Fatigue properties and machinability of ADI

F. Zanardi

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 castings are based on the unique relationship of spheroidal grade and silicon. This relationship allows us to produce the intermediate structure in austempered cast irons, knows as "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, ADI's 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.

Keywords: cast iron, fatigue, heat treatments

This paper presents data and other information about fatigue properties and machinability of ADI (austempered ductile iron), resulting 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.
Machinability has been the primary issue for the development of ADI material at Zanardi Fonderie.
Firstly, grades ADI 800, 900 and 1050 Mp have been developed. High strength grades ADI 1200, 1400, 1600, are now proposed to engineers, with competitive opportunities for machining, integrated in the manufacturing process.

MACHINING

Machinability after heat treatment is a fundamental driver for the development of ADIs. During the last twenty years Zanardi has experienced different approaches to ADI fabrication.
We started with a safe approach, meeting the immediate market requirements for machinability. We were initially subcontracting the heat treatment and we had no direct control for machining operations. In all cases machining was performed by the Customer after the heat treatment.
Since we have integrated all the processes in one place, starting from co-design of new components, casting, heat treating and machining, we have been able to move successfully into an area where the ADI process window is narrower, but offers important opportunities in terms of lead time and total cost of the machined component.
Our machining experience is shown in the map in Figure 1. CHM means coated hard metal tools. CER means ceramic tools. R&D means that further research has to be done to perfect the process.
The typical values of the machining process parameters are indicated in the Figures 2 – 5, where the relative value 100 corresponds to the machinability of a fully pearlitic spheroidal cast iron.
The ISO/DIS 17804 document, "Founding — Ausferritic spheroidal graphite cast irons — Classification" [1], gives some useful indications about the machinability of ADI. Essentially:

	ADI 800	ADI 900	ADI 1050	ADI 1200	ADI 1400
Turning	CHM	CHM	CHM	CER	CER
Milling	CHM	CHM	CHM	CHM	CHM
Drilling	CHM	CHM	CHM	CHM	CHM
Threading	CHM	CHM	CHM	CHM	CHM
Broaching	CHM	R&D	R&D	?	?
Deep drilling (l > 5 d)	CHM	CHM	R&D	?	?

Fig. 1 – Map of Machining Experience in Italy.

Fig. 1 – Esperienza sulla lavorabilità in Italia.

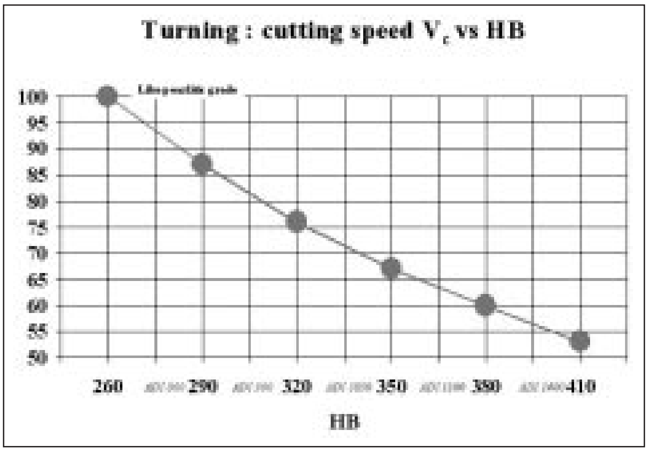

Fig. 2 – Cutting Speed versus Brinell Hardness for turning.

Fig. 2 – Velocità di taglio in funzione della durezza Brinell per la tornitura.

F. Zanardi
Zanardi Fonderie S.p.A., Minerbe, Italy

Paper presented at the 2nd New Developments in Metallurgical Process Technology

1. The chip form and the surface quality that results from machining ausferritic spheroidal graphite cast irons ADI does not differ significantly from the chip form and the surface quality obtained when machining other SG irons. The best surface quality is obtained with sharp positive cutting edges.
2. In general, the mean cutting forces of cast irons (including ADI) are substantially lower than those of steels of comparable hardness. However, the cutting forces for ADI contain higher dynamic force factors compared to steels of comparable hardness and to pearlitic grades of SG irons. Cutting force 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 the chatter vibration tendencies if ADI.

