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Stable Production of High-volume and High-quality ADI and Further Improvement of Consistency

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Abstract

This paper presents 419 test data from 6 months continuous production. The results show that, through strict control of raw materials, melting, and spheroidization processes, high-quality, as-cast ductile iron casting with stable composition and stable as-cast structure are obtained, and with using advanced professional heat treatment equipment for austempering treatment, the ADI properties are excellent, all higher than the minimum requirements of ASTM and Chinese national standards. The results also show that the dispersion of high strength grade ADI properties is relatively small, while that of high ductility grade ADI is relatively high. By analyzing the statistical data, in order to further reduce the dispersion of mechanical properties in high-volume production and improve the stability and consistency of ADI products, it is necessary to strictly control the production process, ensuring that ADI products for one grade have as similar chemical compositions and as-cast microstructures as possible. Additionally, precise control of the austempering treatment process should be implemented in a categorized manner based on factors such as casting section thickness, chemical and alloying composition, and as-cast microstructure.

Keywords: Stable production of high-volume and high-quality ADI, Casting process control, Austempering process control, Statistical data and analysis of ADI production

1. Introduction

Austempered ductile iron (ADI) is a relatively new and high-property engineering material developed in the 1970s. Due to its excellent properties, in the early years, ADI development was very fast throughout the world [1-5]. It was expected that ADI could be 4% or even more of the total ductile iron production. However, in recent years, the development of ADI has not been as fast as people expected. In China, ADI production in 2023 was only about 140,000 tons, representing less than 1% of total ductile iron production. This figure is quite low, and should be increased to 3%, or even more [6-8]. In recent years, in addition to traditional applications, ADI has been applied in renewable energy, such as solar photovoltaic (PV), solar thermal, wind power generation, industry intelligent robots, and new energy vehicles, as well as other new technology applications [9]. ADI is still growing, and there is great opportunity for the development and application of new ADI components throughout the world.

Henan ADI Casting Co., Ltd. is one of the earliest enterprises in China carrying out research, development and production of ADI through technical cooperation with Wuhan Textile University. In the early stages, the quality of pig iron and other treatment materials was not very good in China. By careful selecting furnace charge materials, spheroidization and inoculation and improving techniques, the quality of as-cast ductile iron castings was improved, good ADI castings were produced with the self-made austempering furnace, such as wear resistant discs in paper making machine and ADI pneumatic rock drill housing etc. However, the properties of the ADI were not stable, and although it meets the standard requirements, its mechanical properties fluctuate greatly. After 2000, by using high purity pig and other advanced spheroidization and inoculation materials and technologies and strict controlling austempering process, the properties stability of ADI casting were improved quite a lot. However, due to the disadvantages of the conventional austempering furnaces the properties stability of ADI casting couldn't be further improved.

In 2003, the Shanghai Powermax Furnace Corp. was formed, and the advanced American AFC-Holcraft Universal Batch Ausquench furnace was introduced into China. Recognized the importance of austempering furnace, in 2015, Henan ADI purchased a Powermax UBQA 36-72-56 austempering system made by the Shanghai Powermax, became the company having foundry, machining shop and advanced specialized austempering furnace. Since then, the quality and production of ADI have been significantly enhanced.

In order to improve competition, satisfy the increasingly more stringent requirements for quality stability and consistency and expand business, this paper collected and analyzed 419 test data from 6 months continuous production at the company. The results show that under strict control of casting processes such as raw materials, melting, and spheroidization inoculation, and using advanced professional heat treatment equipment for austempering treatment, the mechanical properties of various grades of the obtained ADI products are superior to the standard technical requirements. The statistical distribution feature of production data was analyzed and suggestions for further improving consistency of ADI products were put forward.

