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THIN WALL DUCTILE IRON CASTINGS AS SUBSTITUTES FOR ALUMINIUM ALLOY CASTINGS

CIENKOŚCIENNE ODLEWY Z ŻELIWA SFEROIDALNEGO JAKO SUBSTYTUTY ODLEWÓW ZE STOPÓW ALUMINIUM

The paper discusses the reasons behind current trends for substituting cast iron castings by aluminum alloys. In particular it is shown that it is possible to produce thin wall castings (control arms, cantilevers and rotors) made of ductile iron without the development of chills, cold laps or misruns, and with a strength to weight ratio of up 87 MPa cm^3/g. In addition, austenitizing at 900 ^{o}C for 20 minutes and then austempering in a salt bath at 350 ^{o}C for 15 minutes promotes the development of a fully ausferritic matrix in thin wall castings with a the strength to weight ratio increase of up to 154 MPa cm^3/g. Finally, it is shown that thin wall castings made of ductile or austemperded cast iron can be lighter and with superior mechanical properties then their substitutes made of aluminum alloy.

Keywords: thin wall, ductile iron, aluminum alloy

W pracy omówiono przyczyny aktualnego trendu zastępowania odlewów z żeliwa przez odlewy ze stopów aluminium. W szczególności wykazano, że możliwe jest wytworzenie odlewów cienkościennych (wahacze, wsporniki, wirniki), wykonanych z żeliwa sferoidalnego bez zabieleń, niedolewów i niespawów oraz posiadających wskaźnik wytrzymałości (stosunek wytrzymałości do gęstości) wynoszący do 87 MPa cm^3/g. Ponadto zastosowanie obróbki cieplnej polegającej na austenityzacji w temperaturze 900°C przez 20 minut oraz hartowaniu izotermicznemu w kąpieli solnej w temperaturze 350°C przez 15 minut powoduje otrzymanie osnowy ausferrytycznej w odlewach cienkościennych, co zwiększa wskaźnik wytrzymałości do 154 MPa cm^3/g. Z przeprowadzonych badań wynika, że odlewy z żeliwa sferoidalnego mogą być lżejsze od ich substytutów ze stopów aluminium, a przy tym charakteryzować się podobnymi lub lepszymi właściwościami mechanicznymi.

1. Introduction

Increase of worldwide automobile usage has resulted in the escalation of the associated environmental problems (global warming, air pollution, acid rain and destruction of the ozone layer). To date, the most effective methods for reducing auto emissions have been improving the combustion cycle, introducing catalytic convertors and making vehicles lighter. An estimate [1] of car fuel consumption reductions indicates lowering the weight of the vehicle by 100 kg leads to fuel savings of 0.5 to 1 liter. As a direct consequence of the race for lower fuel consumption, automotive manufactures have turned to new technologies to make cars lighter. A significant part of this effort includes the substitution of Al alloys for component, which have traditionally been cast in ferrous alloys. This is why cast iron production [2] decline, while there has been a systematic increase in the production of aluminum alloy castings. The main advantage associated with replacing castings made of cast iron by aluminum alloys arises from the low Al alloy density, which is roughly 0.38 that of cast iron. There are other advantages in employing aluminum alloys which can be summarized as:

- Low melting and pouring temperatures. In this case mold heating is relatively low and conventional permanent-mold casting can be employed, which provides superior dimensional accuracy and improved casting surface quality.
- High thermal conduction which promotes efficient cooling of components.
- Finishing and aesthetics.
- Non-magnetic character of aluminum. This facilitates the process of scrap selection and recycling.

However, the decision to substitute cast iron for Al alloys is not always rational and it must be preceded by a thorough analysis of all the factors involved such as: (a) mechanical properties at room and elevated temperatures, (b) wear and material compatibility with parts made of different materials, (c) damping and noise, and (d) total energy consumption as well as (e) production cost.

Mechanical properties. When considering substituting Al alloys by cast iron, one should takes into account the specific (property-to-density ratio) mechanical properties (Fig. 1). In general (Fig. 1a-c), it can be stated that an iron casting can be produced at the same weight as an aluminium casting, and it will have similar tensile strength R_m, yield strength $R_{p0,2}$

