REVIEW ON PRODUCTION PROCESSES AND MECHANICAL PROPERTIES OF DUAL PHASE AUSTEMPERED DUCTILE IRON

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Abstract

During the last few years, researchers have sought new ductile iron (DI) applications focusing on the development of mixed microstructures, such as ferritic-bainitic or ferritic-martensitic. These kinds of structures result in DI with a good combination of mechanical properties, compared to other conventional DI. The combination of properties offered by the mixed structure DI, particularly in "dual phase austempered ductile iron" (ADI) has opened new horizons for cast iron to replace steel castings and forgings in many engineering applications. This new DI has a particular microstructure composed of different amounts and morphologies of ausferrite and free ferrite.

Dual phase ADI microstructures have afforded more opportunities for DI applications, acquiring better combinations of strength, ductility and toughness. This review describes the methodologies used to obtain this new kind of DI and the principal mechanical properties.

Keywords: *ductile iron, dual phase ADI, microstructure, thermal cycles, mechanical properties*

Introduction

The engineering community is constantly pushed towards lighter, stronger and stiffer metallic parts, which is why the worldwide production of ductile iron (DI) has increased during the last few decades. Ductile iron's advantage is that parts can be obtained by casting technologies, making it possible to produce high resistant parts of complex shape at relatively low cost. For this reason, DI has been successfully used to replace cast and forged steels in many applications.[1]

If the graphite phase is adequate, the mechanical properties of cast DI parts depend largely on the matrix microstructure (type, amount and distribution of microconstituents). On the other hand most casting defects (inclusions, micro-shrinkage, and carbides) are present mainly in the last-to-freeze regions. The final microstructure of DI can be conveniently modified by using a wide range of heat treatments, such as ferritizing, normalizing, quenching and tempering and austempering, to obtain ferritic, pearlitic, martensitic and ausferritic matrices.[2,3] Recently, researchers and producers have left no stone unturned in their search for new DI applications, focusing on the development of DI with mixed microstructure: ferritic-bainitic or ferritic-martensitic. These kinds of microstructures make DI a good combination of mechanical properties and physical characteristics, proving advantageous over other conventional DI.[4-8]

Ductile iron researchers are currently working to enhance DI properties, searching for new applications in the critical parts market where high strength, elongation until failure and toughness are pressing requirements. In this regard, a new type of DI, called "dual phase austempered ductile iron" (ADI) or "dual matrix ductile iron" has become an active field of research and development. The dual phase ADI matrix is composed of different amounts and morphologies of ausferrite (regular ADI microstructure) and free (or allotriomorphic) ferrite, which are obtained by subjecting DI to special heat treatments.

The technological interest awoken by this new approach has motivated the execution of several studies to determine the production process and mechanical properties of dual phase ADI. This article summarizes some of the extensive efforts made over the last few years in this respect.

Methodologies to Obtain Dual Phase ADI

Intercritical Interval

To understand the different methodologies used to obtain dual phase ADI, it is necessary to review some concepts regarding the "intercritical interval". Figure 1-a shows a sketch of pseudo binary diagrams (which are cuts from the F-C-Si ternary diagram) where the phases in thermodynamic equilibrium of free graphite cast irons are represented.[9] At temperatures close to the eutectoid, Figure 1-a depicts a region where ferrite, graphite and austenite coexist. This region is called intercritical interval, and it is delimited by the upper and lower critical temperatures. Such temperatures define the starting point at which ferrite transforms into austenite and austenite into ferrite in heating and cooling processes. The position and amplitude of the interval is modified mainly by the alloy chemical composition and the solidification cooling rate. For instance, the presence of Si in DI diminishes the solubility of C in austenite, thereby promoting ferrite formation; this phenomenon leads to an increment of both critical temperatures, as qualitatively illustrated in Figure 1-b.[10] Other elements also generate further modifications over the intercritical interval: Mn leads to a decrease in the intercritical temperature range, while Cr reduces its amplitude increasing mainly the lower critical temperature.[11] The literature reports equations designed to calculate the upper critical temperature, taking into account the influence of some common alloying elements[9,10,12]. However, no equations estimating the lower critical temperature have been reported so far.