2. ADI components, test method, processing control of ductile iron production and austempering treatment at the company

2.1. ADI components produced and property test methods

Henan ADI produces all grades of ADI components for various industries such as heavy tricks, construction/mining, agricultural industry, textile industry, new energy industry, railway industry and general engineering etc., the main thickness of the ADI castings is 10-65mm, the weight is 5-175kg. Some examples of ADI application include upper and lower for independent suspension control arms, connectors, load bearing seats, thrust rod support for heavy trucks, spring brackets, agricultural baler gears etc.

Side-by-side Y block were cast at the same time with the ductile iron castings. 25×25mm section with the same length as Y block were cut from the Y blocks and austempered together with castings. Tensile specimens were machined from the austempered samples conforming to ISO17804-2020 specified dimensions(10 mm diameter and the original gauge length 5d) for tensile property test in a standard tensile test machine WAW-600B, unnotched Charpy specimens of 55×10×10mm were machined from austempered samples and tested in a standard impact test machine JB-30A. Hardness was measured on the austempered samples in HB-3000B. Microstructure specimens were prepared from above austempered samples and examined under microscope TMR2000.

2.2. Processing control of as-cast ductile iron production

Ductile iron castings for austempering are produced under strict and tight process control process. Furnace charge materials in induction furnace and base melt: using high-purity pig iron 50%, ADI returns 30%, high quality scrap steels 20% and other high-quality graphite, ferrosilicon iron-alloy to melt suitable base iron; spheroidizing an inoculation: using high-quality spheroidizing alloy and tundish ladle treatment, using high-quality inoculant and optimized inoculation treatment, including ladle inoculation and instantaneous in-stream inoculation, resulting in over 85% nodularity (according to International Standard ISO 945-4, 2019-05,Microstructure of Cast Irons - Part4), high nodule count, and relatively stable metal matrix structure.

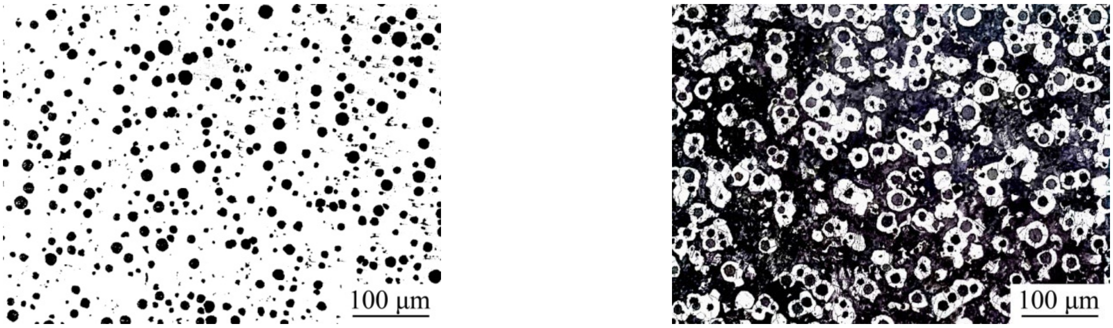
The chemical composition of ADI meets the requirements for producing sound castings without shrinkage defects and with minimal carbides and inclusions [10]. The content of alloying elements copper, nickel, and molybdenum meets the requirements for hardenability for different wall thicknesses. The main elements and alloying element control range for mass production of ADI castings are shown in Table 1, while other trace elements are very low and not listed in the table. For important ADI castings with a wall thickness greater than 30mm, a sufficient amount of alloy is added to ensure the uniformity of the entire cross-sectional structure. When the wall thickness is small, the lower limit of alloy content is used; when the wall thickness is large, the upper limit of the alloy content is used.

Table 1.
Control range of ADI composition (mass%)

Casting thickness	C	Si	Mn	P	S	Cu	Ni	Mo	Mg	Re
≤30mm	3.5-3.8	2.3-2.7	High elongation＜0.20 High strength 0.25-0.4	＜0.03	＜0.02	/	/	/	0.035-0.055	0.01-0.02
＞30mm	3.4-3.6	2.2-2.6	High elongation＜0.2 High strength 0.25-0.4	＜0.03	＜0.02	0.5-0.8	0.5-1.0	0.1-0.3	0.035-0.055	0.01-0.02

In addition, optimum gate and feeder design, reasonable pouring temperature, exothermic feeders and chills for complex or large castings are used to obtain sound castings without shrinkage defects, slag and inclusion defects.

