THICK-WALLED AUSTEMPERED DUCTILE IRON CASTINGS TO BOOST THE TORQUE DENSITY OF WIND TURBINE GEARBOXES

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1 Abstract

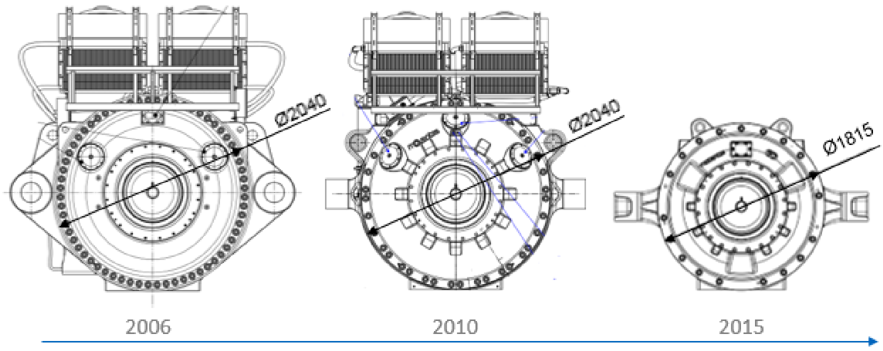
Trend of bigger wind turbines installed on lower wind sites has become evident for on-shore wind turbine component suppliers. As rotor size increases, the input torque to be transmitted through drivetrain also increases. This puts torque transmitting components under increasing strength requirements. A smaller and lighter gearbox leads to decreasing material spend, lower logistics expenses, simpler and lighter supporting structures and smaller lifting equipment.

While developing the concept for the next generation Moventas Exceed gearboxes, it was noticed that a higher strength cast material was needed to fully benefit from the new technologies. The highest strength grades of ductile irons according to standard EN 1563 have already been successfully applied in previous gearbox concepts, but there was a need for higher strength material. After concept cost value analysis, the most feasible solution was observed to be austempered ductile iron (ADI).

ADI provides excellent combination of strength and ductility with reasonable price increase compared to that of high strength cast steels. It has been successfully applied in industrial gearboxes and other industries since its invention in late 1970's, and while having a few successful patented solutions in wind turbine applications, its implementation is very limited. To gain confidence in implementing ADI and familiarizing with austempering heat treatment cycle parameters and mechanical properties for design, simplified experiments were carried out prior to full scale prototype production.

2 Introduction

During the last decade, the size of the 3 MW wind turbine gearbox has decreased along with the overall weight of the gearbox. Figure 1 shows the comparable developments through different iterations of the gearbox design by a single manufacturer. The size reduction can mostly be attributed to improvements in design and in optimizing material usage.



	First 3MW design	Basic 3MW design	Exceed 3MW
Torque density [Nm/kg]	**80**	**100**	**145**
Ring diameter [mm]	2040	2040	1815
Mass [kg]	**29 500**	**24 000**	**19 500**

Figure 1: The evolution of 3MV gearbox from 2006 to 2015 showing the decrease in mass along with increased torque density

While developing the concept for the next generation Moventas Exceed gearboxes, it was noticed that a higher strength cast material was needed to fully benefit from the new technologies. The highest strength grades of ductile irons according to standard EN 1563 have already been successfully applied in previous gearbox concepts, but there was a need for higher strength material. After concept cost value analysis, the most feasible solution was observed to be austempered ductile iron (ADI).

3 Method

3.1 Test samples

Thick walls of the wind turbine gearbox low speed planet carrier were simulated with a simplified cylindrical casting geometry. Multiple samples were used in casting experiments to test different alloy compositions and austempering heat treatment cycles. For reference, a similar cylinder was cast, and heat treated to EN GJS-800-2 grade pearlitic ductile iron. The resulting material microstructure, hardness and static mechanical properties were characterized from different locations in the samples.

