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Research Paper

THIN WALL AUSTEMPERED DUCTILE IRON: A BEST REPLACEABLE MATERIAL TO STEEL AND ALUMINUM

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In this paper the analysis of thin walled castings made of ductile iron is considered. It is shown that thin wall austempered ductile iron can be obtained by means of short-term heat treatment of thin wall castings without addition of alloying elements. Production of Thin Wall Austempered Ductile Iron (TWADI) components can have strength-to-density and elastic-to-density ratios that approach those of cast aluminum, making it theoretically possible to apply ADI in high strength light weight parts. Therefore, development of thin wall ADI technology is essential to permit designers for energy consuming equipment to choose the most appropriate material based on material properties, and not solely on weight or density. In the present work, ductile iron castings with different thicknesses were cast with an appreciate casting design to assure good mold filling. There are shown that thin wall ductile iron is an excellent base material for austempering heat treatments. Tensile strength and hardness increased with decreasing casting wall thickness due to the structure refinement effect and decreasing the volume fraction of retained structure in matrix. As a result high mechanical properties received in thin wall plates made of austempered ductile iron.

Keywords: Ductile iron, Thin wall austempered, Steel, Aluminium

INTRODUCTION

The production of Austempered Ductile Iron (ADI) has shown a sustained rate of growth since itsfirst commercial application in 1972. Currently, producers and designers continue to seek newapplications, making use of the excellent characteristics of this emerging engineering material thatcombines very high strength with good ductility, toughness, wear resistance and productionadvantages. A high number of successful applications in several fields, such as heavy truck,railroad,agricultural and automotive industries, as well as new research results are regularly reported inconferences and journals, reflecting the technologicaland academic interest in ADI.

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It is well known that a ductile iron part, which will be heat-treated in order to obtain a good qualityADI' component, must be free from casting defects and carbides, and have proper chemicalcomposition, modularity and nodule count.

Recent trends in the design of vehicle components have been focused in the production of thin-wall ductile iron castings in order to save materials and energy. In general, there has been an increasing demand for Thin Wall Ductile Iron castings (TWDI) with a wall thickness below 3 mm and with a high strength to weight ratios (Stefanescu *et al.*, 2002). Austempered Ductile Iron (ADI) possesses high wear resistance, strength and damping capacity when compared with forged steels or weldments.

The ADI market has been continuously growing with a rate estimated at 16% per year (Hayrynen and Brandenberg, 2003). There are numerous studies on ADI, particularly on (a) the kinetics of austempered of cast iron (Venugopolan, 1990; and Cisneros *et al.*, 1999), (b) microstructural characterization, (c), mechanical properties (Mallia and Grech, 1997; and Hayrynen and Keough, 2005). (d) fatigue (Zanardi, 2005), properties and machinability (Zanardi, 2005), as well as other applications (Olson *et al.*, 2002). While the parameters for a successful production of high quality ADI are well established, the same cannot be said of Thin Wall Austempered Ductile Iron castings (TWADI).

TWDI castings are characterized by an extremely large nodule count and hence with relatively small interparticle spacings, ^{a} which can be estimated from the Fullman equation (Fullman, 1953).

$$^{a} = (1 - f_{gr})/N_L$$

where N_L is the nodule count per unit of length and f_{gr}, is the volume fraction of graphite at room temperature.

In heavy section castings the interparticle spacing, ^{a} is relatively large. As a result, the segregation of alloying elements such as Si, Mn and Mo is difficult to avoid. Hence, the microstructure is highly inhomogeneous. In TWDI castings, the diffusional distance becomes significantly small so the segregation of alloying elements is minimal and the microstructure is highly homogeneous. Accordingly, TWDI castings can be considered as base and an ideal low cost material in producing of TWADI.

