Strengthening and Toughening of Ni Added Ductile Cast Iron by Heat Treatment in the Eutectoid Temperature Range*

By Toshiro Kobayashi** and Hitoshi Tachibana***

Among various kinds of cast iron, ductile cast iron has good ductility and toughness, for the graphite morphology is spheroidal in this iron. It seems that the possibility of strengthening and toughening of the ductile cast iron lies in the modification of the matrix structure by heat treatment and the addition of alloying elements. In the present study, Ni is added to the ductile cast iron, and various matrix structures are obtained by heat treatment. Effects of these treatments on the toughness are examined.

When the Ni added ductile cast iron is transformed isothermally from the \((\alpha+\gamma)\) eutectoid temperature range after ferritic annealing, the ferrite plus bainite duplex structure is obtained, and this structure shows a good combination of strength and toughness. The most suitable condition for this treatment to give good toughness even at lower temperature is investigated. Then the Ni added duplex structure ductile cast iron is compared with the ferritic cast iron and the austenitic ductile cast iron by the U-notched Charpy test, fracture toughness test, and tensile test. It is shown that the Ni added ductile cast iron with duplex structure exhibits a good combination of high strength, toughness, and fracture toughness.

It is shown, however, that the transition temperature of the Ni added duplex structure slightly increases compared with the one of the usual ferritic structure in the U-notched Charpy test but largely decreases in the unnotched test. This phenomenon may be due to the transformation induced plasticity effect in the retained austenite phase. It is assumed, therefore, that the main part in the improvement of low temperature toughness in the Ni added duplex structure results from the stabilizing effect in the retained austenite phase by the Ni concentration during holding in the \((\alpha+\gamma)\) range.

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I. Introduction

Ductile cast iron is superior to the flaky graphite cast iron in ductility and toughness, for the spheroidal graphite morphology has the least notch effect and, therefore, its use is increasing. In recent years, the demands for the low temperature application of the cast iron is increasing with the development of the petrochemical industry and so on. Concerning the cast iron, it can be said that no large progress in the field of strength has been made since the ductile cast iron appeared. The strengthening and toughening of the cast material is very important, and it has been promoted by the improvement of the matrix structure with heat treatment and the addition of alloy elements\(^{(1)(2)}\). For example, INKO announced the method to toughen the cast iron by obtaining the bainitic matrix structure under the as-cast condition with Ni and Mo additions\(^{(3)}\). As the cast iron contains a large quantity of carbon, it is recognized that the bainitic matrix is preferable to the martensitic one as a basis of strengthening and toughening owing to its smaller lattice strain. On the other hand, Ni-resist austenitic cast iron that contains Ni over 20\% has been designed for low temperature use\(^{(4)}\). In ductile cast iron, it is generally said that the ferritic type has good toughness and the low transition temperature and that, therefore, it is suitable for low temperature use\(^{(5)}\); however, the lower limit temperature of its...
application is said to be 240–220 K\(^{(4)}\), and its low strength is also a problem.

On the other hand, in the case of steel, various kinds of Ni steel that contain Ni up to 9% have been developed for the use in the temperature range down to the liquid nitrogen temperature (77 K). Furthermore, in the case of 6 or 9%Ni steel, the improvement method of toughness by holding in the (\(\alpha + \gamma\)) two-phase temperature range and then quenching is being developed\(^{(6)(7)}\). This method is planned for the purpose of introducing the stable retained austenite and making the matrix structure fine. In cast iron, also, it is hoped to develop a new type one for the low temperature use.

Now, cast iron has some temperature range in the eutectoid transformation for its high Si content. In this study, the authors pay their attention to this point and heat-treat the Ni added ductile cast iron from the (\(\alpha + \gamma\)) range; then, the two-phase duplex structure is obtained. Stabilizing effect of the retained austenite by concentration of alloy elements to the austenitic phase during holding at the (\(\alpha + \gamma\)) range is investigated; and possibility to develop a cast iron that has good low temperature toughness and fracture toughness will be studied in detail.

