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FATIGUE CRACK GROWTH BEHAVIOR OF NODULAR CAST IRON SUBJECTED TO TWO-STEP AUSTEMPERING

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Preliminary Note – Prethodno priopćenje

This research aimed to investigate the fatigue crack behaviorof nodular cast iron heat-treated with two-step austempering. In this study, the material was initially reheated at 260 °C for 10 minutes, and then the temperature was increased to 280 °C, 310 °C, and 340 °C with the holding time of 60 minutes and 120 minutes. The results of these treatments showed that slower fatigue crack propagation occurred at the austempering temperature of 340 °C with 60-minutes holding time than those at lower temperatures (280 °C and 310 °C) and with longer time (120 minutes). The maximum fatigue crack propagation resistance occurred at the holding time of 60 minutes compared to that at the 120 minutes holding time.

Keywords: nodular cast iron, heat treatment, austempering, temperature, fatigue crack

INTRODUCTION

The results of metallurgy test showed that the addition of magnesium to cast iron can produce rounded graphite. Regarding its mechanical properties, the tensile strength of the graphite can double and its ductility is comparable to carbon steel.

The magnesium reacts first with sulfur to form a graphite sphere. Spherical graphite flakes cause the working force not to be concentrated; instead, it spreads to the arc of the graphite sphere so that it can withstand heavier loads [1]. To improve the good properties of nodular cast iron, the addition of certain alloying elements and heat treatment can be performed. The nodular cast iron as a result of the heat treatment is called austempered ductile iron or abbreviated as ADI.

The industry has found a variety of materials and process combinations that exhibit good strength and wear resistance to achieve longer component life. The austempered ductile iron has long been recognized to have high ductility, strength, wear resistance, toughness, and machinability that can replace wrought steel in many purposes [2, 3]. Moreover, ADI has been proven to be the right material for high abrasion wear resistance. ADI is even assumed to have better wear resistance than wrought steel. With this nature, ADI can substitute wrought steel for various applications [4], such as for making plowshares, camshafts, and farming tools [5].

Research associated with mechanical properties was conducted by examining the high tensile strength and fracture toughness of ADI subjected to the two-step austempering [6].

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The fatigue cracks in ADI microstructure propagated following the orientation of the ferrite laths along the ferrite-austenite interface. During the crack propagation, decohesion of the graphite nodules from the matrix often occurred [7]. The rate of fatigue crack propagation was closely related to the nodular graphite of the material; the more heterogeneous the graphite particles, the slower the propagation rate, and the higher the fatigue strength of ADI, the higher the number of nodules [8,9]. The fatigue behavior of IDI was less sensitive to casting defects compared to ADI [10]. Low temperature contributed to the increase of the stress concentration [11].The study was conducted to investigate fatigue crack growth behavior of nodular cast iron by two-step austempering.

METHODS

Prior to being examined for fatigue crack growth, the raw material, a 200-mm cast iron with a diameter of 25 mm, was placed into the furnace for heat treatment. The furnace used for the austemper process is Naber N41/H. The heat treatment was done in two ways, namely single-step and two-step austempering. In both processes, the material was austenitized at 900 °C with 60 minutes holding time and then quenched. Next, in the single-step austempering, the material was reheated at 280 °C, 310 °C, and 340 °C. Meanwhile, in the two-step austempering, the material was initially reheated at 260 °C for 10 minutes, and then the temperature was increased to 280 °C, 310 °C, and 340 °C with the holding time of 60 minutes and 120 minutes. Afterward, the material was cooled in the furnace until it reached room temperature. After the heat treatment, the specimen of the nodular cast iron was prepared using Computer Numerical Control (CNC) machine, and the fatigue crack

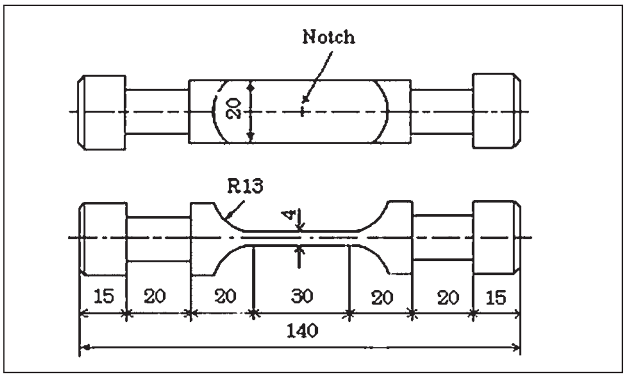

Figure 1 The specimen of the fatigue crack test [12]

initiation was done using Electrical discharge machining (EDM). The specimen of the fatigue crack test shown in Figure 1.

There were three stages of analysis. Firstly, the specimen was examined for its crack length (a) and a number of cycles (N). The test was done at the stress ratio (R=0) and the frequency of 11 Hz. The test results were used to construct a correlation diagram showing the relationship between the crack length (a) and the number of cycles (N).