Figure 1 shows the graphite and metal matrix structure of a typical as-cast ductile iron produced by the company, it shows good nodularity, high nodule count and good matrix structure.



a) graphite structure b) matrix structure

Fig. 1. Typical graphite and matrix structure of as-cast ductile irons

2.3 Austempering process control

Figure 2 shows a typical schematical diagram of the austempering process cycle. The casting is heated to austenitizing temperature (A-B) and holding for one to two hours (B-C) for allowing as cast matrix structure entirely transform to austenite structure and saturated with carbon. Then the high temperature castings with carbon saturated austenite structure are quickly cooled to the salt bath with required austempering temperature, avoiding the formation of pearlite (C-D). After a short time (D-E), stage Ⅰ of the austempering reaction starts, after an appropriate austempering time (E-F), the austenite transforms to ausferrite, which is a mixed structure of high carbon (1.8-2.2%) austenite and acicular ferrite, thereby obtaining the desired strength, plasticity, and toughness. The austempering time should not be too long, if the time is too long, beyond G, stage II of the austempering reaction occurs, the high carbon austenite transforms into bainite (mixed structure of ferrite and carbide) which are detriment to ADI properties.

The austenitizing time and temperature and the austempering time and temperature influence properties of ADI. ADI properties are mainly determined by austempering time and temperature. The austempering time is determined when to obtain entire ausferrite structure. Normally higher austempering temperatures are used to produce the lower-strength and high elongation grades of ADI, lower austempering temperatures are used to produce the higher-strength low elongation grades of ADI. When austempering temperature is lower, there is more ferrite and less austenite in the structure. The structure is finer and the ferrite more needle-like.