II. Experimental Method

1. Test material

Test materials were melted in a 20 kg basic high-frequency induction furnace and were cast into a CO\(_2\) mold having the form of Y block (25 \(\times\) 60 \(\times\) 245 mm\(^3\)) after spheroidization by 0.7% addition of Fe–Si–Mg (8%) alloy and inoculation by 0.8% addition of Fe–Si (50%) alloy. Table 1 shows the chemical composition of materials; there were some differences among lots of DC, N2M, N3, N4 and N4M. The symbols of the materials have the following meanings. Ma; malleable cast iron (ferritic matrix), D2 and D2M; Ni-Resist ductile cast iron, DC; ductile cast iron, N2M~N4M; ductile cast iron with Ni and Mo additions (the materials that contain 2, 3 and 4%Ni are N2, N3 and N4, respectively, and the Mo added alloy has M at the end). A typical microstructure of the as-cast material is shown in Fig. 1.

Samples D2 and D2M are equivalent to ASTM D2 and D2M, respectively, and they have the austenitic matrix. D2M is an improved one of D2; i.e., Cr is decreased to improve the reduction in the toughness by generation of chromium carbides, and, therefore, Mn is increased\(^{(4)}\). They were tested after heating at 1200 K for 2 h (7.2 ks) followed by air cooling.

2. Heat treatment and test method

A specimen for measurement of the transformation temperature, that for the half-size unnotched Charpy impact test (5 \(\times\) 10 \(\times\) 55 mm\(^3\)), that for the U-notched Charpy impact test, that for the fracture toughness test, and that for the static tensile test were all cut from Y blocks and were provided for tests after the

<table>
<thead>
<tr>
<th>Symbol</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mg</th>
<th>Mo</th>
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<tr>
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<td>1.17</td>
<td>2.45</td>
<td>0.016</td>
<td>0.140</td>
<td>0.030</td>
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<tr>
<td>D2</td>
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<td>2.16</td>
<td>0.68</td>
<td>—</td>
<td>—</td>
<td>0.010</td>
<td>0.101</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
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<td>2.45</td>
<td>2.16</td>
<td>4.40</td>
<td>—</td>
<td>—</td>
<td>0.020</td>
<td>0.094</td>
<td>—</td>
<td>22.0</td>
</tr>
<tr>
<td>DC</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
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<td>2.23</td>
<td>0.20</td>
<td>0.010</td>
<td>0.008</td>
<td>0.022</td>
<td>0.034</td>
<td>0.49</td>
<td>1.98</td>
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<td>—</td>
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<td>—</td>
<td>2.97</td>
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<tr>
<td>N4</td>
<td>3.82</td>
<td>2.78</td>
<td>0.44</td>
<td>0.020</td>
<td>0.017</td>
<td>0.057</td>
<td>0.077</td>
<td>—</td>
<td>3.88~3.96</td>
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<tr>
<td>N4M</td>
<td>0.50~0.57</td>
<td>4.01~4.20</td>
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</table>

Ma: Malleable cast iron.
D2, D2M: Ni-Resist ductile cast iron.
DC: Ductile cast iron.
N2M~N4M: Ductile cast iron with Ni, Mo additions.

† Alloy compositions are all in mass%.
To measure the transformation temperature, a specimen (10 x 10 x 20 mm³), that had been ferritized after holding at 1173 K for 4 h (14.4 ks), cooled to 843 K in furnace and held for 24 h (86.4 ks) at this temperature, was quenched into water after heating near the transformation temperature range, and then the martensite content in the matrix was observed.

The impact test was carried out with an instrumented Charpy impact machine (capacity: 98 J), and the absorbed energy was calculated from the load-deflection curve.

