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The Bainitic Phase Transformation in Aluminium Containing Ductile Irons after Short Time of Austempering

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Abstract

The influence of aluminium on the microstructure of austempered ductile cast iron (ADI) has been studied. A number of irons of different compositions have been made by green sand casting and gravity die casting of appropriate design to provide the experimental materials. Austenitising was carried out at different temperatures and holding times for a variety of experimental irons to achieve sufficient homogeneity for further isothermal heat treatment. The transformation to a bainitic microstructure during austempering under different conditions was then examined for the most successful of the experimental casts. Austenitising temperature of 920°C, and austempering temperature of 350 °C for 1 minute have been used. Microstructures have been examined by the light and scanning electron microscopy (SEM). The microstructure of austempered ductile cast iron (ADI) consists of nodular graphite which is randomly dispersed in a bainitic matrix consisting of bainitic ferrite and carbon enriched retained austenite. It has been shown that the former austenite grain boundaries are the preferred sites for bainite nucleation and the best sites for nucleation are grain corners.

Keywords: Aluminium, Austempered ductile cast iron (ADI), Austenitising, Bainitic microstructure, Nucleation, Isothermal heat treatment

Introduction

The use of ADI has continued to increase. A combination of good physical and mechanical properties, lower cost and weight than competing materials, and savings in the energy of production and operating costs, plus ease of recycling give ADI a significant advantage as an engineering material¹⁻³⁾.

The final microstructure of the as-cast ductile iron is related to the melting process and alloying elements and is determined by the following heat treatment. Satisfactory ADI production depends on a technical understanding of the as-cast condition of irons and numerous factors in the various austenitising and austempering heat treatment cycles. Where austenitising is a requirement for high homogeneity and achievement of a fully austenitic matrix, the different austempering temperature introduces a wide range of bainitic morphology to the matrix⁴⁻¹⁰⁾. The idea of substituting Al for Si was first conceived by DeFrancq et al¹¹⁾.

According to Walson¹²⁾, the Al-alloyed cast iron has advantages in applications for light weight components with high strength at room and elevated temperatures. It has been described that Al acts as an inoculant and refiner in grey cast iron and increases the number of eutectic cells. It was reported that Al addition favours tendencies for graphite nucleation in cast irons¹³⁾.

Some advantages that can be gained by aluminium substitution are; higher resistance to thermal shock, better graphitising tendency and higher resistance to oxidation at high temperature¹²⁻¹⁴⁾.

Porter and Easterling¹⁵⁾, explained that in the bainite transformation, the ferrite nucleates on a grain boundary with a Kurdjumov-Sachs (K-S) orientation relationship with one of the austenite grains. According to Bhadeshia¹⁶⁾, in the absence of non-metallic inclusions, the growing bainitic sheaves commence from the austenite grain boundaries and layers of austenite between these sheaves are enriched with carbon and remain untransformed after quenching to room temperature. Furthermore, it has been explained that with a decrease in the austenite grain size, the number of grain boundary nucleation site increases and bainite is obtained in preference to acicular ferrite (Figure 1), thought to be bainite intergranularly nucleated at inclusions.

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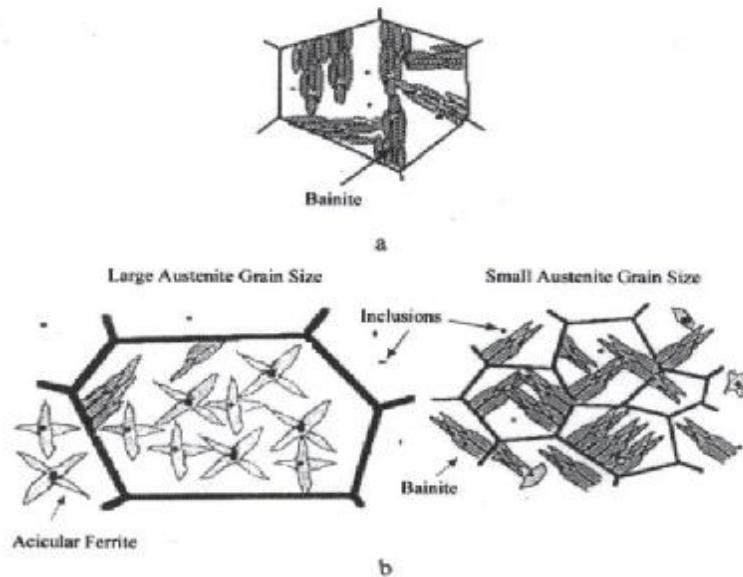


Fig. 1. : a) Schematic illustration of the growing bainite from the grain boundaries of prior austenite, b) the influence of austenite grain size in determining whether the microstructure is predominately acicular ferrite or bainite¹⁶⁾.

