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Optimizing the Properties of Thin Wall Austempered Ductile Iron

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ABSTRACT

Production of thin wall austempered ductile iron (TWADI) components can have strength-to-density and elastic-to-density ratios that approach those of cast aluminum, making it theoretically possible to apply ADI in high strength light weight parts. Therefore, development of thin wall ADI technology is essential to permit designers for energy consuming equipment to choose the most appropriate material based on material properties, and not solely on weight or density. In the present work, ductile iron castings with different thicknesses of 2, 4, 6 and 8 mm were cast with an appreciate casting design to assure good mold filling. Short term austempering treatment process was used to obtain thin wall ADI castings. The samples of 2 and 4 mm thickness were austenitized at 900 °C for 30 minutes followed by holding at 350 °C and 400 °C for 10 minutes for each temperature. While, the samples of 6 and 8 mm wall thickness were austenitized at 900 °C for 30 minutes and followed by holding at 350 °C and 400 °C for 30 minutes. The microstructure of TWADI austempered at 350 °C showed finer structure than that austempered at 400 °C. Tensile strength and hardness increased with decreasing casting wall thickness austempered at 350 °C due to the structure refinement effect and decreasing the volume fraction of retained structure in matrix.

Keywords: ADI, thin-wall, austempering treatment, mechanical properties, casting design.

INTRODUCTION

To achieve fuel economy in automotive industry, reducing the vehicle weight has been a major research area of interest over the last few decades. Although the general trend has been to use low density materials (aluminum, magnesium and composites) instead of cast iron and steel in the automotive industry, numerous examples have been recently noted in the literature where iron castings started again to replace aluminum in this industry. This comparison is encouraged by the increased strength, ductility, stiffness, vibration damping capacity, as well as reduced cost [1]. If the yield stress/cost ratio of the various materials is compared, the new member of the ductile iron family, the ADI, is most of the time the winner. When mechanical properties, density and cost are included in material evaluation, ductile iron may offer more advantages than aluminum, particularly if thin wall ductile iron parts could be produced without further heat treatment processes [2]. The potentials for ductile iron applications for lightweight automotive components have been limited by the capability to produce as-cast carbide free thin wall parts (2-3 mm) [3]. Production of thin-wall ductile iron castings still represents a daily challenge in modern foundries. Review of the recent literature shows that thin-wall ductile iron has been successfully produced for many years, thanks to the optimization of some critical production parameters: pouring temperature, chemical composition, thermal conductivity of the molding materials, type and amount of inoculating material in combination with the spheroidizing method adopted, casting design and other foundry basic practices [4-5].

With the commercial introduction of ADI in 1972, consistent efforts have been made to identify new applications of this new emerging material [6] with excellent combination of high strength with good ductility, toughness, machinability and wear resistance. However, difficulties have been encountered in producing ADI thicker than 100 mm due to the segregation of hardenabilty elements added to prevent pearlite formation. Such difficulty in obtaining the required austemperability and the heterogeneous microstructures do not represent a real problem when producing thin wall ADI castings due to the insignificant segregation tendency associated with rapid solidification of those thin wall castings. The use of ADI in thin-wall and high strength parts has, however, been mentioned in a very limited number of references[7,8]. Successful case was recently reported[7], where a hollow connecting rod for a two-cylinder car engine and a front upright for a racing car were successfully made of thin wall ADI, which confirms the capability of ADI to build complex thin walled parts of high strength. With recent development in inoculation theory and practice, it became possible to cast thin-wall ductile iron parts completely free from carbides. Consequently, further improvements in the properties of thin-wall ADI castings could be achieved with the austempering process. In a recent study [8], the results of a R&D program on the effect of wall thickness (3-10 mm) and silicon content (2.4-2.7%) on the properties of ADI has been reported. It has been shown that thin-wall ADI castings austempered at 360 ºC and containing low silicon can exhibit ultimate strength exceeding 1100 MPa with more than 10% elongation. This is an indication that austempered thin-wall ductile iron is becoming a logical choice for the production of small, light weight and cost effective automotive components. However, more data about the metallurgy of thin-wall ADI castings seems to be of practical interest. The objective of this work is to study the characteristics of thin-wall ADI castings austempered at two different temperatures.