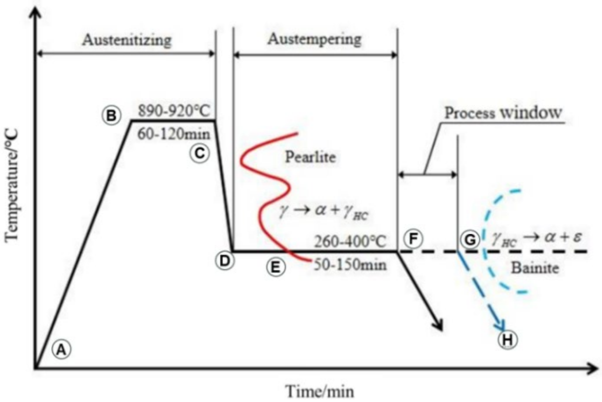


Fig.2 Schematic diagram of the austempering heat treat cycle

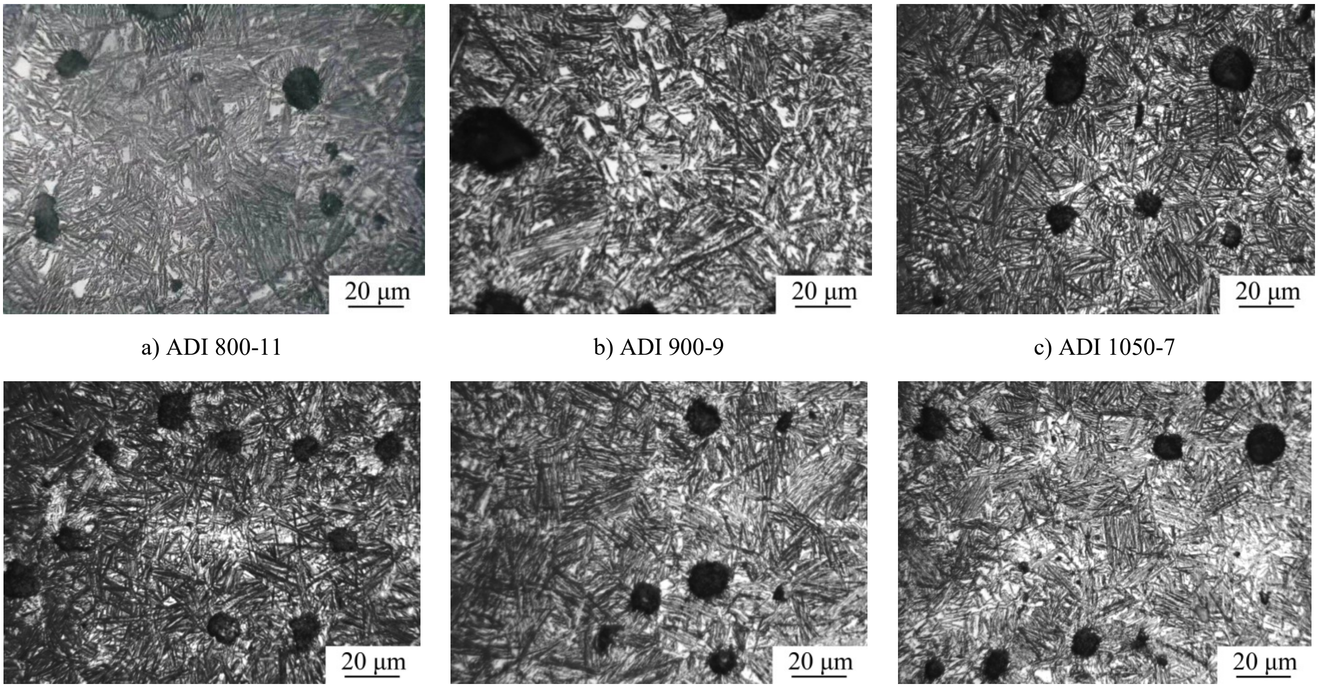
The company uses a Powermax UBQA 36-72-56 controlled atmosphere salt bath line for the austempering treatment. This professional heat-treatment system can ensure that castings heat treated at high temperature during austenitization are quickly cooled to the required austempering temperature, avoiding the formation of pearlite; the salt bath has less instantaneous temperature increase when castings are quenched in the salt bath and also has uniform temperature distribution after salt bath returns to designed temperature.

The company produces ADI components that meet the two ADI standards: ASTM A897M-22 and Chinese national standard GB/T24733-2023. The austempering temperature determines the strength, elongation and impact energy that ADI may achieve. For high-strength ADI such as ADI 1400-2 and ADI 1600-1, the austempering temperature is between 260-280℃; for ADI 1200-4 with high strength and certain ductility, the austempering temperature is between 290-320℃; for ADI 1050-7, high strength and high ductility ADI, the austempering temperature is between 320-340℃; for high ductility grades ADI such as ADI 800-11 and ADI 900-9, the austempering temperature between 360-400℃ is used.

3. Statistical ADI test data from 6 months continuous production

3.1 The ADI test data are higher than the minimum requirements of ASTM A897M-22 standard and Chinese national standard GB/T24733-2023

A typical structure of ADI obtained by austempering is shown in Figure 3. It can be seen that the acicular ausferrite structure in the low strength and high ductility ADI is relatively coarse, and there is a large amount of equiaxed blocky high carbon austenite between the acicular structures. In the high strength ADI, the needle-like ausferrite structure is small and fine, with more obvious needle-like characteristics and a small amount of blocky austenite. In the medium strength and medium ductility ADI, the ausferrite structure falls in between. Different structures endow ADI with various properties. Therefore, by strictly controlling the raw materials and production process, obtaining the required ADI structure can meet the performance requirements of different ADI workpieces.



