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An austempering study of ductile iron alloyed with copper

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Abstract: Austempered ductile iron (ADI) has proved to be an excellent material as it possesses attractive properties: high strength, ductility and toughness are combined with good wear resistance and machinability. These properties can be achieved upon adequate heat treatment which yields the optimum microstructure for a given chemical composition. In this paper the results of an investigation the austempering of ADI alloyed with 0.45 % Cu for a range of times and temperatures are reported. The microstructure and fracture mode developed throughout these treatments have been identified by means of light and scanning electron microscopy and X-ray diffraction analysis. It was shown that the strength, elongation and impact energy strongly depend on the amounts of bainitic ferrite and retained austenite. Based on these results, and optimal processing window was established.

Keywords: ductile iron, austempering, strength, impact energy, fracture, processing window.

INTRODUCTION

Many applications of austempered ductile iron (ADI) have been reported[1,2] since it offers a combination of high strength, toughness and good wear resistance with low cost. In addition, ADI has received a lot of attention in the research literature.

The mechanical properties of ADI depend on the austempered microstructure[3–6] which, in turn, is a function of the austempering time and temperature. Most of the recent research has been focussed on the effect of alloying elements on the microstructure, properties and austempering response of ADI.[7] As an alloying element, copper widens the austenite zone of the phase diagram, increasing both the transformation rate during an austenitising process and the carbon content in the matrix. On the other hand, during the subsequent austempering process, copper

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may restrain carbide formation.[8]

The scope of this research was to study the effect of austempering variables (time and temperature) on the microstructure and mechanical properties of ADI alloyed with copper.

EXPERIMENTAL

Ductile iron keel blocks with a chemical composition in wt.%: 3.6 C; 2.5 Si; 0.28 Mn; 0.04 Cr; 0.45 Cu; 0.014 P; 0.014 S; 0.066 Mg; were produced in a commercial electro-induction foundry furnace. The melt was poured from about 1420 ºC into standard 25.4 mm Y block sand molds (ASTM A-395), which ensured sound castings. Tensile specimens of 6 mm diameter and 30 mm gauge length and unnotched Charpy specimens (55×55×10 mm) were machined from the Y blocks. Specimens austenitized in a protective argon atmosphere at 900 ºC for 2 h were rapidly transferred to a salt bath at the austempering temperature 300, 350 and 400 ºC, held for 1, 2, 3 and 4 h and then air-cooled to room temperature.

Standard metallographic preparation techniques (mechanical grinding and polishing followed by etching in Nital) were applied prior to light microscopy (LM) examinations. A Leitz metalographic microscope was used for microstructural characterization, whereas an Opton Axioplan light microscope equipped with the software Vidas was applied to measure the distribution of the graphite nodules and the volume fraction of retained austenite. The change in the volume fraction of retained austenite during austempering was determined by X-ray diffraction using a Siemens D-500 diffractometer with nickel filtered CuK_α radiation. The diffractograms were analyzed applying the direct comparison method.[9]

Tensile tests of austempered specimens were performed on an 50 kN hydraulic machine with a constant cross-beam travel speed of 1 mm/min. The 0.2 % proof stress, the ultimate tensile stress (UTS) and elongation at failure were measured. The austempered Charpy specimens were tested at room temperature in a standard impact testing machine. At least three specimens were tested for each heat treatment. The fractured surfaces were examined with a JEOL JSM-6460LV scanning electron micrscope (SEM) operated at 25 kV.

RESULTS AND DISCUSSION

Microstructure

The morphology of the graphite nodules in the microstructure of the as-cast ductile iron (Fig. 1a, b) is fully spherical, with the nodule count of 80 to 95 nodules/mm^2. Spheroidization is evident (> 90 %) with an average nodule size of 17 μm (Fig. 1a). The microstructure of the as-cast material is mostly pearlitic, over 80 % (Fig. 1b).