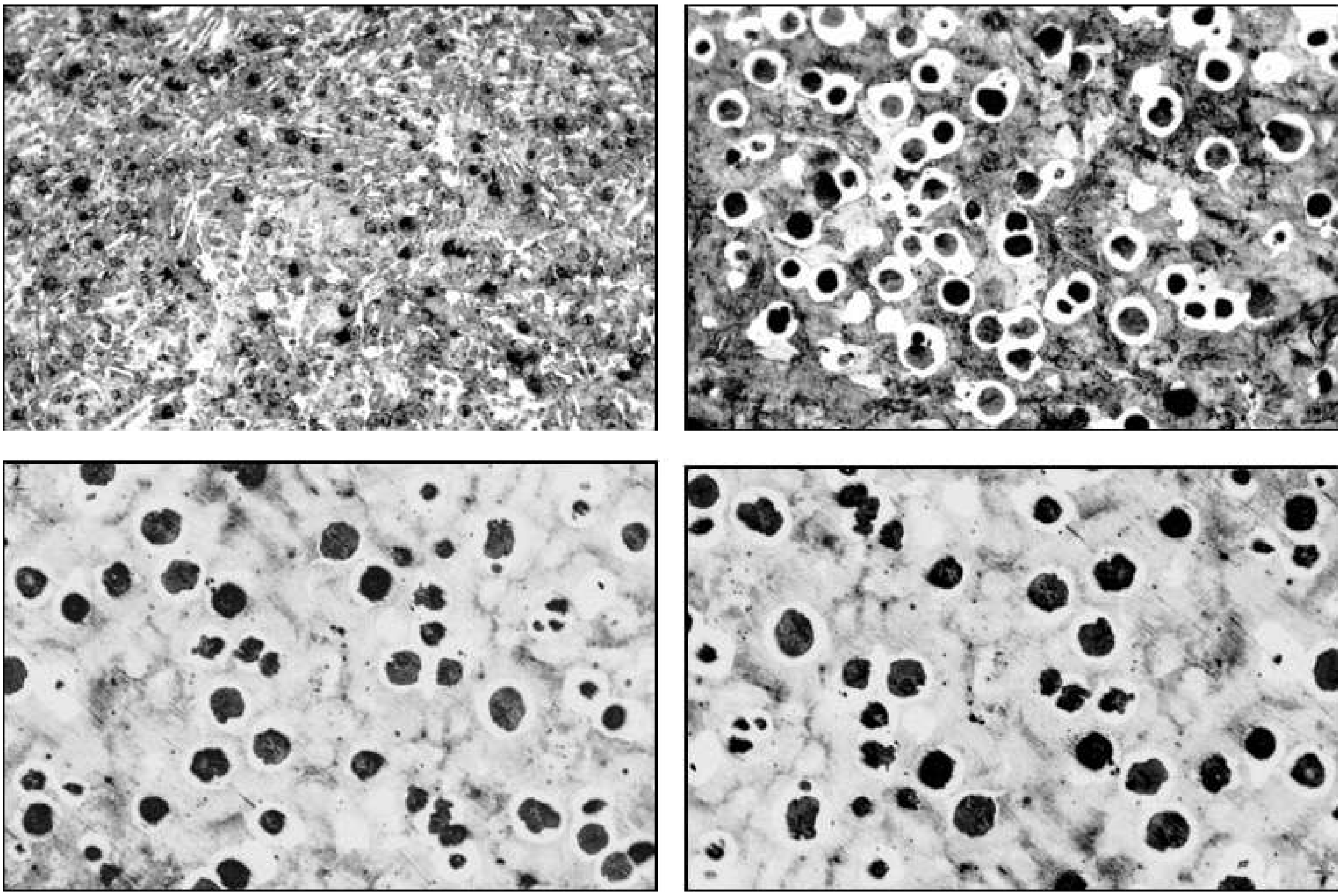

Fig. 1 : Microstructure of the as-cast thin wall ductile iron castings a) 2 mm b) 4 mmc) 6 mm and d) 8 mm

EXPERIMENTAL WORK

The test casting and its gating system were designed, as shown in Fig. 1. The test casting has a plate shape with dimensions of 200 mm x100 mm and 2, 4, 6 & 8 mm thickness. The moulds were made completely of sodium silicate bonded sand. A 100 kg charge, which consists of 60% Sorel metal, 40% steel scrap and the required amounts of copper and ferro-silicon was melted in an induction furnace and then Mg-treated by using Vortex method with FeSiMg alloy [9]. The molten metal was inoculated by foundry grade Fe-Si in two steps, half of Fe-Si quantity was added in the vortex and the rest was added in ladle. The chemical composition of the test casting expressed in mass content of the alloying elements was 3.69% C, 2.6% Si, 0.36% Mn, 0.016% P, 0.005% S, 0.29% Cu and 0.064% Mg. As shown in Fig. 2, the austempering treatment process was carried out by austenitizing at 900 ºC for 30 minutes and then austempering at two different temperatures of 350 °C and 400 °C. Both thicknesses of 2 and 4 mm were soaked at both austempering temperatures for 10 minutes, while the thicker ones (6 and 8 mm) were soaked for 30 minutes. Tensile properties of the material were determined as per ASTM E8. The impact strength was evaluated for the un-notched samples as per ASTM E-23. The volume fraction of retained austenite was also determined using XRD.