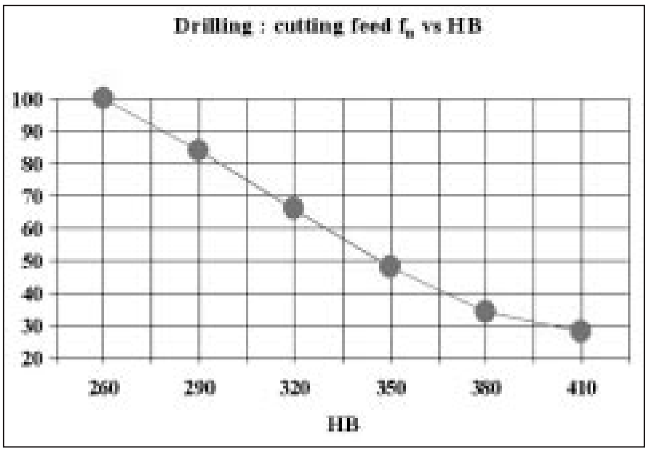

Fig. 3 – Cutting feed versus Brinell hardness for drilling.

Fig. 3 – Velocità di avanzamento in funzione della durezza Brinell per la foratura.

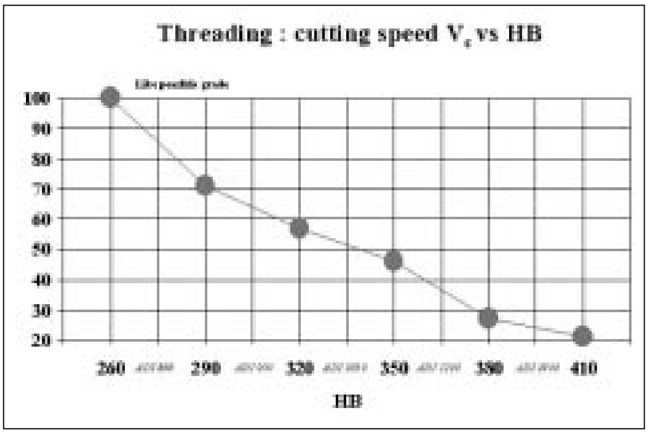

Fig. 4 – Cutting speed versus Brinell hardness for threading.

Fig. 4 – Velocità di taglio in funzione della durezza Brinell per la filettatura.

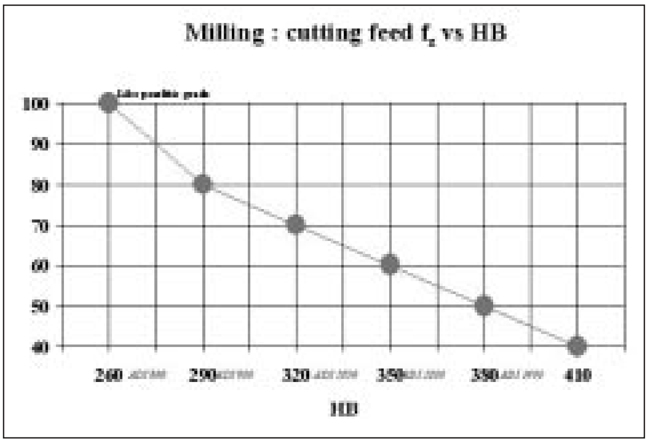

Fig. 5 – Cutting feed versus Brinell hardness for milling.

Fig. 5 – Velocità di avanzamento in funzione della durezza Brinell per la fresatura.

3. 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.
4. The quality of ADI microstructures can affect machinability significantly. The following influences must be considered:
   - Variations in hardness through the microstructure lead to reductions in tool life.
   - Tool wear increases as the tensile strength increases, and the applicable cutting speed must be correspondingly reduced.
   - A higher percentage of alloying elements (in particular, of carbide-forming elements such as molybdenum) increases tool wear.
   - Areas of the casting with insufficiently stabilized austenite have clearly poorer machinability.
   - Increased graphite nodule counts minimize micro segregation and improve machinability.

Machinability after heat treatment is an essential tool for 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, unnotched, dia. 10.6 mm. Vs. minimum tensile strength for thickness less than 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 K1c.

The above indicated fatigue limits refer to unnotched specimens with the surface machined after heat treatment and a casting thickness below 30 mm.

Starting from this baseline, it is necessary to evaluate how fatigue properties will change depending on:

- Loading pattern
- Casting thickness
- Geometric notch / surface defect
- Low cycle range
- Machining before heat treatment
- Surface plastic deformation after heat treatment.