Table 1. Composition of irons, wt. %.

Alloy	C	Al	Si	Ni	Mn	P	S	Mg	Fe
0.08%Al	3.71	0.08	1.08	0.03	0.09	<0.005	<0.005	0.05	balance
0.48%Al	3.68	0.48	1.06	0.04	0.06	<0.005	<0.005	0.05	"
1.71%Al	3.58	1.71	1.18	0.04	0.07	<0.005	<0.005	0.05	"
2.11%Al	3.55	2.11	1.21	0.04	0.11	<0.005	<0.005	0.06	"
3.10%Al	3.48	3.10	1.24	0.05	0.10	<0.005	<0.005	0.06	"
4.88%Al	3.44	4.88	1.22	0.05	0.10	<0.005	<0.005	0.05	"

Boutorabi et al.,¹⁷⁾ have shown that in a SG Al cast iron with 2.35% Al, the austenitising and austempering temperature and time influence the morphology, distribution, volume and size of the microscopic phases. Boutorabi et al.,¹⁸⁾ have reported that austempering temperature determines the morphology of the bainite and the volume of retained austenite and that changes in the austenitising temperature and austempering time have a smaller effect.

The present work is designed to study the effect of aluminium and heat treatment on the microstructure, especially on the bainite reaction.

Experimental

Experimental ductile irons with the composition range given in Table 1 were produced in a Morgan gas - fired furnace (with 25 kg capacity lift - out crucible) and a high frequency melting

furnace of 20 kg capacity (with a tilting crucible). After melting, the iron was superheated at 1550°C and small pieces of solid aluminium were added by plunging into the bottom of the liquid metal. Twenty minutes was given to dissolve the aluminium completely in the molten metal. Following aluminium treatment, 1.2% FeSiMg(5%Mg) alloy was plunged into the liquid iron at 1400°C and ejection of molten metal during solution of magnesium was prevented by use of special enclosed reaction vessels. Finally, post-inoculation with 0.6 wt% of ferro-silicon containing 75%Si was carried out in the crucible. In the casting of ductile irons, late addition of inoculants into the melt is much more effective and can be achieved by an in mould technique. As shown in Figure 2 a reaction chamber which holds the granulated inoculant in the running system was required to ensure a uniform flow of inoculant over the whole of the casting. The melts were cast with a pouring temperature of

approximately 1350°C by both green sand moulding and gravity die casting. Standard 12.5 mm and 25 mm Y-block sand moulds and permanent moulds were used as illustrated in Figure 3 bottom gating introduced the metal smoothly into the mould cavity to ensure a sound casting. Quantitative measurements of the carbon content in the experimental irons were made using equipment at Swinden Technology Centre of Corus Group PLC (formerly British Steel Ltd.). Analyses were performed by an infrared absorption method after combustion in an induction furnace and oxidation to CO₂. In order to determine the amount of aluminium in high-Al content ductile irons, an atomic absorption spectrophotometry (AAS) method was used by Hi-Search Technology (HIST) of Birmingham University.

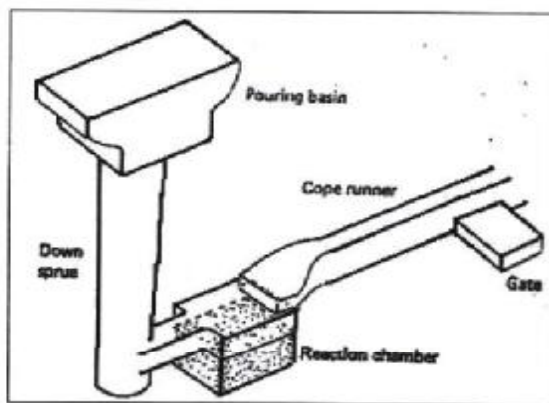


Fig. 2. An in-mold spheroidizing gating arrangement for spheroidal irons¹⁾.

