Phase Transformation and Fatigue Properties of Alloyed and Unalloyed Austempered Ductile Irons

by

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ABSTRACT

Specimens of ductile irons austempered at 320℃ and 360℃ for 2 hrs were conducted with ultrasonic vibration treatment and high cycle fatigue (HCF) testing. Experimental results show that specimens after ultrasonic vibration treatment progressively developed phase transformation induced by plastic deformation. Some stringer-type austenite was found to precipitate carbides, while some island-like austenite was transformed into martensite. The best HCF strength obtained in the alloyed specimens at 360℃ was attributed to its largest amounts of retained austenite with good toughness. This retained austenite was likely to transform to martensite under plastic deformation, resulting in a greater fatigue crack growth resistance.

INTRODUCTION

The austempering reaction of ADI usually occurs in two stages in time sequence [1]. In Stage I, acicular ferrite (α) initially nucleates and grows in the vicinity of graphite and along the grain boundary of prior austenite. With the growth of ferrite, carbon diffuses to austenite and forms carbon-enriched stabilized austenite (γ_{hc}). In Stage II, carbon-enriched stabilized austenite (γ_{hc}) decomposes to ferrite (α) and carbide. Extending the protracted austempering time to Stage II produces a large fraction of ferrite and carbide precipitate.

It is believed that work hardening and stress-induced phase transformation in the matrix are in relation with cavitation erosion[2-3]. Wantang et al[4] demonstrated that structural changes occur after cavitation erosion for a Cr-Mn-Ni stainless steel. The weight fraction of martensite in the surface layer being exposed to cavitation erosion increases gradually.

Some research on high-cycle fatigue behavior of ADI indicated that the fatigue limit increased with the toughness and retained austenite content due to the high strain-hardening nature of austenite[5-6]. Aranzabal et al[7] also remarked that large amounts of retained austenite would undergo martensitic transformation under plastic deformation in ADI austempered at higher temperature and with a greater content of retained austenite. The present research aims to adopt an ultrasonic vibration treatment to investigate the phase transformation in the matrix microstructure of ADI. HCF fatigue testing was also tested to obtain the fatigue stress-life (S-N) curves and to assess fatigue resistance of alloyed/unalloyed ADI.

EXPERIMENTAL PROCEDURE

The chemical compositions of ductile irons used in this study are given in **Table 1.** The ductile irons were poured into 1-inch Y-block sand molds. All specimens were austenitized at 900℃ for 1.5 hrs and then subjected to isothermal heat treatment at 320℃ and 360℃ for 2 hrs.

Table 1 Chemical compositions of ductile iron

Specimens	C%	Si%	Mn%	S%	P%	Cu%	Ni%	Mg%
Alloyed	3.65	2.76	0.36	0.014	0.016	0.6	0.9	0.045
Unalloyed	3.51	2.45	0.30	0.010	0.017	-	-	0.036

Groups of specimens were subjected to 46 KHz ultrasonic vibration at regular intervals of about **5** minutes. The morphologies and microstructural changes in the matrix were observed and assessed by using optical (OM) and/or scanning electron microscopy (SEM). Changes in retained austenite content were measured by X-ray diffraction using a Cu-target tube. A Vickers hardness tester at a test load of 25g was also employed to measure in areas near graphite and in intercellular regions. HCF specimens were tested in a rotary bending fatigue testing machine at a frequency of 2400 rpm (40 Hz) for high-cycle fatigue test. The test was run to failure or to 10^7 cycles at which specimens were considered to be a run-out. S-N curves were established for each specimen. Eight to ten specimens of each material condition were tested at sufficient stress levels to obtain reliable S-N curves and fatigue limits.

RESULTS AND DISCUSSION

Phase transformations during ultrasonic treatment

Ultrasonic waves are periodic sound waves consisting of cycles of compression and expansion. Each cycle exerts a positive pressure and a negative pressure respectively. If a large negative pressure overcomes the liquid's tensile strength at an expansion cycle, a cavity may form in the liquid[8]. When a cavitation bubble collapses at a location away from any solid boundaries, it does symmetrically and emits a shock wave into the surrounding liquid. When a cavitation bubble contacts with or is close to a solid surface, it will collapse asymmetrically and forms a micro-jet impacting directly toward the solid[9].