To measure the fracture toughness, a deep notch specimen (15 x 15 x 82.5 mm³) with side grooves (ligament: 13(width) x 9(depth) mm²) underwent a fatigue crack (notch depth ratio: about 0.6) by load cycles of 3 x 10⁴–5 x 10⁴. It was tested by the instrumented Charpy impact machine at a somewhat low impact speed of 1.2 m/s, in order to avoid the influence of oscillation accompanying the impact load. The crack initiation energy was measured as an energy required up to the maximum load in the load-deflection curve, and the dynamic J integral value was calculated by Rice’s equation(8). However, there were some doubts whether the energy required up to the maximum load point was really equal to the crack initiation energy(9). In the present work, however, the method written above was assumed as a valid one. The J-integral values obtained in this
study satisfied Paris' equation\(^{(10)}\) for the plain strain condition, and they were regarded as \(J_{id} \) (\(J_{ic}\) under the dynamic loading condition). A static tensile test was carried out with an Instron type machine at the strain rate of \(4 \times 10^{-4} \text{s}^{-1}\). Furthermore, the measurement of the retained austenite content with the X-ray diffraction method\(^{(11)}\), the measurement of Ni distribution with an X-ray microanalyzer, the optical micrographic observation, and the fractographic observation with a scanning electron microscope (SEM) were made on the fractured specimens.

III. Experimental Results and Discussion

1. Effect of Ni addition on toughness

Various matrix structures were obtained in the materials DC and N4 by heat treatment, and then the effect of Ni addition on the strength and toughness of these materials was investigated. Figure 2 shows the heat treatment conditions. The result of the half-size unnotched Charpy test at room temperature is schematically shown in Fig. 3. In the case of heat treatments a-3–a-6, they were treated after the ferritization which was equal to the heat treatment a-1, in order to decrease the carbon content in the matrix in advance; because, if a pearlitic ductile cast iron is quenched after austenitization, the high carbon martensite will be generated and it will make the material very brittle. As shown in Fig. 3, it is noted that the toughness of the ferritic iron is decreased by Ni addition; no improvement of the toughness is observed in contrast with the case of ferritic steels. It has already been reported that the Ni addition decreases the toughness of the ferritic cast iron\(^{(4)(12)}\). This tendency has been also observed even in the pearlitic iron; this is due probably to the fact that Ni has little stabilizing effect on pearlite\(^{(12)}\). However, its details will have to be investigated in the future.

On the other hand, it has been observed that the toughness in the bainitic or martensitic iron are largely improved by the Ni addition. In the mechanical properties of cast iron, it is generally said that the ferritic iron has good ductility, the bainitic one has moderate strength balanced with good ductility, but the martensitic one has poor toughness. However these properties tend to change largely by the prior matrix structure or the heat treating condition\(^{(13)}\). Therefore, although some influence of such factors is considered also in the present result, it will be no mistake to assume the bainite or the martensite as a basic structure for strengthening and toughening by the Ni addition. Also for the
ferrite plus bainite (or martensite) duplex structure, the toughness was actually improved by the Ni addition. Especially it is noticeable that this duplex iron has both good toughness and strength that are inherent in each single matrix (phase).

Attempts to improve the toughness of ductile cast iron by changing the matrix structure except the morphology of the graphite have so far been made, and the present study has also a similar object. Recently it has been reported about the application of high ductility in the microduplex structure to cast irons by the heat treatment in the eutectoid transformation range(14)(15). In addition to this treatment, more strengthening and toughening were attempted in this study by the Ni addition. Reasons for good ductility of the duplex structure obtained in this study are considered as follows:

(1) Concerning the ferritic part; (i) recovery effect of the toughness by the dual tempering at high and subsequent usual temperatures; (ii) lowering of the carbon content and purification in the matrix during holding in the (α+γ) range.

(2) Concerning the bainitic part; (i) stabilizing effect of the retained austenite by the concentration of C and Ni into the austenitic phase during holding in the (α+γ) range; (ii) lowering of the carbon content in the matrix, because austenitization is started from the prior ferritic matrix structure and is then quenched from a temperature lower than the usual one.

In this study, it could not be clarified whether the improvement of the toughness by the introduction of stable retained austenite was accompanied with the transformation induced plasticity (TRIP). However, it is assumed that such an effect may be partly included in this result judging from the change in the toughness with the notch effect, which will be described later.

