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Controlling the Strain Hardening Behaviour of Ductile Cast Iron by Austempering Process

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ABSTRACT:

In this study experimental work was carried out to obtain and to control the strain hardening behaviour of ductile cast iron by austempering process. Tensile test, hardness test and micrography examinations were carried out for samples being subjected to 250-400 °C temperature and for time period 30 to 90 minutes austempering conditions. This was done to obtain the variation of strain hardening factor (n) and strength factor (K), hardness and micrography with austempering temperature and time period. The stress-strain curves were obtained. Using Holloman's relationship, the strain hardening factors were calculated. The results showed the improvement in n-value with austempering process. Furthermore, the n and K values decreased then increased with an increase in austempering temperature. The minimum values for n and K are at 300 to 350 °C austempering temperature. Finally, the results were compared with the results obtained by using a two-step austempering process. The results showed that the minimum values for n and K are also at 300 to 350 °C austempering temperature which is in a good correlation with the results obtained by two step method. Finally, it is concluded that the use of austempering process resulted in design flexibility and low cost in tooling machinery.

INTRODUCTION:

Austempering ductile cast iron is finding more application fields because of its excellent combination of high toughness, high strength, high fatigue strength and high wear resistance /1, 2/. In fact, different combinations can be achieved by proper austempering treatments in relation to a unique microstructure consisting of nodular, carbide free ferrite with carbon-enriched austenite /3, 4/. The application of austempering ductile cast iron (ADI) in heavy machinery and transportation equipment has many advantages over forgings due to the low cost and design flexibility /5, 6/. The excellent properties of ADI are related to its unique microstructure that consists of ferrite and high carbon austenite. This is different from austempered steels, where the microstructure consists of ferrite and carbide. Because of this difference, the product of the austempering reaction in ductile iron is referred to as "ausferrite" rather than bainite /7, 8/. In this process, the nodular cast iron is subjected to an isothermal heat treatment called austempering which could be a single step process which consists of austenitizing the casting at the temperature 900 °C for 120 minutes /9, 10, 11/ followed by quenching the casting to an intermediate temperature range of 250-400 °C and then air-cooling to room temperature. See Figure 1.

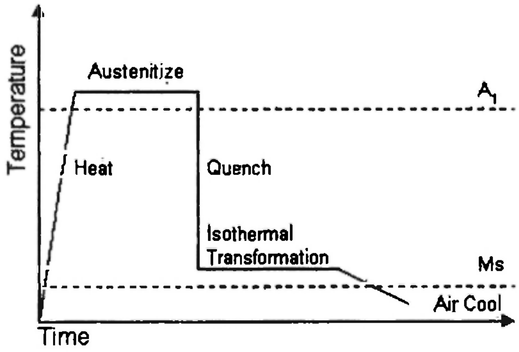

Fig. 1: Single step austempering process

Several mathematical model relations were generated to represent the stress- strain behaviour of the materials. One of the most convenient models for ferrous materials is the Holloman equation. Holloman's equation /8, 12/ is widely used to describe strain-hardening behaviour of metals and alloys under plastic deformation. In this equation, the strain hardening factor (n) of an alloy is an important parameter because it defines the work hardening capacity of the material when it is plastically deformed. It is used to estimate the forming force and the forming machine, forming tool and tool materials /13/. A higher strain hardening factor creates more difficulties in machining. With increasing applications of ADI, the understanding of strain hardening behaviour is more crucial to control the total life cycles of components. In the past, a significant number of works /8,14,15,16,17/ have examined the influence of austempering temperature on microstructure and mechanical properties of ADI. Having said that, very little information is available in the literature on the strain hardening behaviour. Therefore, the main aim of this study is to examine the influence of austempering temperature and period on the strain hardening behaviour and hardness of the materials. Tensile tests, hardness tests and micrography examination were carried out. The obtained n and K values were analysed for a one-step process. Finally, the results were compared and correlated with the results obtained by /8/ using a two-step austempering method.

EXPERIMENTAL WORK:

In this investigation, material samples were prepared from as-cast keel blocks. The microstructure of the as-cast material was predominantly pearlitic in nature. See Table I. The chemical composition of the alloyed spherical cast iron is shown in Table II. Tensile specimens were cut and machined from the keel blocks according to ASTM E-8. Different sets of these samples were heat treated at 250, 300, 350 and 400 °C temperatures and for time periods of 30, 45, 60 and 90 minutes in a 50% $NaNO_3$ and 50% KNO_3 salt bath, prior to cooling in air. Tensile tests were carried out using a ZWICK testing machine and the load–elongation data were obtained. From load-elongation data and volume constancy, the true stress strain curves were calculated. Finally using Holloman's relationship, logarithmic stress - logarithmic strain curves were obtained. The n and k values were obtained by best fit least squares method. The slopes of the straight lines are the strain hardening factor (n) and the intercepts with log stress axis give the strength factor or coefficient (K) values. Brinell hardness tests were carried out to obtained the hardness of the samples. Finally, optical metallography using an OLYMPUS microscope was used to examine the microstructure of the heat treated materials.