Micro-jet impacts and shock waves cause stringer-type stabilized austenite, which was rich in carbon, to undergo Stage II phase transformation, $\gamma_{hc} \rightarrow \alpha +$ carbide. After ultrasonic treatment, the temperature of the water solution was slightly increased from 29℃ to about 40℃ for a treatment time of 10-15 minutes. Micro-jet impact and shock waves may locally raise the temperature of the matrix (ausferrite) and promote the diffusion of carbon to carry out Stage II transformation. Stringer-type austenite gradually decomposed into ferrite and carbides**.**

The micro-jet impact and shock wave energy forced the island-like austenite to carry out a martensitic transformation. **Fig. 1** shows the microstructure of ADI, which had been treated at an austempering temperature

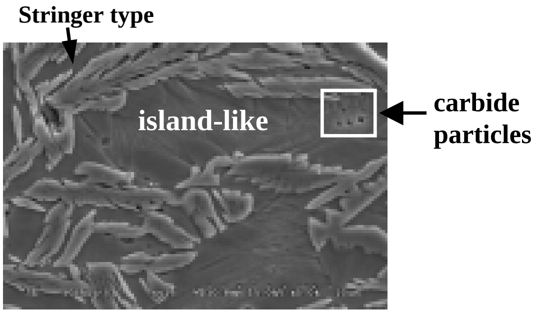

Fig. 1 Microstructure of alloyed ADI 360C/2h after ultrasonic treatment for 15 minutes

of 360℃ for 2 hrs after ultrasonically treatment for 15 minutes. Most researchers agree that ADI exhibits a transformation-induced plasticity effect (TRIP), and martensite formed by deformation was mainly generated from the island-like austenite being present in the microstructure[7,10]**.** Because a lower carbon content existed in the interior of island-like austenite, less strain energy was necessary to produce the mechanical transformation of austenite and less energy had consumed the TRIP.

High-cycle fatigue strength

Results of the rotary bending fatigue S-N curves for the specimens are shown in **Figs. 2a and 2b.** The best-fit lines were used in all subsequent analysis of HCF properties. The estimated fatigue limits are also given in **Table 2.** The estimated fatigue limits at the high austempering temperature (360℃) were higher than those tested at the low temperature (320℃). In addition, the alloyed specimens obtained greater high cycle fatigue strength than the unalloyed specimens.

The fatigue properties are indeed affected by the matrix microstructure of ADI, especially the amount of retained austenite. At lower austempering temperatures, slim acicular ferrite plates are densely distributed in the matrix with a lower volume fraction of retained austenite. Contrarily, at higher austempering temperatures, the matrix presents a coarse ferrite lath and a larger volume fraction of retained austenite. Greater amounts of retained austenite created more barriers for fatigue crack growth and fatigue life was extended. This is also related to the plasticity-induced martensitic transformation of unstable retained austenite during HCF testing. And attributed to the addition of copper and nickel, the alloyed specimens presented a more homogeneous matrix microstructure with large amounts of retained austenite. The addition of alloys formed a diffusion barrier to hinder carbon diffusion at the graphite interface during solid-state transformation. It delayed Stage II reaction, thereby creating a wider processing window for the achievement of high toughness performance. As alloyed specimens austempered at 360℃ had much more blocky retained

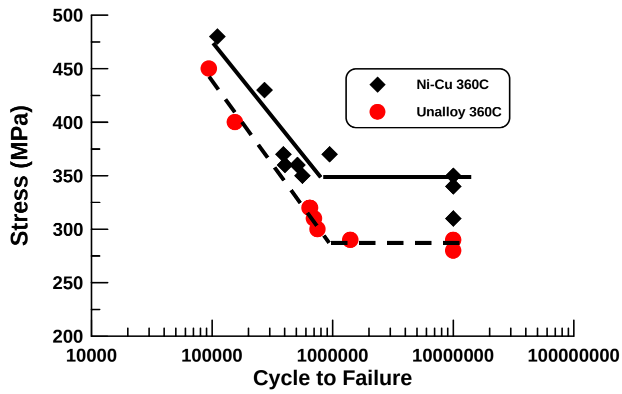

Fig. 2a S-N curve of alloyed/unalloyed specimens at austempering temperature of 360C.