The compositions selected resulted in more than 90% nodularity of graphite. Optical microscopy, and scanning and transmission electron microscopy were used to show the microstructure of the spheroidal graphite (spherulite)²⁰⁾.

For scanning electron microscopy, a Cambridge Series 3 SEM fitted with a Link 860 Series 1 EDX system and a Cambridge Series 4 SEM were used. For the characterisation of microstructure, a working distance between 20 -24 mm was chosen,

and an accelerating voltage of 20 kv and spot size between 4-6 nm were chosen.

Identification of the structure and the phases present in the experimental specimens was determined with series of LM and SEM images. In determining the volume fraction for graphite, point counting was carried out on polished and unetched samples. Volume fraction of ferrite and pearlite in the matrix was measured by the same technique on polished and etched samples.

Results

The microstructural characteristics of the experimental ductile irons are tabulated in Table 2. The structure of nodular cast irons essentially consists of nodular graphite (spherulites) in a ferritic, ferritic-pearlitic or pearlitic matrix with possibly some additional carbides also present. The products of the transformation depend on the composition and cooling rate. The presence of graphitising elements such as Si and Al tends to promote the formation of graphite^{19, 20)}.

The as - cast microstructures that are shown in Figure 4 consist of graphite nodules in a ferrite-pearlite matrix. The amount of free ferrite close to the graphite as can be seen in this Figure changes for different aluminum contents.

The microstructure of ductile irons with 0.48%Al and 4.88%Al have been investigated after austempering at 350°C for 1 min following austenitising at 920°C for 90 min.

Optical microscopy shows that the microstructure consists of bainitic ferrite and martensite (untransformed austenite) (Figure 5). The bainitic reaction is incomplete and untransformed austenite has decomposed to martensite on water quenching. These phases can also be seen in Figure 6 which shows SEM micrographs after the same heat treatment.

The amount of bainitic ferrite obtained by isothermal transformation at 350°C for various times was also examined. It seems that transformation at lower times gives more bainitic ferrite formation for higher Al contents (Figure 5 and 6). This corresponds with a study performed by Boutorabi²¹⁾.

Table 2. Structure and phases for Al - alloyed iron cast in different moulds.

Alloy	Structure on sand mould casting			Structure on permanent mould casting		
	Graphite, %	Ferrite, %	Pearlite, %	Graphite, %	Ferrite, %	Pearlite, %
0.08% Al	13.8	76.4	9.8	13.1	47.1	39.8
0.48% Al	13.9	75.8	10.3	13.0	45.3	41.7
1.71% Al	12.1	24.7	63.2	10.7	21.6	67.7
2.11% Al	11.8	23.7	64.5	9.9	18.8	71.3
3.10% Al	9.8	21.2	69.0	7.8	13.7	78.5
4.88% Al	9.9	10.5	79.6	7.6	8.4	84.0

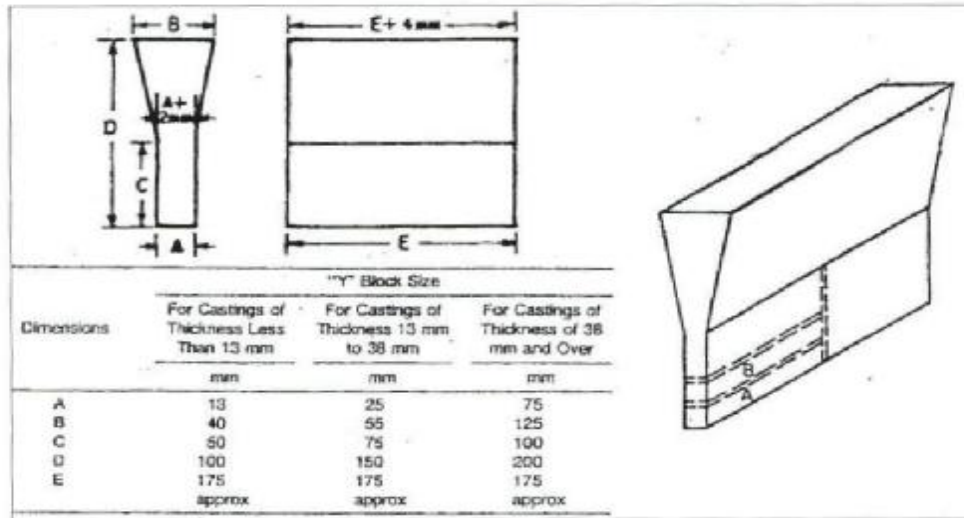


Fig. 3. Standard 12.5 mm and 25 mm Y-blocks for test coupons.