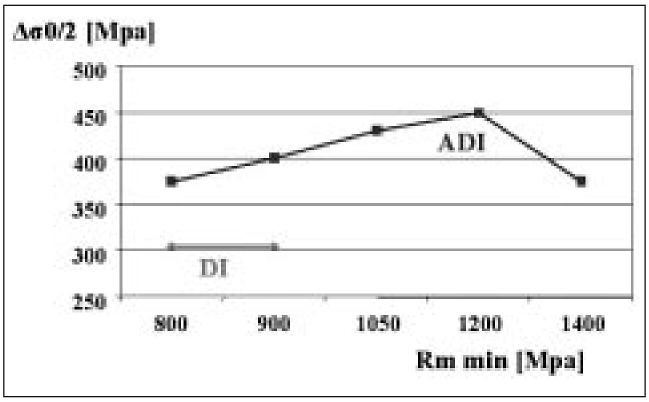

Fig. 6 – Unnotched rotating bending limit for ADIs compared with DI pearlitic grade.

Fig. 6 – Limite di fatica a flessione rotante senza intaglio per ADI comparate con ghisa sferoidale perlitica.

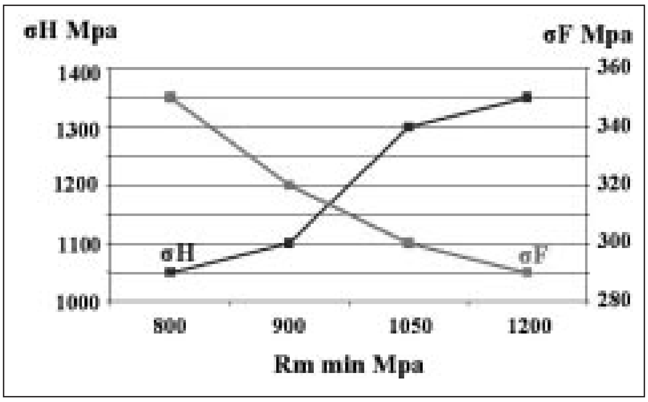

Fig. 8 – Hertzian pressure fatigue strength σH and Tooth root bending fatigue strength σF for ADIs.

Fig. 8 – Limite di fatica pressione Hertziana σH e resistenza a fatica alla radice del dente σF per ADI.

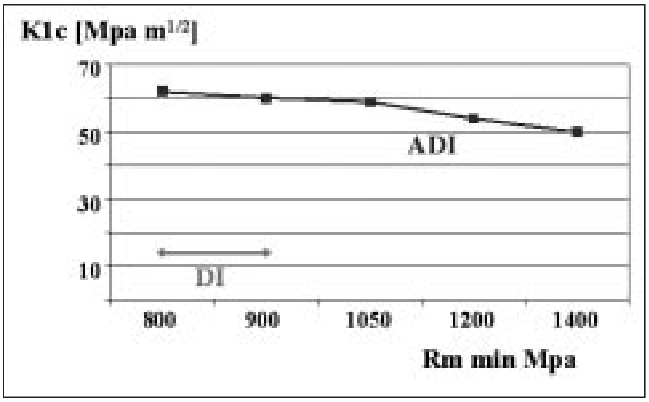

Fig. 7 – Fracture toughness K1c for ADIs compared with DI pearlitic grade.

Fig. 7 – Limite di tenacità alla frattura K1c per ADI comparate con ghisa sferoidale perlitica.

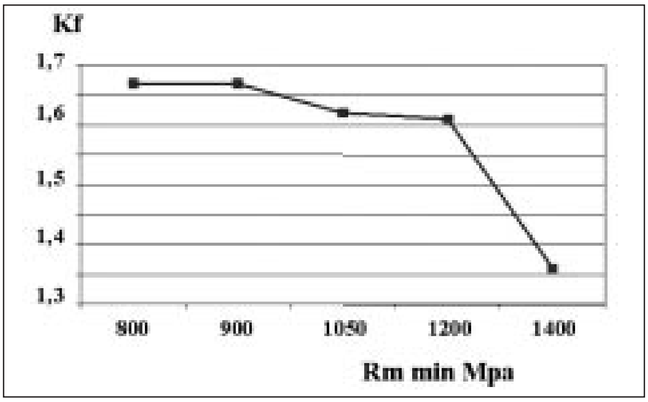

Fig. 9 – Notch sensitivity Kf for ADIs.

Fig. 9 – Sensibilità all'intaglio Kf per ADI.