Lowering the austempering temperature to 350 ºC, both diffusion and growth rates are decreased and the structure consists of fine needles of bainitic ferrite as shown in Fig. 2 E-H. The ADI samples austempered at 350 ºC were noticed to contain higher amount of unreacted austenite (Fig. 3), which may be attributed to the incomplete transformation at 350 C, where the initiation and completion of transformation are retarded with decreasing the austempering temperature.

RETAINED AUSTENITE

Figure 4 shows the variation of retained austenite content with austempering temperature and casting wall thickness. The results showed that the trend of variation of volume fraction of retained austenite with wall thickness is similar for both austempering temperatures (350 & 400 ^{o}C). The austempering temperature of 400 ^{o}C showed relatively higher retained austenite volume fraction than that at 350 ^{o}C. It is obvious that the volume fraction of retained austenite is increased gradually with increasing the wall thickness due to the difference in bainitic transformation rate with changing in casting wall thickness. However, there is relatively small difference in retained austenite for both austempering temperatures at 2-mm wall thickness due to the rapid bainitic transformation rate arising from the high nodule count in this

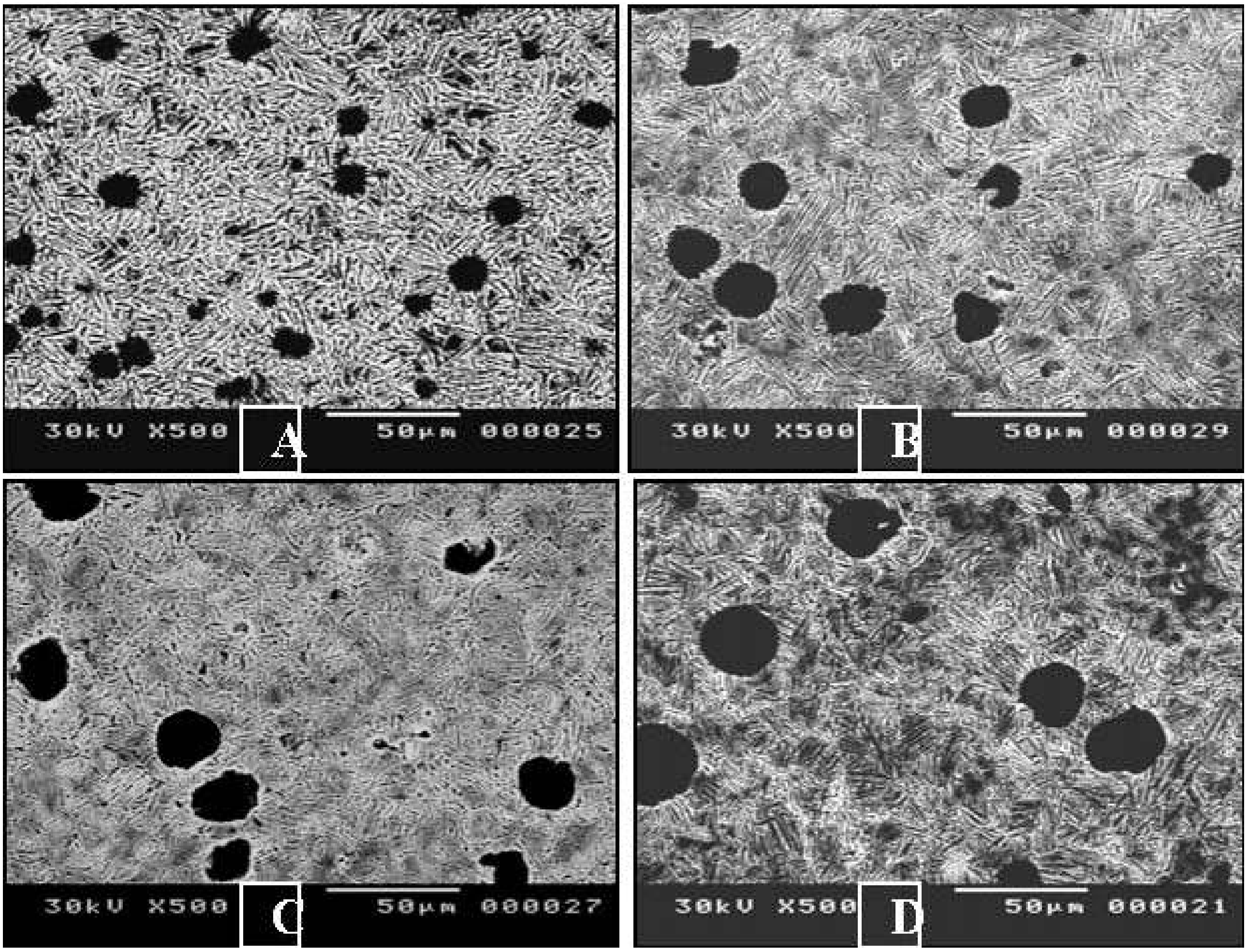

Fig. 2 : Microstructure of the investigated different ADI wall thickness castings A: 2 mm, 400°C - B: 4 mm, 400°C C: 6 mm, 400°C - D: 8 mm, 400°C, E: 2 mm, 350°C - F: 4 mm, 350°C - G: 6 mm, 350°C - H: 8 mm, 350°C