Table I

Properties of as-cast material

Nodule count, 1/mm^2	Nodularity %	Nodul radius, μ	Matrix
180	89	20.8	%70 pearlitic

Table II

Composition of cast iron tested

Element	C	Si	Mn	S	Cr	Cu	Mg	Sn
% Composition	3.64	2.52	0.38	0.01	0.084	0.26	0.042	0.013

RESULTS AND DISCUSSIONS:

Figures 2 and 3 represent the stress- strain behaviour of ADI at different austempering temperatures and time periods. It is clear from these figures that the stress and strain reach their maximum values at austempering temperatures between 300 to 350 °C. The time period influence is generally noticed only at low and high austempering temperatures. The high strength due to austempering is due to the generation of ferrite and an increase of carbon in austenite structure. In fact, the microstructure influences the mechanical properties of ADI and is related to the transformed austenite content, carbon content of the austenite and the morphology of ferrite and austenite known as ausferrite. As the austempering temperature increases above 350 °C, a bainitic (ferrite and carbide) structure reforms which results to low toughness. On the other hand, the austenite phase volume and locations is also playing a big role in controlling the mechanical behaviour of ADI. Between 300-350 °C, a high carbon austenite phase forms, which leads to low strength with high ductility. As the temperature increases above 350 °C, a bainitic phase forms with high strength and low ductility. Figure 4 presents the logarithmic curves for stress and strain in which the slope of the straight lines is the strain hardening factor (n) and the intercepts with log stress axis give the strength coefficient (K) values.

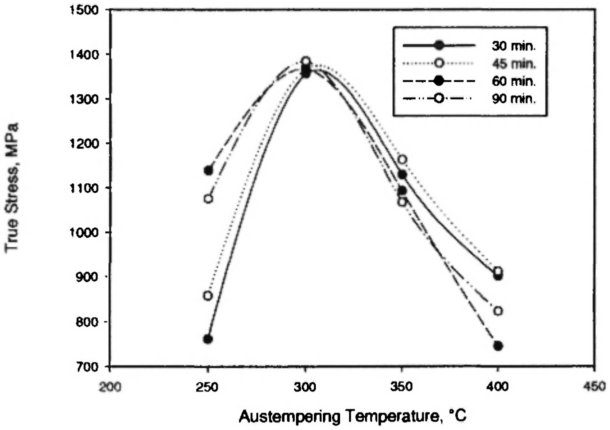

Fig. 2: Variation of true stress of ADI with austempering temperature and time period.

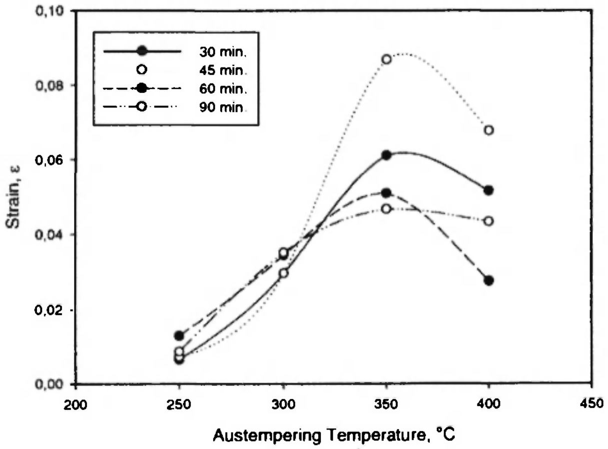

Fig. 3: Variation of strain of ADI with austempering temperature and time period

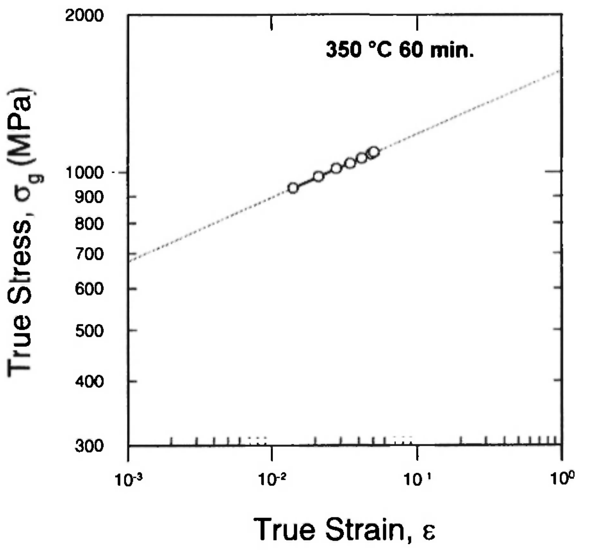

Fig. 4: Log stress-Log strain curve for ADI

Table III

n and K values at different austempering temperatures and time periods.