RESULTS AND DISCUSSION

The behavior of fatigue crack propagation of a nodular cast iron specimen was observed from a fatigue test at a frequency of 11 Hz. The results obtained are presented in the diagrams showing crack length (a) and a number of cycles (N).

Figure 2 shows the fatigue crack propagation (da/dN) and stress intensity (Δk) of nodular cast iron subjected to two-step austempering with temperatures of 280 °C, 310 °C and 340 °C and a holding time of 60 minutes. Figure 3 shows the fatigue crack propagation

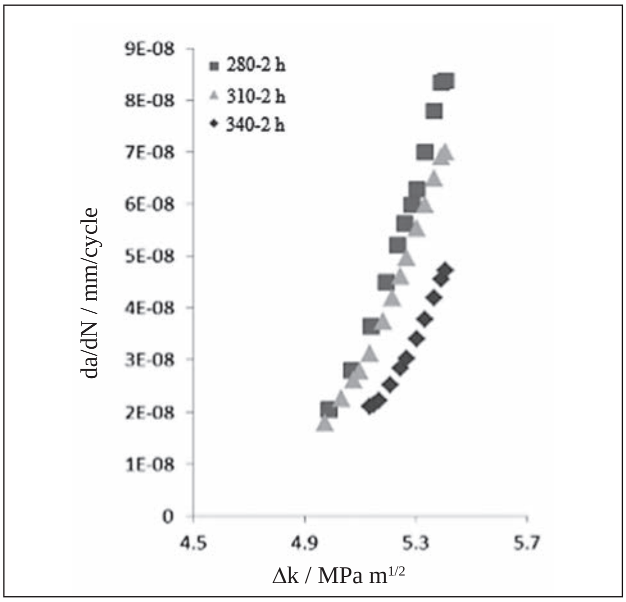

Figure 2 The fatigue crack propagation (da/dN) and stress intensity (Δk) of nodular cast iron in various temperatures and holding time of 60 minutes

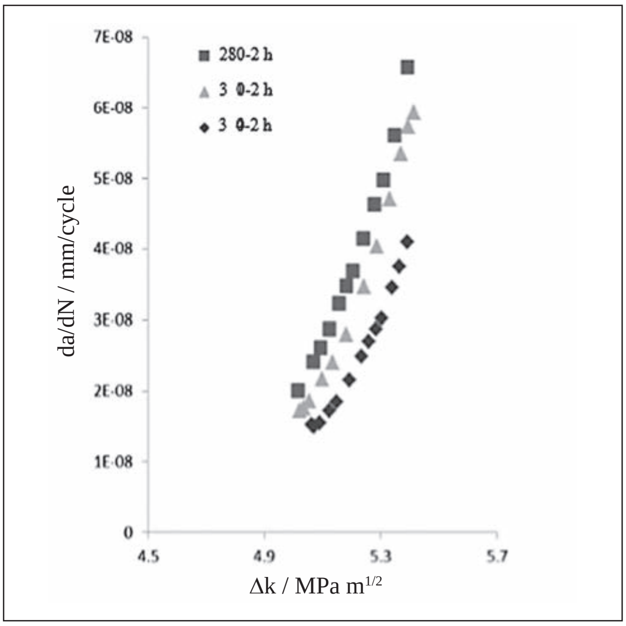

Figure 3 The fatigue crack propagation (da/dN) and stress intensity (Δk) of nodular cast iron in various temperatures holding time of 120 minutes

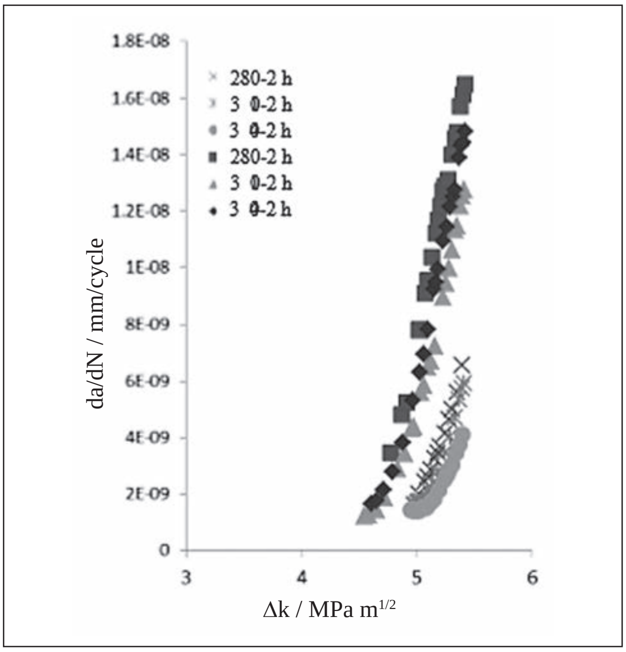

Figure 4 The fatigue crack propagation (da/dN) and stress intensity (Δk) of nodular cast iron in various temperatures and holding time of 60 and 120 minutes

(da/dN) and stress intensity (Δk) of nodular cast iron subjected to two-step austempering with temperatures of 280 °C, 310˝°C and 340 °C and a holding time of 120 minutes. Figure 4 is the composite graph of fatigue crack propagation (da/dN) and stress intensity (Δk) of nodular cast iron subjected to two-step austempering with temperatures of 280 °C, 310 °C and 340 °C for the holding time of 60 minutes and 120 minutes.