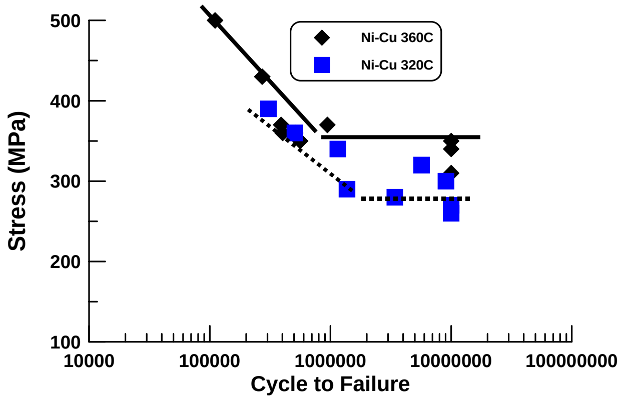

Fig. 2b S-N curves of alloyed specimens at different austempering temperature 320℃ and 360℃

austenite, more stress-induced martensitic transformation occurred during HCF testing and led to a better HCF performance.

Micro-hardness variations

Variations of the micro-hardness values in ADI specimens with ultrasonic cumulative treatment time are shown in **Fig. 3**. The effect of ultrasonic micro-jet caused the alloyed specimens to present a slower and smoother increase of the micro-hardness values with increasing treating time, because alloyed ADI needs to absorb more energy to have carbide precipitates or stress-induced martensitic transformation. HCF testing also reveals that alloyed specimens have better fatigue strengths; that is, they will fracture only by absorbing more energy. So from the viewpoint of energy,

Table 2 Estimated fatigue limits of alloyed/unalloyed specimens austempered at 320℃ or 360℃.

Specimens	Austempering condition ℃	Volume fraction of retained austenite(%)	Fatigue limit (MPa)
Alloyed	360	27.7	350
	320	18.2	270
Unalloyed	360	21.6	290
	320	13.2	220

increasing austempering temperature and alloy (Ni and Cu) addition lead to an increase in retained austenite content. Retained austenite performs a great work hardening capability and can absorb energy resulting in better toughness and fatigue strength.

SUMMARY

1. After subjecting samples to an ultrasonic treatment, some island-like austenite is found to undergo a phase transformation of austenite to martensite induced by shear stresses from impact of micro-jets and shock waves, while some stringer-type austenite is found to precipitate carbides.
2. HCF testing shows that higher austempering temperature and alloy addition result in an increase in the retained austenite content and excellent toughness and fatigue strength.
3. After the process, micro-hardness values of alloyed ADI are slowly increased with increasing cumulative treatment time. It demonstrates that alloyed ADI needs more energy to cause phase transformation. This viewpoint corresponds to the result of HCF testing in which alloyed ADI also needs more energy to reach fracture.

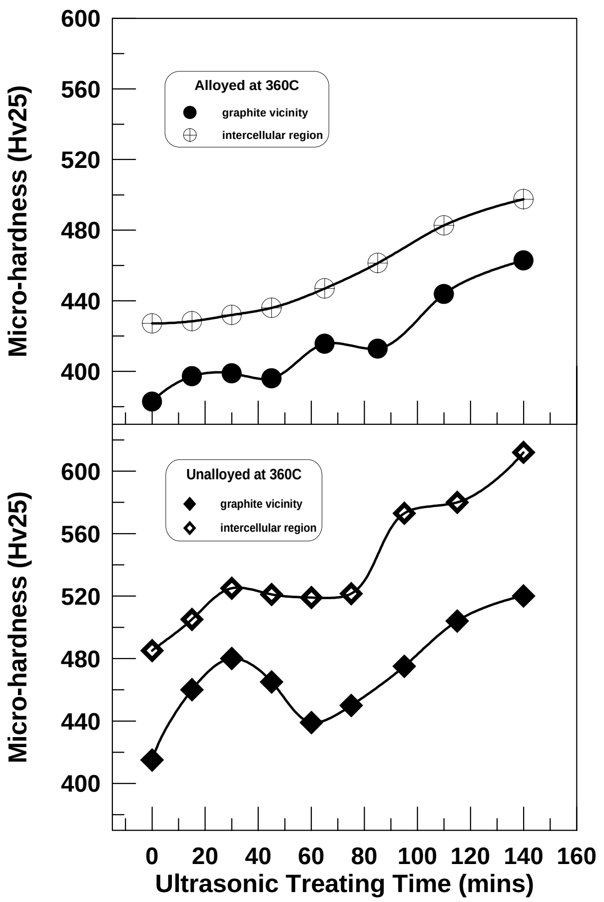

Fig. 3 Variations of micro-hardness in ADI specimens with ultrasonic cumulative treatment time

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