Figure 2 shows a basic drawing of the dimensions for the two castings, along with the locations of the tensile test samples. The illustration was thought to give an adequate overview of the base material, despite the simple geometry. The large wall thickness was chosen so, that it would represent a theoretical worst-case scenario in a real component. Additionally, the effect of chilling was investigated at the same time, for half of the casting.

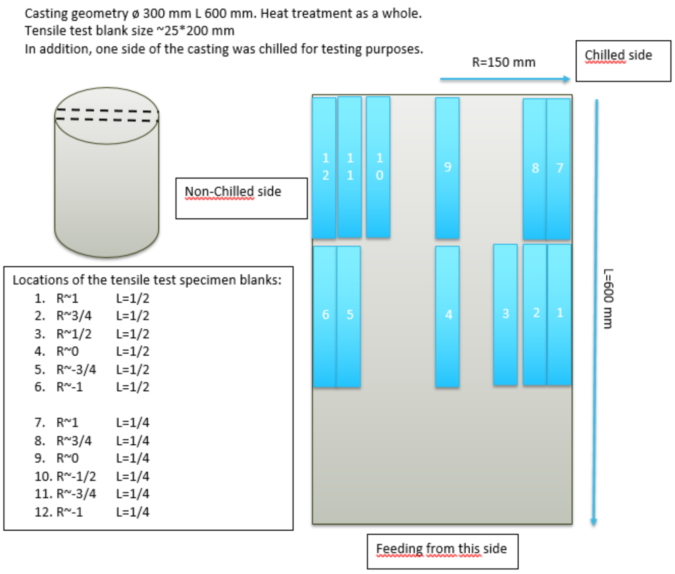


Figure 2: Initial design geometry and test sample locations

Two ADI specimens and a reference GJS-800 specimen were cast to compare how different austemperability affects the mechanical properties. The first sample ADI-2 was alloyed with the foundry's own grade that was meant for larger components, but with the intention that full austemperability would not be reached. The second sample ADI-3 was alloyed so, that the specimen would reach full austemperability.

After casting, the castings were sent to a heat-treatment company and a heat-treatment plan was then produced by them to produce ADI 1050 from both specimens.

3.2 Mechanical properties

Tensile test results made for the test specimen are presented in Figures 3 and 4 with the GJS-800, ADI-2 and ADI-3 samples, respectively. As was previously mentioned, there were twelve test samples taken from both specimens.

All the tests were done according to either ISO 6892-1:2009 B or ISO 6892-1:2016 A standard and with longitudinal specimen orientation.

Macro-hardness tests were done with a King portable Brinell hardness tester, according to standard (ISO 6506-1:2014) testing procedure. The dents were measured using a handheld King Brinell optical microscope. Figure 5 shows the hardness test results for the samples. The values include an estimation of the measuring error, resulting from the handheld microscope that was used. Tests were done in an ambient temperature.

