dendritic arm spacing measurements also showed its relationship to the cooling rate of the casting.

3.3. Mechanical Testing

The variation of the mechanical properties of samples as a function of wall thickness is presented in Table 4, while examples of tensile curves of castings with a wall thickness of 5 mm, obtained using different moulding materials temperature in the stress-strain system, is shown in Fig. 4.

The results of mechanical properties tests indicate a small effect of the initial mould temperature on the obtained mechanical properties of high-nickel ductile iron castings. These results show that in the case of thin-wall castings of high-nickel ductile iron, high strength (over 470MPa) and very good plasticity of over 30%, can be attained. This material shows a high homogeneity of mechanical properties despite a large variation in the number of graphite nodules ($\Delta N = 300\ \text{mm}^{-2}$). In this case, graphite nodules with a small diameter (7-15µm) and with a high coefficient of sphericity to a small extent reduce these mechanical properties. In the case of unalloyed ductile iron, much larger differences in the obtained values of tensile strength and plasticity of castings obtained in moulds of different initial temperature are visible. Ductile iron in this case achieves tensile strength values of almost 1000MPa at moderate elongation (10%). This is a very good result, which is due to the small diameter of graphite nodules, reinforcement of the metallic matrix through alloying additions such as copper and nickel. Heating the mould resulted in a significant reduction in mechanical properties as shown in Fig. 4 and Table 4. The reduction in the cooling rate caused significant differences in the ferrite and perlite fractions, which ultimately contributed to a reduction in strength by approximately 300MPa and an increase in elongation of about 5%.

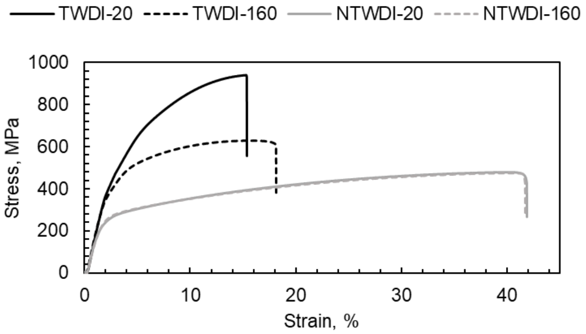

Fig. 4. Stress-strain curves of the castings with 5 mm wall thickness. TWDI-20 and NTWDI-20 – castings obtained, using a mould with an ambient temperature, TWDI-160 and NTWDI-160 – castings obtained using a mould with an elevated temperature

Table 4.
Results of mechanical properties

Sample No.	Mould temperature, °C	Wall thickness, mm	Cast iron	Tensile strenght R_m, MPa	Elongation A, %
1	160	3	NTWDI	483	32.62
2	160	3	NTWDI	487	33.79
3	160	5	NTWDI	466	33.27
4	160	5	NTWDI	474	39.52
5	160	5	TWDI	629	15.34
6	160	5	TWDI	628	12.62
7	160	3	TWDI	615	15.13
8	160	3	TWDI	602	13.70
9	20	3	TWDI	922	8.19
10	20	3	TWDI	847	7.40
11	20	5	TWDI	940	11.52
12	20	5	TWDI	925	10.40
13	20	5	NTWDI	508	34.99
14	20	5	NTWDI	478	39.47
15	20	3	NTWDI	480	34.58
16	20	3	NTWDI	471	32.41

4. Conclusions

Based on this research, the following conclusions can be drawn:

- Increasing the wall thickness of thin-walled castings, irrespective of the type of ductile iron and mould temperature, increases the size of graphite nodules (reduces their number) and increases the distance between them (λ).
- The highest structure homogeneity (from the point of view of differences in the number of graphite nodules) is characterized by castings obtained in heated moulds.

- Heating the mould eliminated the occurrence of primary graphite nodules located around the center of the casting section.
- The temperature of the mould significantly influences the ferrite fraction. The change in mould temperature from 20°C to 160°C increased the proportion of ferrite by 30-40%.
- Regardless of the wall thickness and mould temperature, columnar austenitic dendrites were observed.
- Analysis of the N_L parameter shows that the higher the wall thickness of the casting, the smaller the number of dendrites (primary grains) per unit length. Decreasing dendrites is also promoted by heating the mould.
- The initial temperature of the mould has little effect on the attained mechanical properties of high-nickel ductile iron castings.

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