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and stiffness (assumed as the ratio of yield strength $R_{p0,2}$ to Young modulus E) and/or higher the elongation. An exception in making these comparisons is the case of austempered ductile iron (ADI), which posseses properties that are far superior to any Al-alloys. Aluminium alloys have no endurance limit (Fig. 1d) and therefore require oversizing to prevent fatigue failure in critical chassis and body components. Hence, it is evident that cast iron posses similar of better relative properties (property/density) than aluminum alloys. Moreover, there are other several disadvantages to using Al over alloys. In some cases it is important to have high temperature mechanical integrity such as in internal combustion engine, housing of catalysts. From Fig. 1e it is found that above 100°C the relative strength of aluminum alloys drops sharply. In contrast, above 200°C the relative strength of ductile iron with a pearlitic matrix exceeds considerably the relative strength of aluminum alloys. Hence, in high temperature applications cast iron is a better option in terms of mechanical integrity. High temperature properties particularly strength can be a major concern, particularly in compression-ignition engines due to the high compression ratios involved. In Al alloys, a relatively low strength combined with a relatively low elastic modulus leads to low stiffness in engine blocks. In turn, this can adversely influence the mechanical integrity around the crankshaft bearings. In order to avoid any potential failures in the cranckshaft bearing regions, increasing volumes of Al metal are introduced and/or additional ribs are implemented in the casting design.

Wear properties. Other factors which need to be considered in the casting design are the wear properties. Cast iron posses an inherent ability for surface hardening, (i.e. the generation of a hard and wear resistance surface layer with a soft and plastic core). This is not the case in Al or Mg alloys without additional processing which results in expensive layers. The relatively low wear resistance of Al alloys has made it necessary to use cast iron sleeves in the bores of the engine blocks. However, additional surface machining is needed and there are thermal mismatch issues due to thermal expansion at the sleeve-Al alloy interfaces that can result in thermal stressing and failure of the cylinder regions.

Damping capacity. The relatively low damping capacity of Al alloys when compared with cast iron (Fig. 1f) generally results in high engine or box gear noise. In order to reduce noise, there are various methods, but they all are associated with increasing costs and engine weight. These problems do not exist in engine blocks and box gear made of cast iron.

Total energy consumption. It is known that in order to produce 1 ton of primary aluminum by electrolysis, the energy required is of the order of 164 to 171 GJ [4]. This amount of energy is approximately 10 times the energy needed to produce 1 ton of pig iron in the blast furnace (from 16.8 to 18.8 GJ) [4]. Although the melting temperature of Al alloys is half the one for cast iron, the melting enthalpies are very similar (Fig. 2) due to the high heat capacity of Al (nearly twice the one corresponding to Fe) and the high heat of solidification (approximately 30 % high) of Al when compared to cast iron. Moreover, most castings made of aluminum alloys are produced from secondary alloys from raw materials consisting of scrap and primary aluminum. In turn, this means that Al casting production involves at least two melting processes and a double use of energy. In contrast, the production of castings made of cast iron is usually a single-stage process. In general, it is evident that the production of cast iron is related to energy savings when compared with aluminum alloys. Notice that cast iron can be remelted as many times as needed without deterioration of the cast iron quality.
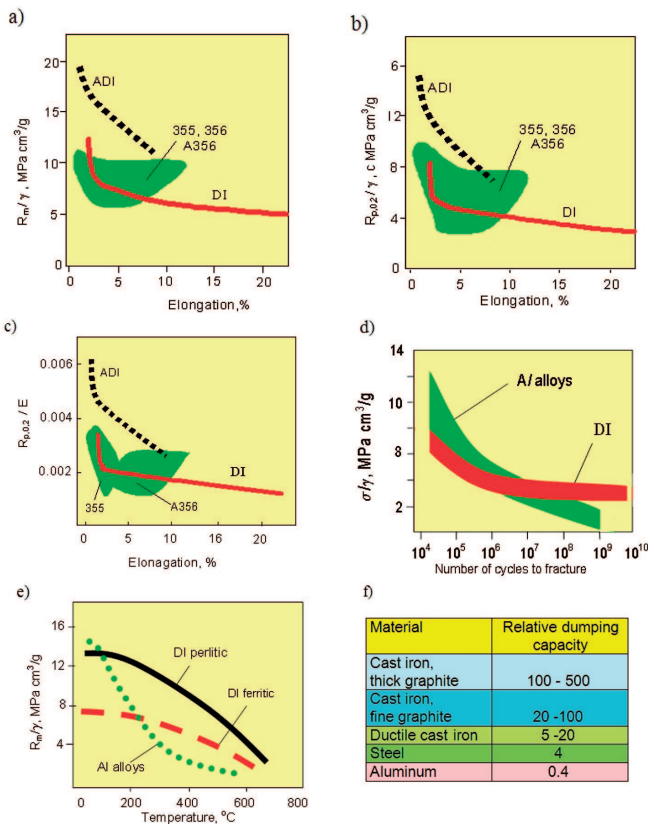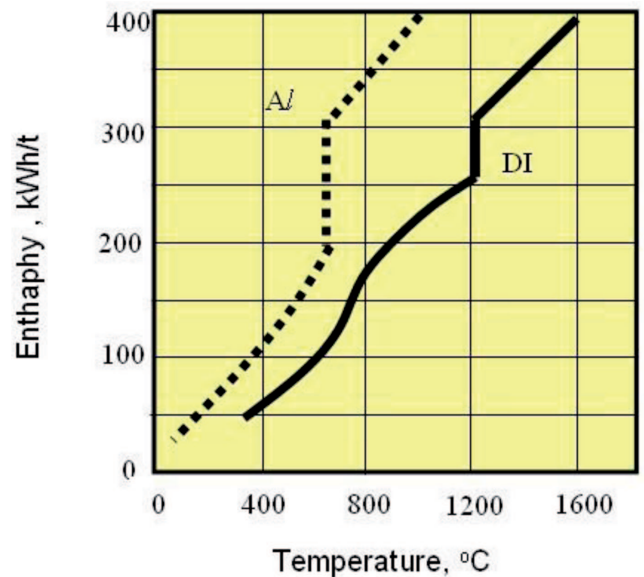