a) ADI 800-11 b) ADI 900-9 c) ADI 1050-7

d) ADI 1200-4 e) ADI 1400-2 f) ADI 1600-1

Fig. 3 Typical microstructure of different grades of ADI product

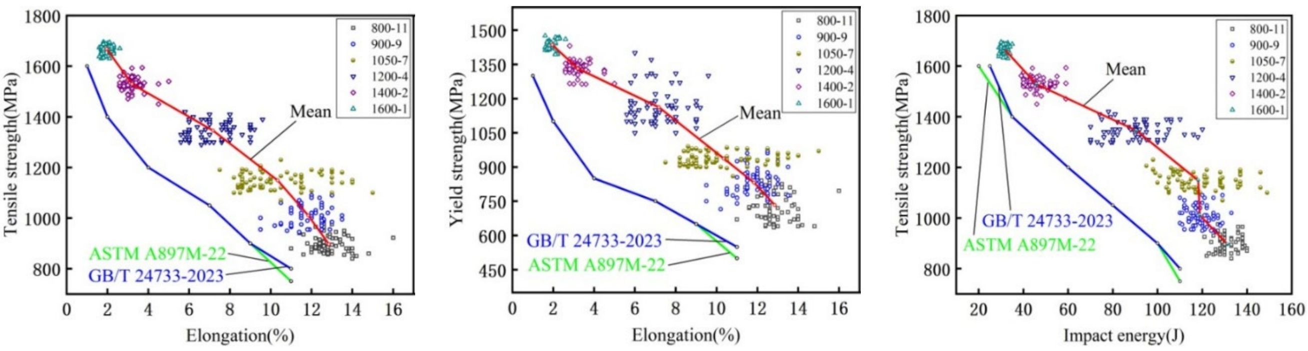
Table 2 shows the property ranges and average values of 6 grades ADI using the test data from 6 months continuous production at the company. Figure 4 shows the ADI test data and the requirements of ASTM A897M-22 and Chinese national standard GB/T24733-2023. It can be seen that the ADI properties are excellent, all higher than the minimum requirements of ASTM and the Chinese standards.

The various ADI applications have helped the company's customers to solve their engineering problems by improved component performance, so reducing cost and increasing profit.

Table 2.
The property ranges and average values of 6 grades ADI of 419 test data from 6 months continuous production

Property	ADI 800-550-11		ADI 900-650-9		ADI 1050-750-7		ADI 1200-850-4		ADI 1400-1100-2		ADI 1600-1300-1	
	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.
UTS (MPa)	870-975	897	945-1090	1011	1070-1230	1149	1290-1420	1346	1450-1594	1529	1630-1695	1668
YS (MPa)	635-865	734	715-970	832	860-990	937	1050-1400	1162	1263-1431	1332	1393-1475	1436
Elongation (%)	11.0-16.0	12.8	9.5-13.5	11.8	7.5-15.0	10.4	5.6-9.6	7.1	2.6-5.0	3.2	1.6-2.6	2.0

Impact (J)	121-140	131	110-133	119	95-149	118	70-120	90	39-59	46	29-35	31
Hardness (HBW)	263-298	280	273-318	294	318-370	347	360-418	401	433-456	444	454-488	468



a) Elongation-Tensile strength　　b) Elongation-Yield strength　　c) Impact energy-Tensile strength

Fig. 4. ADI test data from 6 months continuous production and the requirement of ASTM A897M-22 and Chinese national standard GB/T24733-2023

The reasons for obtaining the excellent results are because：

The as-cast ductile irons have good nodular graphite structure and metal matrix structure with minimum carbides, inclusions and shrinkage defects due to strict and tight control of every production process of ductile iron.

The application of advanced atmosphere controlled commercial austempering furnace which can control most accurately the selected correct austenitizing temperature and time, and the optimized austempering temperature and time. It can be said that austempering furnace is key to achieving high-quality ADI components and and also gives opportunity to develop more demanded ADI casting such as CADI (carbidic austempered ductile iron), two phase structure ADI and heavy section (100-200 mm) ADI.

The excellent results again show that good ADI, higher than the minimum requirements of ASTM and Chinese standards, can be obtained in the high-volume production to satisfy the needs of various industries for improving components properties, reducing cost and saving weight.

