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The Effects of Two-StepsAustempering Heat Treatment on the Tensile Strength and Toughness of Nodular Cast Iron

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ABSTRACT

This research aims to examine the effect of the change of tensile strength and the impact toughness as a result of two-stepsaustempering heat treatment. The result of the heat treatment then was compared to the single-step austempering one, conducted at the austenite temperature of 900°C within 60 minutes prior to be quenched in salt solution with varied austempered temperatures: 280°C, 310°C and 340°C within 60 minutes and 120 minutes. Meanwhile, two-stepsaustempering heat treatment was given austenite, equal to the temperature to the single-step austempered, namely at temperature of 900°C within 60 minutes. Following this, the first step was started by quenching nodular cast iron at the austempered temperature of 260°C within 10 minutes and in the second step, the austempered temperature was gradually increased at 280°C, 310°C and 340°C, each of which was in the holding time of 60 minutes and 120 minutes. The result of two-stepsaustempering heat treatment to the tensile strength and toughness shows a higher value compared to the result in single-step austempering one. The maximum value of tensile strength, in this case, occurred at the austempered temperature of 340°C with the holding time of 60 minutes. It was then followed by the value at the austempered temperature of 310°C and 280°C, respectively. Conversely, the highest impact toughness was achieved at the temperature of 280°C within 60 minutes. On the other hand, the toughness decreased at temperature of 310°C and 340°C with the holding time of 60 minutes.

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INTRODUCTION

In response to the weakness of ferro casting, British Case Iron Research Association in 1948 mixed the alloying cerium, nickel and other alloying elements to cast iron, thus resulting in nodular cast iron. Since then, a number of testing on iron cast emerges in order to result in a better quality, one of which is by adding magnesium to cast iron. Based on the result of the metallographic testing, the addition of the magnesium to the cast iron could result in nodular graphite. It is found that the nodular graphite in cast iron based on a laboratory test, in fact, had the twofold tensile strength closer to the carbon steel. This finding then was patented in 1949 in USA as a year of Nodular Cast Iron (NCI) (AFS, 2011; Karsay, 1985).

The graphite in nodular cast iron occupies 10-15% of total volume of materials and is evenly spread in the basic structure (matrix) resembling to the carbon steel. Hence, the mechanical properties of nodular cast iron can be directly correlated to the tensile strength and ductility of the matrix it owns as occurred in carbon steel. However, as the structure of nodular cast iron also contains graphite, the tensile strength, elasticity modulus and impact tenacity proportionally will be lower than the carbon steel, in this case, with an equal matrix. The matrix of nodular cast iron is varied started from the soft and ductile structure of ferrite to the harder and strong structure of pearlite and even to the structures that can only be reached through the addition of alloying materials or through the heat treatment such as martensite and bainit (Karsay, 1985; Siefer, 1970).

Bish (Bish, 2009) of alloying copper of NCI to the hardness, tensile strength. The study was aimed to compare NCI with the alloying copper and NCI without the alloying copper and the result of this study then shows that both NCI with and without the alloying copper experienced an increase in tensile strength and toughness. Here, the maximum tensile strength and toughness were obtained at the austempered temperature of 260°C with the holding time of 60 minutes (Bish, 2009). Meanwhile, Panda (Panda, 2011) also conducted a similar study through the single-step austempering heat treatment to NCI with a number of slight varied temperatures and times but substantially was still equal that is on the effect of the alloying copper in nodular

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cast iron on tensile strength and toughness. Based on the result of the study, the maximum value of hardness and tensile strength are obtained at the austempered temperature of 250^{o}C with the holding time of 60 minutes (Panda, 2011). As previously discussed, the improvement of mechanical properties of NCI with the heat treatment resulting in ADI recently has been conducted conventionally using single-step austempered (Hayrynen,2002). This, for example, can be found in a study of single-step heat treatment by Sheikh (Sheikh, 2008) aimed to observe the characteristics and mechanical properties of ADI given a single-step austempering heat treatment. The optimum results of the characteristics and mechanical properties in this study have been obtained at the austenite temperature of 250^{o}C and at the austempered temperature of 270^{o}C with the holding time of 90 minutes (Sheikh, 2008).