Furthermore, it seems that there is the most suitable range in the Ni addition. When Ni is added over 6%, the cast structure will become the martensite-bainite one that has very high strength and poor toughness, and it will be difficult to ferritize by heat treatment. Therefore, in this study, the amount of Ni addition was limited to 4%.

2. Effect of heat treatment condition from the (α+γ) range

In this section, the effects of various heat treatment conditions on the bainitic transformation from the (α+γ) range in the material N4 investigated with the half-size unnotched Charpy test are mentioned. Figure 4 shows the relationship between the holding condition in the (α+γ) range and the absorbed energy. The typical microstructures and load-deflection curves are shown in Fig. 5.

When the holding time in the (α+γ) range was 1 h (3.6 ks), the absorbed energy decreased a little at room temperature, but increased at 77 K with a rise of the holding temperature. When the holding time was 5 h (18 ks), the absorbed energy increased a little with the holding temperature. Further, the sample austenitized at 1173 K, which was considerably higher than the (α+γ) range, showed a drop in the absorbed energy both at room temperature and at 77 K. This fact may be due to the transition from the matrix structure into the high carbon single phase bainite. The maximum load in Charpy test increased with a rise of the
Figure 5 Typical microstructure and load-deflection curves of material N4 heat treated at various temperatures in the \((\alpha + \gamma)\) range.

holding temperature and the holding time at the same temperature. This corresponded to the increase in the amount of bainite. In this case, the retained austenite in tested Charpy specimens, which were examined separately, increased with the holding temperature. But it changed little at higher temperatures than the \((\alpha + \gamma)\) range.

Figure 6 shows the relationship between the retained austenite content in the fractured Charpy specimen and the absorbed energy at 77 K. It is observed that the absorbed energy increases with the increase in the retained austenite content. The retained austenite, in this case, is regarded as considerabily stable, for it remains even after the immersion at subzero
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Fig. 6 Relation between the absorbed energy at 77 K and the retained austenite content. Temperature of 77 K; therefore, it is assumed that this stable retained austenite has effectively contributed to the toughness at low temperature.

Figure 7 shows the result of examination on the Ni distribution with an X-ray microanalyzer. Figure 7(a) is the result from the as-ferritized sample. It is recognized that Ni segregates a little in a long range over ferrite grain boundaries, but the distribution is almost uniform. Figure 7(d) shows the result from the sample transformed to bainite after holding for 1 h (3.6 ks) at the mid-temperature in the (α+γ) range; and this sample corresponds to Fig. 5(b). The concentration of Ni in the bainitic phase is observed. The amount of the bainite in the matrix is about 40%, and the difference between the maximum and the minimum content of Ni is about 1% in this analysis. This shows that the diffusion of Ni into the austenitic phase takes place during holding in the (α+γ) range. Therefore, it is considered that this treatment

Fig. 7 EPMA results of Ni distribution and microstructure of the typical samples. Heat treatment condition: (a) as ferritized (b) 1063 K, 1 h-573 K, 1 h A.C. (c) 1043 K, 5 h-573 K, 1 h A.C. (d) 1043 K, 1 h-573 K, A.C.
toughens the bainite, stabilizes the retained austenite in the bainitic phase and then contributes to the improvement of low temperature toughness. Figure 7(c) shows the result from the sample transformed to bainite after holding for 5 h (18 ks) at the mid-temperature in the \((\alpha+\gamma)\) range. The amount of the bainite increased to about 55\%, but no large difference in the Ni content was observed compared with Fig. 7(d). Figure 7(b) shows the result from the sample transformed to bainite after holding for 1 h (3.6 ks) near the highest temperature in the \((\alpha+\gamma)\) range, and this sample corresponds to Fig. 5(c). The amount of the bainite in this case is about 70\%, and the difference in the Ni content attains about 2\%. It is observed that Ni concentrates more into the bainitic phase as shown in Fig. 7(b), compared with Fig. 7(c) and (d). It seems that this result shows the reason for the good low temperature toughness in the sample of Fig. 7(c).

