Ductile Iron for Heavy Section Wind Mill Castings: A European Experience

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ABSTRACT

During the five year period from 1996 to 2001, the capacity of the installed wind energy plants worldwide has been multiplied by four, increasing from 6×10^3 MW to 25×10^3 MW. This increase has mainly taken place in Europe where many countries have embraced this source of energy as part of the solution to dependence upon foreign energy sources (gas and oil), environmental problems, and unsolved risks of nuclear power.

The European Ductile Iron industry fully participated in this development. When compared to steel castings, Ductile Iron offers weight reduction and can meet the mechanical requirements of many wind mill parts (tensile, impact, fatigue) without heat treatment. Indeed, low Mn low P low Si ferritic Ductile Iron, produced under carefully controlled parameters, exceeds the targeted properties in the as-cast condition.

The objectives of this paper are to review the development history of the Ductile Iron wind mill industry in Europe, to present typical wind mill applications for Ductile Iron and to describe the process parameters that allow the production of these castings in the as-cast condition.

INTRODUCTION

Since the beginning of history, humanity has explored a large number of sources of energy to assist in making every day work easier and more productive; one of the first sources used was wind. Indeed, Chinese built wind mills more than 4 000 years ago! However, the use of wind energy for electrical generation dates back to the 1880's when a Danish inventor converted classical wind mills to DC electricity generation. Today, more than 120 years later, the Danish wind turbine industry has a 50% share of the world market.

The development of wind energy in Europe has been promoted by a number of factors. They include:

- Reduction of dependence on oil producers;
- Need for alternative sources of electricity to replace coal, oil or gas, whose availability could be limited in the future and price subject to significant increase;
- Elimination of more risky technology such as nuclear energy;
- Free, renewable fuel;
- Environmentally clean, although not completely problem free;
- Absence of waste generation.

These factors, and others, have created conditions particularly favorable to the development of wind energy in Europe. The objectives of this paper are to present an outline of the development of the wind energy industry in Europe, to describe the major role played by Ductile Iron as a structural material in wind mills, to present a perspective of development of this industry in North America, and how it could benefit Ductile Iron foundries.

DEVELOPMENT OF WIND POWER INDUSTRY IN EUROPE

As previously indicated, wind energy for electricity generation dates back to the 1880's when Danish physicist Poul La Cour (1846-1908) converted classical wind mills to DC electricity generation. In the 1910's, wind mills for electricity generation became part of the Danish scenery with several hundreds operating wind mills generating 5 to 25 kW each. Construction of wind mills also took place in Germany and other European countries, but cheaper energy sources at an assumed nearly unlimited availability made the development of wind mill technology very slow.

In the 1970's the oil crises (1973 and 1978), the increased concern of the public in general about the quality of the environment (global warming, acid rains,….) and the unsolved risks of nuclear energy forced the West-European governments to start looking at clean renewable energy. Nevertheless, it was 20 years after the first oil crisis that wind energy was clearly identified as an alternative source of energy to fossil and nuclear energy and, in the 1990's, construction of wind power plants boomed. Figure 1[(1)] presents the evolution of the installed wind energy capacity in Europe from 1997 to 2002; during that time period, the yearly installed capacity increased at an average rate of ~ 640 MW. A total of 32 037 MW, including the capacity installed before 1997, is in production in Europe. For comparison purposes, the installed capacity in North America is also shown in Figure

1; an increasing trend is seen during that period, but at a much lower rate. These developments led to the production of 16% of the total energy produced by wind in Denmark. In Germany, 2002 was a record year with 2 328 new units installed for a capacity of 3 247 MW; 12 000 MW of capacity is now in production representing 4.7% of the total electric energy produced. The turnover of this industry in Germany exceeds 3.5 billion US dollars.