Thermal Cycles

Special thermal cycles have been developed in order to obtain dual phase ADI. The first paper concerning this subject matter was written by Aranzabal et al.[13] The authors obtained different variants of dual phase ADI by modifying the silicon level of the melt and heat treating ferritic DI at fixed austenitizing temperatures. During the austenitizing stage different amounts of austenite nucleate and grow as a function of the position (temperature) inside the intercritical interval of the melts, which vary according to the different silicon contents. The austenitizing stage is followed by an austempering step in order to produce the austenite to ausferrite reaction, thus obtaining a final microstructure composed of free (allotriomorphic) ferrite and ausferrite.

On the other hand, Wade et al.[14] and Verdu et al.[15] obtained dual phase ADI microstructures by means of heat treatments based on quick and incomplete austenitizations in the austenitic field (over the upper critical temperature). The austenite, nucleated at high temperature, mainly surrounds graphite nodules and then is transformed into ausferrite as a result of an austempering step. The relationship between the relative quantities of each phase is controlled by the austenitizing time; the longer the time, the higher the amount of austenite and, therefore, the larger the amount of ausferrite in the final microstructure.

Basso et al.[16, 17] and Kilicli et al.[18] utilized an alternative methodology to obtain dual phase ADI. It consists of subjecting a fully ferritic DI (with a fixed chemical composition) at an incomplete austenitization stage at different temperatures within the intercritical interval followed by an austempering step to transform austenite into ausferrite. This heat treatment results in microstructures made up of different percentages of ausferrite and allotriomorphic ferrite (original matrix of the samples), depending on the austenitizing temperature. The amount of ferrite increases when the austenitization step is closer to the lower critical temperature. On the other hand, when using austenitizing temperatures close to the upper critical temperature, the amount of allotriomorphic ferrite diminishes and it is present as a dispersed microconstituent in an ausferritic matrix. Figure 2 shows these kinds of microstructures obtained for different samples of the same melt austenitized at different temperatures within the intercritical interval and then austempered at 662F (350C).

Druschitz et al.[19,20] and Valdés et al.[21] employed the same heat treatment as Basso et al. and Kilicli et al. did to obtain dual phase ADI microstructures. However they started from ferritic–pearlitic as-cast microstructures, avoiding the ferritizing stage. Obtaining dual phase ADI microstructures by means of the methodology applied by Basso et al. and Kilicli et al. is considered to offer an important advantage over the methodologies proposed in the other two studies mentioned. Microstructures with well controlled phase percentages are obtained. In this case, the amount of austenite during the partially austenitizing step is as indicated by the phase diagram in thermodynamic equilibrium. It has