Austempering temperature , °C	Austempering time, min.	strain hardening factor(n)	strength factor (K)
250	30	0.4851	869
	45	0.4872	921
	60	0.4890	950
	90	0.5080	1100
300	30	0.2194	300
	45	0.1673	252
	60	0.1551	234
	90	0.1349	222
350	30	0.1470	172
	45	0.1364	161
	60	0.1251	158
	90	0.1368	163
400	30	0.2386	185
	45	0.2164	163
	60	0.1555	129
	90	0.1758	143

Table III presents the n and K values obtained from these types of curves at different austempering temperatures and time periods.

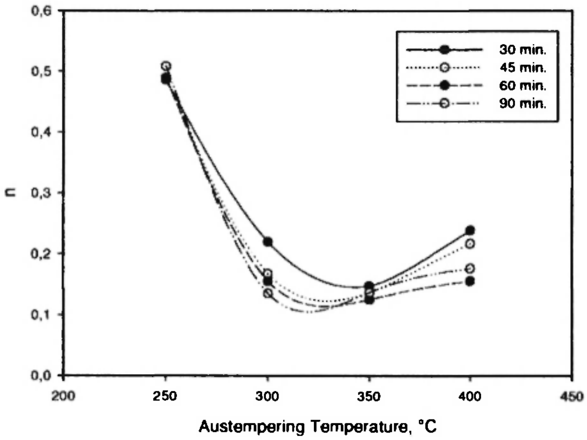

Fig. 5: Variation of n value of ADI with austempering temperature and time period

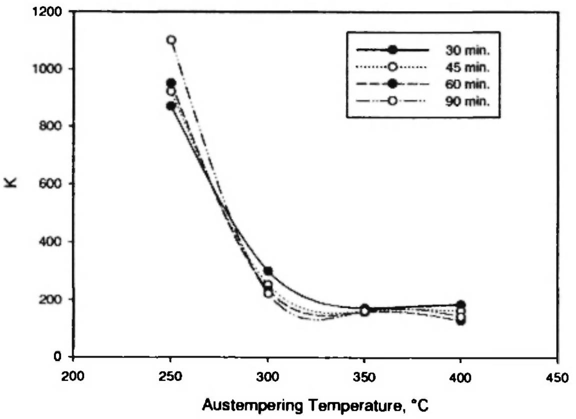

Fig. 6: Variation of K value of ADI with austempering temperature and time period

Figures 5 and 6 present the variation of n and K value with austempering temperature and time periods. These figures show that the n and K values initially decrease sharply with increasing temperature and reach minimum values at a temperature around 300-350 °C before increasing sharply with an increase in austempering temperature. This large increase in temperature corresponds to a substantial decrease in ferrite volume fraction. This is replaced by a large volume fraction of austenite, which result in a sharp increase in n-value. This indicates that the strain hardening behaviour is sensitive to the microstructure that forms. This observation is in the line with findings reported in the literature /18, 19/. The results were compared to those from a two-step austempering method /8/ (Figure 7).

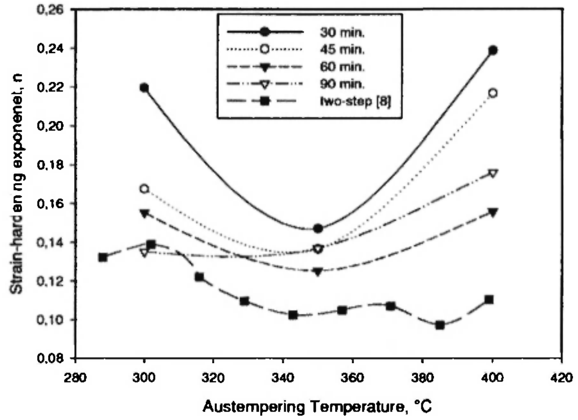

Fig. 7: Variation of n value of ADI with austempering temperature for single and two step austempering process

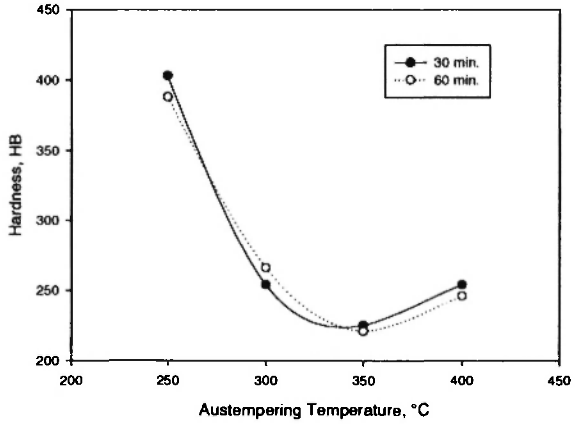

Fig. 8: Variation in Brinell hardness with austempering temperature

In a two-step process, the decreasing rate in n-value is more gradual and the minimum value is around 385 °C while the increasing profile is not so noticeable with austempering temperature. This is due to slower formation of finer size ferrite and slower replacement by austenite, which is the dominant factor in controlling the n-value /12/. Figure 8 shows the variation in Brinell hardness with austempering temperature. In this figure, the hardness of ADI again decreases sharply with increasing austempering temperatures. This is due to the formation of ferrite, which again above 300-350 °C is starting to be replaced by austenite that raises the hardness value.