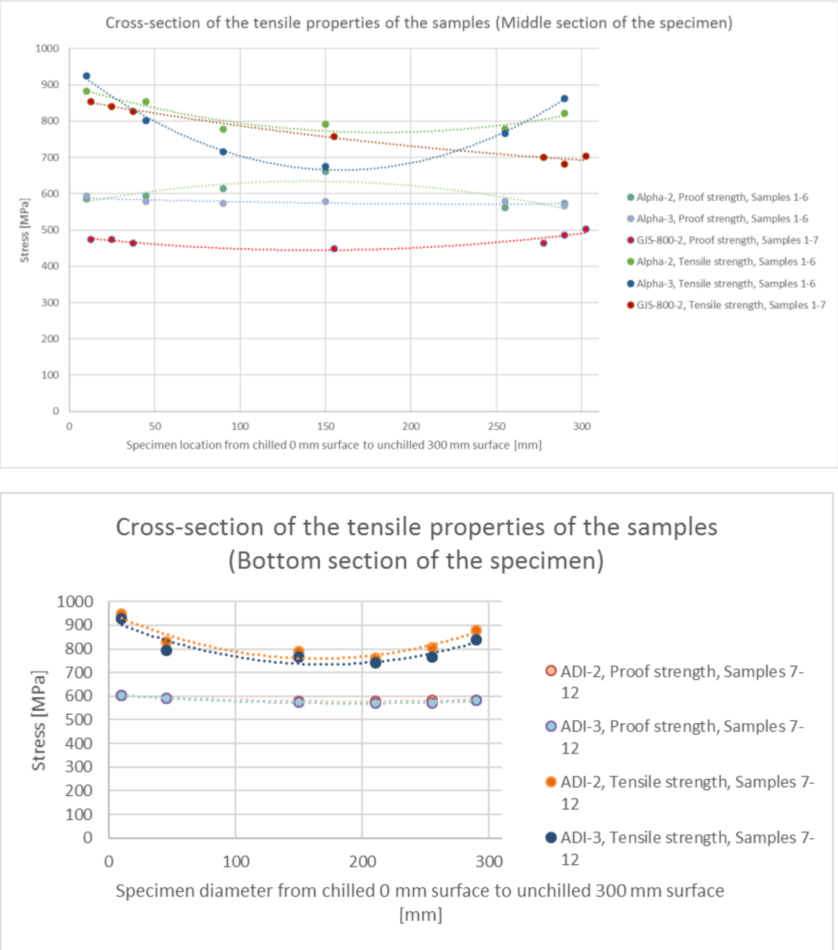


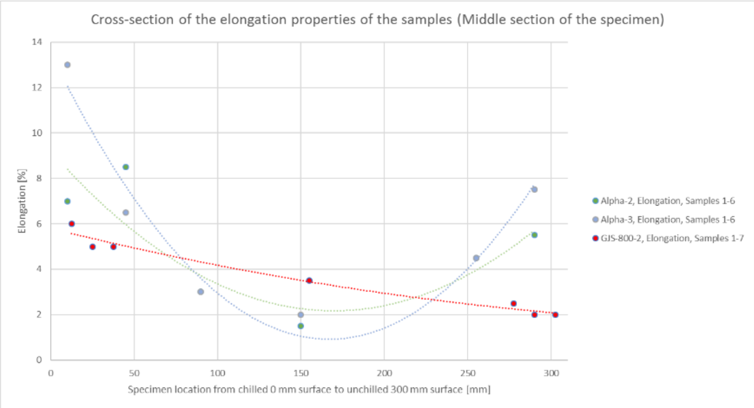
Figure 3: Tensile properties for the middle and bottom cross-section of the specimen, measured from the chilled to the unchilled surface.

3.3 Microstructure

To reveal the different microstructural phases and matrices, a solution of ethanol and nitric acid (98 %C_2H_6O and 2 %HNO_3) called Nital was used. Since different phases corrode at different speeds, the etching was done in multiple steps. The steps varied from small etching times to reveal the pearlitic structure, to significantly longer times when revealing ausferritic matrix.

SEM investigation pictures shown in Figure 6 indicates that the fracture behavior of ADI-2 material transforms from ductile, dimple fracture surface to brittle cleavage in the middle of the material. This is detrimental to the overall fracture behavior of the material and is generally avoided. In contrast, ADI-3 retains the ductile dimple pattern all the way to the middle of the material, implying that it will fracture at least partly in a ductile manner.

Figure 7 highlights the change in microstructure, in relation to wall thickness. In this case, ADI-3 seems to retain pearlite free, while ADI-2 forms some after 90 mm from surface.