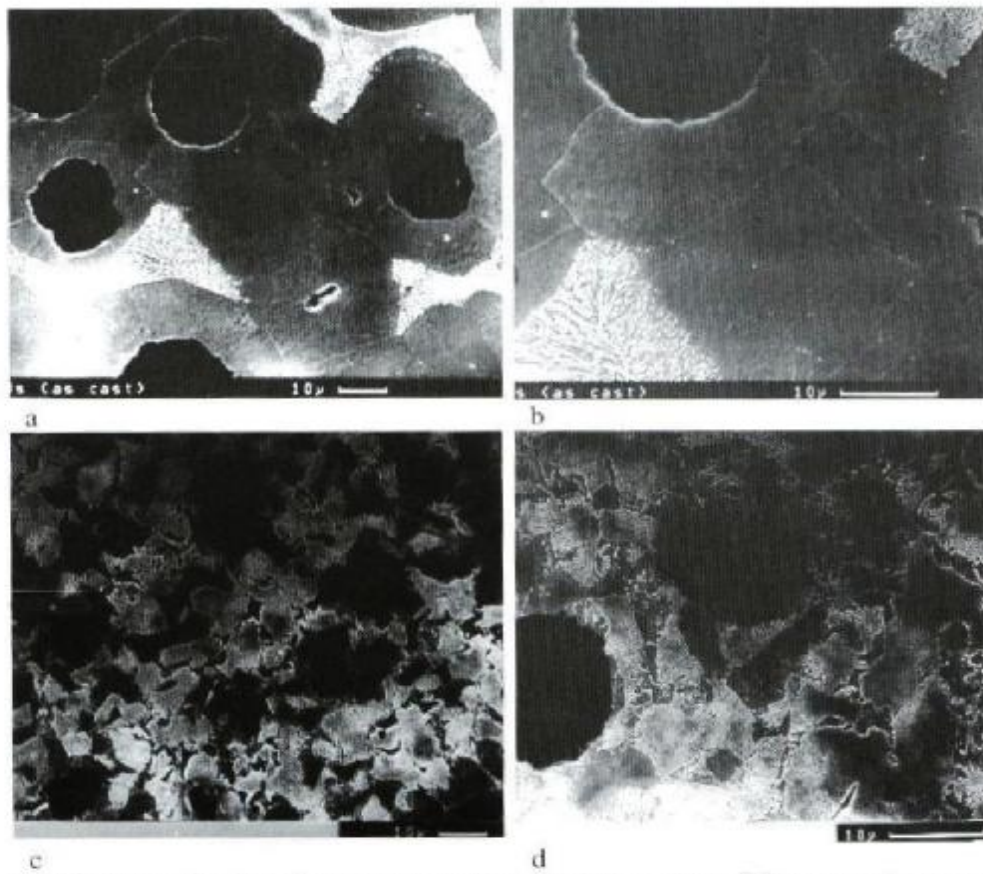


Fig. 4. SEM micrographs of initial microstructure of two ductile irons at two different magnifications. Graphite, ferrite and pearlite are present in the structure (etched 2% nital); a and b, 0.48% Al and c and d, 4.88% Al.

Discussion

The structure and properties of as-cast irons are dependent on numerous factors, one of the most important being composition which must be controlled during melting. Also, the form and distribution of graphite are associated with the composition^{1,5}. In producing the experimental ductile cast irons, careful control was necessary to achieve graphitisation and to keep the variation of elements within the required range. It is well known that deviation from a spheroidal graphite shape leads to a serious reduction in the properties of irons, such as tensile strength and impact resistance^{12,19}.