Fig. 1. (a) Relative tensile strength, (b) yield strength, (c) stiffness, (d) fatigue strength [3], (e) high temperature strength [3] and (f) relative damping capacity: 355, 356, A356 – aluminum alloys according to American Standard. DI – ductile cast iron and, ADI – austempered ductile iron

Fig. 2. Enthalpy of aluminum and of ductile iron as a function of temperature [4]

Production costs. From an economics point of view, the most important argument in favor of cast iron is the low production costs when compared with aluminum alloys (Table 1).

TABLE 1
Cost comparisons for materials per unit tensile strength

Cast iron	$\dfrac{1500\$/t}{200\ to\ 250\ MPa}$ = 6.0 to 7.5\$ / MPa
Ductile iron	$\dfrac{1700\$/t}{350\ to\ 900\ MPa}$ = 1.8 to 4.8\$ / MPa
ADI	$\dfrac{2500\$/t}{900\ to\ 1400\ MPa}$ = 1.7 to 3.1 \$ / MPa
Steel	$\dfrac{3000\$/t}{450\ to\ 700\ MPa}$ = 4.3 to 6.6\$ / MPa
Aluminum alloys	$\dfrac{8000\$/t}{158\ to\ 310\ MPa}$ = 25. 8 to 50.6\$ / MPa

From the mentioned arguments it is evident that the decision to substitute cast iron for Al alloys is not always rational. In the cast iron foundry industry, it is common practice to solidify iron castings at relatively low cooling rates in order to avoid the development of defects (chills, misruns and cold shuts). In turn, this imposes a constraint on the minimal cast iron wall thickness of more than 3 mm. The main reason for the substitution of cast iron by aluminium in many applications seems to be the inability of iron foundries to produce thin wall (<3 mm) ductile iron castings which can lighter than counterparts made of Al alloys with an information deficiency on cast iron properties available to designers. This technology should have been developed years ago when lightweight alloys started to penetrate the iron market. The main problem related to such technology is linked to cast iron solidification in the range of very high cooling rates. Accordingly, the cooling rate of liquid cast iron at the onset of graphite eutectic solidification can be given by [7]:

$$Q = \frac{8\ T_s\ a^2}{\pi\ \ln\left(\frac{T_i}{T_s}\right)\ c^2\ s^2} \qquad (1)$$

In this equation: T_s is the equilibrium temperature for the solidification of the graphite eutectic, a is the material mold ability to absorb heat, c is the specific heat of cast iron, T_i is the initial liquid metal temperature just after filling of the mold and, s is the wall thickness.

Figure 3 shows the predicted cooling rates as a function of the wall thickness, s for castings made of conventional molding sand, including a comparison with experimentally reported data. From this figure (curve 2) it is evident that when the wall thickness is reduced by 2 mm, there is an almost negligible change in the cooling rate of the conventional castings (i e., when the wall thickness shifts from 10 to 8 mm). When the casting wall thickness is reduced from 5 into 3 mm there is an appreciable effect on the cooling rate changes (from about 14 to 34°C/s) and it becomes critical when the wall thickness is reduced from 3 to 1 mm as the cooling rates dramatically change from roughly 34°C/s to above 300°C/s. Hence, the production of thin wall castings demands very high constraints on dimensional tolerances for the mould cavities as the casting wall thickness decreases. Dimensional tolerances of ±0.5 mm are clearly unacceptable. For example, from Fig. 3 (curve 2) results that in 3±0.5 mm thick castings the cooling

rate changes from 25 to 50°C/s while in the 2±0.5 mm thick casting the cooling rates change from 50 to 140°C/s and in 1.5±0.5 mm thick castings the cooling rate changes from 80 to over 300°C/s. In fact, such "drastic" changes in cooling rates in castings can lead to chills, cold shuts and misruns. On the other hand, thin wall ductile iron castings (TWDI) are characterized by extremely high nodule count and in consequence small interparticle spacing, λ which can be estimated from the Fulman equation [8]