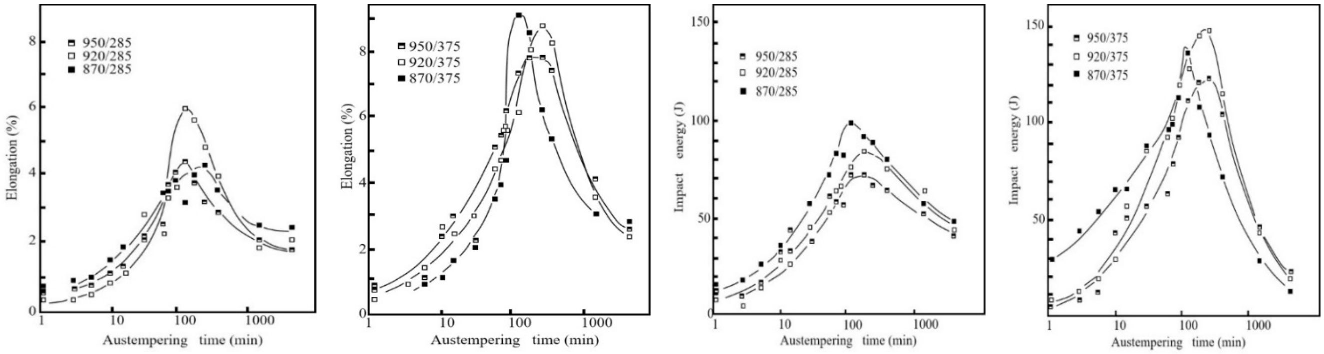
3.2. Properties dispersity of high-volume and high-quality ADI production

It can be seen from Figure 4 that all different grades of ADI have a certain degree of dispersity in properties, especially in elongation and impact value. The ADI grade 1600-1 and 1400-2 have least properties dispersity; the ADI 1050-7 and 1200-4 grades have highest properties dispersity, the ADI 800-11 and 900-9 have properties dispersity in between. The following section will discuss and analyze why this dispersity happens and the dispersity features.

4. Discussion and analysis of the test data

4.1. For the same composition of ductile iron, the properties vary with austempering time at different austempering temperature

Experimental results carried out in Manchester University show that for a certain composition of ductile iron, properties change with austempering time, and at high austempering temperature, properties variation is evident, as austempering temperature decrease, in general, the changes in mechanical properties with time are more gradual [11-13]. Figure.5 shows the experimental results[11].



a) Austempering time-Elongation c) Austempering time-Impact energy b) Austempering time-Elongation d) Austempering time-Impact energy

Fig. 5. Variation of impact energy and elongation with austempering time, for austenitizing temperatures of 870, 920 and 950°C and austempering temperatures of 285 and 375°C. Iron composition: 3.39%C, 2.56%Si, 0.25%Mo, 0.29%Cu, 0.37%Mn and 0.04%Mg, carbide 0.033%, nodule count 104/mm^2 [11]

It is seen from Figure.5 that as the austempering time increases, elongation and impact energy increase and reach maximum values, then decrease. The low value of properties at short austempering times is due to the brittleness associated with the large amount of martensite, which is derived from the unreacted austenite during cooling to room temperature. This martensite forms along continuous paths in the intercellular boundaries in the matrix. A further contribution to the low ductility may come from any austenite that is thermally stable but mechanically unstable. During deformation these areas may transform into martensite and reduce the ductility.

As the austempering time increases, the amount of martensite decreases and that of ausferrite increases, producing an improvement in the mechanical properties. However, this improvement does not continue indefinitely. At longer austempering times the strength remains relatively unchanged but a reduction in elongation and impact energy occurs, particularly at higher austempering temperatures in the upper ausferrite range. After 100% ausferrite has been transformed (stage I reaction completed), stage II reaction commences with an increase in austempering time. This results in a fall in the amount of transformed high C austenite in the structure and an increase of carbides due to the stage II reaction, resulting in a fall in ductility. This carbide cannot be observed under normal microscopy, and can only be detected by using X-ray diffraction techniques. The retained austenite level falls to zero as the stage II reaction is completed. Normally it is defined that 3% unreacted austenite is the start-time of the processing window and 10% fall in the maximum volume of reacted austenite (VRA) as end time of processing window. Between these two points (the processing window), optimized properties are obtained, particularly the ductility.

