IMPROVEMENT OF MECHANICAL PROPERTIES OF AUSTEMPERED DUCTILE CAST IRON BY A TWO-STEP AUSTEMPERING PROCESS

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ABSTRACT

Austempered ductile cast iron (ADI) has emerged as an important engineering material in recent years because of its excellent mechanical properties. These include high strength with good ductility, good wear resistance, fatigue strength and fracture toughness. In this investigation, a nodular or ductile cast iron with predominantly pearlitic as-cast structure was processed by a novel two-step austempering process. Two batches of samples were prepared. The first batch of samples wasaustenitized at 927 °C for 2 h and then austempered at several temperatures like 260 °C, 288 °C, 316 °C, 343 °C, 371 °C, and 400 °C respectively, for 2 h, and then air cooled. The second batch of samples was processed by the two step austempering process. These samples were austenitized at 927 °C for 2 h and then quickly quenched to 260 °C for 5 min and immediately subjected to austempering temperatures, such as 260 °C, 288 °C, 316 °C, 343 °C, 371 °C, and 400 °C. Austempering for 2 h and air cooling were done. Influence of this two-step austempering process on mechanical properties of ADI was examined. Test results show that this two-step austempering process has resulted in significant improvement in yield and tensile strengths of the material over the conventional single-step austempering process.

Keywords: Austempered ductile cast iron (ADI), Mechanical properties, Two-step austempering process

I. INTRODUCTION

Austempered ductile cast iron (ADI) is considered tobe an important engineering material because of its attractive properties such as good ductility at high strengths [1–3], good wear resistance [4,5], fatigue strength [6–8] and fracture toughness [9–12]. Because of these combinations of properties, ADI is now used extensively in many structural applications in automotive industry, defense and earth moving machineries, etc.

The attractive properties of ADI are related to its unique microstructure that consists of ferrite (α) and high carbon austenite (γ_{HC}). This is different from the austempered steels where the microstructure consists offerrite and carbide. Because of this difference, the product of austempering reaction in ductile iron is often referred to as ausferrite rather than bainite. Large amount of silicon present in ductile ironsuppresses the precipitation of carbide during austempering reaction and retains substantial amount of stable high carbon austenite (γ_{HC}). Small amounts of alloying elements such as nickel, molybdenum and copper are generally added to ADI so that it has sufficient hardenability to be quenched to the austempering temperature without forming pearlite.

Austempered ductile cast iron is an alloyed and heattreated nodular cast iron. The starting material for the development of ADI is the high quality ductile or nodular cast iron. It is then subjected to an isothermal heat treatment process known as ''austempering''. Conventional austempering process (referred to as single-stepaustempering) consists of austenitizing the casting in the temperature range of 871–982 °C for sufficient time to get a full austenite (γ) matrix, and then quenching it to an intermediate temperature range of 260–400 °C. The casting is maintained at this temperature for 2–4 h. A schematic of the conventional single-step austempering process is shown in Fig. 1. During austempering, a two-stage phase transformation reaction takes place in ADI. In the first reaction, austenite (γ) decomposes into ferrite (α)and high carbon or transformed austenite (γ_{HC}) asshown in equation (1):

$$\gamma \rightarrow \alpha + \gamma_{HC} \quad (1)$$

If the iron is held at the austempering temperature for too long, a second reaction occurs, which causes further decomposition of the high carbon austenite into ferrite and ε-