METALLURGY OF THIN WALL ADI PARTS

The metallurgy of ADI has been extensively studied, and the general procedures to obtain a goodquality material are relatively well known. Nevertheless, when parts to be austempered are thinwalled, some particularities may have to be accounted for. In order to evaluate the feasibility of using ADI for high strength thin wall parts, the role of the following factors needs to be discussed in advance:

- Chemical composition
- Molding and casting
- Solidification structure, micro segregation and carbides
- Solid state transformation kinetics, final microstructure and properties

Chemical Composition

The chemical composition of the ductile iron used to cast thin wall parts must be selected in order tosatisfy several requirements. Castability must be maximized in order to assure complete mold filling. To satisfy this requirement it is advisable to use hypereutectic alloys (carbon equivalent: 4.4-4.6%). Meanwhile, it is also advisable to limit the silicon content in order to avoid detrimental effects inthe ductility. Regarding other alloying elements, the austemperability required to produce thin wall ADI is minimal, therefore, the use of alloying elements is unnecessary. The conditioning of the meltmay also be specific to this application, in particular what relates to nodulaization and inoculation.

Molding and Casting

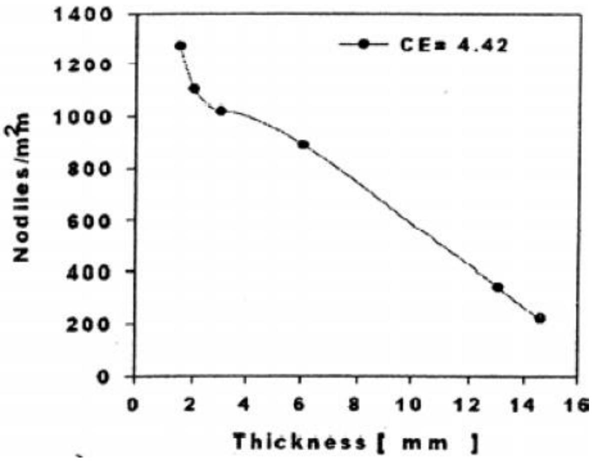
Proper design of the mold and casting procedure is critical when making thin wall ductile iron. Anyinternal or surface defect will have a strong detrimental effect in a high strength part. Dimensionaltolerances are also much more severe. This requires the use of high precision molding methods, andcareful design of the mold assembly, so as to guarantee proper positioning of cores. Careful study ofthe metal flow during filling is also recommended. Some studies have evaluated the use of countergravity casting procedures to improve flow during filling (Massone *et al.*, 2001). Different aspects must be taken intoaccount during the fabrication process of the parts such as: mold design, preheating of molds, use ofheaters, filters and the painting of the mold cavities to obtain good surface finish. Each type of part needs its specific analysis.

Solidification Structure, Micro Segregation and Carbides

It is well known that, as a result of the increased solidification rate imposed on the ductile iron whencast in thin walled parts, the nodule count rises noticeably (Dav Sahoo and Javaid, 2000). Figure 1 shows the variation in nodulecount for different thickness of the same melt, cast in the metal casting laboratory of OMI (Achour *et al.*, 2000). A 3 mm thickness part can show nodule counts up to 1000 nodules per square millimeter, as compared to the100-200 nodules per square millimeter usually found in conventional parts of about 25 mm thickness.

The solidification structure is other feature that may be significantly different in thin wall ductile iron. In fact, recent studies showed that the Last To Freeze (LTF) melt locates at intra-dendritic liquid pools (Boeriand and Sikora, 2001). The dispersion of the LTFbecomes finer as the solidification rate increases. The LTF shows higherconcentration of alloying elements of direct segregation behavior (Boeriand and Sikora, 2000), and will have greater tendencyto show inclusions and microvoids. The austenite dendrites armspacing is affected by the solidification

Figure 1: Nodule Count as a Function of Thickness



Source: Lambhe (2007)

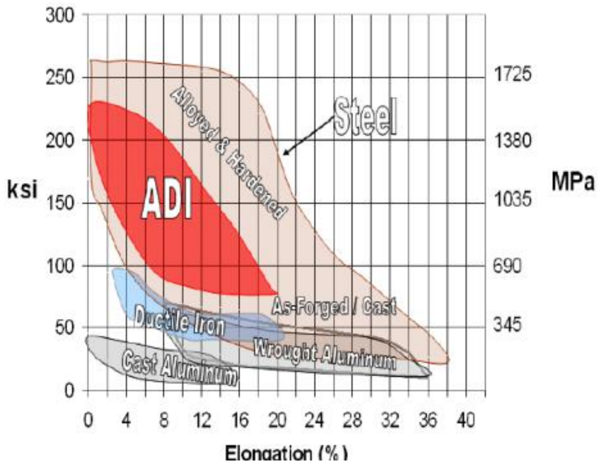
rate. The finer the austenitic microstructure, the higher the dispersion ofmicrosegregation, as it was confirmed by means of EOX determinations and qualitative color metallography techniques. These are positive effects of the high solidification rate. On the otherhand, there are also negative effects. The high solidification rate strongly promotes carbide formation. Carbides are detrimental to the ductility, the toughness, and the machinability of DI. However, since base material is unalloyed DI, these carbides will show small contents of carbide stabilizing elements, and are basically unalloyed cementite. This suggests that a dissolution annealing couldeasily eliminate them. In addition, the large density of graphite particles that act as carbon sinks during carbide dissolution, and the short distance between themwouldalso favor dissolution during annealing.

