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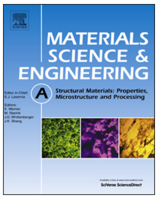

The effects of solidification on the microstructure and mechanical properties of modified ductile Ni-resist iron with a high manganese content

M. Mohd Rashidi [a,b,*], Mohd Hasbullah Idris [a]

[a] *Department of Materials Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia*
[b] *Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia*

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ABSTRACT

In this study, ductile Ni-resist with a minimum nickel content of 18 wt% was modified. Up to 12 wt% manganese was added together with 10 wt% nickel to investigate the effects of the alloying elements on the solidification, microstructure and mechanical properties of the Ni-resist. The effects of the solidification stage on the primary dendrite arm spacing (DAS), secondary dendrite arm spacing (SDAS), graphite aggregates, carbide formation and a series of mechanical properties were evaluated. The results indicate that the DAS, SDAS, graphite aggregate and carbide are directly dependent on the solidification cooling rate. Consequently, various mechanical properties of the Ni-resist are also affected by the addition of manganese. The tensile strength of the modified ductile Ni-resist decreased as the manganese content increased.

1. Introduction

High-alloy ductile iron, known by the trade name ductile Ni-resist, was developed to meet the chemical, mechanical and physical property requirements for a wide range of applications. This material also provides corrosion and wear resistance, and its production is economical and facile. In addition, ductile Ni-resist (DNR) alloys, as an austenitic matrix at all temperatures, are potentially useful materials for high-temperature applications. DNR alloys are an austenitic matrix at all temperatures because of volume changes. For applications at high temperatures of up to 948 K, cast iron and steel pass through a critical range, which frequently results in cracking and distortion of castings. These problems never occur in DNR because its structure consists of an austenitic matrix at all temperatures. The austenitic matrix is obtained through the use of a proper alloying technique in base iron during the material casting process. With the suitable addition of alloying elements, the Time–Temperature–Transformation (*T–T–T*) curve generally shifts to the right, making it possible to avoid the 'nose' of the *T–T–T* curve [1]. Furthermore, the transition of the martensite due to the addition of these elements begins below room temperature. Thus, the austenitic microstructure may exist and remain stable at room temperature. This process is achieved without the use of any heat treatments. Generally, the as-cast austenitic microstructure of DNR arises due to the influence of nickel present in the composition that acts as the austenite matrix promoter. A minimum of 18 wt% nickel suppresses the austenite (γ)→ferrite (α) transition in conventional ductile iron [2]. Although nickel is widely accepted by industry as the main alloying element to produce DNR, its usage nevertheless possesses some drawbacks, especially with respect to production costs. Nickel is expensive, and its cost is six times greater than that of alternative alloying elements such as manganese. Reducing the amount of nickel used to obtain DNR is still achievable, as indicated by Fatahalla et al. [3], who reduced the amount of nickel in DNR to 13 wt%. Rashidi and Hasbullah [4] investigated the role of manganese in place of nickel as an austenite matrix promoter on the mechanical and corrosion properties of modified ductile Ni-resist. They observed that the corrosion resistance of the obtained Ni-resist is comparable to that of the unmodified DNR type D-2 required by industries. There is a possibility that replacing nickel with manganese may affect the chemical interaction and modify the phase of the iron matrix. An interaction may occur because molten iron is melted with a considerable amount of nickel and manganese before solidification. For example, Elliot [5] reported that manganese acts as an austenite stabilizer while simultaneously promoting carbide formation. Morrison [6] suggested that

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* Corresponding author at: Department of Materials Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia. Tel.: +60 133203462; fax: +60 75566159.
E-mail address: rashidimaarof@gmail.com (M.M. Rashidi).

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increasing the manganese content to approximately 6 wt% will enhance carbide formation. Moreover, Jabbari et al. [7] investigated the effect of the cooling rate on gray cast iron and reported that the DAS and SDAS characteristics are highly dependent on the solidification cooling rate. The DAS and SDAS characteristics decreased as the cooling rate increased. Stefanescu [8] verified that the morphology of the solid-liquid interface of conventional ductile cast iron is influenced by the chemical composition and solidification rate. However, no reports have yet been published on the effects of solidification on modified DNR with higher manganese contents. Determining whether the effects of adding high contents of manganese to DNR are equivalent to those of nickel is of importance. Thus, the objective of this study is to explore the solidification characteristics, microstructure and mechanical properties of modified DNR with high manganese contents. An attempt was made to combine as much as 9–12 wt% of manganese with as low as 10 wt% of nickel to produce the austenitic structure.