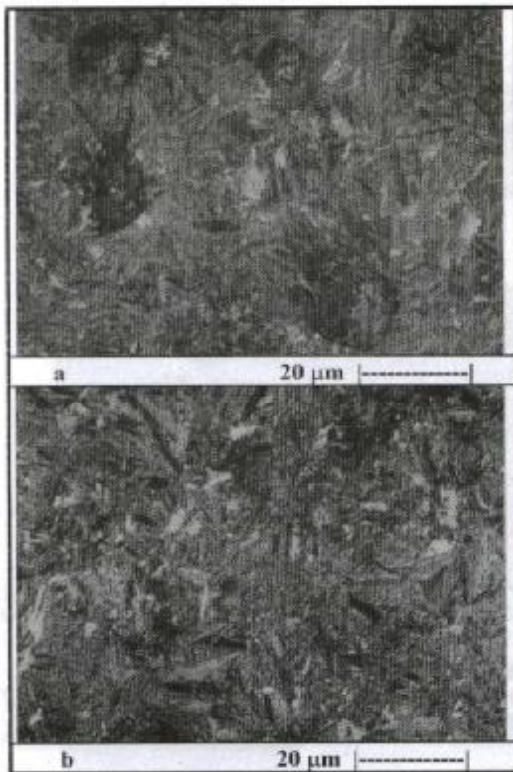


Fig. 5. Optical micrographs of Al-alloyed ductile irons austenitised at 920°C for 90 min and austempered at 350°C for 1 min; a) 0.48%Al, b) 4.88%Al.

The influence of composition and cooling rates on the structure and properties of as-cast experimental ductile iron with different aluminium contents has been shown in Table 2. It shows an increase in the pearlite fraction, with an increase in aluminum content. This was accompanied by a reduction in the graphite nodules and a lower ferrite content. In addition, the higher cooling rate induced by casting in a permanent mould compared with a sand mould, probably due to the increased

undercooling, also gave a similar result. The structures and phases for Al-alloyed iron with different mould casting are given in Table 2.

It has been found that as the amount of aluminium decreased a bull's-eye structure forms. In agreement with the present study, Watson¹² reported a pearlite-type matrix in Al-alloyed gray iron with a range between 2 to 5 wt.% Al, but this is contrary to reports in another study by Smickley and Rundman¹³. They believed that the free ferrite content in the structure of gray cast iron shows an increase with additions of 0.6%, 1.02% and 1.5% aluminium.

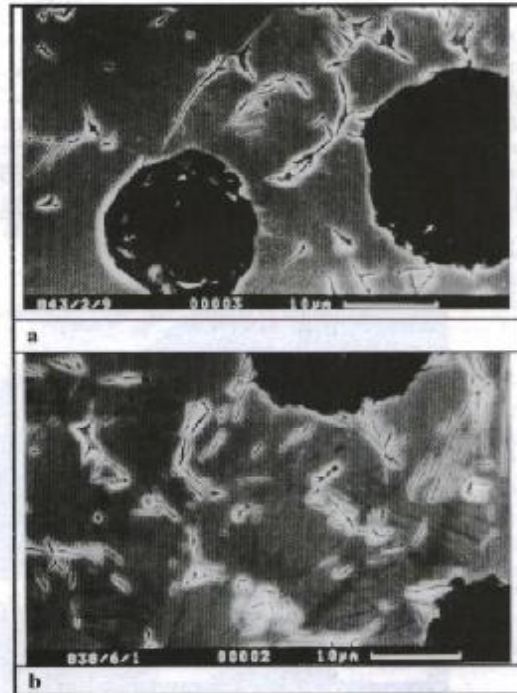


Fig. 6. SEM micrographs of Al-alloyed ductile irons austenitised at 920°C for 90 min and austempered at 350°C for 1 min; a) 0.48%Al, b) 4.88%Al.

Ductile irons containing 0.48% and 4.88%Al were austenitised at 920°C for 90 min and then isothermally heated at 350°C. The influence of Al content upon the structural stability of the austempered ductile irons was investigated. The optical microscopy and SEM illustrate the bainitic ferrite transformation which commences at austenite boundaries and especially at austenite grain corners (Figure 7 and 8). These results are in agreement with previous studies^{22, 23}. It was suggested that the nucleation rate was related to the prior austenite grain size, due to the larger number of nucleation sites in boundaries for finer grain size structures.