ADI and Sustainability

Any comparison of material/process combinations must begin with the engineering properties of the materials under consideration. Figure compares the strength and ductility of ADI to that of other, selected engineering materials.

As seen in Figure 2 ADI is competitive with steel in strength for a given level of ductility. What that figure does not show is the relative density of the materials in the comparison. Ductile iron and ADI are 8-10% lower in specific gravity than wrought steel (This is due to the presence of graphite in the cast iron matrix). Therefore, if the component stiffness is sufficient and a steel part can be replaced with an ADI component of the exact same configuration, the part will weigh 8-10% less.

Figure 2: A Comparison of the Yield (Proof) Strength of ADI to that of Several Engineering Materials



Source: Keough (2011)

ADI is typically lower in cost (per unit of mass) than steel. By implementing a same-configuration steel to ADI conversion, less material (mass) will be bought and less will be paid for the material (per unit of mass).

Specific Gravity of Several Engineering Materials

The density of ADI is 2.4 times that of aluminum alloys (7.2 versus 3.0), but so is the stiffness (168 GPa versus 70 GPa). Figure 1 shows that the allowable yield stress for ADI is about 3-5 times that of cast aluminum and 2-3 times

Table 1: Compares the Density (Specific Gravity) of Several Engineering Materials

Material	**Specific Gravity (gm/cm^3)**
Carbon Steel	7.8
Ductile Iron/ADI	7.2
Titanium Alloys	4.5
Aluminum alloys	3.0
Carbon Fiber Composite	2.3
Magnesium Alloys	1.7
Polymers	0.95-2.0

Table 2: Embodied Energy in Selected Engineering Materials Expressed in (MJ/Kg)

Materials	**MJ/Kg**	**Materials**	**MJ/Kg**
Wrought Aluminum (primary, average)	255	Stainless Steels (average)	79
Copper (average)	151	Rubber (average)	70
Magnesium (average)	80	Plain Carbon and Low alloys steels (average)	51
Cast Aluminum (primary, average)	58	Cast aluminum (secondary, average)	23
Malleable Iron (average)	35	Ductile Iron/CG Iron (average)	26
ADI (average)	30	Structural Polymers (primary, average)	84
Gray Iron (average)	23	Glass (primary, average)	30

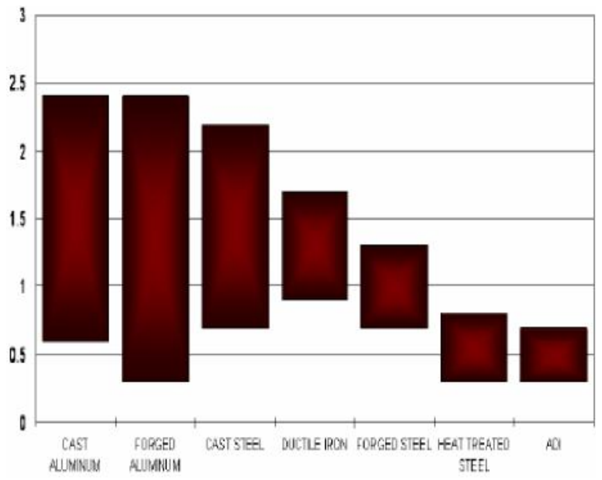
that of forged aluminum. Therefore, a properly designed ADI component can replace an aluminum component at equal (or lower) mass, provided that a (commercially available) minimum wall thickness of about 3 mm is acceptable.