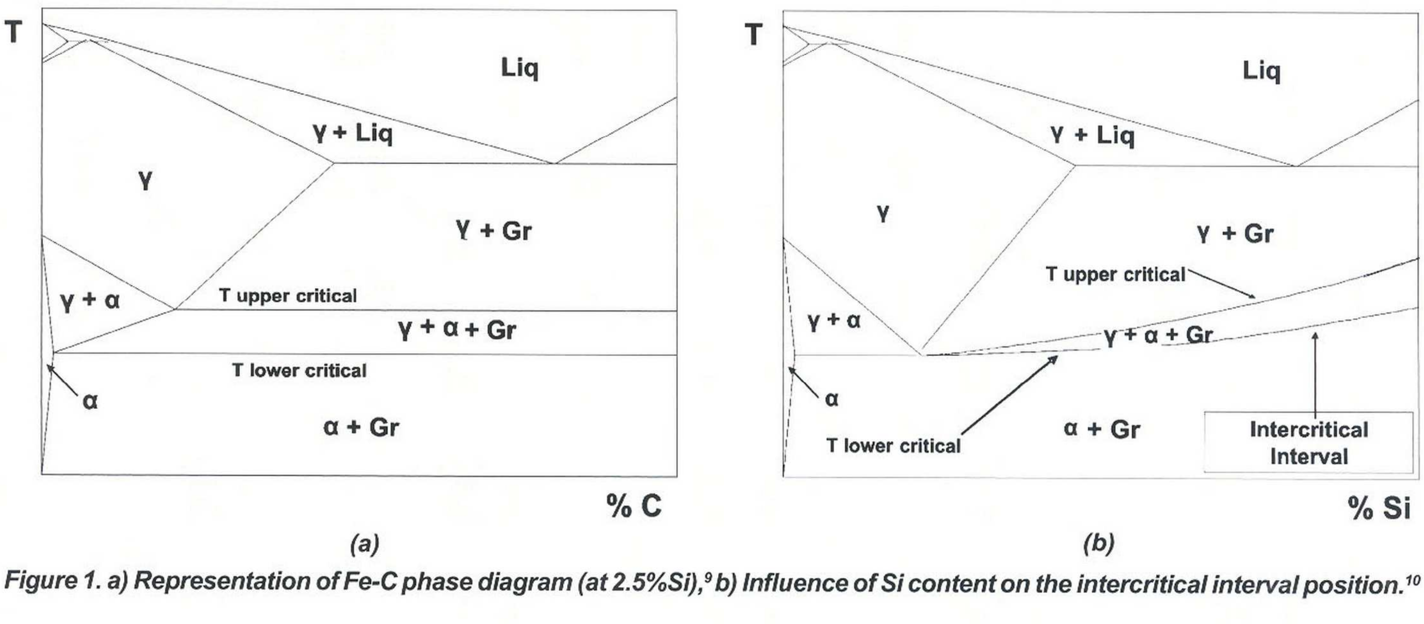

Figure 1. a) Representation of Fe-C phase diagram (at 2.5%Si),[9] b) Influence of Si content on the intercritical interval position.[10]

been extensively proven that the kinetic transformation of ferrite into austenite occurs very quickly-45 minutes is enough to reach the equilibrium. Then, it is possible to obtain accurate percentages of phases in the microstructure as a function of the intercritical austenitizing temperature. Indeed this is of special relevance when industrial production is considered, as it does not depend on time (austenitizing time in this case).

Mechanical Properties of Dual Phase ADI

Tensile Properties

Due to the technological interest in the new kind of DI, several studies have been conducted to determine its mechanical response, centering mainly on evaluating tensile properties. A review of the main mechanical properties (tensile strength, yield stress, elongation until failure and hardness) obtained by the authors cited above for dual phase ADI are particularized in Table 1. The mechanical properties correspond to dual phase ADI structures obtained from heat treatments such as those particularized above, starting from fully ferritic matrices (except those reported by Druschitz et al. [19, 20] and Valdés et al.[21] who employed ferritic-pearlitic as-cast matrices). In all cases, the chemical composition of the DI melts were in the following range: C: 3.2-3.6%; Si: 2.3-3.0%; Mn: 0.1-0.5%; Mg: 0.03-0.05%; Cu: < 1%; Ni: <1%.

The results reveal that dual phase ADI can offer a wide range of mechanical properties depending on the relative percentage of microconstituents present in the matrix (Table 1). Aranzabal et al.[13] developed dual phase ADI for use in the production of suspension automotive parts and reported remarkable improvements in mechanical properties. The reported results revealed that the yield stress, tensile strength and hardness values were similar to those of fully pearlitic DI, while ductility kept the same level of ferritic DI. Wade et al.[14] and Verdu et al.[15] studied the mechanical properties of dual phase ADI microstructures austempered at 707F (375C), with ferrite as the majority phase and encapsulating graphite nodules with ausferrite. These authors focused on improving the mechanical properties of ferritic DI, by surrounding graphite nodules (which can be considered a phase with no resistance) with a high resistant second phase (in this case, ausferrite). They found that yield stress, tensile strength and hardness increased when the ausferrite volume fraction did so in the microstructure. In particular, the presence of 20% ausferrite in the microstructure achieved increments in tensile strength and yielding stress of about 30 percent, compared to fully ferritic DI. Kilicli et al.[18] and Sahin et al.[22] explored the mechanical properties of dual phase ADI on a wide range of microstructures composed of different ausferrite volume fractions and morphologies austempered at 689F (365C). These microstructures showed, once again, that the yield stress and tensile strength increased when the quantity of ausferrite was