$$\lambda = \frac{1 - f_{gr}}{N_L} \qquad (2)$$

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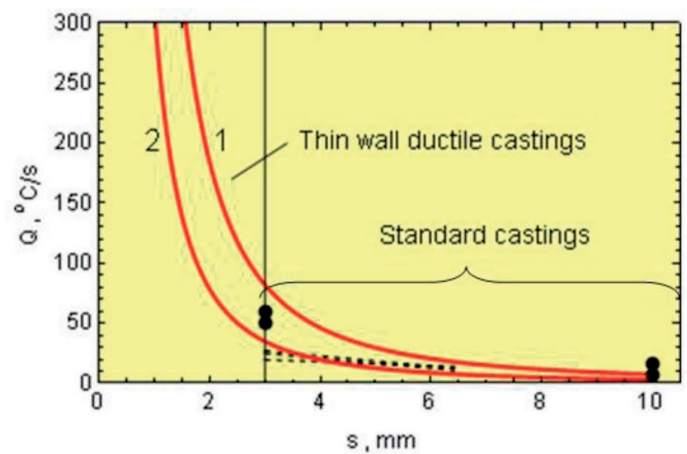

Fig. 3. Influence of wall thickness, s and temperature, T_i of the liquid metal on the cooling rate of castings: line 1 – eq. (1) for C=3.6%; Si = 2.7%; T_i = 1340°C, c = 5.95 J/cm³a = 0.11 J/(cm² s$^{1/2}$ °C), line 2 – eq. (1) for C=3.6%; Si = 2.7%; c = 5.95 J/cm³, T_i = 1450°C, a = 0.09 J/(cm² s$^{1/2}$ °C), dots – experimental data [5], lines —— experimental data [6]

The interparticle spacing, λ can be related to the characteristic diffusional distance for alloying elements. For fabrication of austempered ductile iron (ADI) with typical sections sizes, alloying additions (Ni, Cu and Mo) must be made to the iron in order to increase of austemperability (ability of material to permit quenching to austempering temperature without formation of pearlite) [9]. Contrary, the nature of thin wall in TWDI castings makes it possible to eliminate the use of alloying elements. In heavy section castings the interparticle spacing is big and in consequence the segregation of alloying elements is difficult to avoid so, the microstructure is highly inhomogeneous. In TWDI, the diffusional distance is small, so the segregation of alloying elements is minimal and highly homogeneous microstructure can be obtained. Moreover, it is known that the extremely high nodule count combined with short diffusional lengths for carbon effectively reduce the required austempering times [10]. Hence, one can think of TWDI castings as an ideal material to obtain of austempered ductile iron castings (TWADI).

Numerous studies [11-16] have been published on thin wall ductile iron. Yet, these works are limited to simple plate shaped castings. Accordingly, the aim of this work is to produce sound TWDI and TWADI iron castings which are lighter

than counterparts made of Al alloys, but with improved mechanical strength, superior damping capacity and lower final costs.