RESULTS AND DISCUSSION

MICROSTRUCTURE

The microstructures of the as-cast DI castings with different wall thicknesses are shown in Fig. 1. It is clear that the structure of 2-mm wall thickness contains a considerable amount of carbides, whereas the 4-mm wall thickness contains only traces of carbides (~ 2%). Increasing the wall thickness to 6 and 8 mm resulted in complete disappearance of carbides. The nodule count decreased with increasing the wall thickness with maximum count of 300 nodules/mm^2 in the 2-mm sections. Nodule count of 180, 165 and 115 were reported in the 4, 6 and 8 mm sections respectively. Figure 4 shows that the microstructure of the austempered samples strongly depends on the austempering temperature as well as wall thickness. It is noteworthy that the carbides noticed in the as-cast 2 and 4 mm thickness samples completely dissolved during the austenitization step of the austempering treatment. The structure of the samples austempered at 400 C is characterized by coarse ferrite platelets isolated by austenite regions. The structure resulted from austempering at such relatively higher temperature of 400 ºC showed a homogenous structure of coarse bainitic ferrite associated with relative higher diffusion and growth rate at such temperature.

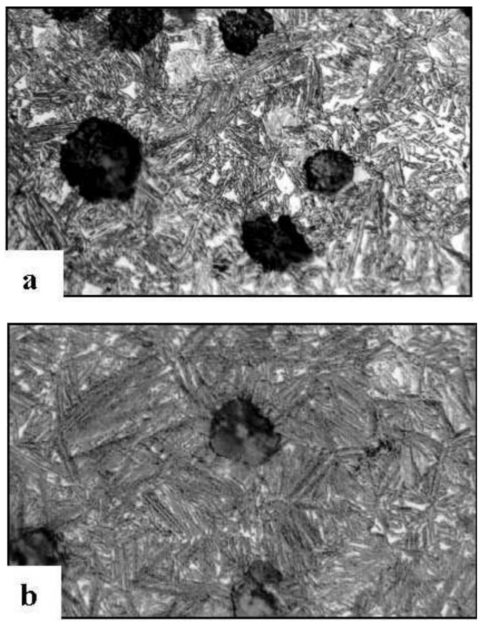

Fig. 3 : Microstructure of the studied samples showing the unreacted austenite in matrix, a- TA= 350 °C b- TA= 400 °C

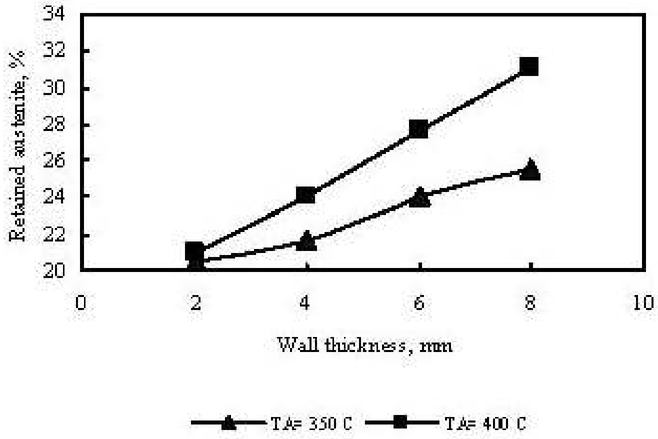

Fig. 4 : Effect of wall thickness and austempering temperature on retained austenite volume fraction