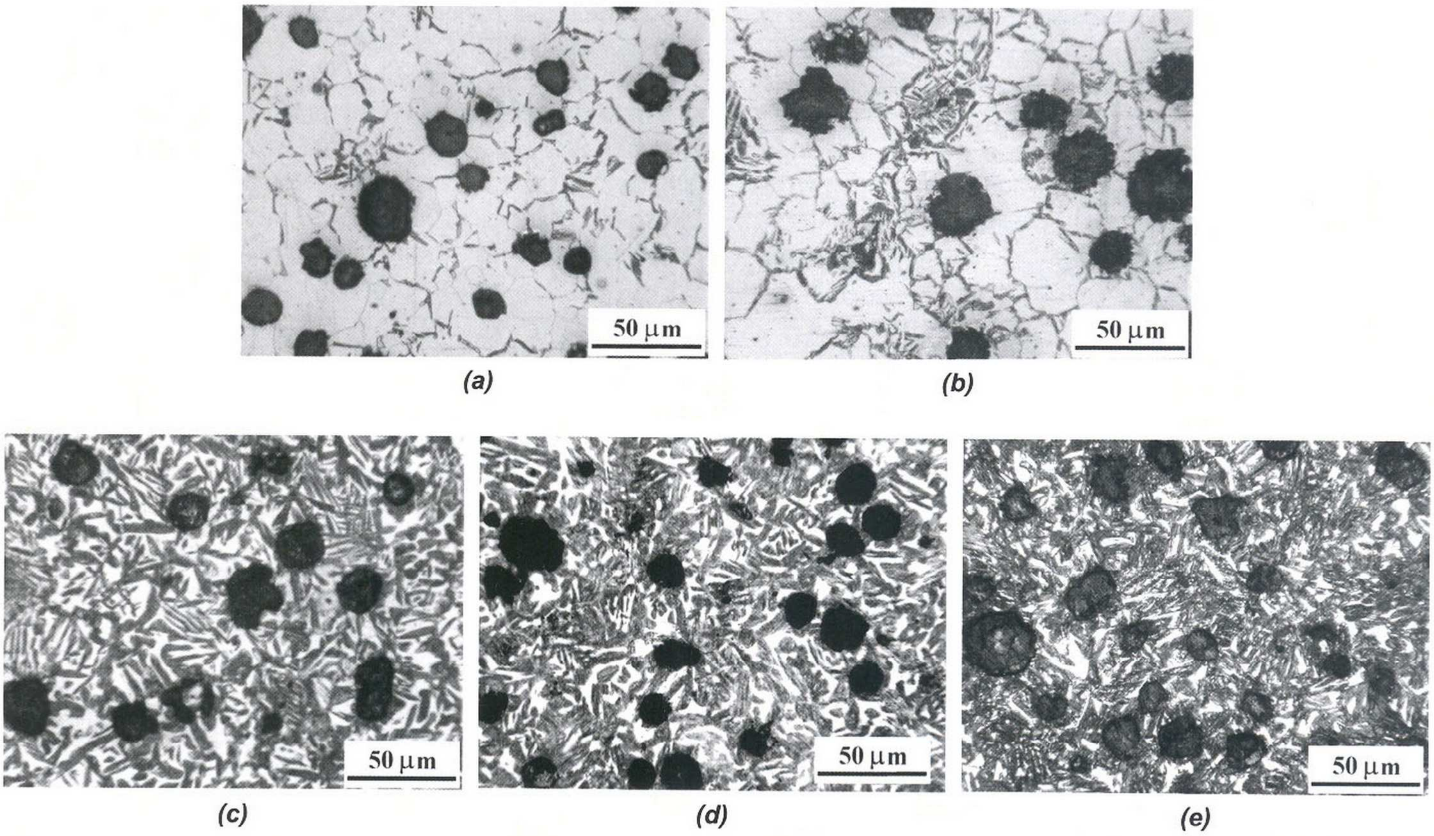

Figure 2. Microstructures obtained for samples partially austenitized at different temperatures within the intercritical interval and then austempered at 662F (350C). a: 92% Ferrite-8% Ausferrite; b: 80% Ferrite-20% Ausferrite, c: 50% Ferrite-50% Ausferrite, d: 35% Ferrite-65% Ausferrite, e: 15% Ferrite-85% Ausferrite. (The graphite areas were not considered in the percentage of the reported microconstituents.)

incremented and exhibited higher ductility than the fully ausferritic ones. In particular, samples with 45% ausferrite and 65% ferrite yielded the best combinations of strength and ductility[18] (see Table 1). Druschitz et al. [19] reported that dual phase ADI ("called machinable austempered cast iron or MADI") improved strength and ductility when compared to conventional DI. The improved strength and ductility is attributable to the microstructure composed of a continuous matrix of equiaxed ferrite with islands of ausferrite.