The two-step austempering with the temperature of 340 °C and the holding time of 60 minutes resulted in NCI microstructure which had a refined ausferrite matrix with the remaining austenite phase, as well as the number, size and the evener distribution of graphite. The longer the austempering time was, the more the ausferrite matrix was formed. As a result, the tensile strength and toughness became slightly higher. The transformation at higher temperatures above 350 °C can result in the coarser ausferrite matrix called upper ausferrite presenting an acicular structure [12-14], whereas the process at lower temperatures below 350 °C can result in the more refined ausferrite called bottom ausferrite showing a structure that closely resembles the martensitic temper [15, 6]. In the two-step austempering with 60 minutes holding time, the highest toughness occurred at 340 °C, whereas the one with 120 minutes holding time, the highest toughness occurred at 340 °C and the lowest at 280 °C. This was due to the matrix formed at 310 °C was the lower ausferrite with few of the remaining austenite with a higher percentage of acicular ferrite phase of the ferrite compared to the remaining austenite. At the temperature of 280 °C, the matrix structure formed was the upper ausferrite (coarse ausferrite) resembling the fine pearlite.The more refined ausferrite phase in the two-step austempered microstructure, and the number, size and the evener distribution of carbon result in the higher strength and toughness. This is consistent with the theory that the transformation at higher temperatures above 350 °C can result in the coarser ausferrite microstructure (upper ausferrite) having a higher ductility, and the one at lower temperatures can result in a more refined ausferrite with higher tensile stress and lower ductility. The longer the austempering, the lower the toughness of the resulting material. This is in line with the theory that the longer the austempering, the coarser the ausferrite microstructure [6, 13, 14, 16].

The increasing toughness was found through the two-step austempering, which was associated with the size of refined ferrite particles, the increasing carbon content and the stability of the remaining austenite. The combination of high toughness could be obtained by adopting the two-step austempering. The result of the enhancement of ADI showed that the tensile and yield strength increased with the rising time, while the ductility and toughness decreased [13, 6, 14].

The mechanism of the formation of round-shaped graphite in nodular cast iron and the result of two-step austempering have been studied by many researchers. The graphite became round when austenite could form around it perfectly. In contrast, vermicular graphite formed when canals connecting graphite with liquid emerged in austenite due to the intruding elements. When the growth of graphite in gas bubbles stopped, and the graphite from new nuclei around austenite grew, the graphite chunk would occur [17-19].

Based on the observation results, crack length and cycle were strongly influenced by the presence of nodular cast iron matrix phase subjected to the two-step austempering. The percentage of pearlite matrix phase in the two-step austempering was relatively high.

The fatigue crack path changed the behavior controlled by the presence of nodular graphite. Crack propagation always occurred in the interface of graphite matrix [19], whereas the nodular graphite remained unbroken or undamaged.

As described previously, the matrix resulted from the heat treatment consisted of ferrite and pearlite. The crack always started in the graphite matrix and spread along the energy course commonly as an interface between laths of ferrite and pearlite. The main fore space increases the value the stress intensity factor at the point of crack initiation. This causes the propagation of microcracks from the nodules towards the main space to the opposite direction of the propagation with the general crack growth until it joins the main crack [20]. In this case, the common crack path continuously occurs at some other points in all nodules where favorable conditions exist at the beginning of a new space that makes the propagation process and repeats the process when facing other nodules. This mechanism justifies the existence of crack branching observed from the concurrence between the main crack and the nodules.

The initiation of the fatigue crack occurred exclusively in pores present both on the surface and directly beneath the surface. Decohesion of the nodular graphite and the subsequent initiation and the microcrack growth may cause deflection of the dominant crack system. It also indicates that there is a significant increase in the frequency of the nodular graphite along the crack paths as the tension level increased and the further initiation (limited to the nodular graphite on the crack tip plastic zone) for the crack occurred to propagate the dominant crack tip throughout the specimen period. Thus changes in the cast micro caused by the heat treatment have resulted in the more fatigue level in the performance of the crack propagation. This was due to the lack of eutectic carbide and the relatively high amount of austenite in the micro.

CONCLUSIONS

1. The optimum rate of fatigue crack propagation occurred at the austempering temperature of 340 °C compared to that at lower temperatures (280 °C and 310 °C).

2. The maximum fatigue crack propagation resistance occurred at the holding time of 60 minutes compared to that at the 120 minutes holding time.

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Note: The responsible translator for the English language is IdeliatresnaningsihTyas – English-speaking translator at Malang, Indonesia