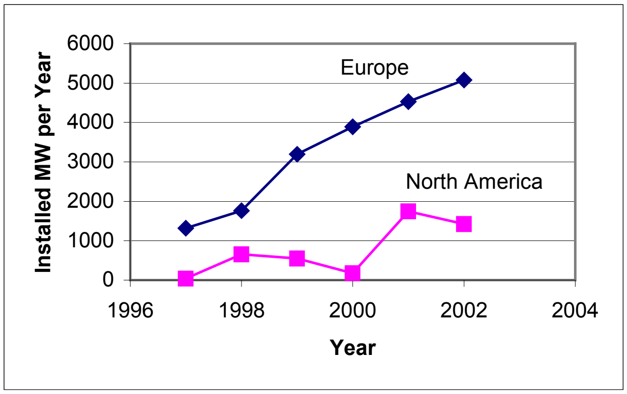

Figure 1 : New Installed Wind Power Capacity in Europe and North America for the 1997-2002 Period.

Projections for the period 2003-2007 show an acceleration of the installed capacity in Europe, as seen in Table 1, to reach a total approaching 60 000 MW in 2007.

Table 1
Projected Wind Mill Power Development 2003-2007 [1]

Year	New Capacity MW	Cumulative MW	Annual Increase %
2002	-	23 832	-
2003	6200	30 032	26.0
2004	6420	36 452	21.4
2005	6600	43 052	18.1
2006	7500	50 552	17.4
2007	8080	58 632	16.0

WIND POWER GENERATION: A MARKET FOR DUCTILE IRON

The increase in demand for wind mills has stimulated the research and development in this area. Table 2 illustrates the evolution in size and capacity of the equipment, which went from 3.0 kW in 1980 to 1.5 MW in 2000 with experimental units of 4.5 MW to be put in service in 2005. Such a 4.5 MW unit is shown in Figure 2.

Table 2
Evolution of Wind Mill Characteristics

Year*	Power MW	Height m (ft)	Rotor Diameter m (ft)
1980	0.030	30 (98)	15 (49)
1985	0.080	40 (131)	20 (66)
1990	0.25	50 (164)	30 (98)
1995	0.60	78 (256)	46 (151)
2000	1.5	100 (328)	70 (230)
2005	4.5	124 (407)	114 (374)

* Estimated.

Figure 2 : View of a 4.5 MW Prototype Unit [2].

The increase in power and size has also resulted in the optimization of the structural materials used in the fabrication of the wind mills. It became rapidly clear that lighter weight materials meeting the required mechanical performance would be needed. Ductile Iron which offers a 10% weight reduction compared to steel was then considered by the designers for many components. Figure 3 presents a schematic of a wind power unit with a gear box. Gearless machines are also available and represent about 20% of the world market.

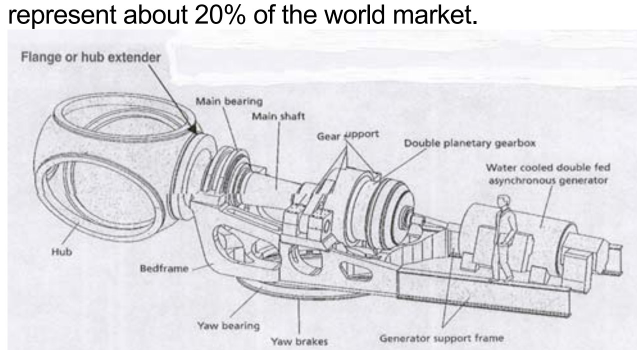

Figure 3 : Cross Section of a Wind Mill Unit with a Gear Box.

Table 3 lists the major Ductile Iron components utilized in the construction of wind power plants and the average weight of the parts per MW. Note that certain wind mill designs contain significantly more Ductile Iron than others. For example, the nacelle frame may weight up to 10 tons, which results in 19t of Ductile Iron castings in this particular 1 MW design. Note, however, that this ratio is usually not valid for large units (4.5 MW) for which bigger castings are required. All parts must meet the EN-GJS-400-18 LT specification, the impact toughness requirement being 12 J (8.8 ft-lb) (Charpy V-notch) at -20°C (-4°F). Examples of wind mill Ductile Iron castings are shown in Figures 4 (hubs) and 5 (shaft).