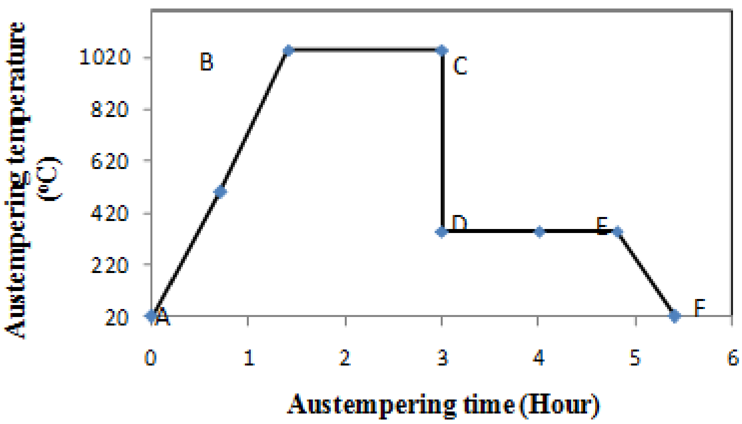

Fig. 1. Schematic of single step austempering process

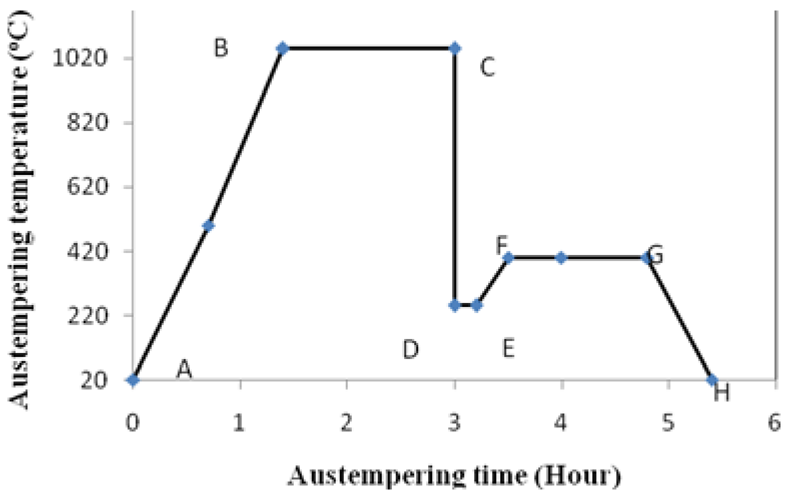

Fig. 2. Schematic of the conceived two-step austempering process

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carbide as shown in equation (2):

$$\gamma_{HC}\alpha \xrightarrow{\pm \varepsilon} \quad (2)$$

The microstructure in this case will contain εcarbide which makes the material brittle [13]. Since the ε carbide is a detrimental phase constituent, this reaction must be avoided during austempering process. It has been well established [14] that the best combination of mechanical properties (tensile strength and ductility) is obtained in ADI after the completion of the first reaction but before the onset of the second reaction. The time period between the completion of the first reactionand the onset of the second reaction is termed as‘‘process window’’. One important function of the alloying elements added to ADI is to enlarge this process window.

1. A-B: heat up to the austenitizing temperature;
2. B-C: hold at the austenitizing temperature (usually 2 hours);
3. C-D: quench to first austempering temperature;
4. D-E: hold at the first austempering temperature (for a few minutes until nucleation is completed);
5. E-F: raise temperature immediately to second austempering;
6. F-G: hold at the second austempering temperature (usually 2 hours);
7. G-H: Air cool to room temperature.

It is now well established [6, 14] that the important microstructural features influencing the mechanical properties of ADI are:

1. transformed austenite content (volume fraction of
2. austenite, $X\gamma$);
3. carbon content of the austenite (Cγ) as well as
4. morphology of ferrite (acicular α) and austenite.

When ADI is austempered at lower temperatures, e.g., 260 °C, it has finer ferrite and austenite and this results in higher yield and tensile strength but with lower ductility. On the other hand, when ADI is austempered at higher temperatures, e.g., 371 °C, it has coarser or feathery ferrite and austenite and this reduces the yield and tensile strengths but imparts higher ductility.