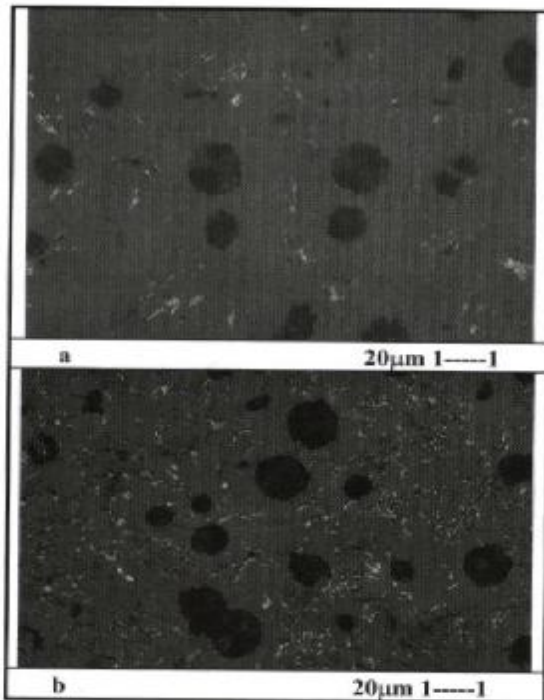


Fig. 7. Optical micrographs taken from the ductile irons austenitised at 920°C for 90 min followed by austempering at 350°C for 1 min for different Al content; a) 0.48%Al, b) 4.88%Al. These micrographs show that the formation of bainitic laths commences preferentially at grain boundaries.

It was also suggested that the mechanism of bainite formation from prior austenite commences from the grain boundaries. The association of grain boundaries with nucleation and growth of bainitic ferrite is indicated by a number of studies^{10,14,16}. Bhadeshia¹⁶ explained that a decrease in grain size of austenite accelerates the rate of bainite reaction, due to the increase of suitable sites for nucleation per unit volume of matrix. It was first reported by Barford and Owen²⁴, and discussed for different steels, that the bainitic hardenability increases as a result of a reduction in austenite grain size¹⁶.

The increased Al content is another factor promoting the more rapid bainitic transformation. The addition of aluminium acts as a grain refiner and this could influence the total amount of bainitic ferrite, due to the associated increase in austenite grain boundary area. However, in contrast, it has also been argued that the limited solid solution of alloying elements in iron causes solute segregation of atoms in front of the moving interface, creating a drag effect on the transformation²⁵. Thus, it is believed that for a higher concentration of Al in the alloy, the rate of bainitic growth is slowed down and transformation occurs at lower temperatures.

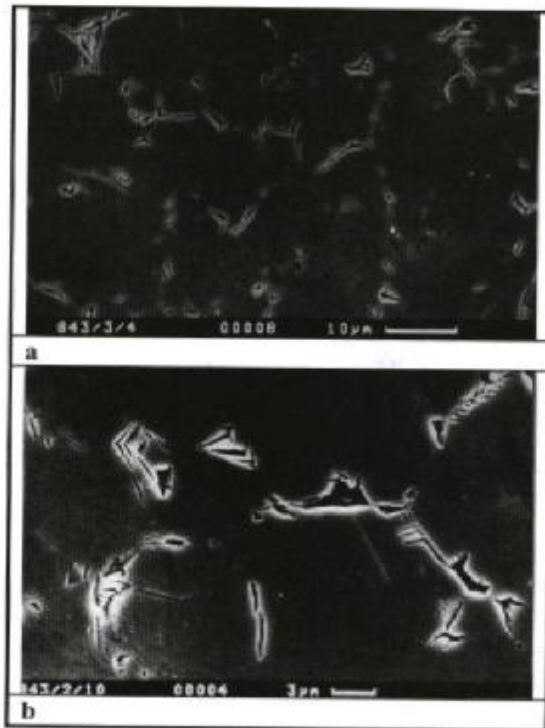


Fig. 8. SEM micrographs taken from a 3.10%Al ductile iron austenitised at 920°C for 90 min followed by austempering at 350°C for 1 min in two different magnifications which show the formation of bainitic laths which commences preferentially at grain boundaries

Conclusion

1) Examination of the as-cast Al-alloyed ductile irons revealed that the microstructure normally consists of nodular graphite in a ferritic-pearlitic matrix, and the aluminium addition decreased the extent of bulls-eye structure to give a higher volume fraction of pearlite in the matrix.

2) The following results were obtained from the isothermal bainitic transformation after austenitising at 920°C for 90 min and austempering at 350 °C for different holding times which were found to be consistent with heat treatments used in previous studies:

2.1) Generally, the microstructures show typical austempered bainitic microstructures for different Al contents consisting of alternative laths of bainitic ferrite and high carbon retained austenite .

2.2) There was some evidence that the preferred sites for bainitic transformation are grain boundaries and the best sites for nucleation are grain corners.

2.3) The volume fraction of bainitic ferrite increases as the Al content increases.

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