After the austempering temperature has been determined, the selection of austempering time is the most important parameter. An important feature of any irons with normal ductile iron composition and alloying addition is the considerable variation in mechanical properties, particularly ductility, with austempering time. The austempering time must be selected to optimize the mechanical properties for a chosen austenitizing and austempering temperature. The variation of mechanical properties with austempering time depends on the change in nature and amount of phases and structure present as the austempered structure evolves.

At high austempering temperature, the austempered structure changes to upper ausferrite. This structure, with its coarse, carbide free, ferrite-austenite mixture (ausferrite), which contains a greater volume of retained austenite, results in reduced strength and increased ductility. At higher austempering temperature, the driving force for the stage I reaction is lower and that for reaction II is higher. As a result, the austempered microstructure is less uniform and contains blocky austenite areas in which martensite formation also occurs more readily at the higher austempering temperature, the result is a continued fall in strength and reduced ductility.

At low austempering temperature, the lower ausferrite structure predominates in the microstructure, the austenite carbon content is close to 2.2% and its fine structure of ferrite platelets dispersed carbide and low level of retained austenite promote strength and contribute to the low ductility at low austempering temperature.

As the austempering temperature decrease, the stage II reaction requires a longer austempering time, in general, the changes in mechanical properties with austempering time is more gradual.

The chemical composition and alloying composition influence the austempering process and the changes in properties with austempering time, therefore for different irons with different chemical and alloying composition, the changes in properties with austempering time are different, although their change rule is similar. Normally Mn, Cu, Ni and Mo will delay stage I reaction and extend stage II reaction, and generally increase the width of processing window and move the processing window to longer time.

4.2. Properties dispersity with austempering time and temperature for high-volume production ADI

The above paragraphs discussed the property changes with austempering temperature, austempering time and influence of austempering temperature on the variation of properties for a certain composition of ductile iron. For high-volume production of

ADI, even for the same grade and thickness, the composition of ductile irons made from iron melted in different furnace-batches and treated in different ladles, are different in carbon, silicon, manganese and alloying content. Ductile irons from different batches, having differences in composition, may be austempered in the same heat-treatment batch. However, as the austempering cycle progresses, these compositional differences lead to different rates of transformation and properties, when these irons are taken out from the salt bath at the same time, resulting in a different effective austempering time for each ductile iron. Thus, having the same austempering time, the obtained properties are different due to actual different effective austempering time, resulting in a certain degree of dispersity.

Different from the variations in properties with austempering time for the same composition of ductile irons, for high-volume industrial production ADI, at higher austempering temperature (for ADI 800-11 and 900-9), the variation in elongation and impact energy is large. At lower austempering temperature (for ADI 1400-2 and 1600-1), in general, the change in mechanical properties is more gradual. At the austempering temperature in between (for ADI 1050-7 and 1200-4), the change in mechanical properties is the highest as shown in Table 2 and Figure 4.

For high-volume production, the property dispersion of the intermediate grade (ADI1050-7 and 1200-4) is the highest. Normally for these two grades of ADI, medium range of austempering temperature is adopted and the medium austempering temperatures have the widest process window range compared with the higher and lower austempering temperatures which implying within wider austempering time, properties satisfying standard can be achieved [1,11]. This also causes more different actual effective austempering time, thus, resulting in increased dispersion although the properties, especially elongation and impact values are higher than ADI standards. Further study is needed for this phenomenon.