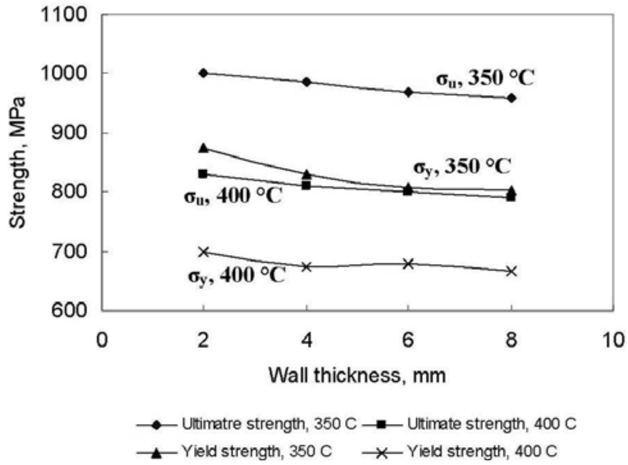

Fig. 6 : Effect of wall thickness and austempering temperature on tensile properties.

thin section. The enhanced transformation due to shortening the diffusion distances in this case may dominate structure formation rather than the difference in austempering temperature.

MECHANICAL PROPERTIES HARDNESS

Figure 5 presents the average hardness values measured on different thin-wall test plates. It is noticed that lower austempering temperature of 350 °C showed higher hardness values compared to the other austempering temperature of 400 °C. At 350 °C, the average hardness values ranged from 330 to 380 HV20 with decreasing the wall thickness from 8-mm to 2-mm. On the other hand, at 400 °C the hardness values varied from 309 to 340 HV20. It is clearly shown that the hardness increases with decreasing the wall thickness due to the structure refinement effect and increasing the bainitic transformation rate.

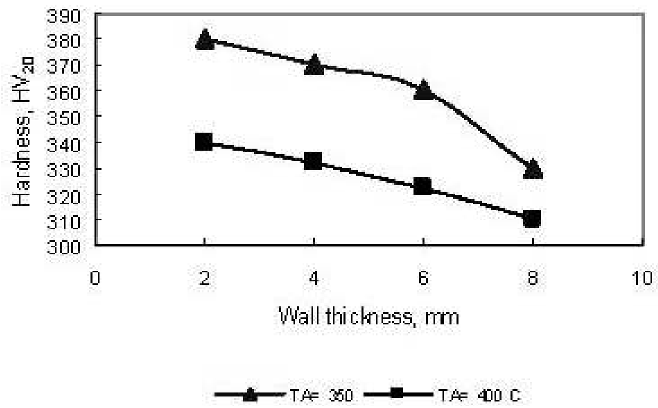

Fig. 5 : Effect of wall thickness and austempering temperature on 9 hardness

TENSILE PROPERTIES

The correlation between tensile strength and wall thickness is shown in Fig. 6. The samples austempered at 350 ºC showed higher tensile properties than those austempered at 400 ºC mainly due to the structural refinement effect and the existence of less amounts of retained austenite associated with lower austempering temperatures. In addition, a slight decrease in tensile properties was noticed with increasing the plate thickness from 2-mm to 8-mm. For samples austempered at TA= 350 ºC, the ultimate tensile strength decreased from 1000 to 950 MPa with increasing the wall thickness from 2-mm to 8-mm, whereas at TA= 400 ºC the ultimate tensile strength decreased from 825 to 775 MPa for the same wall thickness. Whereas the tensile strength values showed low sensitivity to the wall thickness, the elongation percentage increased dramatically with increasing the wall thickness (Fig. 7). It has been indicated in the literature that high nodule count reduces ductility and toughness [3], which may partially contribute to the lower ductility and toughness values reported for the plates with thinner walls. Moreover, the higher amounts of retained austenite in thicker sections may as well play an important role in increasing ductility and toughness values of these plates. From Fig. 7, it is shown that elongation increases with increasing the austempering temperature from 350 ºC to 400 ºC, which is expected due to the higher retained austenite fraction in plates austempered at higher temperature. It is interesting to notice from Figs. 4 and 7 that the retained austenite in the structure as well as the elongation of the 2-mm plates were not affected by the