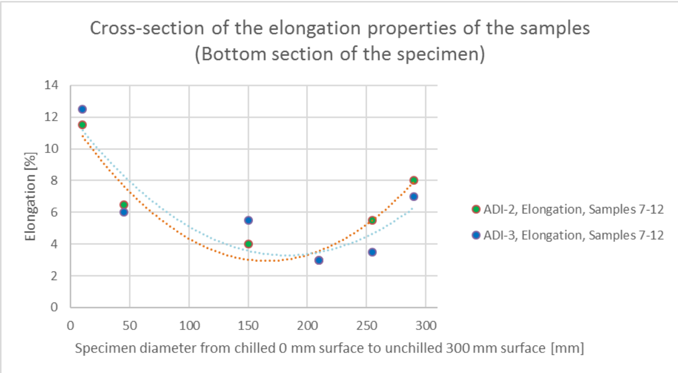
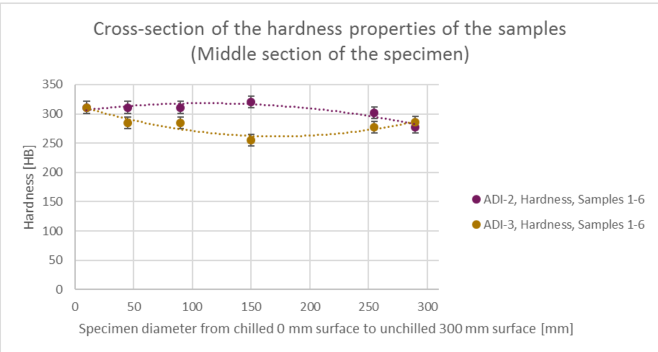


Figure 4: Elongation properties for the middle and bottom cross-section of the specimen, measured from the chilled to the non-chilled surface.



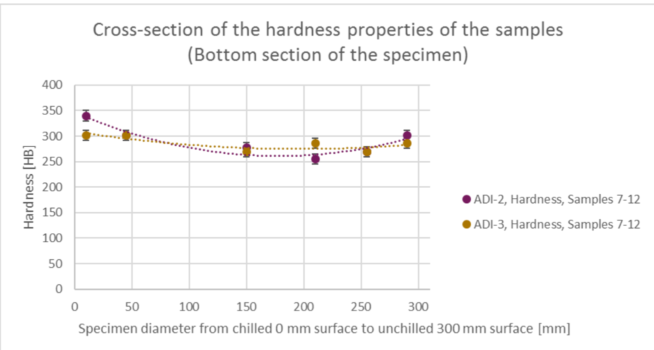


Figure 5: Hardness properties for the middle and bottom cross-section of the specimens, measured from the chilled to the non-chilled surface.

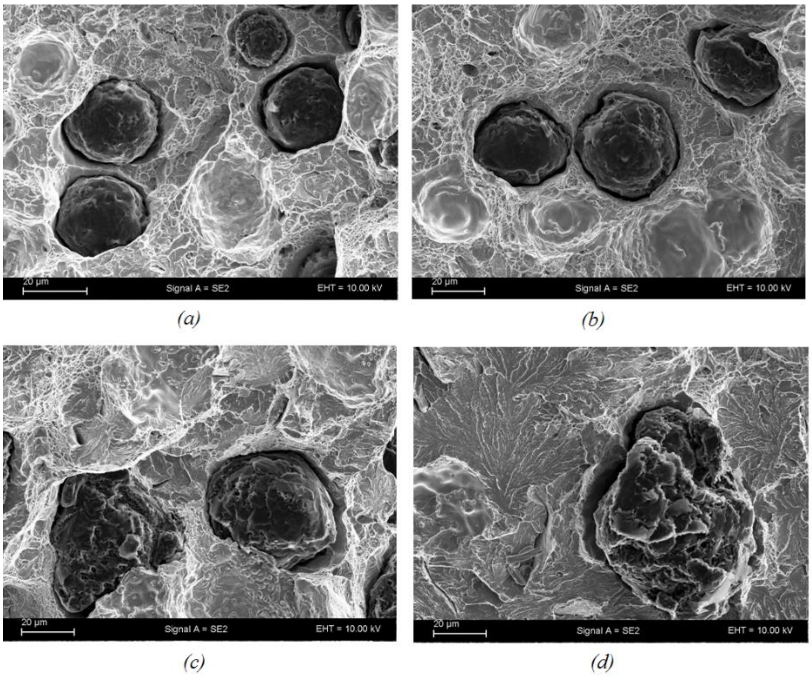


Figure 6: Fracture surfaces of ADI-2 samples at (a) 10 mm, (b) 45 mm, (c) 90 mm and (d) 150 mm depth starting from the chilled side.