CONCLUSIONS:

1. Up to 300 °C austempering temperature, the ADI has high strength and low ductility. Between 300 to 350 °C austempering temperature, ADI showed low strength and high ductility with a high carbon austenite and ferrite microstructure.
2. For austempering temperature from 250- 400 °C, the n -values for ADI vary from 0.5 to 0.12 and K values varies from 129 to 1100 Kg/mm^2.
3. The lowest n and K values are reached between 300-350 °C austempering temperature.
4. Hardness is changing with the change in austempering temperature and following the same profile of the change of n and k values with austempering temperature.
5. The change in strength, n-value and K value of ADI is related to the change in microstructure of the material.

REFERENCES

1. K.L. Hayrynen, K.R. Brandenberg and J.R. Keough, "Applications of austempered cast irons". *AFS Trans.* **02-084:** 1-10 (2002).
2. K.B. Rundman and R.C. Klug, "An X-ray and metallographic study of an austempered ductile cast iron", *AFS Trans.* **90**, 499 (1982).
3. A. Kutsov, Y. Taran, K. Uzlov, A. Krimmel and M. Evsyukov, "Formation of bainite in ductile iron", *Mater. Sci. Eng. A* **275**, 480 (1999).
4. C.S. Choi, W. Sharpe, J. Barker and R.J. Fields, "Neutron diffraction study of austempered ductile iron", *Metall. Mater. Trans. A* **27**, 923 (1996).
5. R.B. Gundlach and J.F. Janowak, "Development of a ductile iron for commercial austempering", *AFS Trans* **94**, 377–388 (1983).
6. G.J. Cox, "The Effect of Austempering Time on the Properties of High-Strength S.G. Iron", *The British Foundryman*, June 1986.
7. B.V. Kovacs, "Austempered ductile iron, facts and fiction", *Modern Cast.* **36**:37–41 (1990).
8. J. Yang and S.K. Putatunda, "Influence of a novel two-step austempering process on the strain-hardening behaviour of austempered ductile cast iron (ADI)". *Mater. Sci. Eng. A* **382**, 265-279 (2004).
9. J.F. Janowak and R.B. Gundlach, "Approaching austempered ductile iron properties by controlled cooling in the foundry", *J. Heat Treating*, **4** (1), 25-31, (1985).
10. M. Grech and J.M. Young, "Effect of austenitizing temperature on tensile properties of Cu-Ni austempered ductile iron", *Materials Science and Technology*, **6**, 415-421, (1990).
11. R.A. Harding, "Effect of metallurgical process variables on austempered ductile irons", *Metals and Materials*, **2** (2), 65 (1986).
12. G.E. Dieter, *Mechanical Metallurgy*. 3rd ed. New York: McGraw-Hill; 1986.
13. J.W. Simmons, "Strain hardening and plastic flow properties of nitrogen-alloyed Fe-17Cr-(8-10)Mn-5Ni austenitic stainless steels", *Acta Mater.* **45**, 2467-2475 (1997).
14. S.K. Putatanda and I. Singh, "Fracture toughness of unalloyed austempered ductile cast iron", *J Test Eval* **23**(5), 325–32 (1995).
15. D.J. Moore, T.N. Rouns and K.B. Rundman, "The effect of heat treatment, mechanical deformation and alloying elements on rate of bainitic formation in austempered ductile cast iron.", *J Heat Treat* **4**(1), 7–24 (1985).
16. P.P. Rao and S.K. Putatunda, "Influence of microstructure on fracture toughness of austempered ductlie cast iron ", *Metal Mater Trans* **28**A(7), 1457–70 (1997).
17. J.L. Garin and R.L. Mannheim, "Strain-induced martensite in ADI alloys", *Materials Processing Technology*, **143**, 347-351 (2003).
18. A.M. Sarosiek and W.S. Owen, "The work hardening of dual-phase steels at small plastic strains", *Mater.Sci.Eng.* **66**, 13-34 (1984).
19. Z. Fan, H. Mingzhi and S. Deke, "The relationship between the strain-hardening exponent n and the microstructure of metals", *Mater. Sci. Eng. A* **122**, 211-213 (1989).