2. Experimental procedure

2.1. Material preparation

The melting process was conducted in an induction furnace with a holding capacity of 100 kg of molten metal, an input power of 200 kW and a voltage frequency of 3000 Hz to produce 30-mm-thick Y-block castings of modified DNR (shown in Fig. 1) [9–11]. The charge materials (steel scrap, pig iron and pure nickel) used were selected to produce modified DNR with the following compositions: (a) 9Mn–10Ni; (b) 10Mn–10Ni; (c) 11Mn–10Ni; and (d) 12Mn–10Ni wt% [1–4]. After the stirring process, Ferro-Manganese (FeMn) and Ferro-Chrome (FeCr) were added to increase the Mn and Cr contents, and then they were poured into green sand molds at 1773 ± 20 K [6]. Nodulant and inoculant contents of 1.0 and 0.5 wt%, respectively, were added to the mold [12]. Table 1 lists the chemical compositions of the experimental iron, nodularizer, inoculant, nickel, FeMn and FeCr.

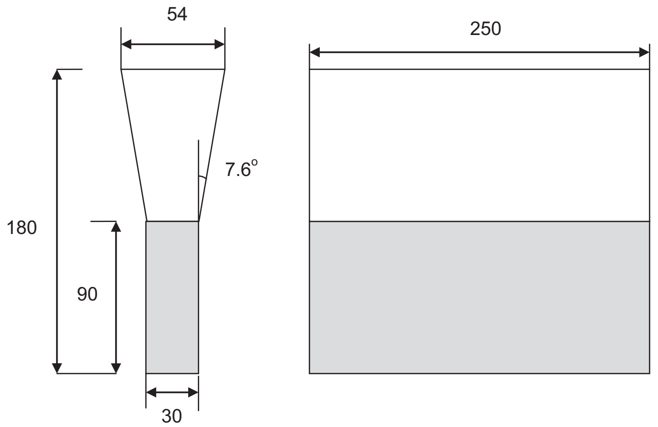

Fig. 1. Dimensions of the Y-block castings used in this experiment. Test specimens cut and machined from the lower part of the Y-block (dimensions in mm).

2.2. Magnesium treatment and inoculation process

The nodulant and inoculant were used at concentrations of 1.0 and 0.5 wt%, respectively, in the mold reaction chamber, as shown in Fig. 2. The runner system for each casting contains a specially designed chamber in which both the nodulant and inoculant were placed. In this system, the reaction chamber and in-gate were separated by 120 mm. The fading effect and material dissolution were encouraged by utilizing a 0.2–0.7 mm grading size of both added elements. After pouring, molten metal flowed over both the nodulant and inoculant and produced a continuous reaction, resulting in a consistent pick-up of nodulant and inoculant throughout the pouring period. Table 2 lists the actual chemical compositions of all of the alloyed irons investigated in this study.

2.3. Solidification cooling curve

The temperatures during the cooling period were measured using thermocouples placed at the positions shown in Fig. 2, as suggested by Sahoo and Pathak [13]. Two *R*-type thermocouples were used to measure the temperatures inside the cavity, and thin-walled alumina glass tubes were used to protect both of the thermocouples. The thermocouple output was measured using a dataTaker DT80 multichannel analog/digital data logger (Datataker Pty Ltd, Melbourne, Australia). The measured voltages were converted to temperature values using a polynomial function specified by the data logger for the thermocouple [14]. The accuracy of the temperature measurement was estimated to be ±7 K based on the calibration using an electrolytic copper melt. The temperature was measured every 1/10 s during the experiment. Cooling

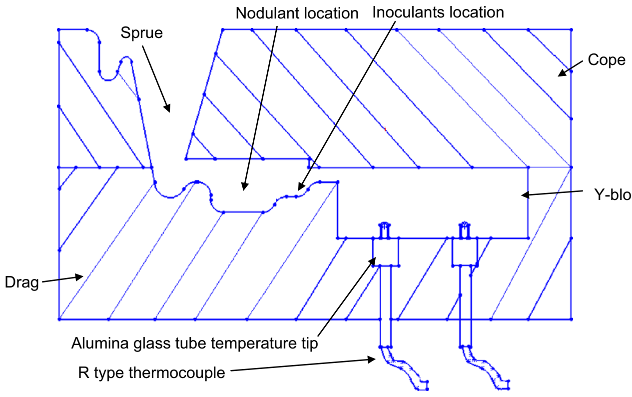

Fig. 2. Schematic of the magnesium treatment of the In-mold.

Table 1
Chemical composition of iron, alloyed materials, nodularizer, inoculant, FeMn and FeCr (wt%).

	Element										
	C	Si	Mn	P	S	Mg	Ni	Ca	Cr	R.E	Fe
Pig iron	2.91	2.28	0.12	0.07	0.02	–	0.02	–	–	–	Balance
Steel	0.20	0.15	0.60	0.03	0.02	–	–	–	–	–	Balance
Nickel	–	–	–	–	–	–	99.00	–	–	–	Balance
FeMn	–	1.00	86.00	0.10	0.02	–	–	–	–	–	–
FeCr	8.00	4.00	–	0.04	0.04	–	–	–	60.0	–	–
Nodularizer	–	44.00	–	–	–	5.00	–	2.00	–	1.90	–
Inoculant	–	70.00	–	–	–	–	–	2.00	–	–	Balance