Following this, a new model of heat treatment called as two-step austempering heat treatment was developed in the beginning of 2005. The result of the development towards ADI materials shows that tensile strength and yield strength increased with the increasing holding time. However, ductility and toughness, in this case, decreased. The best fracture toughness was obtained at two-step austempered (24%) higher than that of single-step heat treatment (Ravishankar, 2008). In the same year, Yang (Yang, 2005) examined the mechanical properties and near-threshold fatigue crack behavior and conducted both single-step and two-step austempering heat treatment on ADI materials. The result then shows that toughness and tensile strength of ADI under two-step austempering heat treatment resulted in higher values compared to the one under single-step austempered heat treatment (Yang, 2005). On the other hand, the result of review conducted by Nofal (Nofal, 2009) about the two-stepsaustempering heat treatment had supported the result of the previous study in which the morphology formed in two-stepsaustempered was highly influenced by form, number and size of plate ferrite at the initial step of austempered or at transformation stage that finally controlled the microstructure and mechanical properties (Ritha, 2009).

The most basic distinction of the heat treatment between the previous study and this study lies on the austempered temperature and time both in single-step and two-stepsaustempered. In the previous study, the austempered temperatures ranged from 250 to 270^{o}C with the holding time of 60 minutes and 90 minutes. Meanwhile, in this study, the austempered temperature was at 280, 310 and 340^{o}C with the holding times of 60 minutes and 120 minutes. Besides, if the two-stepsaustempering heat treatment in the previous study was conducted using the ADI materials at the initial austempered temperatures at 260^{o}C within 5 minutes, this study uses NCI with the initial austempered temperatures at 260^{o}C within 10 minutes. It was then followed by the second step with a variety of temperatures at 280, 310, and 340^{o}C within 60 and 120 minutes. Thus, this research is able to complete the result of the information from the previous study related to the heat treatment both for single-step austempered and for two-steps one towards the change of tensile strength and impact toughness.

MATERIAL AND METHODS

Prior to conduct the heat treatment and testing, the raw material of nodular cast iron in the 25-mm-cylindric form was cut partly in order to have a sample and for examining the chemical composition using spectrograph. The result of the testing chemical composition of nodular cast iron primarily included carbon (3.8%), silicone (2.3%), phosphorus (0.05%) in accordance with the standard of ASTM A 395 (ASTM). In the following phase, before making a specimen, the material of nodular cast iron firstly was under the heat treatment based on the designed temperatures and time. The following figures illustrate the process of single-step austempering heat treatment (Figure 1) and two-stepsaustempering heat treatment (Figure 2). In this case, the heat treatment was conducted in a furnace that was manually controlled based on the following phases:

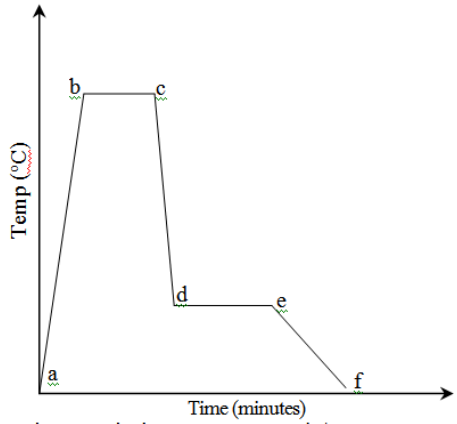

Fig. 1: Single-step austempered (Hayrynen,2002).

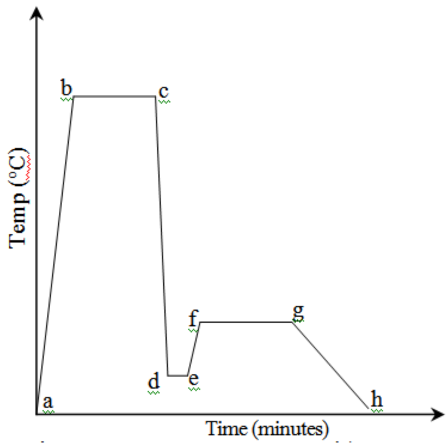

Fig. 2: Two-stepsaustempered (Karsay, 1985).