2. Experimental

The cantilever, rotor castings and forging control arms made of aluminum alloy (Fig. 4a-6a) was selected in order to show that they can be replaced by of lighter castings made of ductile iron castings. The cantilever and control arm moulds were made using the chemically bonded 75-mesh silica sand. In the case of rotor parts the moulds were made using the Shaw process. It is well known that fading in nodule count, N and in consequence changes in chilling tendency of ductile iron [17] are extremely rapid during the first minute following post inoculation. At the time of inoculation the liquid iron is in a "super-inoculated" state (Fig. 7) and exhibits the maximum nodule count and hence a minimal chilling tendency. Therefore, inmold process was chosen. Melts were produced using an electric induction furnace. The raw materials were Sorel-metal, steel scrap and commercially Fe-Si alloy. The metal was preheated at 1500°C and then poured into the molds, which was equipped with a reaction chamber containing a mixture of 0.85% spheroidizer (44-48% Si, 5-6% Mg, 0.25-0.4% La, 0.8-1.2% Al, 0.4-0.6 Ca) and 0.5% of inoculant (73-78% Si,
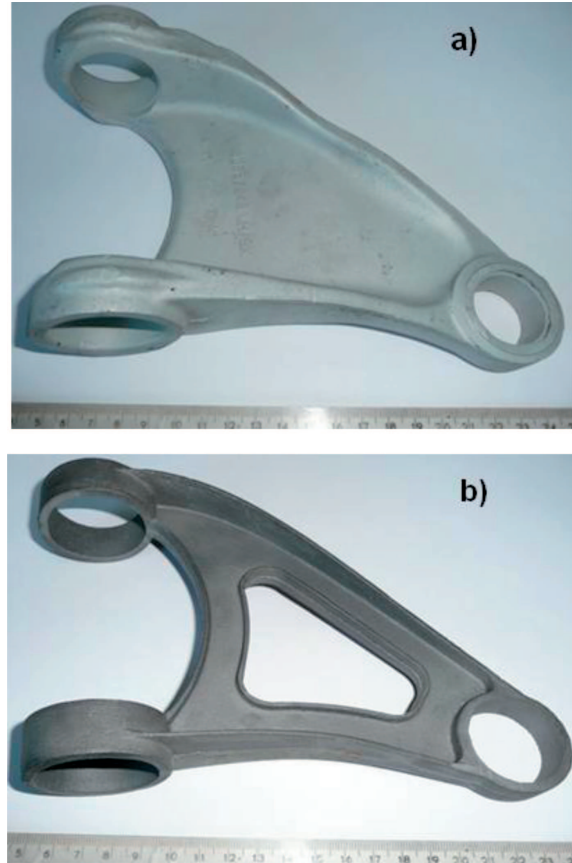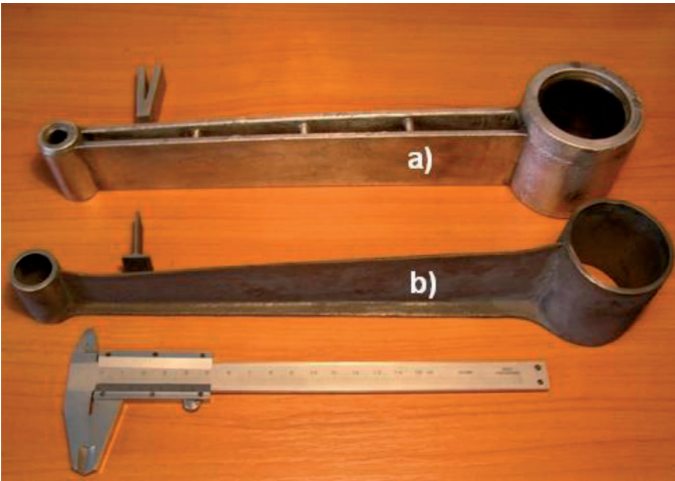

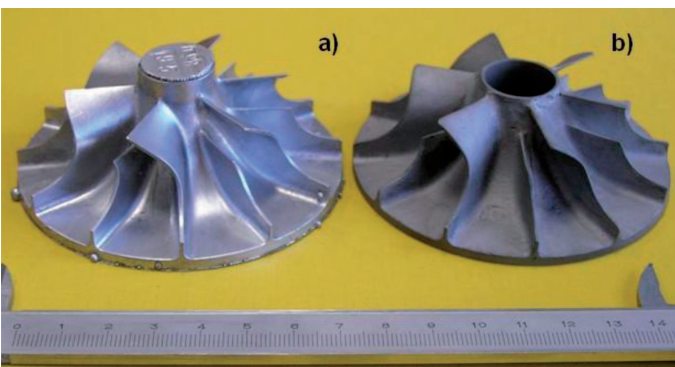Fig. 4. Cantilevers: (a) aluminum alloy (weight 580 g), (b) thin-walled ductile iron cantilever (weight 380g)

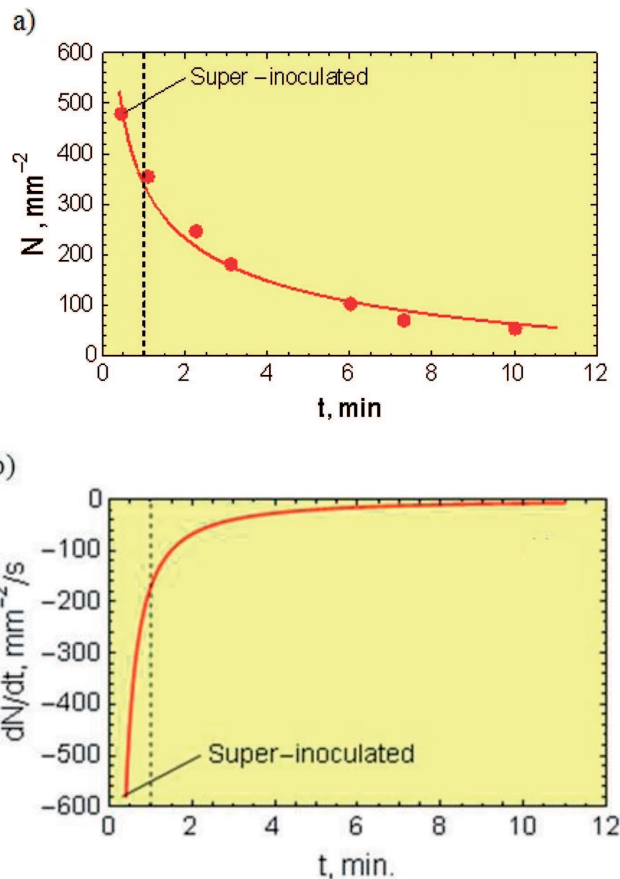Fig. 5. Rotors: (a) aluminium alloy and (b) thin-walled ductile iron casting