Thus, in summary, mechanical properties of ADIhave been found to be dependent on the fineness offerrite and austenite and the austenitic carbon [6,14,15][(XγCγ), where Xγ is thevolume fraction of austenite andCγ is the carbon content]. Therefore, it will be possibleto optimize the mechanical properties of ADI if one canproduce very fine ferrite and austenite as well as veryhigh austenitic carbon. It has also been observed thatthe transformation of austenite to ferrite during the firstreaction of ADI occurs by the nucleation and growthprocess [6–9]. Nucleation depends on the supercoolingand it is possible to obtain higher carbon in austenite(Cγ) if the austempering temperature is higher. Thus, itwas theorized here that by combining large supercoolingand higher austempering temperature, it may be possibleto increase the parameter (XγCγ) and at the same timewe can have very fine ferrite and austenite in the matrix.This is expected to enhance the mechanical properties ofADI. This two-stepprocess involves first quenching the alloy to a lowertemperature after austenitizing and thus increasing thesupercooling, and then immediately (once the nucleationis complete), raising the temperature of the quenchingmedia to a higher temperature to facilitate faster diffusionof carbon and thereby increasing the carbon contentof the austenite and hence increasing the austeniticcarbon (XγCγ) in the matrix. A schematic of the two-step austempering process is shown in Fig. 2.

A preliminary study by one of these investigators(S.K.P.) on a low manganese ADI [15] has shown thatthe two-step austempering is a feasible process for developmentof ADI. The present investigation is a continuationof that study where the two-step process hasbeen applied to an ADI with conventional composition.The primary objective of this investigation was thus toexamine the validity of the hypothesis, i.e., whether largesupercooling and carbon partitioning will indeed producethe desired microstructure. The secondary objectivewas to examine whether finer ferrite and austenitetogether with higher austenitic carbon will improve themechanical properties ofADI of conventional composition. The final objectivewas to compare these properties with ADI processed bysingle-step process, so that to establish a novel route bywhich ADI can be further strengthened and toughened.

II. EXPERIMENTAL PROCEDURE

2.1. Material

The material used in the present investigation is an alloyed nodular cast iron of conventional composition. The chemical composition of the material is reported in Table 1. The microstructure of the as-cast material is shown in Fig. 3. The as-cast material was predominantly(over 80%) pearlitic in nature. The material was cast in the form of round cylindrical bars of 25.4 mm(1 in.) diameter and 370 mm (14 in.) long and keel blocks. Cylindrical samples for tensile testing were prepared as per ASTM standard E-8 [16] from these round bars.

Table 1. Chemical composition of the material (wt%)

Carbon	3.48
Silicon	2.40
Manganese	0.31
Nickel	1.50
Copper	0.50
Phosphorous	0.01
Sulphur	0.01
Magnesium	0.05

Two batches of samples were prepared. One batch of samples was processed by single step, i.e., conventional austempering process and the second batch of samples was processed bytwo-step process. This was done for comparison purpose.The first batch of samples were initially austenitized at 927 °C for

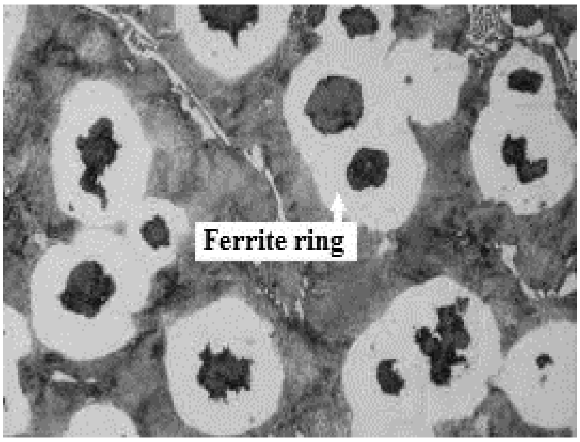

Fig. 3.Microstructure of the ductile iron in as-cast state. Etched by 2%nital etched, 100x

2 h and then austempered at several temperatures like 260 °C, 288 °C,316 °C, 343 °C, 371 °C, and 400 °C respectively, for 2 h, and then air cooled. The austempering treatment parameters were so chosen so that the processing will be within the process window of ADI. The second batch of samples was processed by the twostep austempering process. These samples were also initially austenitized at 927 °C for 2 h and then quickly quenched into molten salt bath maintained at 260 °C for 5 min to obtain sufficient supercooling and nucleation of ferrite. Immediately after that, the samples were transferred to another salt bath which was maintained at predetermined austempering temperatures, such as 260 °C, 288 °C, 316 °C, 343 °C, 371 °C, and 400 °C. The samples were austempered at these temperatures for 2 h and finally air cooled.