LOADING PATTERN

The above mentioned standards for ductile iron and ADI, indicate, for all grades, a ratio between shear (or torsional) static strength and tensile strength equal to 0.90 .
For steels, a ratio of 0.58 (Von Mises) is usually assumed.
A recent research program [4] compared the fatigue properties of Zanardi process, ADI grade 900 Mpa.
Ten couples of test specimens for each load type have been tested at 2 millions cycles, comparing completely reversed R-1 torsional vs axial fatigue strength and pulsating R0.1 torsional vs axial fatigue strength.
The following results have been obtained :
Torsional / Axial R-1 = 0.75
Torsional / Axial R0.1 = 0.92
ISO/DIS 17804 [5] gives also an indication on Hertzian pressure fatigue strength σH lim 99 % and Tooth root bending fatigue strength σF lim 99 %.

CASTING THICKNESS

ISO/DIS 17804 "Founding — Ausferritic spheroidal graphite cast irons — Classification" [6] gives an indication of tensile strength (Rm) reduction as a function of thickness, for a given yield strength and hardness range.
Table 1 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

Table 1 – Tensile strength Rm reduction as a function of thickness.

Tabella 1 – Riduzione del carico di rottura Rm in funzione dello spessore.

Rp0.2 min Mpa	500	600	700	850
HB	250-310	280-340	320-380	340-420
Rm min t<= 30 mm	800	900	1050	1200
Rm min 30 < t <= 60 mm	750	850	1000	1170
Rm min 60 < t <= 100 mm	720	820	970	1140

mm diameter at notch with a circumferential 45° V-notch having a radius of 0.25 mm, ADI specimens notched after heat treatment).
In Figure 9, 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 [7] investigated the fatigue properties of Zanardi process, ADI grades 900, 1050, 1200.
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 Table 2.

D (mm)	a (mm)	ρ (mm)	K_{tg}	α
6.5	0		1	1
6.5	0.1	0.2	2.423	1.125
6.5	0.1	0.1	3.075	1.125
8.0	1	0.1	10.321	1.437
8.0	1	0.08	11.458	1.437
10	2	10	5.028	2.088
10	2	0.1	20.827	2.088
10	2	0.08	23.17	2.088
12	3	5	9.335	2.978
12	3	2	11.109	2.978
12	3	1	13.638	2.978
12	3	0.5	17.683	2.978
12	3	0.1	36.203	2.978
12	3	0.08	40.298	2.978

Table 2 – Samples dimensions for fatigue testing.

Tabella 2 – Dimensioni dei campioni per la prova di fatica.

D is the sample external diameter, a is the notch depth, ρ is the notch bottom radius, K_{tg} is , α is the shape factor.
The investigation methodology was conforming to the referenced paper "Fracture Mechanics and Notch Sensitivity" [8] 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 a0 (material property) were calculated for the three grades of ADI.

ADI grade (Rm min Mpa)	a0 (µm)
900	147
1050	91
1200	90

Table 3 – a0 parameter for different ADI grades.

Tabella 3 – Parametro a0 per differenti gradi di ADI.

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 Δσ0 (Wöhler) (rotating bending) un-notched of each tested material.
The diagram suggests that ADIs and, in general, all spheroidal graphite irons, may be less notch sensitive than steels with comparable unnotched fatigue limits. This is not yet an absolute statement, because comparison is made between directly measured data and literature data. However, further research in this direction shall be encouraged. Information about the influence of the quality surface on the fatigue properties can be found in the referenced paper "Bending Fatigue Behaviour of Ductile Iron with As-Cast Surfaces" [9].
Essentially, it is confirmed how the influence of the defect increases when the tensile strength increases.
For this reason, pearlitic ductile irons and low grade ADIs require more attention to unmachined surfaces quality than ferritic ductile irons. High strength grades ADI could be compared to high strength steels.
An intensive shot-blasting is beneficial to reduce the influence of surface defects.

LOW CYCLE RANGE

The same research program gave also a measure of the K and C parameters in the Wöhler equation:
$(\Delta\sigma 0 / 2) \times n^{1/K} = C$
where
- Δσ0 = fatigue limit amplitude rotating bending unnotched MPa
- n = number of cycles.