Fig. 6. Control arms: (a) forged aluminum alloy (weight 585 g) and (b) thin-walled ductile iron casting (weight 480 g)

Fig. 7. (a) Fading of nodule count N, and (b) rate fading dN/dt

0.75-1.25% Ca, 0.75-1.25% Ba, 0.75-1.25% Al) connected to a mixing basin. In addition, post-inoculation ocurrs in the mixing basin by introducing 0.1% of inoculant. The chemical composition of the cast iron: 3.59-3.68% C; 3.01-3.10% Si; 0.10-0.12% Mn; 0.02% P; 0.01% S; and 0.023-0.027% Mg. One part of castings were investigated "as cast" while second part were austenitised in a digitally controlled muffle furnace at 880°C for 20 min., quenched and austempered in a salt bath ($NaNO_2$- KNO_3) held at 350°C. for time 15 min and then air cooled. In Fig. 8 there is shown sketch with spots of cantilever,
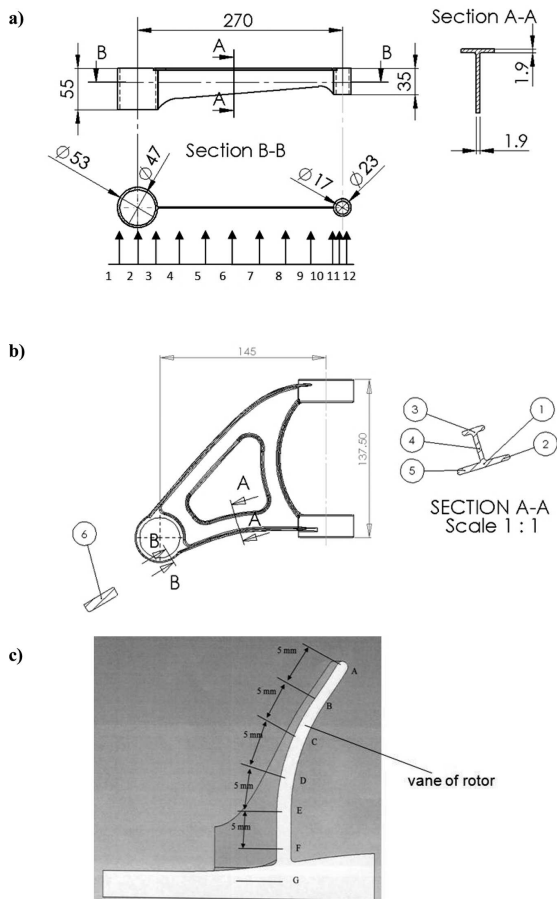

Fig. 8. Dimensions (mm) of the thin-walled ductile iron castings and spots where the metallographic examinations were made, cantilever (a), control arm (b) and rotor (c)

control arm and rotor where metallographic examinations were made. Metallographic determinations of the nodule count, as well as of the cementite and ferrite fractions were made on samples cut from the experimental casting. The average nodule count (average number of graphite nodules per unit area), N_F was measured using a Leica QWin quantitative analyzer at 200 x. The mechanical properties were determined using a flat specimens cut from cantilever and control arms using an Instron universal testing machine. Also shape strength investigations were made of the cantilever and the control arms made of aluminium alloy and their super-thin wall ductile cast iron substitutes. To do this photo-elasticity layers method was used and the Von Mises stress were determined using a SolidWorks program. Using these methods it is possible to optimize the part design in order to have a uniform distribution of stress and strain at any part section, which is particularly relevant in thin wall castings.

3. Results and discussion

Metallographic examinations

Results of nodule count, as well as ferrite fraction are summarized in Table 2. It can be observe that in areas of thicker wall castings the nodule count is lower than in areas of thin wall. Moreover, the metallographic examinations show that microstructure in all TWDI castings is chill free, without porosity and pearlitic-ferritic or ferritic-perlitic (Fig. 9) or in TWADI -ausferritic matrix (Fig. 10).

