Fatigue properties and machinability of ADI
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ABSTRACT
This paper presents data and other informations about fatigue properties and machinability of ADI (austempered ductile iron), coming from twenty years of development at Zanardi Fonderie in Italy. Additional data are given, taken from ISO/DIS 17804 “Founding — Ausferritic spheroidal graphite cast irons — Classification” and from ISO/FDIS 1083:2003 “Founding — Spheroidal graphite cast irons” prepared by ISO TC/25.

THE COMPANY
Zanardi Fonderie is a family Company, situated in Italy, near Verona. Figures 1 and 2 show the location as well as a photograph of the foundry.

We started producing ADI in 1982, licensed to use the “Germanite Dr. Muehlberger” patent which best fitted our base metallurgy and market characteristics.

Right from the start, we realised that the ADI market would develop only if we could get our austempered castings through our customers’ machining shops within any hold-ups. The Germanite patent process using a low manganese iron with low carbon in the primary austenite, proved to be the right way to achieve this goal, with low strength grades of ADI, ADI 800, ADI 900 (corresponding to Grade 850-550-10 of ASTM A897-90).

Our experience with ADI (and its future) has guided our investment strategy since 1995. We have concentrated all our processes in one plant from engineering design to ADI heat treatments, painting and machining.

The layout of the Zanardi facility is shown in Figure 3.

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Figure 1: Map of Italy; Verona is marked in red

Figure 2: Photo of Zanardi Fonderie

Figure 3: The layout of the Zanardi Fonderie facility.
We currently produce 5,000 tons/year of ADI castings which are all machined after heat treatment, as well as ADI 1400 grade, with hardness up to 480 HB. Heat treatment is performed by using three AFC-Holcroft UBQA 36x72x36 furnaces, each one equipped with 50 tons salt bath and endo gas atmosphere. Photos of the furnaces are shown in Figure 4.

Figure 4: Views of an AFC-Holcroft UBQA 36x72x36” furnace.

The actual production percentages are given in Figure 5 with ADI 800 and ADI 900 (grade 1) comprising 59% by turnover with the remaining 36% being ADI 1050 (Grade 2) and 5% being ADI 1400 (grade 4). The last material started recently into production, when satisfactory techniques for machining were developed.

MACHINING

Machinability after heat treatment is a fundamental driver for the development of ADIs. During the last twenty years we experienced different approaches to ADI fabrication.

We started with a chemistry characterized by a low Manganese content, alloying with Nickel, Copper and Molybdenum in an appropriate balance, able to minimize segregations during the heat treatment. By this approach, we have been able to meet immediately the market requirements in respect to machinability, even if we were subcontracting the heat treatment and we had no direct control on machining operations, in all cases performed by the Customer after the heat treatment.

When we could integrate all the processes in one place, starting from co-design the new components, casting, heat treating, machining, we have been able to move successfully into an area where the ADI process window is narrower, but offers important opportunities in cost saving, reducing the content of expensive alloy elements and partially substituting them with increased Manganese content and heat treatment cycle redesigning.

Figure 6: ADI process map
Area 1 represents the recommended area for a foundry that wants to start with machinable ADI production, area 2 is typical of a mature situation when the necessary investments have been done but all the know-how has not yet been developed, area 3 is the target for a machinable ADI foundry, area 4 corresponds to a market area where machinability after heat treatment is not critical as, for instance, for wear parts and/or for castings machined prior to heat treatment.

Our machining experience is shown in the map in Figure 7.

CHM means coated hard metal tools CER means ceramic tools, R&D means that further research has to be done.

The typical values of the machining process parameters are indicated in the Figures 8 – 11, where the relative value 100 corresponds to the machinability of a pearlitic spheroidal cast iron.
The ISO/DIS 17804 “Founding — Ausferritic spheroidal graphite cast irons — Classification” gives some useful indications about the machinability of ADI. Essentially:

- The chip form and the surface quality that results from machining spheroidal ausferritic graphite cast irons does not differ significantly from the chip form and the surface quality obtained when machining other spheroidal graphite cast irons. The best surface quality is obtained with sharp positive cutting edges.