Heat treatment was given to line a-b both in single-step and in two-stepsaustempered at the equal austenite temperature (900°C) with the holding time of 60 minutes. Furthermore, line c-d at the single-step was dipped into salt solution of 50% $NaNO_3$ + 50% KNO_3 and then heated at the austempered temperatures at 280°C, 310°C, and 340°C with the holding times of 60 minutes and 120 minutes. In two-stepsaustempered, it began by quenching lines *d-e* at the austempered temperatures at 260°C with the holding time of 10 minutes. It was then followed by the second step in which the austempered temperatures of lines *e-f* were increased into 280°C, 310°C, and 340°C with the holding time of 60 minutes and 120 minutes. Afterwards, air cooling was conducted to lines *e-f* in single step and to lines *g-h* in two-step.

Once the process of single-step and two-stepsaustempering heat treatment was completed, the next step was to make test specimen that consisted of tensile test, impact test, and microstructure test. The tensile test in this case used standard of ASTM (A379-2002). To observe the toughness of Nodular Cast Iron (NCI) towards the shock load, the testing was conducted using Charpy Impact Test in accordance with the standards of ASTM A327M towards both raw materials and materials under heat treatment. In consideration to the high influence of microstructure towards the tensile strength and the toughness of NCI, the observation then was conducted using an optic lens and SEM in order to identify the characteristics of microstructure. Meanwhile, the analysis of microstructure on the nodular distribution, and the grain size in the matrix phase was conducted using Lince Software.

RESULTS AND DISCUSSION

Figure 3a below illustrates the result of the tensile test on the raw materials of nodular cast iron and the result of the tensile strength of the material as a result of the single-step and two-stepsaustempering heat treatment. Based on the test of the tensile strength, it is found that the tensile strength increased along with the increasing austempered temperature. The highest tensile strength in this case occurred at the austempered temperature at 340°C with the holding time of 120 minutes. On the other side, in two-stepsaustempered, the highest tensile strength occurred at the austempered temperature at 340°C with the holding time of 60 minutes (Figure 3_{ab}).

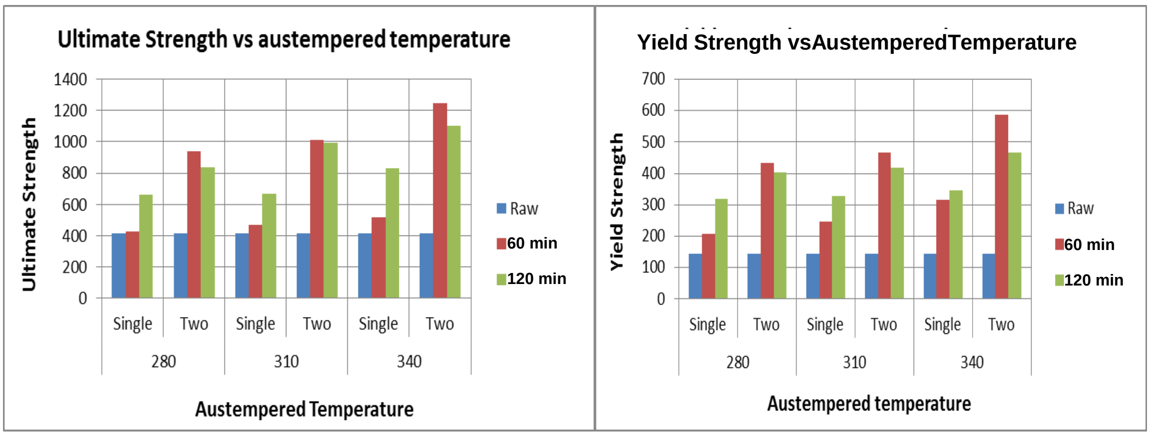

Fig. 3a: Correlation graph between ultimate strength and austempered temperature and the correlation between ultimate strength and holding time.