TABLE 2

Nodule count and ferrite fraction

| Spot x mark	Wall thickness, mm	Nodule count N_F, $1/mm^2$	Ferrite fraction, %
cantilever			
1*	3.0	1736	44
2*	3.0	1766	41
3*	3.0	1563	56
4	1.9	2245	58
5	1.9	2194	49
6	1.9	2229	46
7	1.9	2779	49
8	1.9	2582	47
9	1.9	2646	37
10*	3.0	1529	52
11*	3.0	1606	49
12*	3.0	1849	45
control arm			
1	2.3	1510	60
2	2.0	2101	40
3	2.0	1925	40
4	2.1	1350	55
5	2.0	2050	40
6	3.7	1300	80
rotor			
A	1.01	3072	85
B	1.03	2560	83
C	1.02	2667	82
D	1.06	2781	82
E	1.56	2274	83
F	3.06	1045	85
G	4.60	818	77
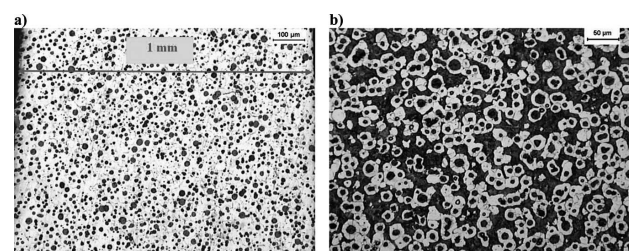
Fig. 9. Microstructure of on a cross section of the rotor vane with wall thickness 1.0 mm (a), and of the rib of the cantilever with wall thickness 1.9 mm (b)
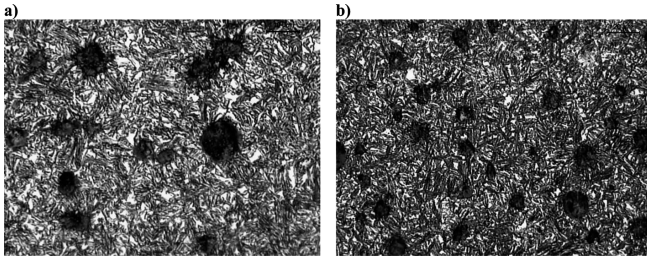
Fig. 10. Microstructure of cantilever (a) and a control arm (b) after a short-term heat treatment, Nital etched, mag. 500x

Mechanical testing

The results of mechanical testing for the Al alloy castings and both TWDI and TWADI counterparts are given in Table 3 and examples of the stress-strain curves corresponding to flat samples taken from the aluminium alloy and TWDI as well as TWADI cantilever rib are shown in Fig. 11.

TABLE 3

Mechnical properties of Al alloy, TWDI and TWADI materials

Material	R_m, MPa	$R_{p0,2}$, MPa	E, %	R_m/γ, MPa cm^3/g
Original cantilevers	170	46	1.9	62
TWDI cantilevers	630	310	7.0	87
TWADI* cantilevers	1112	-	6.1	154
Original control arm	290	149	9.2	63
TWDI control arm	526	318	6.7	73
TWADI** control arm	850	-	5.5	118

*880/20/350/15
** 880/20/400/15
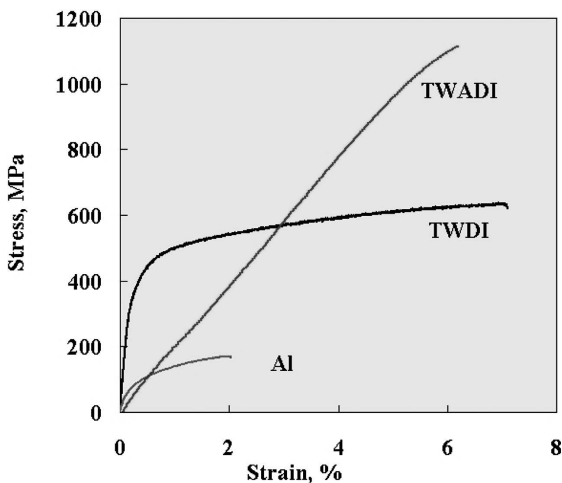austenitise temperature/ time/ austempering temperature/ time

Fig. 11. Stress-strain curve of the sample taken from the rib of the cantilevers

Cantilevers

From tests (Table 3) results that the ultimate tensile strength, R_m and yield strength, $Rm_{0,2}$ of TWDI and TWADI cantilever are far superior the ones corresponding to the aluminum alloy ($Rm = 170$ MPa and $Rp_{0,2} = 46$ MPa). Moreover,