- In general, the mean cutting forces of cast irons, including ausferritic spheroidal graphite cast irons, are substantially lower than those of steels of comparable hardness. However, the cutting forces for ausferritic spheroidal graphite cast irons contain higher dynamic force factors compared to steels of comparable hardness and to pearlitic grades of spheroidal cast irons. Cutting forces oscillations are relatively independent of the tensile strength of ausferritic spheroidal graphite cast irons and increase with higher feed rates and lower cutting speeds. A short and rigid design of the tool holder system and rigid clamping of the work piece are important because tool oscillations can reduce tool life due to chatter vibration tendency.

- Tool wear increases with material hardness, and cutting speed must be reduced approximately in proportion to increases in hardness. In addition, wear resistant cutting tools materials and coating should be applied. For turning, drilling, and milling, wear resistant tungsten carbides (K-grade) show good performance. Furthermore, higher strength and ductility lead to higher cutting temperatures, which can be counteracted by suitable coatings, for example, titanium aluminium nitride or aluminium oxide. Ceramic tools are applicable in some cases. Tool life improvements can be attained (for example, when milling and drilling with tungsten carbide tools) by using optimised tool geometries that consider the high specific mechanical load on the cutting edge.

- The quality of ausferritic spheroidal graphite cast iron microstructures can affect machinability significantly. The following influences must be considered:
  
  o Variations in hardness through the microstructure lead to reductions in tool life.
  o Tool wear increases as the tensile strength increases, and the applicable cutting speed must be correspondingly reduced.
  o A higher percentage of alloying elements (in particular, of carbide-forming elements such as molybdenum) increases tool wear.
  o Areas of the casting with insufficiently stabilized austenite have clearly poorer machinability.

Machinability after heat treatment is an essential tool for the ADI market development. In many instances, this feature gives the opportunity to implement the simplest fabrication cycle: casting – heat treating – machining at final tolerances.
FATIGUE PROPERTIES
From ISO/DIS 17804 “Founding — Ausferritic spheroidal graphite cast irons — Classification”\(^2\) and ISO/FDIS 1083:2003 “Founding — Spheroidal graphite cast irons”\(^3\) we can plot the fatigue limit (Wöhler) (rotating bending) un-notched (dia. 10.6 mm) vs. minimum tensile strength (thickness < 30 mm), representative of the material grade.

For the same tensile strength, ADIs show a better fatigue limit than Pearlitic grades, because of improved ductility, represented by fracture toughness \(K_{1c}\).

Starting from this baseline, it is necessary to evaluate how fatigue properties will change depending on:
1. Loading pattern
2. Casting thickness
3. Geometric notch / surface defect
4. Low cycle range
5. Machining before heat treatment
6. Surface plastic deformation after heat treatment

### Loading pattern
Fatigue properties for all bending loads are easily predictable using the Goodman – Smith diagram.

The above mentioned standards for ductile and austempered ductile irons, indicates, for all grades, a ratio between shear (or torsional) static strength and tensile strength equal to 0.90. The standard for austempered ductile irons indicates also a ratio between shear (or torsional) and tensile 0.2% proof stress strength equal to 0.70.

For steels, a ratio of \(1/\sqrt{3}\) (Von Mises) • 0.60 is usually assumed.

If the indication of the standard will be confirmed by further research work on fatigue properties, ADIs and, in general, all spheroidal graphite irons will be confirmed as preferred materials in case of torsional stresses.
ISO/DIS 17804\textsuperscript{4} gives also an indication on Hertzian pressure fatigue strength $\sigma_{H\text{lim}} 99\%$ and Tooth root bending fatigue strength $\sigma_{F\text{lim}} 99\%$

Casting thickness
ISO/DIS 17804 “Founding — Ausferritic spheroidal graphite cast irons — Classification”\textsuperscript{5} gives an indication of tensile strength $R_m$ reduction as a function of thickness, for a given yield strength and hardness range.