Table 2 shows the relative (average) energy required to produce various materials from their raw materials. The numbers utilize the "typical" process from ore extraction to heat treatment.Where not specified, the numbers assume average levels of commercial recycling within a process. The architecture community employs a useful term "embodied energy" to describe the material feature.

Figure implies that with proper design, ADI can replace aluminum at equal mass. Extrapolating that to embodied energy leads to the conclusion that a thin-walled ADI part that is of equal weight to its larger thicker cast aluminum counterpart embodies 48% less energy (30 MJ/Kg for ADI versus 58 MJ/Kg for cast primary aluminum). This is reflected in the market price and ADI components are typically priced at 25-50% less than the aluminum components they replace.

ADI will not replace a 3 mm wall aluminum die casting at equal mass. However leading-edge metal casting techniques can produce 3 mm wall ADI components that will replace 8-10 mm wall aluminum components 23 at a significant lower price. Figure shows a prototype ADI bracket with a (typical) 3 mm wall.

Figure 3: Relative Mass per Unit of Yield Strength for Various Materials (Forged Carbon Steel Centered on Unity)



Source: Keough (2011)

A European automakers had experienced a noise problem with an aluminum alloy component produced with a squeeze casting process.That bracket is shown in Figure 4. Aconservative ADI design produced by the green sand casting process was proposed to

Figure 4: An ADI Prototype Bracket with a Continuous 3 mm Wall

Source: Fras and Gony (2009)

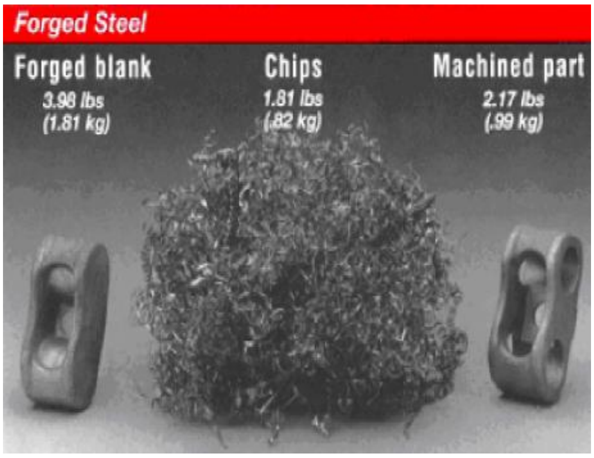
replace the existing aluminum design. The Aluminum bracket volume was 370 cm^3, weighing 1 Kg with an embodied energy of approximately 58 MJ. Thin-walled ADI design was 160 cm^3 in volume weighing 1.1 Kg and embodying 33 MJ, over 40% less energy. The ADI, with its higher damping coefficient, also proved to be cost effective, low energy solution to the noise problem.

Figure 5: The ADI Bracket (Right) Replaced the Aluminum Bracket (Left) to Solve a Specific NVH Problem

Source: Fras and Gony (2009)

Wrought steel bars and plate can be purchased for very low per-Kg prices. For example merchant steel bar prices in 2009 average about 0.77$US Kg, but 25-75% of the material is generally removed during the machining process.Taking low cost shapes (bars and plates) and forging (or forming) them adds energy, but reduce the material to a near net shape. Certain features, like though holes and bollows, cannot be formed into wrought parts. The end-connector link shown in figure is steel forging weighing 1.81 Kg with an embodied energy of approximately 92 MJ. Finish machining removed 0.82 Kg of chips resulting in a machined part weighing 0.99 Kg.

Figure 6: 0.99 Kg Steel and End Connector is Produced from a 1.81 Kg Forging

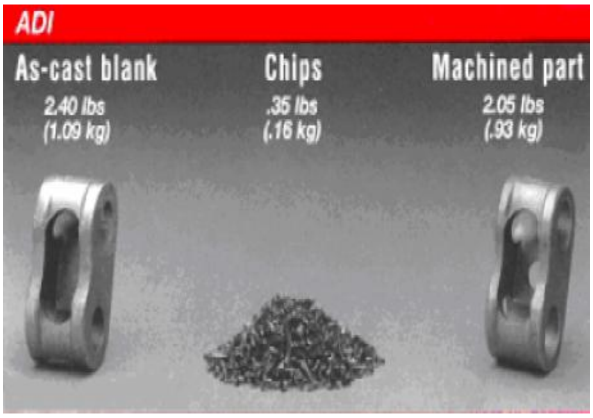


Source: Keough (2011)

Figure shows an ADI solution to the end connector depicted in figure. It is a 1.09 Kg ADI casting produced by the green sand process. This finished ADI end connector weighed .93 Kg with a total embodied energy of 33 MJ, a 65% reduction compared to the steel forging (92 MJ).