The ADI microstructures are shown in Fig. 2a–d. The specimen austempered at 300 ºC for 1 h consisted of bainitic ferrite, retained austenite, and some amount of martensite (Fir. 2a). When the austempering time was increase up to 2 h, the martensite disappeared from the microstructure. Specimens austempered at 300 ºC showed a typical lower bainitic microstructure with an acicular appearance of bainitic ferrite. The acicular appearance of bainitic ferrite in the matrix of retained austenite (with an average amount of 15–25 vol%) was also present in the microstructure after austempering at 350 ºC (Fig. 2c). The highest austempering temperature yielded a plate-like morphology of bainitic ferrite with a higher amount of retained austenite (Fig. 2d). It is ob-

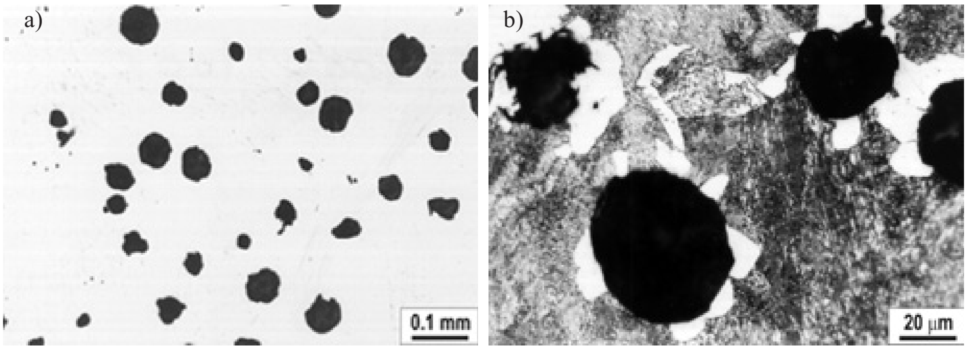

Fig. 1. LM. Microstructure of an as-cast specimen: (a) unetched specimen; (b) etched specimen.

vious that after an austempering time longer than 1 h, no martensite could be detected and the structure consisted only of bainitic ferrite and retained austenite. This may be explained by the fact that at short austempering times, the carbon content was insufficient to retain the stability of the austenite and, therefore, it was transformed to martensite. However, at longer austempering times, the carbon enrichment was sufficient to stabilize the austenite even after air-cooling.

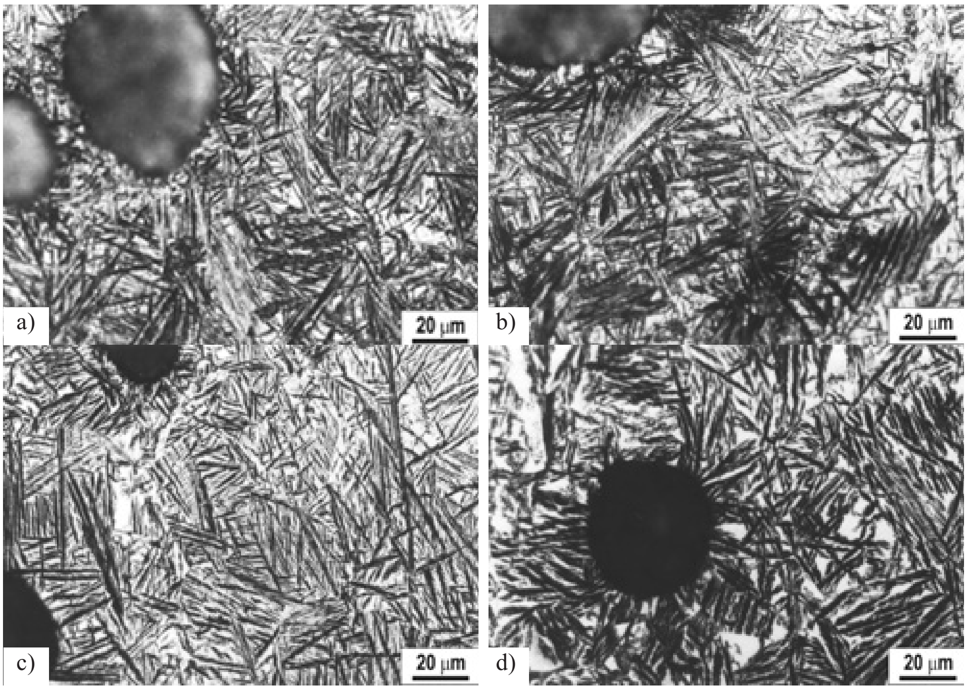

Fig. 2. LM. Microstructure after austempering for 1 h at (a) 300 ºC and for 2 h at: (b) 300 ºC: (c) 350 ºC and (d) 400 ºC. M-martensite.