It is seen from Table 2 and Figure 4 that the tensile and yield strength for all grades ADI also have certain degree of dispersity. This is due to that for every grade, not one austempering temperature, but small range of temperatures are adopted, as described in previous section. The different austempering temperature may also make some contribution to the variation in elongation and impact values.

5. Suggestions for reducing dispersity and improving consistency of high-volume ADI production

Although the properties of ADI in high-volume production are excellent, all much higher than the minimum requirements of ASTM and Chinese standards, reducing dispersity in properties and improving their consistency is still significant. Providing consistent, high-quality products allows customers to know exactly what to expect every time they purchase products, enhancing brand reputation and credibility, increasing customer satisfaction and repeat purchases and increase foundry's competitiveness.

For high-volume ADI production, two aspects can be considered to reduce dispersity and improve consistency.

5.1. For reducing dispersity in properties and increasing consistency of high-volume produced ADI, it is need to more tightly control chemical and alloying composition of ductile iron

Further, strictly control melting process, nodulization and inoculation process to make the as-cast nodular irons for the same grade ADI and similar thickness to have the same chemical and alloying composition as possible, even those iron castings made from different melt batches and different ladles.

The reason is that normally one batch of austempering nodular iron castings may be from different melt batches and different ladles. Alloy element manganese, copper, nickel and molybdenum increase hardenability, but need a long austempering time to obtain entire ausferrite microstructure in the whole section. If these nodular irons have very similar chemical and alloy composition, during austempering, the variation in properties with austempering time will be very small; when the austempering process is completed (take out from salt bath), they will have similar properties and better consistency.

5.2. Arrange ductile irons having similar thickness and similar chemical and alloy composition together in one austempering batch

For thick section ADI to obtain sound casting and full ausferrite structure, C and Si, carbon equivalent must be selected to obtain optimized graphite and matrix structure and sound casting without shrinkage defects. In addition, alloying elements Cu, Ni and Mo must also be added to increase hardenability to obtain a fully ausferrite structure across the section. The Si and Mn will influence the upper-critical temperature in phase diagram; Cu, Ni and Mo will delay the stage I reaction and extend stage II reaction and have different width of processing window. Different contents of Si, Cu, Ni and Mo have different changes in properties with austempering time.

When producing the same grade ADI, if austempering these castings having different chemical composition and alloy composition together in one batch, it will result in higher variation in properties, particularly in elongation and impact energy since one batch will have the same austempering time. Therefore, for the same grade ADI, it is better to arrange those ductile iron castings having as similar thickness and similar alloying composition as possible together in one austempering batch to reduce the dispersity in properties and improve the consistency.

6. Conclusions

1) Statistical ADI test data from 6 months continuous production shows that the properties of all grades produced are excellent, all much higher than the minimum requirements of the ASTM and Chinese standards. This is

due to the strict and tight control of ductile iron production and the austempering process and also proves that high-volume and high-quality ADI can be produced stably.

2) During austempering, the mechanical properties change with austempering time, and the variation in properties depends on the change in nature and amount of phases and structure present as the austempered structure evolves. At higher austempering temperature (for ADI 800-11 and 900-9), the variations in elongation and impact energy are large. At lower austempering temperature (for ADI 1400-2 and 1600-1), in general, the change in mechanical properties is more gradual. At the austempering temperature in between (for ADI 1050-7 and 1200-4), the change in mechanical properties is the highest. This may be due to the widest process window range for this austempering temperatures and more different actual effective austempering time during austempering.

3) Reducing dispersity in properties and improving ADI casting consistency is significant. It will enhance brand reputation, credibility and increase the foundry's competitiveness. In high-volume ADI production, in order to reduce dispersity in properties and increase consistency of ADI castings, more strict control of the whole casting process is needed for obtaining as similar chemical composition and alloying composition as possible for one grade ADI casting with similar thickness. In addition, for making the same grade ADI, it is necessary to arrange those castings to have as similar thickness and similar chemical composition and alloying composition in one austempering batch as possible to reduce the dispersity in properties and improve their consistency.

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