2.2. Tensile testing

Tensile testing of samples was performed as per ASTM standard E-8 [16]. Three identical samples were tested from each heat-treated conditions. The tests were carried out at a constant engineering strain rate of 4 x 10^{-4} s^{-1} on an MTS (material test system) servo-hydraulic machine at room temperature and in ambient atmosphere. Load and displacement plots were obtained on an X–Y recorder and from these load–displacement diagrams yield strength, ultimate tensile strength and % elongation values were calculated. The average values from three test samples are reported in this paper.

III. RESULTS AND DISCUSSION

3.1 Tensile Properties

Fig. 4 shows the influence of austemperingtemperature on yield strength of the ADIprocessed by single- and two-step processes, respectively. Fig. 5 shows the effect of austempering temperature on the tensile strengths of the materials (single step as well as two-step process). From these figures, it is evident that both hardness and yield strength decrease as the austempering temperature increases. Since

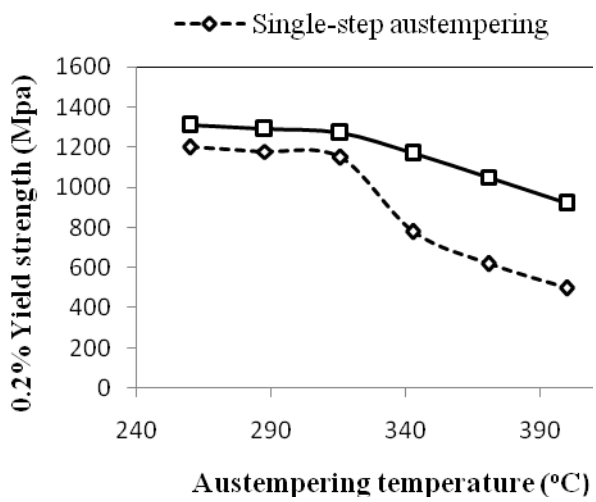

Fig.4. Influence of austempering temperature on 0.2% yield strength

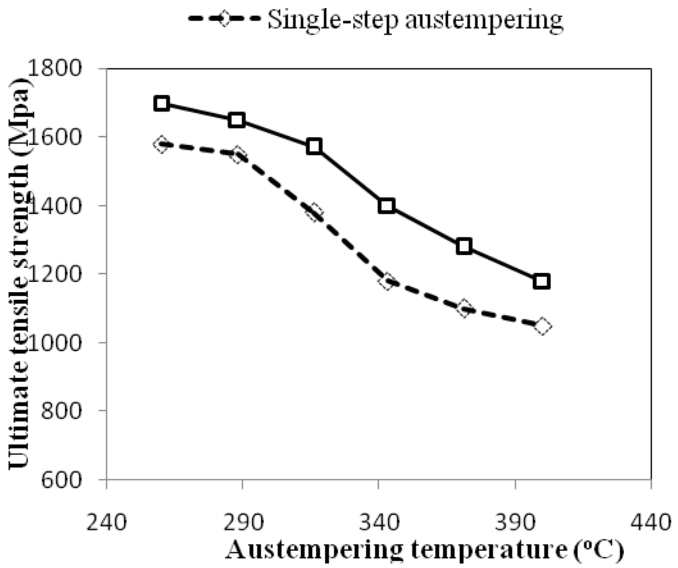

Fig. 5. Influence of austempering temperature on ultimate tensile strength

boththe austenite and ferrite becomes coarser with the increase in austempering temperature, the yield and tensile strengths decrease. It must be pointed out that the yield and tensile strengths of the materials obtained by single-step process are comparable to the values reported in literature [6–12].