Valdés et al.[21] evaluated the microstructural changes and mechanical properties exhibited by DI when it was heat treated in the intercritical interval at different temperatures and then austempered at 707F (375C). The authors indicated that tensile strength and yield strength increased when the amount of ausferrite was increased, while elongation and toughness exhibited the best values when the intercritical heating was carried out between 1427-1526F (800-830C).

The authors of this paper have also addressed this topic, analyzing the effect the amount and morphologies of phases, austempering temperature and cast part size have on the final microstructure and its properties.[16,17] As expected, as the amount of ausferrite increased, tensile strength and yield stress also increased, while elongation diminished for all the austempering temperatures analyzed. The best combinations of strength and elongation were found in dual phase ADI microstructures austempered at 662F (350C). For example, the microstructure composed of 35% ferrite-65% ausferrite combines a tensile strength of 730 MPa

Table 1. Mechanical Properties of Dual Phase ADI Obtained by Different Authors

Author	Austenitizing temperature, time	Austempering temperature, time	Ausferrite volume fraction	Ferrite volume fraction	σ_{max} [MPa]	$\sigma_{0.2}$ [MPa]	δ [%]	Hardness [Brinell]
Aranzabal et al.	Not reported	Not reported	≈20	≈80	654	539	14	212
Aranzabal et al.	Not reported	Not reported	≈50	≈50	728	565	16	241
Verdu et al.	1472°F (800°C), 120 min.	698°F (370°C), 60 min.	≈15	≈85	517	365	20	≈192
Verdu et al.	1742°F (950°C), 90 sec.	698°F (370°C), 60 min.	≈20	≈80	660	480	17	≈207
Kilicli et al.	1500°F (815°C), 20 min.	689°F, (365°C), 180 min.	≈25	≈75	530	370	23	≈228
Kilicli et al.	1526°F, (830°C), 20 min.	689°F (365°C), 180 min.	≈30	≈70	685	518	15	≈267
Sahin et al.	1463°F (795°C), 60 min.	689°F, (365°C), 120 min.	≈30	≈70	440	306	28	≈180
Sahin et al.	1500°F (815°C), 60 min.	689°F, (365°C), 120 min.	≈70	≈30	529	370	19	≈228
Druschitz et al	1460°F, (793°C), 60 min.	575°F, (300°C), 90 min.	Not reported	Not reported	789	497	20	241
Druschitz et al	1500°F (815°C), 60 min.	575°F, (300°C), 90 min.	Not reported	Not reported	894	579	17	272
Valdés et al.	1472°F,(800°C), 90 min.	707°F (375°C), 60 min.	≈85	≈15	≈900	≈600	≈7	Not reported
Valdés et al.	1526°F, (830°C), 90 min.	707°F (375°C), 60 min.	≈90	≈10	≈970	≈700	≈5	Not reported
Basso et al.	1436°F, (780°C), 60 min.	662°F, (350°C), 90 min.	≈20	≈80	550	380	24	186
Basso et al.	1508°F, (820°C), 60 min.	662°F,(350°C), 90 min.	≈60	≈40	690	550	22	215
Basso et al.	1544°F, (840°C), 60 min.	662°F (350°C), 90 min.	≈80	≈20	800	620	20	250
Basso et al.	1562°F, (850°C), 60 min.	662°F,(350°C), 90 min.	≈95	≈5	1150	950	16	325

**** The graphite areas were not considered in the percentage of the reported microconstituents.***

with an elongation of about 18%.[16] Regarding the influence of the section size on mechanical properties, tensile strength and elongation until failure decrease as the cast part size increases, while the yield stress remains unchanged. Elongation until failure was also affected by the cast part size.[17] Tadayon et al.[23] studied the mechanical properties of dual phase ADI microstructures austempered at different temperatures, ranging from 662F (350C) to 743F (395C). The authors reported that suitable tensile properties could be achieved by austenitizing at 1562F (850C) and austempering at 743F (395C).