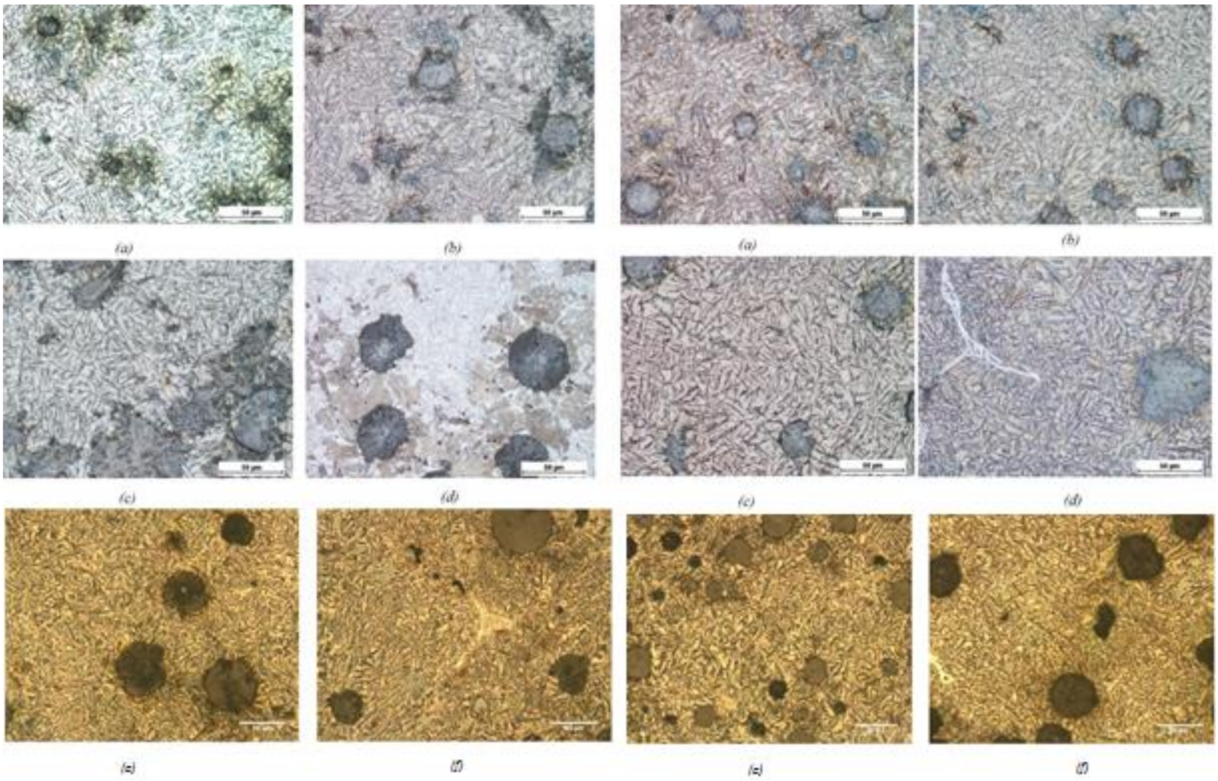


Figure 7: ADI samples (ADI-2 left, ADI-3 right) etched with Nital (2%) and numbered from 1-6 at (a) 10 mm and 75 s etching time, (b) 45 mm and 75 s, (c) 90 mm and 75 s and (d) 150 mm and 75 s and samples 5 and 6 etched with Nital (5%) at (e) 255 mm and 6 s etching time, (f) 290 mm and 6 s and depth starting from the chilled side. Pictures were taken with a 50x objective.

It was suspected that the white areas in the microstructure were Mo-carbides. Because of this, the carbides were also analyzed with EDS, and results in Figure 8 confirm that the zones are indeed Mo-carbides.