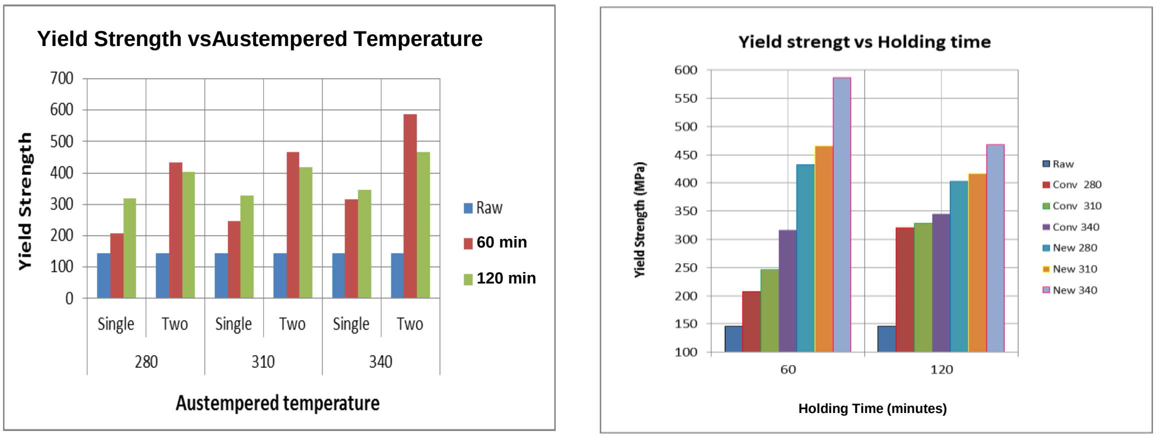

Fig. 3b: Correlation graph between yield strength and austempered temperature and correlation between yield strength and holding time.

Figure 3b shows the relations between yield strength and the austempered temperature and time to the raw material of nodular cast iron, single-step and two-stepsaustempered. Being identical with the result of the maximum tensile strength, the yield strength shows a linear value with the tensile strength. It means that the tensile strength increased in accordance with the increase of austempered temperature and thus, its yield strength would experience the same thing. Hence, the highest yield strength at the single-step occurred at the austempered temperature of 340^{o}C with the holding time of 120 minutes. On the other hand, the highest yield strength in the two-stepsaustempered occurred at the austempered temperature at 340^{o}C with the holding time of 60 minutes (Figure 3ab).

As a whole, the change of the mechanical properties – particularly the tensile strength in the single-step and two-stepsaustempered – was very influenced by the change of the austempered temperatures and time. In the single-step the optimal value of tensile strength occurred at the austempered temperature at 340^{o}C with the holding time of 120 minutes. Meanwhile, in the two-stepsaustempered, the optimum tensile strength occurred at the temperature at 340^{o}C with the holding time of 60 minutes. The value of the optimum tensile strength occurred both in single-step and two-stepsaustempered was comparable to its yield strength value – indicating the high value of the tensile strength at the austempered temperature and time, as previously mentioned, would also be followed by the high value of its yield strength. However, elongation would, conversely, have an opposite value in which, when the austempered temperature and time in both single-step and two-steps resulted in the maximum tensile strength and yield strength, its elongation, in fact, would be minimal.

Result of Impact Test:

Figure 4 illustrates the graphs of the results of the impact toughness test. Similar with the previous testing, the result of the impact test was conducted to the raw material and materials given with the heat treatment using both single-step and two-stepsaustempered. The result of the impact toughness test shows that the impact toughness was inversely proportional with the tensile strength and toughness. In other words, if the toughness is high, the tensile strength will decrease.