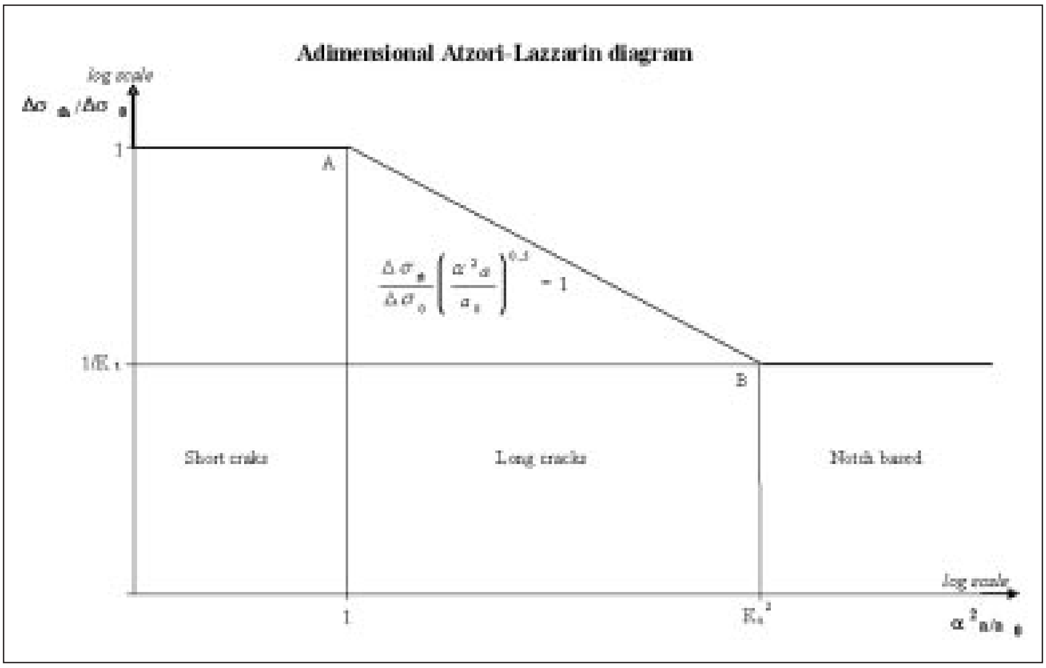

Fig. 10 – Fracture mechanics and notch sensitivity.

Fig. 10 – Meccanica della frattura e sensibilità all'intaglio.

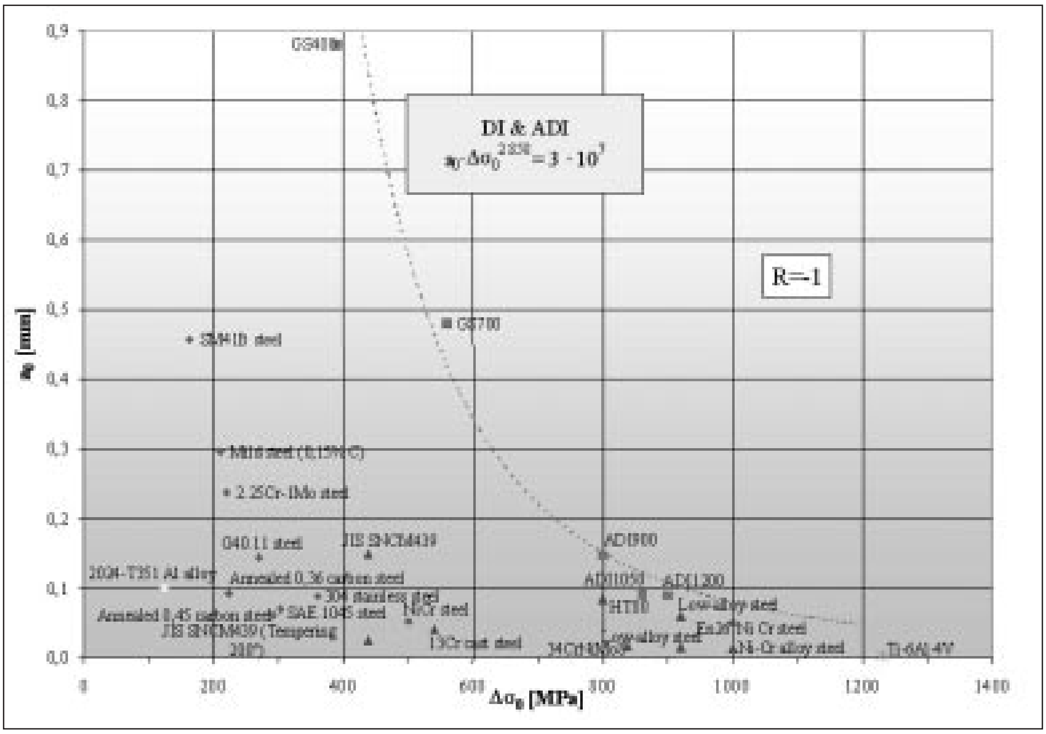

Fig. 11 – Notch sensitivity of DI & ADI vs. Steels and Aluminum.