Figure 8 shows the result from the sample transformed to bainite after holding for 5 h (18 ks) at the mid-temperature in the \((\alpha+\gamma)\) range. The amount of the bainite increased to about 55\%, but no large difference in the Ni content was observed compared with Fig. 7(d). Figure 7(b) shows the result from the sample transformed to bainite after holding for 1 h (3.6 ks) near the highest temperature in the \((\alpha+\gamma)\) range, and this sample corresponds to Fig. 5(c). The amount of the bainite in this case is about 70\%, and the difference in the Ni content attains about 2\%. It is observed that Ni concentrates more into the bainitic phase as shown in Fig. 7(b), compared with Fig. 7(c) and (d). It seems that this result shows the reason for the good low temperature toughness in the sample of Fig. 7(c).
energy. The bainitic transformation was produced for 1 h (3.6 ks) in the temperature range from 473 K to 723 K; the holding condition in the \((\alpha + \gamma)\) range was for 1 h (3.6 ks) at the mid-temperature in the \((\alpha + \gamma)\) range. The absorbed energy at room temperature increased with the rise in the bainitic transformation temperature up to 673 K. One reason for this lies in the increase of the ferrite content in the matrix. The ferrite in this case has been tempered during holding in the \((\alpha + \gamma)\) range, therefore, the samples heat-treated at 623 K and 723 K, that contain a large amount of ferrite in the matrix, show good toughness. It seems that the lowering of the absorbed energy at 723 K is caused by the start of pearlitic reaction and by the so-called temper embrittlement in the cast iron\(^{16}\). Thus it is found that the toughness is superior in the sample transformed in the upper bainitic transformation range. On the other hand, in the test result at 77 K, the sample heat-treated at 623 K showed the maximum absorbed energy, and it also showed the maximum retained austenite content. It seems that the stable retained austenite tends to be introduced by the treatment near this temperature, and then it contributes to the improvement of toughness.

Figure 10 shows the effect of the bainitic transformation time on the absorbed energy and on the retained austenite content. The bainitic transformation was carried out at 527 K after holding for 1 h (3.6 ks) at the mid-temperature in the \((\alpha + \gamma)\) range. The absorbed energy at room temperature showed the maximum at 2 h (7.2 ks). It was 3 h (10.8 ks) in the case at 77 K. Although it is observed that the amount of the bainite in the matrix increased a little up to 2 h (7.2 ks), it changed little after then; the duplex structure changed somewhat to the finer one with the transformation time. On the other hand, the retained austenite content in the specimen tested at room temperature showed the maximum at 2 h (7.2 ks) and then decreased, but in the specimen tested at 77 K it increased with the transformation time up to 5 h (18 ks), where it coincided with the one at
room temperature. This shows that the retained austenite is stabilized with the transformation time and that which is stable at 77 K contributes to the improvement of low temperature toughness. However, the reason for the decrease of the absorbed energy over a certain critical time is assumed to be the influence of the temper embrittlement(16).

Therefore, it was found that the bainitic transformation condition influenced largely the toughness and that the stable retained austenite contributed to the improvement of the low temperature toughness. However, it must next be noted that the \((\alpha + \gamma)\) range changes largely with the content of alloy elements or with another condition and that it may influence the final properties.

3. Transition properties and fracture toughness

In the next, the transition curves of various samples were measured by the U-notched Charpy test, in order to compare the sample bainitic-transformed from the \((\alpha + \gamma)\) range with the other ductile cast irons or the usual malleable cast iron and to investigate the effect of Ni addition. Especially, samples DC and N4 were also tested with the half-size unnotched Charpy specimen; Fig. 11(a) and (b) show the results. Circle symbols on each transition curve in Fig. 11 show the transition temperatures at which the absorbed energy was decreased to a half of the upper shelf value. The matrix structure is shown in the parentheses; F, B and M show ferrite, bainite and martensite, respectively. Sample DC was ferritized in the same manner as the heat treatment a-1 shown in Fig. 2. The cooling condition after annealing was either furnace cooling or air cooling; the air cooled sample was indicated by the symbol “a.c.” in Fig. 11. On the other hand, the Ni added samples (N2M~N4) were heat-treated by the method corresponding to Fig. 5(c).