The time and temperature of isothermal transformation during the austempering treatment have a marked influence on the relative amount of retained aus-

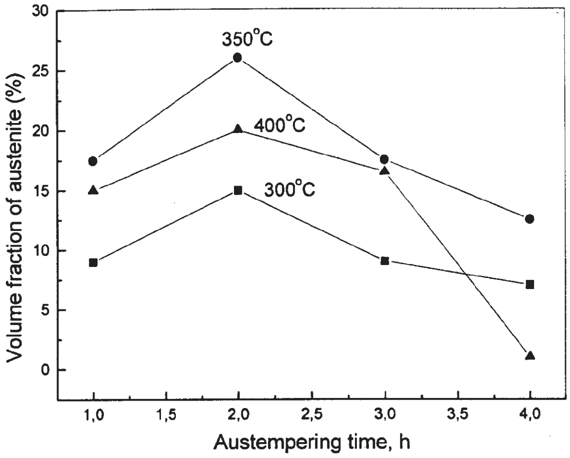

Fig. 3. The effect of austempering time on the volume fraction of retained austenite at different austempering temperatures.

tenite (Fig. 3). From the shape of the curves in Fig. 3, it is apparent that two stages are involved in the isothermal transformation. In the Stage I (times less than 2 h), the amount of retained austenite increases with time. This may be explained by the fact that the transformation to bainite was not completed. It is well documented[10] that austenitic regions having low silicon and high carbon concentrations, *e.g.*, regions between graphite nodules, will not undergo transformation (to bainitic ferrite and retained austenite) during short austempering times and the formation of martensite cannot be prevented during the subsequent cooling from the austempering to room temperature. With somewhat longer austempering times, the amount of retained austenite increases reaching a maximum after 2 h. However, after 2 h the amount of retained austenite decreases, indicating the start of Stage II of the austempering reaction, when the retained austenite decomposes to bainitic ferrite and carbide. This decrease is more pronounced at 400 °C and is associated with the decomposition of austenite to ferrite and carbide.[6]

Fractogrpahy

The fractured sufrace of an impact tested specimen austempered for 1 h at 300 °C shows a fully brittle fracture (Fig. 4a). The fractographs of impact tested specimens austempered at 300, 350 and 400 °C for 2 h and impact tested are shown in Fig. 4b–d. The specimen austempered at 300 °C exibits a mixture of ductile and brittle fracture, *i.e.*, dimples and cleavage fracture appear (Fig. 4b). Only the specimen austempered at 350 °C reveals a fully ductile dimpled fracture (Fig. 4c), whereas at 400 °C the fracture mechanism is generally brittle cleavage (Fig. 4d).

The effect of austempering variables on the mechanical properties

The variation of 0.2 % proof stress, UTS, elongation and impact energy with austempering time for austempering tempeatures 300, 350 and 400 °C is shown in Fig. 5a–c. The strength remains basically unchanged, although some increase is visible after 3 h of austempering at 300 and 350 °C (Fig. 5a, b). The low values of