After reviewing the papers referenced above, it can be concluded that dual phase ADI can combine interesting mechanical properties, especially good tensile strength/elongation until failure relationships, when compared to other conventional DI matrices. This behavior has been described in a previous work by the authors[24] and is summarized in Figure 3, where the dual phase ADI region is added to a tensile strength/elongation until failure graph for the different DI types. Several points obtained by Basso et al.[16, 17] showing the effect of austempering temperatures also are included.

Impact and Fracture Toughness Properties

So far, few results have been reported in the bibliography about impact and fracture toughness properties of dual phase ADI. Basso et al.[16] studied the impact energy absorbed in unnotched Charpy tests for dual phase ADI with different amounts of ferrite and ausferrite in the microstructure, austempered at 662F (350C). The results did not reveal noticeable variations for the dual phase ADIs studied, showing that impact energy values, in all cases, lie within the range values reported in the literature for fully ferritic DI and ADI (i.e., between 115 and 145 J/cm^2).[25] Verdu et al.[15] also reported that impact strength remains unchanged, or is even slightly higher when compared to fully ferritic DI. Moreover, he stated that new microstructures do not embrittle the material.

Valdés et al.[21] reported a similar tendency in the impact properties of dual phase ADI. The best results of impact strength were found when the ductile irons were heat treated in the intercritical region between 1427 - 1526F (800 – 830C) and austempered at 707F (375C). Impact strengths of 130 - 145 J and 100 - 140 J were obtained for unalloyed and alloyed ductile iron, respectively.

The fracture toughness properties of this new type of DI have been characterized by Basso et al.[16] who reported K_{IC} values for different dual phase ADI matrices. These values were compared to fully ferritic DI and ADI austempered at the same temperature, which were used as reference values. Figure 4 summarizes these values. The authors reported that the fracture toughness (K_{IC}) for different variants of dual phase ADI increases with the ausferrite content in the microstructure. The curve begins with the lower K_{IC} values corresponding to fully ferritic samples, which is in agreement with the data accounted for in the literature.[25] An increase in the amount of ausferrite in the matrix promotes higher values of K_{IC}, up to the value found for the fully ausferritic matrix. It is worth pointing out that a peak value corresponding to samples with mainly ausferritic matrices and ferrite acting as second disperse phase was found.[16] This result improved the ADI K_{IC} values by approximately 14% and was considered promising since this kind of dual phase ADI combines high strength and elongation values (typical for ADI) with enhanced fracture toughness properties. On the other hand, the authors also reported the relationship $(K_{IC}/\sigma_{YS})^2$, which is a fractomechanical parameter proportional to the critical crack size (see Figure 4). This index proves to be useful when measuring the relative toughness of the material, given the fact that it is desirable that a part in service tolerates large flaws without fracture. The relationship $(K_{IC}/\sigma_{YS})^2$ yielded its highest value for dual phase ADI matrices composed of allotriomorphic ferrite and small amounts of ausferrite (less than 25%). This was attributed to the encapsulating effect of the ausferrite located around the last-to-freeze zones. These areas have the highest concentrations of small casting defects, such as,

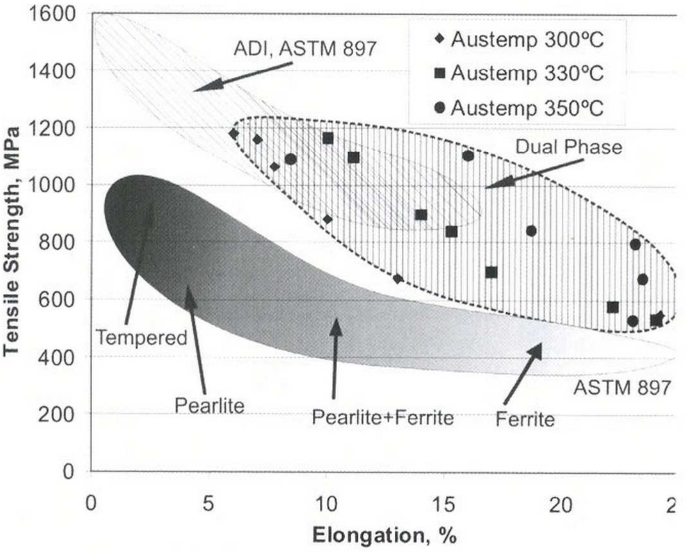

Figure 3. Tensile strength vs. elongation until failure for DI with different microstructures.[20]