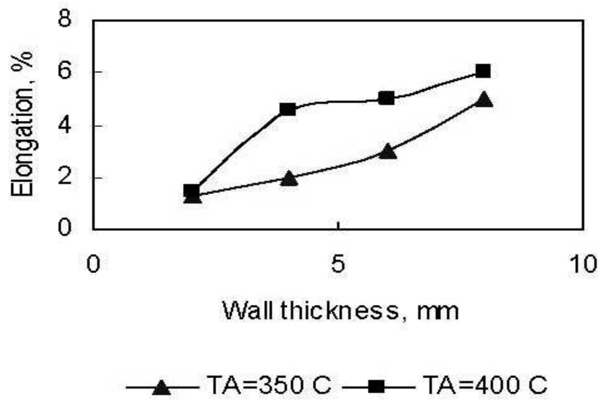

Fig. 7 : Effect of wall thickness and austempering temperature on impact elongation percentage

austempering temperature, whereas retained austenite and consequently elongation increases with increasing the wall thickness of the plates. It is well established that the austempering reaction starts by nucleation of ferritic platelets at the graphite/matrix interface. With the rather high nodule count encountered in the structures of 2-mm plates, it is expected that the transformation will proceed at rather high speed, independent on the austempering temperature. In other words, it may be assumed that the enhanced transformation rate due to the high nodule count will mask the influence of austempering temperature on diffusion and the structure and the elongation of the 2-mm thick plate will be almost the same.

IMPACT ENERGY

The effect of wall thickness on impact energy of the specimens austempered at 350 °C & 400 °C is illustrated in Fig. 8. The results show that the impact energy is increased gradually with increasing the wall thickness due to the formation of more percentage of retained austenite in the final structure. In addition, the austempering temperature of 400 °C showed higher impact energy in all ranges of wall thicknesses than at 350 °C due to the presence of higher amount of retained austenite at 400 °C than at 350 °C [10]. On the other hand, the nodule count plays an important role, with increasing the graphite nodule count the probability of failure (decreasing the impact energy) will be increased [11]. Moreover, by increasing the nodule count the distance between graphite nodules will decrease and then the resistance to impact energy will be decreased. Therefore, the impact energy of the studied samples depended on:

Austempering temperature: higher austempering temperature of 400 °C obtained higher impact energy than at 350 °C.

Amount of retained austenite: higher amount of retained austenite in matrix lead to higher values of impact energy.

Nodule counts: higher counts of graphite nodules showed lower impact energy.

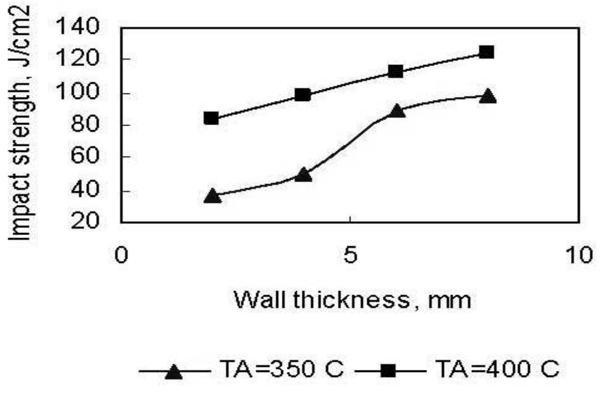

Fig. 8 : Effect of wall thickness and austempering temperature on strength

In accordance with the ASTM standard A897-06, there are 6 different grades of ADI depending on their ultimate tensile strength [12]. In this study, the samples austempered at 350°C can be considered as grade 2 because they have tensile strength more than 900 MPa and impact energy of more than 100 J; while the other samples austempered at 400 °C can be characterized as grade 1 with lower strength. Minimum required strength for this grade is 750 MPa and 110 J impact toughness.

CONCLUSIONS

- 2 mm ADI plate exhibits a homogenous ausferritic structure with nodule count of 300/mm^2.
- Retained austenite volume fraction increased gradually (in both austempering temperatures of 350 & 400 °C) with increasing wall thickness due to the difference in bainitic transformation rate.
- Hardness increases with decreasing casting wall thickness due to structure refinement effect.
- The austempering temperature of 350 °C showed tensile strength in the range of 1000 to 950 MPa with increasing casting wall thickness from 2 to 8 mm, while these tensile values become lower (825 – 775 MPa) at austempering temperature of 400 °C.
- Impact strength increased gradually with increasing wall thickness. The austempering temperature of 400 °C resulted in higher impact strength than of 350 ºC because of the higher retained austenite associated with 400 °C.

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