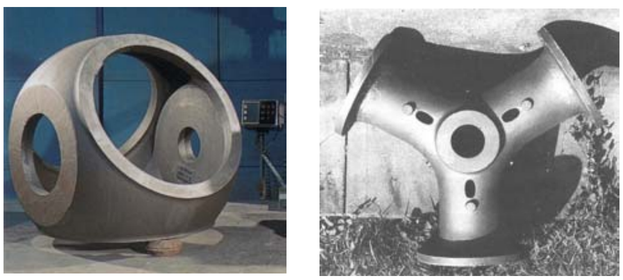

Figure 4 : Ductile Iron Hubs for Wind Mills.

Figure 5 : Ductile Iron Shaft for Wind Mills (390 kg).

Table 3
Ductile Iron Wind Mill Castings

Assembly	D.I. Parts	Average Weight t/MW
Rotor System	Hub, blade adapter, bearing	6.44 (hub : 4.5 t/MW)
Shaft	Shaft, bearings	0.44
Turbine Frame	Nacelle, bed plate, yaw ring	3.85 (nacelle : up to 10t)
Gear Box	Housing, support, bearings	1.71
Others		1.00
TOTAL		13.44

MANUFACTURE OF WIND MILL CASTINGS

Specifications and Properties

Table 4 lists the minimum mechanical properties required for wind mill castings, in order to comply with the European EN-GJS-400-18LT (previously GGG 40.3) specification for ferritic Ductile Iron.

Table 4
EN-GJS-400-18 LT Specification for Wind Mill Castings

Property	Metric	Imperial
Tensile Strength	400 MPa	58 000 psi
Yield Strength	240 MPa	35 000 psi
Elongation	18%	18%
Hardness	160-170 BHN	160-170 BHN
Impact Energy at -20°C (-4°F)		
Average of 3 tests	12 J	8.8 ft-lb
Minimum (1 specimen)	9 J	6.6 ft-lb

The high ductility and toughness (as measured by V-notched impact Charpy tests) are of paramount importance for these castings because of the harsh weather conditions to which they may be exposed in Northern countries or offshore. In addition, the soft ferritic matrix, in conjunction with the lubricating effect of the graphite spheroids, eases the finishing machining operations to which the castings are submitted.

In order to achieve the mechanical properties required for the castings, the microstructural targets are as follows:

- Nodule Count: 100-200 nodules/mm^2; excessively high nodule counts impair impact strength, while very low nodule count may result in intercellular brittle phases that are also detrimental to strength and ductility;
- Nodularity: a minimum nodularity level of 95% is critical; poorly shaped nodules act as stress risers and as initiation sites for fracture under impact;
- Matrix: fully ferritic, without cell boundary carbides or pearlite due to segregation of trace elements, non-metallic inclusions or other constituents;
- No microshrinkage, or dross can be tolerated.

Experience has shown that these microstructural characteristics can be achieved in the as-cast condition, avoiding a costly annealing heat treatment, by tightly controlling the chemical composition of the castings, by carefully selecting the charge materials and by optimizing the process parameters.

Chemical composition

Table 5 lists the typical chemical composition of finished wind energy castings.

Table 5
Chemical Composition of Wind Mill Castings

Element	wt %
C	3.3 – 3.5
S	0.008 – 0.012
Si	1.9 – 2.2
P	< 0.030
Mn	< 0.15
Mg	0.040

The rationale behind the selection of this chemical composition is as follows:

- Carbon: As shown in Figure 6, a high carbon content increases the graphite fraction in the casting and lowers the absorbed impact energy, although lowering the transition temperature. A low carbon content is favorable to the upper shelf impact energy, but increases the transition temperature. The 3.3 – 3.5% C range was found to offer the best compromise to both properties.
- Silicon: The effect of silicon content on absorbed impact energy of ferritic Ductile Iron is shown in Figure 7. Because of the strong solid-solution hardening effect of silicon in ferrite, the lower the silicon content, the lower the transition temperature. However, a minimum silicon, although kept at a minimum level, is needed in the base iron to maintain its graphitization potential and as post-inoculant addition.
- Sulphur: It is recognized that a minimum sulphur content is required for inoculation (0.006%), while a sulphur content exceeding 0.012% may affect graphite nodularity. As shown in Figure 8, high nodularity is needed for optimum impact properties.
- Phosphorus: As shown in Figure 9, phosphorus is an embrittling element and every effort should be made to keep it to an absolute minimum. Phosphorus forms steadite, a low melting point eutectic, that segregates to cell boundaries during solidification. In heavy section castings, such as wind mill castings, the cell boundary regions can contain as much as 10 times the bulk P concentration. It is a requirement for such castings to maintain P content to less than 0.030% preferably below 0.025%. Although steadite may not be observed in the casting, phosphorus atoms present at cell boundaries reduce the cohesion level of the grain boundaries (4).
- Manganese: It is well known that manganese segregates to cell boundaries, especially in heavy section castings requiring long solidification time, and promotes the formation of pearlite in these regions. As shown in Figure 10, pearlite embrittles Ductile Iron and, in order to avoid its formation, 0.15% Mn is recommended as the maximum concentration in wind energy castings. Note that all other pearlite promoting elements should be maintained at trace levels as well. The beneficial effect of low phosphorus content is also shown on this figure.
- Magnesium: Usually, a Mg content below 0.045% is recommended as this will ensure good nodularity while minimizing the formation of dross.

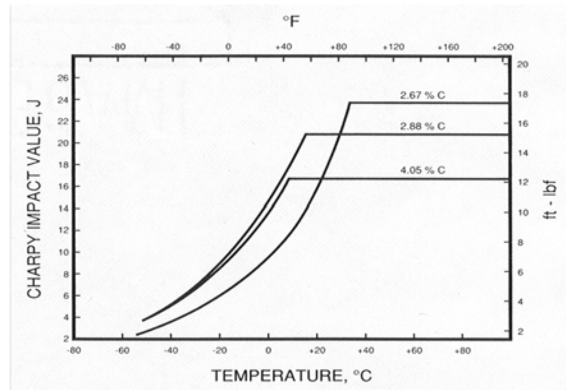

Figure 6 : Effect of Carbon Content on V-Notched Charpy Impact Energy of Ferritic Ductile Iron (3).

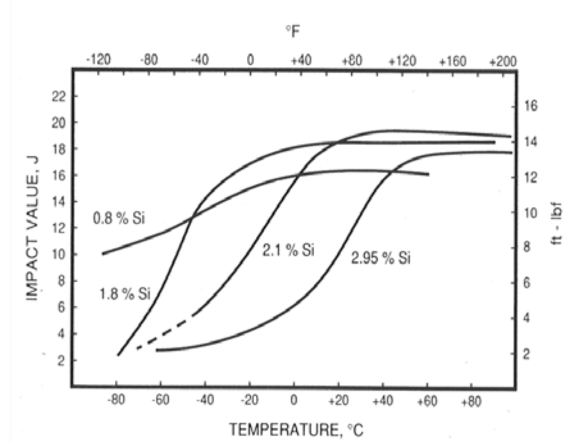

Figure 7 : Effect of Silicon Content on V-Notched Charpy Impact Energy of Ferritic Ductile Iron (3).

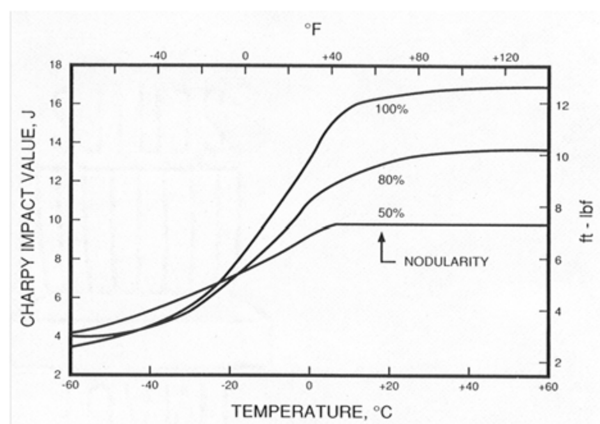

Figure 8 : Effect of Graphite Nodularity on V-Notched Charpy Impact Energy of Ferritic Ductile Iron (3).