Fig. 11 – Sensibilità all'intaglio per GS & ADI confrontate con acciaio e alluminio.

We obtained the results of Table 4.
When these figures are used together with the fatigue limits in ISO/DIS 17804, the Wöhler curves as in Fig. 12 can be drawn.

MACHINING BEFORE HEAT TREATMENT

Research work [10] 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.

ADI grade (Rm min MPa)	K	C
900	7.5	2081
1050	8.9	1904
1200	5.9	3732

Table 4 – Wöhler equation: $(\Delta\sigma 0 / 2) \times n^{1/K} = C$.

Tabella 4 – Equazione di Wöhler: $(\Delta\sigma 0 / 2) \times n^{1/K} = C$.

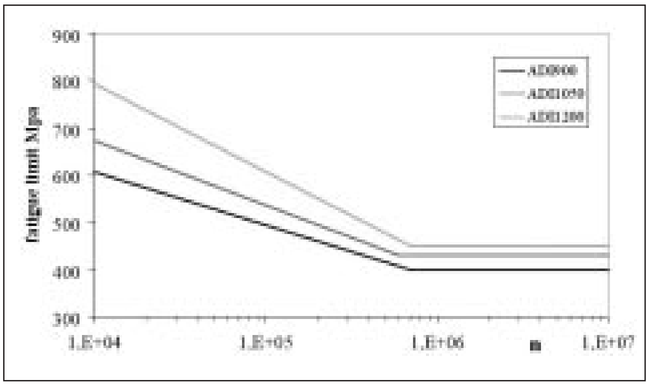

Fig. 12 – Wöhler curves for ADIs.

Fig. 12 – Diagramma di Wöhler per ADI.

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.

REFERENCES

[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] Atzori B., Lazzarin P., Meneghetti G., Department of Mechanical Engineering University of Padova
[5] Annex F, Table F.2, "Technical data of ausferritic spheroidal graphite cast iron"
[6] Table 1, "Mechanical properties measured on test pieces machined from separately cast samples or cast-on samples"
[7] Cagol M., Atzori B., Lazzarin P., Meneghetti G., Department of Mechanical Engineering University of Padova
[8] Atzori B., Lazzarin P., Meneghetti G., "Fracture Mechanics and Notch Sensitivity", © 2003 Blackwell Publishing Ltd. Fatigue Fract Engng Mater Struct 26, 257-267
[9] Bauer W., Austrian Foundry Institute (ÖGI) "Bending Fatigue Behaviour of Ductile Iron with As-Cast Surfaces"
[10] Gasparini E., Atzori B., Lazzarin P., Meneghetti G., Department of Mechanical Engineering University of Padova.

ABSTRACT

LA RESISTENZA A FATICA E LA LAVORABILITÀ DELLA GHISA SFEROIDALE AUSTEMPERATA (ADI)

Parole chiave:
ghisa, fatica, trattamenti termici

Questo articolo presenta i dati ed altre informazioni sulla resistenza a fatica e sulla lavorabilità della Ghisa Sferoidale Austemperata (ADI, Austempered Ductile Iron), derivanti da venti anni di sviluppo alla Zanardi Fonderie S.p.A. Ulteriori informazioni provengono dagli Standard Europei ISO/DIS 17804 "Founding — Ausferritic spheroidal graphite cast irons — Classification" e ISO/FDIS 1083:2003 "Founding — Spheroidal graphite cast irons".
La lavorabilità è stato il principale requisito nello sviluppo della Ghisa Sferoidale Austemperata alla Zanardi Fonderie S.p.A..
Inizialmente sono stati sviluppati i gradi ADI 800, ADI 900 e ADI 1050. I gradi ad alta resistenza, ADI 1200 ADI 1400 e ADI 1600, sono oggi proposti ai progettisti con competitive opportunità per la lavorazione meccanica integrata nel processo di fabbricazione.