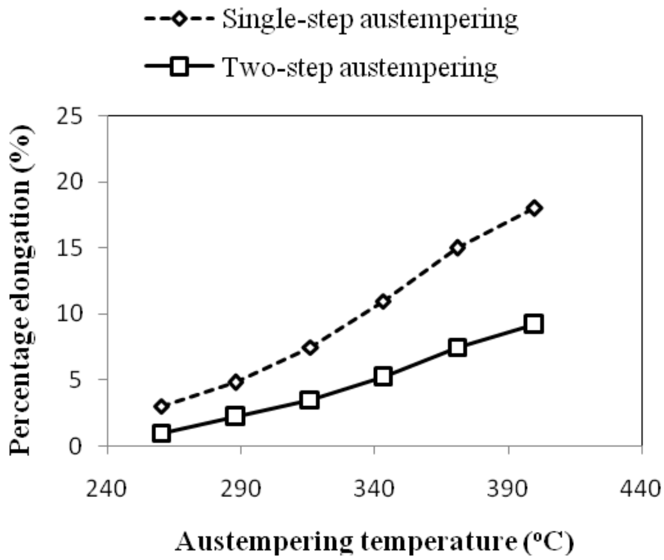

Fig. 6. Influence of austempering temperature on ductility (percentage elongation)

For example, ASTMGrade 4 ADI specifies aminimum yield strength of 1100 MPa for Grade 4 ADI. After austempering at 260 °Cby single-step process, an average yield strength of 1210 MPa was obtained. Similarly, yield strength acquired in ADI by single-step process after austemperingat 330 °Cwas 950 MPa, which was more than 10% higher than the specified value of 850 MPa for the ASTM Grade 3 iron. This implies that the austemperingprocesses were successful and produced the anticipated results. Figs. 4 and 5 show that the two-step austempering process has resulted in higher yield and higher tensile strengths than the singlestep process. This is due to the finer ferrite and austenite produced by two-step austempering process. It is well known (Hall–Petch equation) that the finer grains result in higher yield and tensile strengths.The ductility of the materials (two-step as well assingle step) is displayed in Fig. 6. Increased ductility was obtained at higher austempering temperature. However the two-step process has resulted in lower ductility than the single-step process. This reduction in ductility is probably related to two reasons. First of all, ductility generally decreases as the strength increases. Moreover, it is possible that there was the formation of ε or Hagg carbides within ferrite matrix during the two-step process. As mentioned earlier, the two-step austempering process forms finer ferrite as well as austenite cells. During austempering, carbon atoms diffuse out of ferrite needles into the surrounding austenite. Since the diffusion paths are much shorter and the diffusion rate higher, in the two-stepprocess, time needed to saturate austenite with carbon will be less. In this sense, the current 2 h austemperingtime would be probably beyond the ‘‘process window’’ of the material, causing the second reaction to take place. Dubensky and Rundman[17] observed unstable transition carbides of ε (Fe_2C with a hexagonal structure) and Hagg carbide (Fe_5C_2 with a monoclinic structure) at prolonged austempering process. They argued that the presence of a particular carbide or carbides will greatly depend on alloy composition and heat treatment, and it is also likely that the times when they first appear will also vary significantly from alloy to alloy. Dorazil and Svejcar [18] indicated the existence of carbides at an early austempering time. It is therefore reasonable to deduce that presence of carbides may have partly contributed to the reduction of ductility. However, a TEM analysis is being carried out to examine any presence of carbides. Interestingly, it appears that when we apply two-stepaustempering process, full 2 h may not be necessary for successful austempering of ADI. In this way, there may be an economical advantage for two-step process since comparable mechanical properties can be obtained at a much shorter duration of austempering.

III. CONCLUSIONS

A concept of two-step austempering process for ADI was conceived. This two-step process has resulted in higher yield strength, tensile strength and ductility than the conventional single-step austemperingprocess. The two-step process has also resulted infiner ferrite and austenite as well as higher austenitic carbon ($X\gamma C\gamma$) in the matrix. This has contributed toimproved strength and ductility in ADI.

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