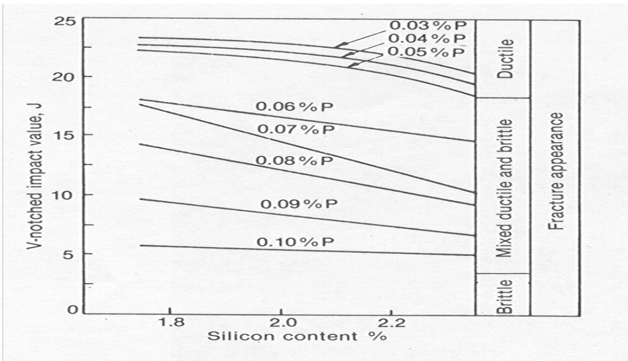

Figure 9 : Effect of Phosphorus on V-Notched Charpy Impact Energy of Ferritic Ductile Irons [5].

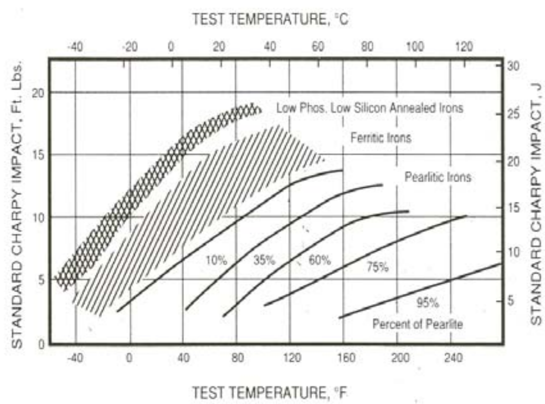

Figure 10 : Effect of Matrix Microstructure on V-Notched Charpy Impact Energy of Ductile Iron [3].

Manufacturing Process

The manufacturing process for as-cast wind energy castings does not differ significantly from the one used in foundries producing high quality ferritic Ductile Iron castings. Nevertheless, certain parameters need special attention in order to obtain, casting after casting, the same outstanding quality. Repeating and documenting every process step is key in succeeding in the manufacture of these demanding castings.

- Charge Materials: A typical charge includes a minimum of 40% high purity iron exhibiting consistently low concentrations of residual elements (P, Mn, Cu, Cr,…). Steel scrap, which is needed to lower the carbon content of the melt, should be certified low P low Mn steel, free of protective coatings (galvanizing, paint,….) and tramp elements. Ductile Iron returns from the production of wind energy castings are high quality materials that can be recycled in the charge. Preconditioning with SiC[6] is also recommended.
- Melting: In order to retain the required high metallurgical quality and nucleation potential of the liquid iron, superheating should be restricted to 1500°C (2730°F) for a short period of time.
- Magnesium Treatment: Treatment methods using elemental magnesium or high magnesium alloys can result in excessive deoxidation of the iron and are not recommended. Tundish cover ladle treatment that minimizes the amount of Mg alloy used is particularly well adapted for this type of production. One could consider the use of nickel-magnesium alloy. It has the advantage of minimizing the amount of silicon added at this process step while alloying with nickel is beneficial to impact energy without, at this level, enhancing pearlite formation.
- Inoculation: This is the key process step to ensure a high nodule count that would prevent intercellular segregation of phosphorus and pearlite promoting elements such as manganese, and avoid the formation of porosity. Powerful inoculants with good fading resistance should be used. Inoculation should be carried out in two steps: 0.4 to up to 0.8% inoculant during transfer to the pouring ladle and late inoculation (in-stream or in-mold) with 0.10 to 0.20% inoculant.
- Pouring Temperature: The castings are usually poured at 1370-1400°C (2500-2550°F), but the pouring temperature needs to be determined carefully, depending on the casting section size and rising technique used; the foundryman should take advantage of the self-feeding characteristics of a high metallurgical quality liquid Ductile Iron.
- Molding: Rigid, well compacted molds are key elements for the production of sound heavy section castings. Filters are often utilized to ensure inclusion free castings. Use of chills in critical areas and of mold wash is often practiced. Venting should be sufficient to ensure fast filling of the mold.