the ductile and austempered iron ductility is 6 to 7% can be compared with only 1.9% for the aluminum alloy. Ductile and austempered iron castings also have a higher strength to weight ratio, R_m/γ. In addition, the investigations of stress distribution (using photo-elasticity layer coatings) indicate (Fig. 12) that the light-weight cast iron cantilever can easily handle the stress concentrations (3-order isochromatic). In contrast, the cantilever made of aluminium alloy, is under significant stress concentration effects at the large hub-rib joint location (4-order isochromatic) which can lead to part failure and disqualification.
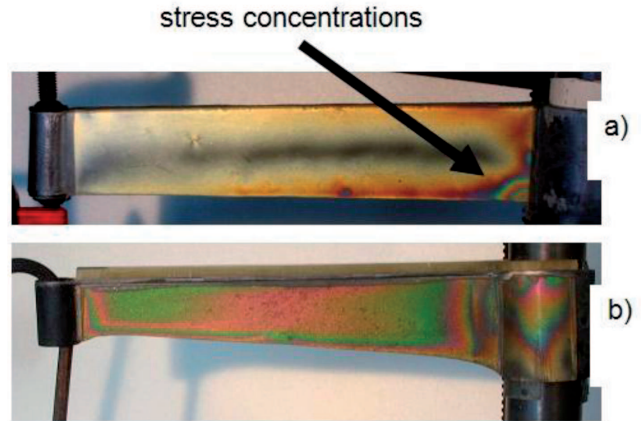

Fig. 12. Isochromatic lines on cantilevers casting made of: (a) aluminium alloy casting, (b) thin wall ductile casting
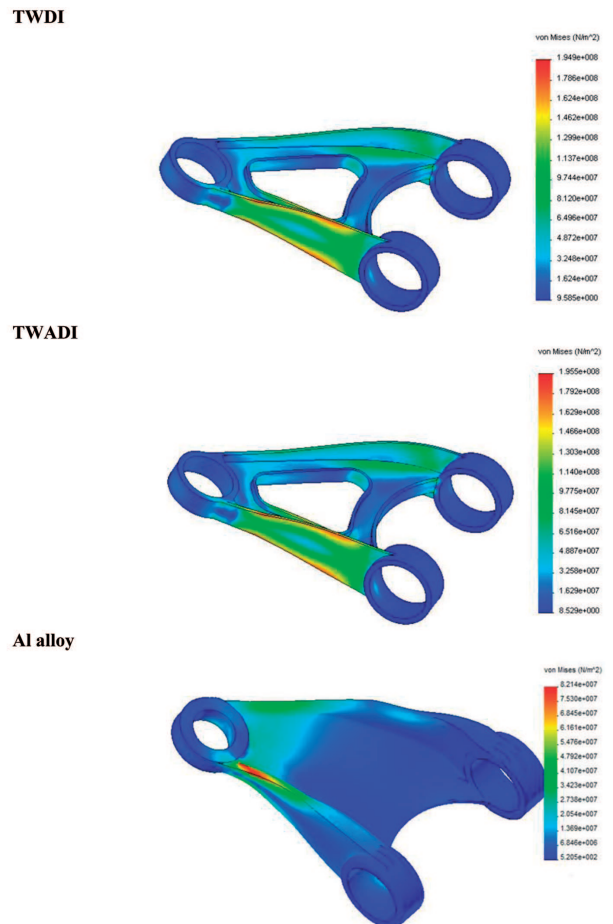

Fig. 13. Von Mises stress concentrations of control arm

Control arms

Control arms made of TWDI and TWADI show (Table 3) superior ultimate tensile strength, $R_{m.}$, yield strength $R_{p0,2}$ and slightly lower elongation, E than the parts made of forged aluminium alloy (6061-T6). In addition, ductile iron castings possess a high strength to weight ratio, R_m/γ. Moreover, from the computer simulation based on the SolidWorks program, Von Mises stress concentrations (Fig. 13) were not very different among the forged aluminium alloy, the TWDI and the TWADI. In all the cases, the level of stress concentration does not exceed the yield strength, $R_{p0,2}$. The calculated safety coefficients (defined as the yield strength divided by the maximum equivalent stress) used in our analysis yields values: of 2.49, 1.60 and 1.81 for control arms made of TWADI, TWDI and forged aluminium alloy. Thus, the light-weight nodular iron castings can be loaded to similar (TWDI) or higher (TWADI) working conditions as the forged aluminium alloy without any potential failures.

4. Conclusions

1. Through super inoculation of the liquid cast iron it is possible to produce thin wall castings made of ductile iron without the development of chills, porosity, cold laps or misruns, and with a strength to weight ratio from 73 to 87 MPa cm^3/g.
2. Austenitizing at 880°C for 20 minutes and then austempering in a salt bath at 350°C for 15 minutes promotes the development of a fully ausferritic matrix in thin wall castings. In turn, this results in an increase in the strength to weight ratio from 73-87 to 118-154 MPa cm^3/g.
3. TWDI and TWADI castings have a high potential for replacing aluminium alloy parts in diverse applications, particularly those that have high mechanical requirements and can bring substantial savings.

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