The growth of ADI is as much an economic as a technical event. In North America a typical

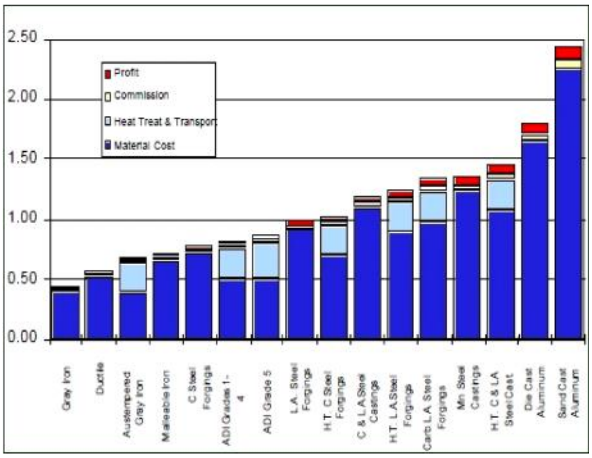
Figure 7: The Finished 0.93 Kg ADI End Connector was Produced from a 1.09 Kg Green Sand Casting



Source: Keough (2011)

saving for converting a medium volume steel component to ADI is approximately 20%. That saving rises to 30% or more when replacing Aluminum with ADI. The relative pricing of engineering materials in North America (Figure) makes the high strength-to-weight ratio ADI material an attractive alternative. When you consider that, with proper design, ADI can replace aluminum at equal or lower weight, the economic opportunities are apparent. Foundries have an economic incentive to produce ADI.

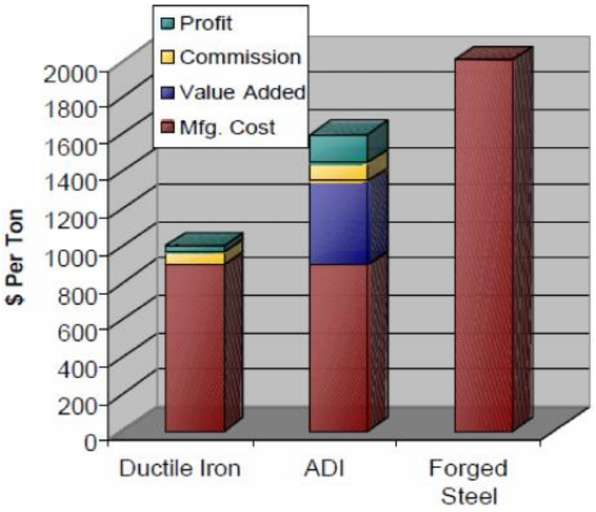
Figure 8: Relative Materials Price (North America)



Source: Keough (2011)

Foundries have an economic incentive to produce ADI. The value added Austemper heat treatment is sold as a "margin added" enhancement (Figure 9), thus increasingthe producer's profits while providing their customer with a "double digit" cost savings. Further more (in the caseswhere commercial heat treating sources are used), a foundry that already produces good quality ductile ironcan enter the ADI market with no additional capital orpersonnel costs. The capital equipment costs for the Austempering of ductile iron are rather high. Therefore, a very large volume of ADI must be produced by one source to cost-justify the investment of a captive Austempering facility.

Figure 9: Comparison of Price / Margin



Source: Keith (2003)

CONCLUSION

- Thin wall ductile iron is excellent base material for heat treatments as it does not require expensive alloying elements nor long heat treatment time.

- Extremely high nodule counts in thin wall ductile iron and short difussional lengths for alloying elements lead to reduced austempering time.
- ADI's high strength-to-weight ratio and stiffness allow it to replace materials like aluminum atequal mass in sections over 3 mm. Furthermore; its low embodied energy and recyclability give it superior sustainability compared to steel or aluminum.

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