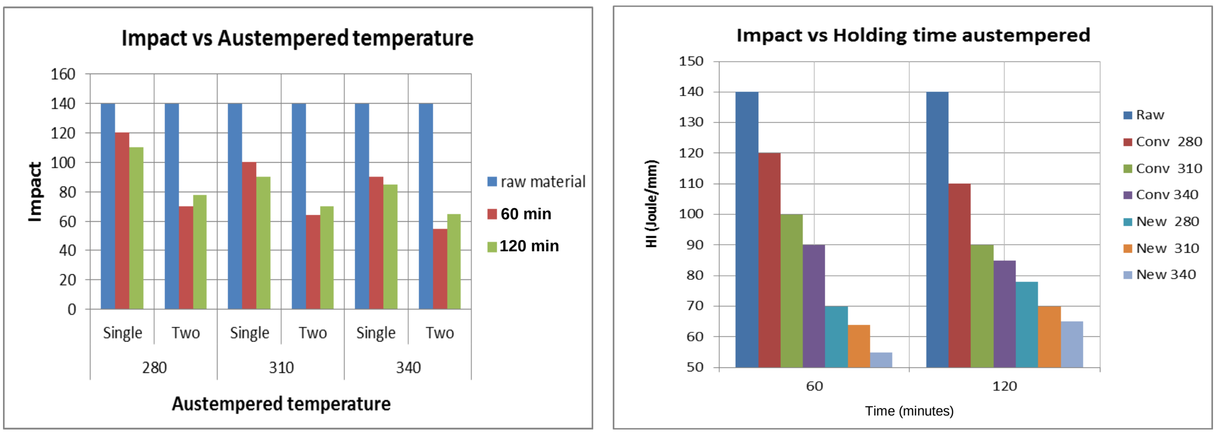

Fig.4: Correlation graph between the austempered temperature andcorrelation between toughness and holding time.

Discussions:

As shown in the graphic of testing result above, it is found that two-stepsaustempered resulted in a higher result of mechanical properties compared to the single-step austempered and raw material. The maximum tensile strength of two-stepsaustempered, in this case, occurred at the austempered temperature at 340°C with the holding time of 60 minutes. Meanwhile, the maximum tensile strength at single-step austempered occurred at the temperature of 340°C with the holding time of 120 minutes.

The impact energy increased in the increase of austempered time until reaching a maximum value. Subsequently, it would decrease. It is also found out that the impact energy was highly correlated to the morphology of nodular graphite. Specifically, the impact energy increased in nodularity and added the number of nodules. In this case the size of the nodules will decrease. The best toughness was found at two-steps (24%) higher than the single-step heat treatment (Ayman, et. Al, 2008; Horstmann, 1985; Corobo, 2009).

The increasing toughness was found through two-stepsaustempered correlated to the size of the refined ferrite particles, the increasing carbon content and stability of the remaining austenite. The combination of high toughness could be obtained by adopting two-stepsaustempered. The result of the enhancement of ADI shows the increase of tensile strength and yield strength along with the increasing time. By contrast, the ductility and toughness decreased (Ravishankar, 2008; Yang, 2005;Aymanet. Al. 2008). On the other side, the review about the two-stepsaustempering heat treatment support the result of the research above that the morphology of two-stepsaustempered matrix is determined by form, number and the size of ferrite plate at the first step or transformation phase that in turn can control microstructure and mechanical properties (Ayman et.al., 2008; Nofal, 2009).

A number of fracture surfaces from the result of the tensile test (NCI with the heat treatment of single-step austempered and two-stepsaustempered) are presented below. Based on the form of surface fracture, it is found that the ductile fracture occurred at the result of the tensile test of two-stepsaustempered with the austempered temperature of 340°C of *holding time* of 60 minutes. On the other side, the brittle fracture occurred at the fracture surface resulted from the test of tensile strength at the temperature and time as equally as the two stepsaustempered. It is found also in the brittle fracture of the result of the tensile test that along with the value resulted from the optimum tensile test and hardness. The minimum impact tenacity occurred at two-stepsaustempered at the austempered temperature of 340°C during 60 minutes with the domination of ferrite and pearlite matrix structure. This also similarly occurred at the lower temperature (310°C and 280°C. (Figure 10,11, 12).