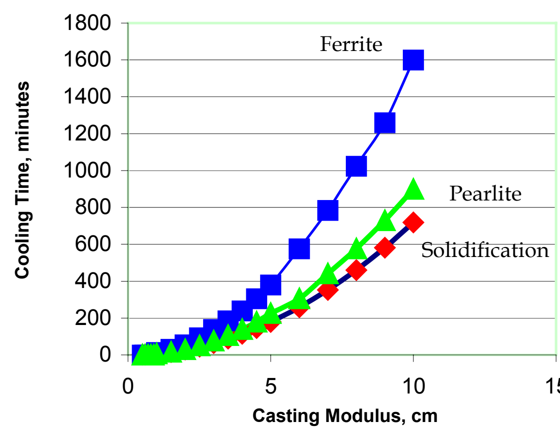

Figure 11 : Recommended Shake-Out Times as a Function of the Targeted Matrix and Modulus [7].

- Shake-out: Cooling time in the mold is critical to avoid/minimize pearlite. Figure 11 presents the recommended minimum shake-out time to obtain a ferritic structure as a function of the casting modulus. For comparison purpose, those required for a pearlitic matrix are also shown.

Repeating procedures and documenting process parameter data are essential components of the production of wind energy castings. Consistent, high quality castings can only be achieved by controlling each process step. The foundry must then be able to measure accurately, heat after heat, all the input materials, to control the process variables and to verify the final quality of the castings:

- Base iron: Weight and chemistry controls of charge materials, chemical composition within specified target, exact weight of the metal to be treated, close temperature control to meet the targeted pouring temperature range;
- Mg Treatment: Control of the alloy (chemistry, size,…), accurate weight control of the added amount;
- Inoculation: Control of the alloy (chemistry, size, …), exact and timely additions of the inoculant;
- Casting Quality Control: Mechanical testing and metallographic examination of test bars, hardness check of the castings.

PERSPECTIVE OF THE NORTH AMERICAN MARKET

As shown in Figure 12, in 2002, USA produced about 15% of the world wind energy, which corresponds to 4 685 MW, or enough to serve 1.2 million households.

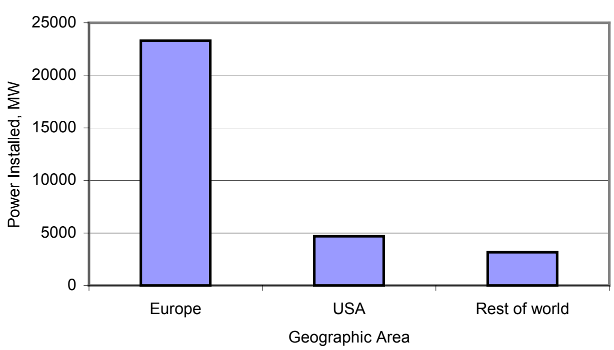

Figure 12 : World Wind Energy Generated by Region in 2002 [8].

Like elsewhere in the world, wind energy in USA is largely dependent on government incentives. The lull in the US market is primarily due to the uncertain status of the wind energy tax credit (PTC), a key federal incentive. PTC was established in 1992 but expired twice during the past five years. The industry is seeking a multi-year extension that would provide a more stable investment environment in the US wind power market. Although this situation creates uncertainty, the American Wind Energy Association (AWEA) forecasts positive growth of the installed capacity for the coming years. Figure 13 presents the AWEA forecast of the installed capacity for the period 2003-2010. In 2020, it is estimated that 6% of the US electricity will be sourced from wind power plants.