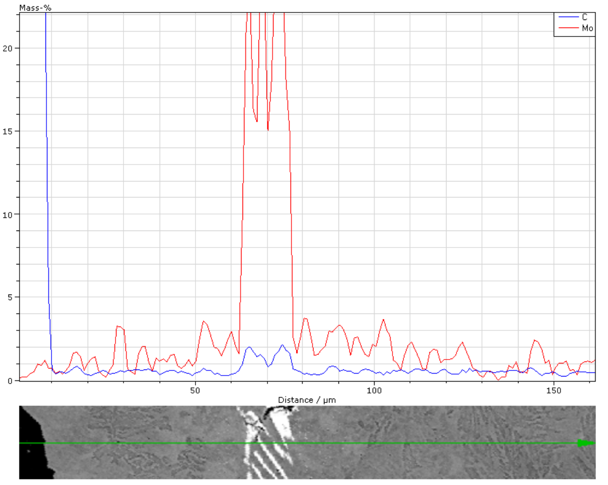


Figure 8: EDS line scan analysis measured starting from a graphite nodule through a Mo-carbide.

4 Conclusions

4.1 Discussion

Main observation from the tensile results was that despite extremely thick walls, ausferritic structure resulting in high strength with sufficient ductility can be achieved with adjusted heat treatment cycle. It was also seen from the results that through-hardening doesn't make the static mechanical properties crash, even though some ductility is lost as a function of depth.

It is evident from Figure 7 that the ADI-2 matrix is not fully ausferritic but has also some pearlite. Moreover, there are small amounts of pearlite around the graphite, at the depth of 45 mm from the surface. In contrast, it seems ADI-3 would have completely ausferritic matrix, as little or no pearlite is seen throughout the samples.

For both GJS-800 and ADI, there seems to be a slight increase of mechanical properties on the chilled side. This is more noticeable on tensile strength and elongation, with ADI-3 having superior elongation and ADI-2 having superior tensile strength. Moreover, the proof strength seems to be relatively unaffected throughout the structure, even with the alloying differences between ADI-2 and ADI-3 specimen. Curiously, ADI-2 showed a small increase in proof strength at the middle of the specimen. Finally, the drop in tensile strength for ADI-3 at the middle of the specimen seems likely to be a result of the effects of segregation.

The results of the hardness tests support the theory concerning chilling, along with the tensile test results. The chilled side of the casting is slightly harder, with an expected decrease in the middle of the specimen. Surprisingly, the test also shows an unexpected hardness spike in the middle of the ADI-2 specimen that was also observed with the proof strength.

4.2 Final thoughts

The austemperability diagram [DOR91] gives each specimen material the following austempering depths:

- ADI-2 with 119.42 mm
- ADI-3 with 150.86 mm.

The theoretical results indicate that while the ADI-3 sample would be fully austempered, the ADI-2 also has a relatively high austemperability. Moreover, ADI-2 should only show signs of pearlite at 150 mm depth. However, pearlite was found from 45 to 90 mm depth, implying a small discrepancy between theory and what was observed. Although, from the design engineering point of view which revolves around proof strength, full austemperability may not be essential for the use of the material. Effects on ductility however, need to be investigated in detail.

ADI is a material that the industry forgot, despite it possessing numerous advantages to traditional ductile irons. Mechanical properties of ADI are a complex result of alloying, graphite distribution, austenitizing and austempering temperature, salt bath temperature, holding time and quenching. The designer aiming to take advantage of ADI should aspire to find a balance between the different parameters, while keeping the costs down. Overcoming the challenges cost efficiently will, however, allow the use of easily cast, high strength and high ductility material in demanding applications. Raising the demand for ADI manufacturing capacity would benefit not only wind industry, but the whole heavy machine industry.

5 Bibliography

[DOR91] Dorazil, E. (1991). Vysokopevná bainitická tvárná litina, High Strength Austempered Ductile Cast Iron, Praque, Academia, Chichester, Ellis Horwood. 226 p. ISBN 0-13-388661-1