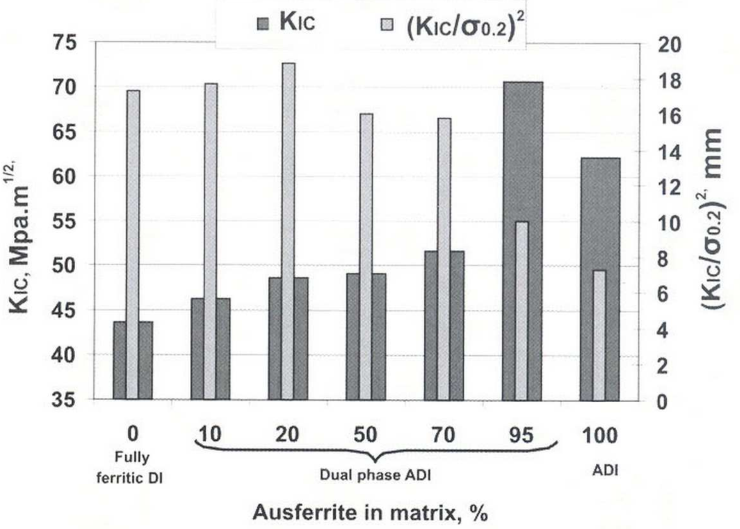

Figure 4. Review of K_{IC} and $(K_{IC}/\sigma_{YS})^2$ values for different kinds of dual phase ADI. Comparison with fully ferritic DI and ADI properties.

inclusions, porosity, carbides, etc. (see Figure 5). In this case, ausferrite acts as a reinforcing phase of the weakest zones, increasing fracture toughness.

Fatigue Properties

The first results about fatigue properties of dual phase ADI reported in the literature corresponded to Verdu et al.[15] As mentioned above, the authors centered on the development of thermal cycles, to obtain dual phase ADIs with graphite nodules surrounded by different amounts of ausferrite as a way to enhance mechanical and fatigue properties. The authors sought to favor the fatigue properties of ferritic DI by surrounding graphite nodules with ausferrite, a high resistant second phase, thus providing higher resistance to the crack initiation stage. They found that, microstructures composed of 80% ferrite and 20% ausferrite (austempered at 707F [375C]) yielded values as high as 25% in fatigue life compared to those of fully ferritic DI.[15]

Basso et al.[23] also worked in this area using four different dual phase ADI matrices austempered at 350C (662F), containing different percentages of ferrite and ausferrite. The authors reported the endurance limit as a function of the amount of ausferrite in the dual phase ADI matrix, and it was compared against fully ferritic DI and ADI values (see Figure 6). The fatigue tests revealed that an increase in the ausferrite percentage incremented the endurance limits compared to a fully ferritic matrix. A small amount of ausferrite (20% approximately) in the microstructure, in this case located mainly around last-to-freeze zones, improved the endurance limit around 25%. These results confirm the effectiveness of the ausferrite phase as a reinforcement of the ferritic matrix via the encapsulation of the brittle and weak last-to-freeze zones and are similar to the values accounted for by Verdu et al.[15] Higher amounts of ausferrite in the dual phase ADI microstructures increase the endurance limit, reaching values corresponding to ADI. Figure 6 summarizes the results of the fatigue tests. In the figure, values of endurance limits corresponding to fully ferritic DI and ADI reported in the bibliography [25-29] are added.

