Materials and Design 87 (2015) 450–465

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/jmad

Alloy and process design of thermo-mechanically processed multiphase ductile iron

M. Soliman [a],*, A. Nofal [b], H. Palkowski [a]

[a] *Institute of Metallurgy, Clausthal University of Technology, D38678 Clausthal-Zellerfeld, Germany*
[b] *Central Metallurgical Research and Development Institute — CMRDI, Helwan, 11421 Cairo, Egypt*

ARTICLE INFO

Article history:
Received 20 May 2015
Received in revised form 27 July 2015
Accepted 29 July 2015
Available online 31 July 2015

Keywords:
Ductile iron
Thermo-mechanical processing
Dual matrix
Austempering
Aluminum effect
Intercritical annealing

ABSTRACT

This work highlights the transformation kinetics, microstructure evolution, hardness and compression properties of four thermo-mechanically processed ductile irons (DIs) having from 0 to 1.7 wt.% aluminum. The DIs are subjected to different true strain values of 0, 0.3 and 0.5 by deformation in the austenite region. Additionally, four types of matrix were produced, namely martensitic, martensitic–ferritic, ausferritic and ferritic–ausferritic. The ferrite introduction is accomplished by isothermal holding in the intercritical region. Aluminum increase widened the intercritical region and shifted it to higher temperature range. The former effect rendered the intercritical annealing more controllable. The latter caused substantial discrepancy in the chemistry of the intercritical austenite by varying the aluminum content. The subsequent transformation kinetics, microstructure evolution and mechanical properties of the intercritically annealed DI are governed by the chemistry of the intercritical austenite. Whereas, those with fully martensitic and fully ausferritic matrices are governed by the aluminum variation. It is also shown that the kinetics of ausferrite formation is accelerated by both increasing the deformation and introducing ferrite to the matrix. The strength and hardness are increased by the former and declined by the latter factor. The fracture strain has not shown a continual increase by increasing the ferrite content.

1. Introduction

Ductile irons (DIs) are very unique engineering materials, possessing good castability, machinability, wear resistance and mechanical properties. The mechanical properties of ductile irons are controlled primarily by their matrix structure. A number of variables including chemical composition, cooling rate, type, amount and method of post-inoculation, amount of residual magnesium and pouring temperature can control the matrix structure of the DI in the as cast condition [1–3]. Heat treatment of DI is another rout to produce a family of materials offering a wide range of properties obtained through matrix microstructure control [4]. The newly developed DI with dual matrix (DM) is the most recent member of this family. The matrix structure of DM–DI consists of a soft phase — ferrite and a hard phase — either martensite or ausferrite (acicular ferrite and high carbon austenite). Special interest for such material is due to the improved combination between its strength and ductility and its enhanced machinability compared to the single hard phase matrix [5,6]. Wade et al. indicated that the mechanical properties of DM–DI with ausferrite are improved, more than those of the same ductile iron with martensite [6]. Ferrite in the DM is obtained by either an incomplete austenitization step (by isothermal holding at temperatures within the intercritical interval) [5,6] or by controlled cooling of the austenite in the intercritical region [7].

On the other hand, certain characteristics still impose limitations on the widespread use of DI. Among these limitations is the lack of control on the scale of microstructure and hence on the properties together with the non-uniformity of alloying elements and structure at cell boundary and cell interior, caused by the segregation tendencies of alloying elements. Hot and warm working is a vital processing method to overcome these drawbacks.

Hot and warm working provides deformed and/or recrystallized austenite depending on the temperature and other hot working parameters resulting in an increased number of sites for the subsequent transformation processes. This method has recently attracted research and industrial interest as a technique of the strength improvement in DI [7–9]. It refines the as-cast structures, closes up the internal shrinkage cavities and gas porosity, and reduces the segregations of alloying elements. Additionally, it increases the dimensional accuracy and improves surface finish of the products which would finally reduce the manufacturing cost. Forged ductile iron products have been promoted as replacements of some types of steel forgings.

Ausforming of DI is a subdivision of the above-mentioned processing method. The deformation in ausforming is introduced into the austempering schedule just after quenching but before any substantial

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* Corresponding author.
E-mail addresses: mohamed.soliman@tu-clausthal.de (M. Soliman), adelnofal@hotmail.com (A. Nofal), heinz.palkowski@tu-clausthal.de (H. Palkowski).

http://dx.doi.org/10.1016/j.matdes.2015.07.159
0264-1275/

Table 1
Composition of the ductile irons with different aluminum-contents (wt.%).

Alloy	C	Si	Mn	Al	Mg	S	P
A00	3.60	2.60	0.29	–	0.06	0.018	0.028
A03	3.68	2.48	0.29	**0.31**	0.035	0.011	0.029
A10	3.57	2.59	0.33	**0.96**	0.046	0.011	0.025
A17	3.70	2.66	0.31	**1.74**	0.040	0.017	0.026

transformation of austenite. It is shown that ausforming could provide mechanical driving force in the form of strain defects in addition to the chemical thermodynamic driving force. This can be used to accelerate the rate of stage I of austempering. The enhanced nucleation rate of ferrite and C-enriched austenite leads to finer and more homogeneous ausferrite, which in turn, results in a dramatic increase in strength, hardness and wear resistance [10–13].