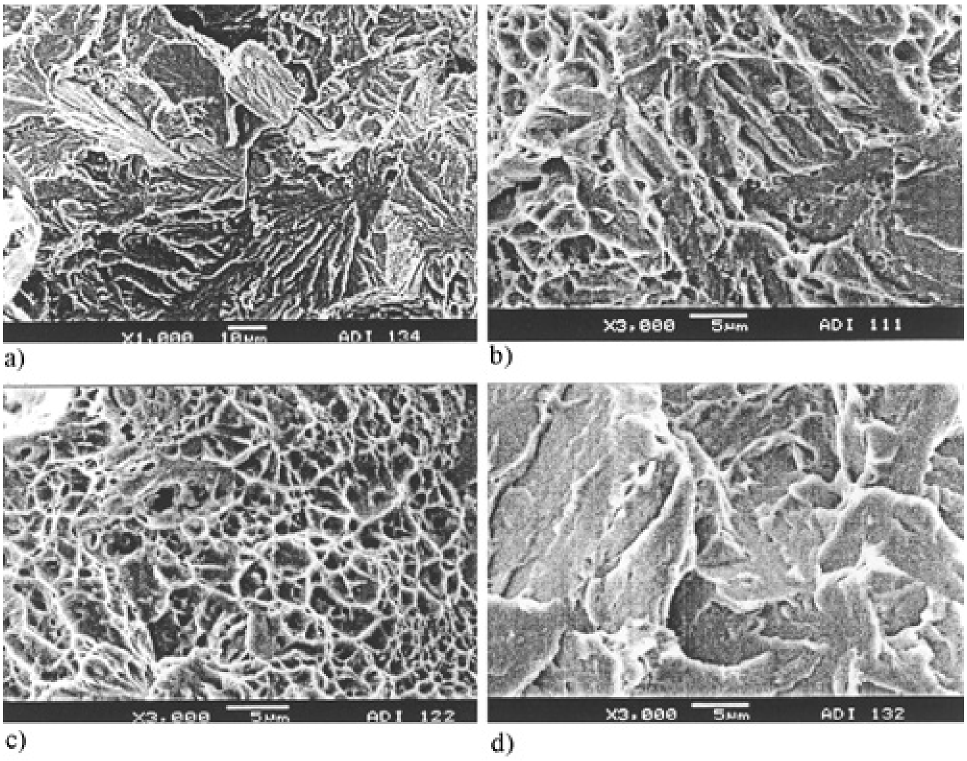

Fig. 4. SEM. Fractographs of impact tested specimens austempered for 1 h at 300 ºC (a) and austempered for 2 h at: (b) 300 ºC; (c) 350 ºC and (d) 400 ºC.

elongation and impact energy (Fig. 5c) at short austempering times are connected with the significant amount of brittle fracture caused by the presence of martensite in the structure. With longer times, the martensite disappears from the structure, whereas the amount of bainitic ferrite and retained austenite increases, resulting in a maximum of elongation and impact energy after 2 h of austempering. With further increasing of the time, a decrease in elongation and impact energy occurs. This decrease is evident especially at 400 ºC. The low values of elongation and impact energy correspond to a decrease in the amount of retained austenite at longer austempering times.

The variation of the 0.2 % proof stress, UTS, elongation and impact energy after 2 h of austempering at different temperatures is shown in Fig. 6a, b. The high strength at the low austempering temperature (Fig. 6a) is associated with an acicular appearance of bainitic ferrite with some martensite and retained austenite. The fine structure of ferrite platelets and the low amount of retained austenite contribute to this high strength. Also, the effect of other parameters must not be neglected, *i.e.,*: dispersed carbide formation, high dislocation density and the lattice distortion of the ferrite due to carbon supersaturation.[11] As the austempering temperature increases, the martensite disappears from the structure and the amount of

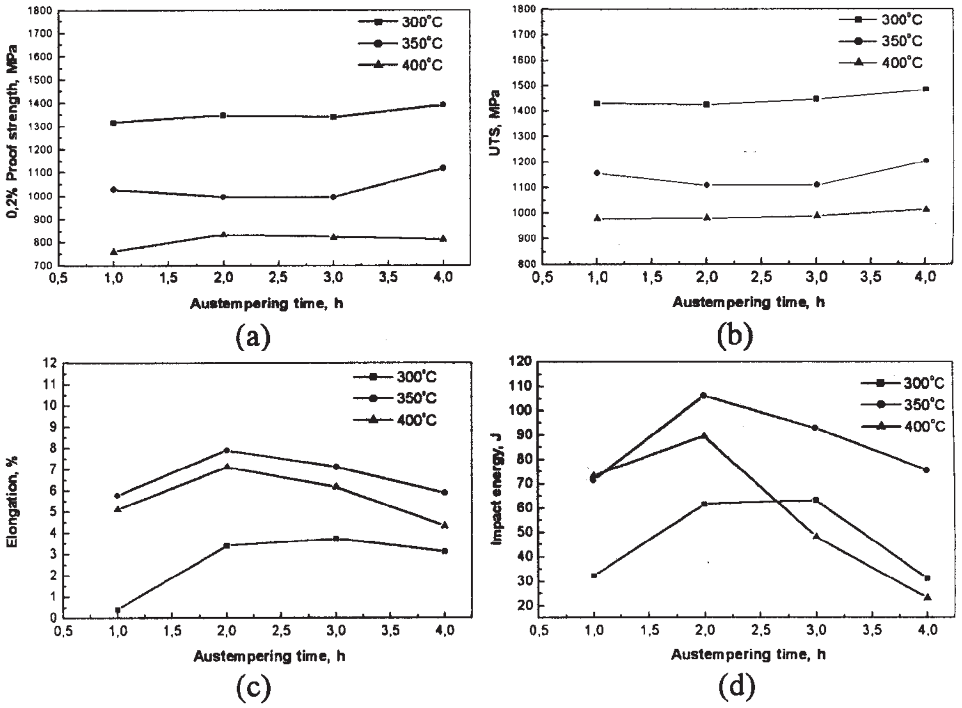

Fig. 5. The effect of austempering time on: (a) 0.2 % proof stress; (b) UTS and (c) impact energy at different austempering temperatures.

retained austenite increases. These changes result in reduced strength. Values of elongation and impact energy show a maximum at 350 ºC, which coincides with the highest amount of retained austenite (see Fig. 3).