<table>
<thead>
<tr>
<th>$R_{p0.2}$ min Mpa</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>850</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB</td>
<td>250-310</td>
<td>280-340</td>
<td>320-380</td>
<td>340-420</td>
</tr>
<tr>
<td>$R_m$ min t &lt;= 30 mm</td>
<td>800</td>
<td>900</td>
<td>1050</td>
<td>1200</td>
</tr>
<tr>
<td>$R_m$ min t &lt; 30 - 60 mm</td>
<td>750</td>
<td>850</td>
<td>1000</td>
<td>1170</td>
</tr>
<tr>
<td>$R_m$ min t &gt; 60 - 100 mm</td>
<td>720</td>
<td>820</td>
<td>970</td>
<td>1140</td>
</tr>
</tbody>
</table>

This table could be used for an approximate estimation of fatigue limit as a function of wall thickness.

Geometric notch / surface defect
When a geometric notch and/or a surface defect have to be considered, it is necessary to know the so called “notch sensitivity”, usually measured as the rate between fatigue limit on unnotched and notched specimens, for a given notch geometry. The above mentioned standards provides figures also for fatigue limit on notched specimens (test piece of 10,6 mm diameter at notch with a circumferential 45° V-notch having a radius of 0,25 mm, ADI specimens notched after heat treatment).

In the following diagram, the notch sensitivity, as fatigue limit unnotched / fatigue limit notched is plotted (pearlitic grades showing the same values as ADIs of equal tensile strength).

Alternatively, notch sensitivity can be evaluated by a more extensive approach.

A recent research program investigated the fatigue properties of Zanardi process (area 3 in fig.6), ADI grades 900, 1050, 1200\textsuperscript{6}.

Eighty test samples for grade 900, sixty for grade 1050 and sixty for grade 1200 have been tested with rotating bending $R = -1$, in the unnotched and notched conditions.

The samples dimensions are given in the following table:
D (mm) a (mm) $K_{eq}$ $\alpha$

<table>
<thead>
<tr>
<th>D (mm)</th>
<th>a (mm)</th>
<th>$\rho$ (mm)</th>
<th>$K_{eq}$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>0</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6.5</td>
<td>0.1</td>
<td>0.2</td>
<td>2.423</td>
<td>1.125</td>
</tr>
<tr>
<td>8.0</td>
<td>1</td>
<td>0.1</td>
<td>10.321</td>
<td>1.437</td>
</tr>
<tr>
<td>8.0</td>
<td>1</td>
<td>0.08</td>
<td>11.458</td>
<td>1.437</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>10</td>
<td>5.028</td>
<td>2.088</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>0.1</td>
<td>20.827</td>
<td>2.088</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>0.08</td>
<td>23.17</td>
<td>2.088</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>5</td>
<td>9.335</td>
<td>2.978</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>2</td>
<td>11.109</td>
<td>2.978</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>1</td>
<td>13.638</td>
<td>2.978</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>0.5</td>
<td>17.683</td>
<td>2.978</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>0.1</td>
<td>36.203</td>
<td>2.978</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>0.08</td>
<td>40.298</td>
<td>2.978</td>
</tr>
</tbody>
</table>

$D$ is the sample external diameter, $a$ is the notch depth, $\rho$ is the notch bottom radius.

The investigation methodology was conforming to the referenced paper “Fracture mechanics and notch sensitivity” where the following diagram summarizes the behaviour of a material in fatigue tests, when affected by cracks and/or notches.

The values of the length parameter $a_0$ (material property) were calculated for the three grades of ADI:

<table>
<thead>
<tr>
<th>ADI grade (Rm min Mpa)</th>
<th>$a_0$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>147</td>
</tr>
<tr>
<td>1050</td>
<td>91</td>
</tr>
<tr>
<td>1200</td>
<td>90</td>
</tr>
</tbody>
</table>

These values and the ones of some steels and one aluminium alloy, as reported in the above referenced paper, are plotted vs. actual fatigue limit amplitude $\Delta\sigma_0$ (Wöhler) (rotating bending) unnotched of each tested material.