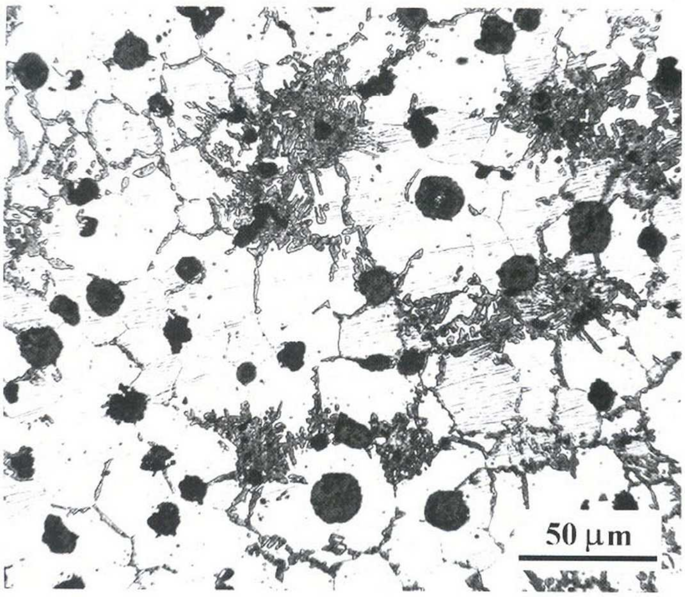

Figure 5. Last-to-freeze zones encapsulated with ausferrite.

Conclusions

A review of the main mechanical properties and methodologies employed to obtain dual phase ADI ductile irons is presented.

The microstructure of this new kind of ductile iron can be composed of different amounts and morphologies of free ferrite and ausferrite, depending on the parameters of the thermal cycle employed. Heat treatments involving a partial austenitizing stage within the intercritical interval followed by austempering led to the production of dual phase ADI structures with controlled amounts of microconstituents.

It was found that dual phase ADI can confer a wide range of mechanical properties based on the relative percentage of microconstituents present in the matrix. As a general rule, when the amount of ausferrite increases, tensile strength, yield stress and fracture toughness increase too, while elongation slightly diminishes.

The best combinations of mechanical properties for these new mixed structures were found when using high austempering temperatures, around 662F (350C). In particular, dual phase ADI microstructures containing approximately 20% of ausferrite in their microstructures have widely superseded the mechanical and fatigue properties of fully ferritic DI, at the same time, preserving a high ductility. This combination of properties is appreciated in safety parts.

Dual phase ADI offers a wide range of mechanical properties in view of the relative microconstituents percentage present in the matrix and could replace other conventional microstructures (fully ferritic, ferritic-pearlitic, pearlitic, or tempered martensitic) since dual phase ADI provides enhanced mechanical properties combinations.

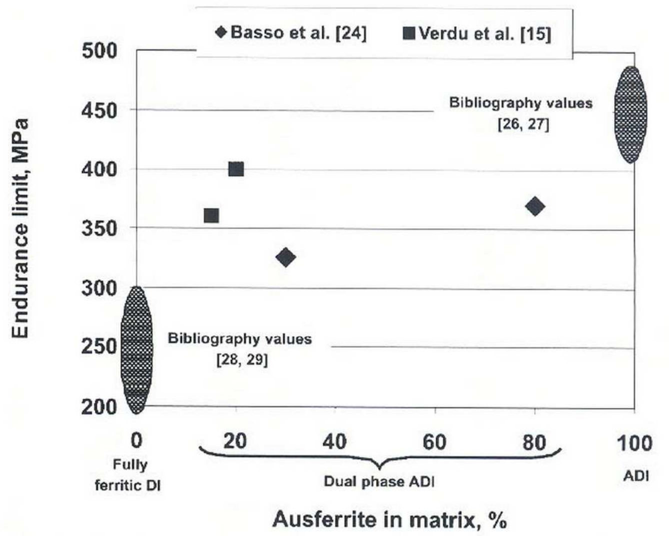

Figure 6. Endurance limit vs. % of ausferrite in matrix in dual phase ADI. Values corresponding to fully ferritic DI and ADI are added.

Acknowledgements

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Technical Review & Discussion

Review on Production Processes and Mechanical Properties of Dual Phase Austempered Ductile Iron

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Reviewer: Authors may want to review the following papers/patents from the US, Mexico, Spain, Italy, Iran and Egypt:

- H. Muhlberger, Spain Patent #ES8104423 (1981).
- F. Zanardi, "The Development of Machinable ADI in Italy," in the Proceedings of the 2002 World Conference on ADI, Louisville, KY (2002) pp. 69-72.

Authors: *These two works have been carefully read and considered a good contribution to the development of Austempered Ductile Iron (ADI). However, they have not been cited in our manuscript for not focusing on its main objective, i.e., the study of DI with mixed microstructures composed of ferrite and ausferrite. The other references cited by the reviewer have been reviewed and incorporated as references to the new version of our manuscript.*