According to the above results, the optimal processing window, *i.e.*, austempering at 350 ºC for 2 h, yields mechanical properties which are as follows: UTS: 1180 MPa; elongation: 8 %; impact energy: 106 J. These properties correspond to a microstructure consisting of a plate-like morphology of bainitic ferrite and re-

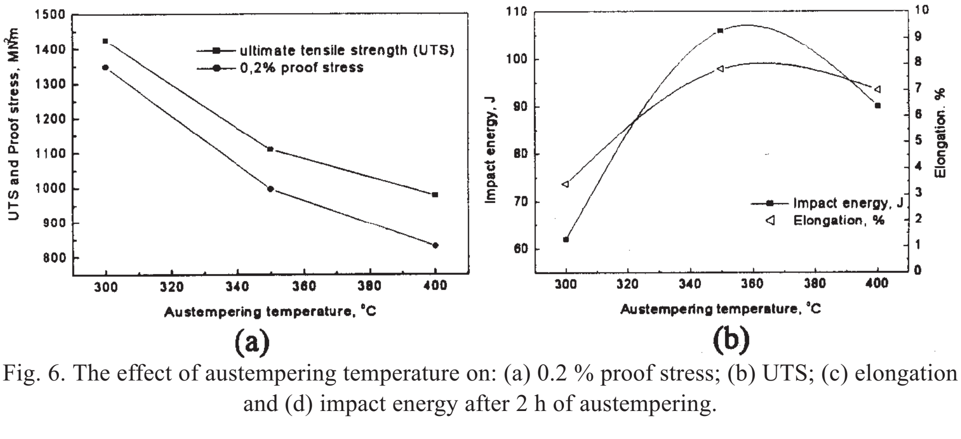

Fig. 6. The effect of austempering temperature on: (a) 0.2 % proof stress; (b) UTS; (c) elongation and (d) impact energy after 2 h of austempering.

tained austenite with a volume fraction of austenite of about 22 vol.%, whereby the fracture mode is fully ductile. Comparing these values with the results referring to the same processing window of ADI without copper addition (UTS: 1320 MPa; elongation: 3.4 %; impact energy: 90 J),[12] it is obvious that alloying with copper decreases the strength, but improves the elongation and impact strength.

CONCLUSIONS

The microstructural and mechanical properties of ADI alloyed with 0.45 % Cu were studied by means of light and scanning electron microscopy, X-ray diffraction analysis, as well as tensile and impact tests. It was shown that:

– The as-cast microstructure was a predominantly (over 80 %) pearlitic with 95 % nodularity of graphite nodules

– the strength, elongation and impact energy strongly depend on the amounts of bainitic ferrite and retained austenite

– the optimal processing window for austempering was established to be 350 ºC, 2 h. The obtained microstructure consisting of bainitic ferrite and retained austenite, yields the best combination of mechanical properties, *i.e.,*: UTS: 1180 MPa; elongation: 8 %; impact energy: 106 J;

– alloying with copper improves the elongation and impact energy, but decreases the strength of ADI.

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ИЗВОД

ИСПИТИВАЊЕ АУСТЕМПЕРОВАЊА ДУКТИЛНОГ ЖЕЛЕЗА ЛЕГИРАНОГ СА ДОДАТКОМ БАКРА

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Аустемперовани нодуларни лив (ADI) показао се као одличан материјал који поседује привлачна својства: високу чврстоћу, пластичност и жилавост који су повезани са добром отпорношћу на хабање и машинском обрадивошћу. Ова својства могу бити постигнута одговарајућом термичком обрадом која производи оптималну микроструктуру за дати хемијски састав. У овом раду истраживање било је спроведено на нодуларном ливу легираном са 0,45 % бакра ADI и аустемперовано у опсегу времена и температуре. Микроструктура и облик прелома постигнути кроз ове третмане били су идентификовани помоћу светлосне, скенинг електронске микроскопије и рендгеноструктурне анализе. Показано је да чврстоћа, издужење и ударна енергија строго зависе од количине беинитног ферита и задржаног аустенита. Оптимални опсег процесирања био је утврђен на основу ових резултата.

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