An attempt was made by Shi et al. to describe the anisotropy of tensile strength in terms of the deformation of graphite nodules of deformed ductile iron [14]. Furthermore, Hervas et al. proposed a relationship between the nodule strain, experimentally determined at different stress–strain stages, and the numerical simulation [15].

In the frame work of the current study both of hot deformation in the austenitic region and introducing the pro-eutectoid ferrite to the DI matrix by Intercritical annealing after austenitization are combined to produce thermo-mechanically processed DM ductile iron in a single process chain. For the proposed process, a wide range of intercritical region would ease controlling the pro-eutectoid ferrite volume fraction. For this purpose aluminum is added for its effect of widening the intercritical region.

Therefore, the current investigation has the aims of:

1. Studying the effect of aluminum content and deformation value on the kinetics of ferrite formation.
2. Selecting thermo-mechanical processing (TMP) parameters depending on this study.
3. Investigating the effect of the TMP-parameters and the aluminum content on the microstructure development and mechanical behavior.

2. Experimental procedure

2.1. Material

Four ductile irons with different aluminum-content were investigated. The chemical composition of the alloys is given in Table 1. Melting was performed in an induction furnace. The base irons were treated with a 9.5 wt.% MgFeSi alloy for spheroidisation followed by post-inoculation with 75 wt.% FeSi. The alloys possess different aluminum contents. The selection of the compositions is based on the thermodynamic effect of aluminum in DI as will be shown later.

2.2. Thermo-mechanical processing and dilatometry

For thermo-mechanical processing and dilatometric study, a Baehr Dil 805D thermo-mechanical simulator, shown in Fig. 1, was used. The thermo-mechanical simulation was performed on cylindrical samples of 5 mm diameter and 10 mm length. Sheathed type S "Pt/Pt-10% Rh" thermocouples with a nominal diameter of 0.2 mm were individually spot welded to the specimens' surface in central position. The sample was mounted horizontally between two SiN stamps. The thermal cycles were performed under vacuum of 0.005 Pa by inductive heating using a high frequency (HF) generator. Helium was used for cooling. The stamps are not directly heated by induction field and therefore the specimen temperature at the stamps is always lower than that in the middle of the specimen because of heat transfer to the stamps. This results in a temperature gradient toward the stamps. To overcome this problem, two molybdenum disks (∅ 8 × 0.36 mm) were spot welded at the parallel ends of the samples to reduce this gradient. Using this method the specimen temperature was homogenized within +/− 3 K. The Mo disks also reduce friction during the compression test, i.e., serve as a lubricant and so improve the homogeneity of deformation. The dimension variations of the specimens during the thermal-deformation cycle are transmitted via a moving quartz pushrod to a LVDT sensor. A computer and data acquisition system recorded the dilatometric change, temperature and load as a function of time, and cross correlated the relative change in length as a function of temperature.

The specimens are subjected to thermo-mechanical schedules shown in Fig. 2. In these schedules, the specimens were heated up to 960 °C and subjected to two deformation steps at 960 °C and 940 °C. The main objective of these deformation steps is to refine the structure through work hardening, recovery and recrystallization effects in austenite. The very slow deformation rate of 0.5 s^{-1} is adopted to minimize the susceptibility of the specimen to cracking by decreasing the strain hardening effect during deformation [16]. In schedule I: After the last deformation step the material is either quenched to RT to form a martensitic matrix (M) or quenched to isothermal holding temperature T_A of 375 °C to obtain ausferritic matrix (Af). In schedule II: After the last deformation step the material is isothermally held at temperatures within the intercritical region (T_i), so as to form certain amounts of ferrite before quenching to RT. Subsequently, the material is either quenched to RT to form a martensite + ferrite matrix (M + F) or quenched to isothermal holding temperature of 375 °C to obtain ausferrite + ferrite matrix (Af + F). For the "M" and "M + F", the

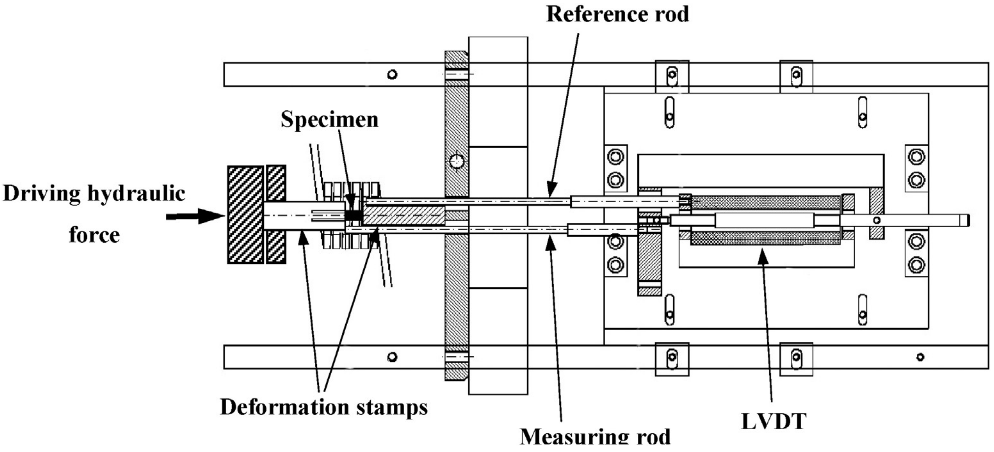

Fig. 1. Schematic drawing of the deformation dilatometer Dil 805D.