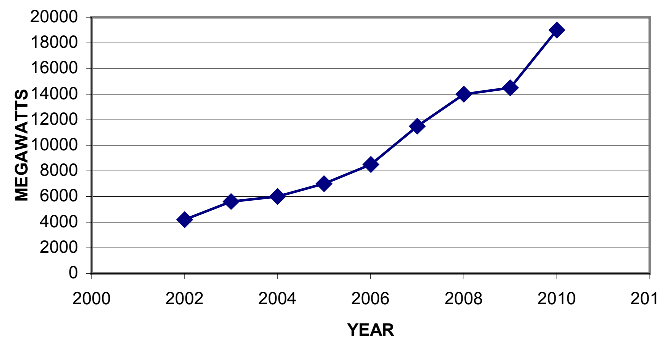

Figure 13 : Wind Energy Installed Capacity Forecast in North America [8]. (Data for years 2008 and beyond is based on hypotheses that may change).

Based on these previsions, forecasts have been made for three different Ductile Iron parts currently used in wind mill construction: hub, rotor flange and nacelle frame. Note that the number of units varies from one part to the other because certain wind mill designs use other materials than Ductile Iron in this application; that is particularly the case for the nacelle frame. Figure 14 presents the forecasts for Ductile Iron hubs, rotor flanges and nacelle frames needed in North America up to 2010. It is seen that, in 2010, more than 36 000 tons of Ductile Iron castings will be needed for these three parts. The total tonnage for all Ductile Iron components will exceed 50 000 tons.

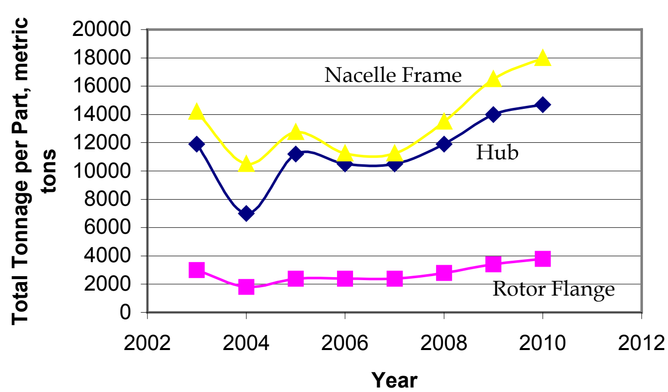

Figure 14 : Projected Ductile Iron Needs for Specific Castings for the Period 2003-2012.

The scenario presented in Figures 13 and 14 may be influenced by many factors, including the uncertainty regarding the PTC. The data presented assume that PTC will be renewed or, globally speaking, that the support of wind energy by North American governments will not drastically be reduced in the coming years. This is considered, from the PTC point of view, as a minimal scenario which could be positively influenced by new political measures (eg. reduction of CO_2 emissions).

Ductile Iron has a well established reputation in the wind energy casting market, due to the high quality castings delivered up to now. This performance and the relatively low cost of the material have contributed to protect the market from other materials. Maintenance of this quality level would confirm the dominating position of Ductile Iron in the future.

CONCLUDING REMARKS

- The development of wind power in Europe has accelerated, especially in the 1990's, and this trend is expected to continue in the coming decade. Although the relative increase curve tends to flatten, the new installed power capacity is believed to exceed 9000 MW per year for many years to come.
- Ductile Iron has been selected by the producers of wind energy power plants for many mechanical components because of its lower density and excellent reliability, even at low temperatures (-20°C) (-4°F).
- For such applications, ferritic Ductile Iron with high impact toughness at -20°C (-4°F) (EN-GJS-400-18 LT) is the selected material for all Ductile Iron parts.
- European foundries have shown that this grade can consistently be produced in the as-cast condition by carefully selecting charge materials, controlling the chemical composition and optimizing the manufacturing parameters.
- The North American market for wind energy power plants is expected to follow the same trend as the European market during the 2000-2010 decade.
- Ductile Iron will remain a material of choice for wind mill components in the North American market. In 2010, the tonnage of Ductile Iron hub, rotor flange and nacelle frame castings needed in the North American wind energy sector will exceed 36 000 tons. The total market for wind energy castings may then exceed 50 000 tons.

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