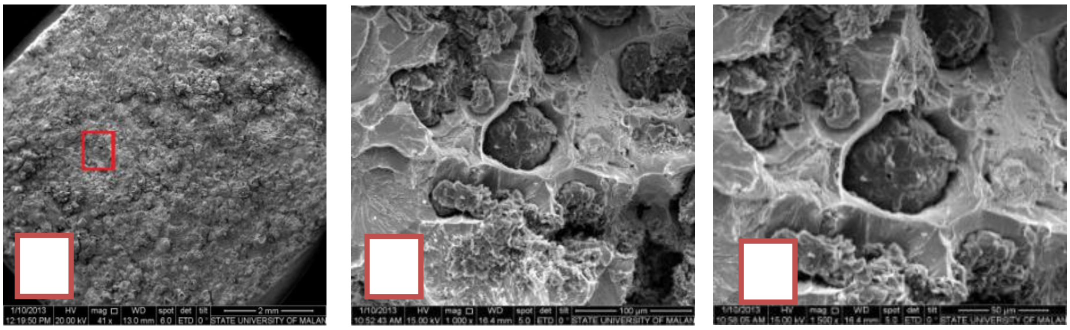

Fig. 10: Surface fracture of tensile test result from two-stepsaustempered 280°C/ 60'
a) Macro Photo, b) Magnitude in 1000x, c) Magnitude in 1500x

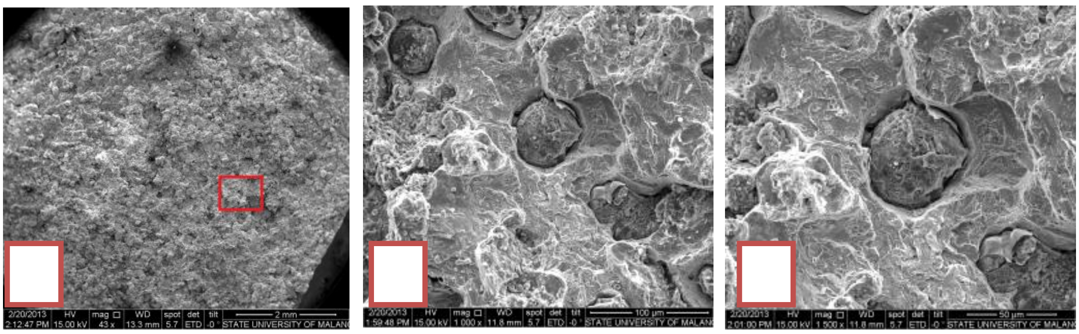

Fig. 11: Surface Fracture of tensile test result from two-stepsaustempered 310⁰C/60'
a). Macro Photo, b) Magnitude in 1000x, c) Magnitude in 1500x

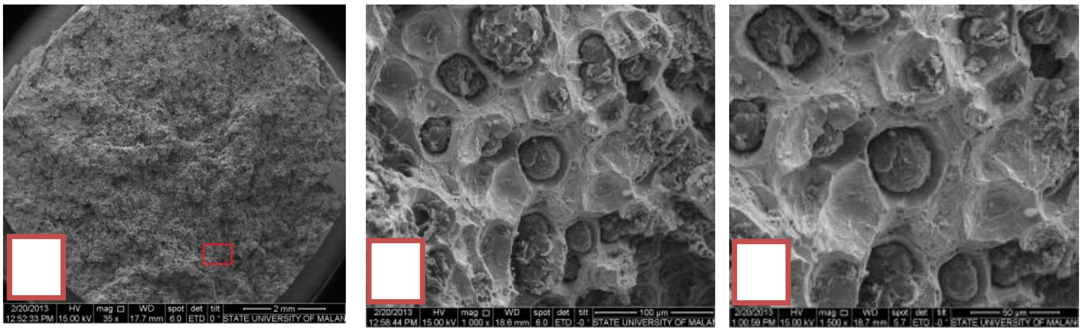

Fig. 12: Surface fracture of tensile test result from two-stepsaustempered 340^{o}C/60’
a) Macro Photo, b) Magnitude in 1000x, c) Magnitude in 1500x

Conclusions:

1. Two-stepsaustemperedresults in a better change in tensile strength in comparison to the single-step austempered.
2. The austempered temperature of 340^{o}C with the holding time of 60 minutes at two-stepsaustemperedis recommended as a suitable temperature and time in order to result in a maximum tensile strength.
3. The austempered temperature of 280^{o}C with the holding time of 60 minutes at two-stepsaustempered is recommended as a suitable temperature and time in order to result in an optimum toughness.

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