The diagram suggests that ADIs and, in general, all spheroidal graphite irons, could show a notch sensitivity better than steels with comparable unnotched fatigue limit. This is not yet an absolute statement, cause comparison is made between directly measured data and literature data. However, further research programs in this direction shall be encouraged.

**Low cycle range**

The same research program gave also a measure of the $K$ and $C$ parameters in the Wöhler equation:

$$\left(\frac{\Delta\sigma_0}{2}\right) \times n^{1/K} = C$$

where

- $\Delta\sigma_0$ = fatigue limit amplitude rotating bending unnotched Mpa
- $n$ = number of cycles

We obtained the following results:

<table>
<thead>
<tr>
<th>ADI grade (Rm min Mpa)</th>
<th>$K$</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>7.5</td>
<td>2081</td>
</tr>
<tr>
<td>1050</td>
<td>8.9</td>
<td>1904</td>
</tr>
<tr>
<td>1200</td>
<td>5.9</td>
<td>3732</td>
</tr>
</tbody>
</table>

When these figures are used together with the fatigue limits in ISO/DIS 17804, the following Wöhler curves can be drawn.
Machining before heat treatment

Research work made on material coming from our process (area 1 in fig.6), processed with different atmospheres into the austenitizing furnace, showed a reduction in fatigue limit up to 20% on test bars machined before heat treatment, when compared with the same material machined after heat treatment. The amount of reduction is mainly depending on the degree of surface decarburization, induced by the heat treatment atmosphere. For this reason, a well controlled protective atmosphere into the austenitizing furnace is necessary when machining is done before heat treatment and/or unmachined surfaces are critical for fatigue loads.

Surface plastic deformation after heat treatment

It is known that surface plastic deformations after austempering, obtained by shot peening or cold rolling, have a beneficial effect on fatigue properties. We did not yet measure directly the effect of shot peening and cold rolling, for which is possible to find results by other sources in technical literature.

SUMMARY

Cost competitive machining of ADI after heat treatment has been a normal practice for about twenty years. In order to be successful with machining after austempering all the metallurgical processes, both in the liquid and solid states, must be carried out at the best level of available technologies, involving all necessary investments to ensure consistent and reproducible quality. A high nodule count and a narrow range of hardness are the first indexes to be monitored. This will ensure the safety of the casting design. Research programs on material properties and material design, together with the success of running applications, are increasingly indicative of the high potential of ADI as a benchmark material for engineering applications.

Metallurgical processes applied to ADI castings are based on the availability of all the necessary Carbon right to the centre of the casting. Moreover the Silicon makes the Carbon highly mobile. This confers to Carbon the typical structure of austempered cast irons, called “Ausferrite”. When compared with steels, ADI castings are less dense, less likely to crack and have excellent wear resistance.

Being a multi-phase high performance material, its process window is narrower than other conventional materials.

For this reason ADI processes require large investments in the foundry and heat treatment, with maximum integration between engineering design and machining operations.

ADDITIONAL RESOURCES

+ Zanardi Fonderie - internal research
+ www.zanardifonderie.com
+ zfr@zanardifonderie.com

1 Annex H, “Machinability of ausferritic spheroidal graphite cast iron”
2 Annex F, “Technical data of ausferritic spheroidal graphite cast iron”
3 Annex E, “Additional information on mechanical and physical properties”
4 Annex F, “Technical data of ausferritic spheroidal graphite cast iron” Table F.2
5 Table 1, “Mechanical properties measured on test pieces machined from separately cast samples or cast-on samples”
6 M.Cagol, B.Atzori, P.Lazzarin, G.Meneghetti, Department of Mechanical Engineering University of Padova
7 Fracture mechanics and notch sensitivity, B.Atzori, P.Lazzarin, G.Meneghetti, Department of Mechanical Engineering University of Padova, © 2003 Blackwell Publishing Ltd. Fatigue Fract Engng Mater Struct 26, 257-267
8 E.Gasparini, B.Atzori, P.Lazzarin, G.Meneghetti, Department of Mechanical Engineering University of Padova