It is found from the results in the U-notched Charpy test of Fig. 11(b) that samples D2 and D2M show no transition behavior. But D2 has considerably less absorbed energy than D2M; this is due to the existence of chromium carbide in the matrix. It is recognized that D2M which has been decreased in Cr and added with Mn shows good toughness. DC that has a ferritic matrix showed a larger absorbed energy and a lower transition temperature than those in the malleable cast iron, Ma. It also showed no large difference between the furnace cooled and the air cooled samples. It is generally said that the toughness of cast iron will become worse due to the effect of temper embrittlement when it is held for a long period near 720 K; therefore, the decrease of the toughness in the furnace cooled sample is assumed(16)(17). In the present work, however, it is considered that the difference in the toughness has not been observed as a result of a little difference in the cooling rate between the furnace and the air cooling.

Concerning N2M, N3 and N4, which were added with Ni and had a ferrite and bainite duplex structure, the absorbed energy at room temperature increased with the amount of added Ni. But the absorbed energy in N4M, which was added with Mo in order to prevent temper embrittlement and to activate bainitic transformation, decreased largely. It is supposed that this is due to the appearance of martensite in the matrix and to the existence of carbides on the eutectic cell boundaries. These Ni added cast irons have much larger strength than DC which has a ferrite matrix. Moreover, although their transition temperatures are a
little higher than the ones in DC, but they have larger absorbed energy than DC above the transition temperature. Therefore, it can be said that they possess both good strength and toughness. Moreover, the Si content in DC was about 0.5% lower than in N4, N3 and N2M; therefore it is considered that more improvement of their low temperature toughness will be expected by decreasing the Si content\(^{18}\).

On the other hand, the result of the unnotched Charpy test shown in Fig. 11(a) shows that Ni added samples with a ferrite plus bainite (or martensite) duplex structure are very excellent in toughness and, therefore, the development of cast iron having good low temperature toughness is expected. However, it is found from the comparison between Fig. 11(a) and (b) that the transition temperature of N4 in the U-notched Charpy test is considerably higher than that in the unnotched Charpy test. A part of this difference in the transition temperature may arise from the difference in the alloy content, for there were some differences between the specimens provided for both tests. This phenomenon is, however, noticeable as a matter showing that the effect of notch sharpness on the toughness of this material depends mainly on the introduction of the stable retained austenite in the matrix, and it tends to become more unstable in the early stage in the U-notched test and will transform to martensite by stress concentration at the notch root; then this phenomenon will have no contribution to the improvement of toughness by the good toughness in austenite itself or by the transformation induced plasticity effect. Although this phenomenon must be investigated more in the future, but it has been found that the sample N4(F+B) has an excellent property as a cast iron for a low temperature use.

Figure 12 shows the results of measurements on J-integral value under a dynamic loading condition \(J_{td}\), the absorbed energy and the maximum load in Charpy impact test at room temperature. It is considered that the absorbed energy in Charpy test corresponds well to \(J_{td}\); Ni added samples show high maximum load. Moreover it is noticeable that N4 has much better toughness and strength than the ductile cast iron having a ferritic matrix, DC.

4. Static tensile properties

Figure 13 shows the results of static tensile test. The strength and ductility of Ma and D2 are rather inferior. D2M and DC(F) are much superior in ductility. N3 and N4(F+B) have very high strength, but they are a little inferior in ductility to D2M and DC. The ductility of N2M and N4M that were added with Mo decreased largely, though their strength was high. In this study, the addition of Mo to cast iron was not useful.

IV. Conclusion

Various heat treatments were made on Ni added ductile cast iron, and its strengthening and toughening were investigated by obtaining the ferrite plus bainite duplex structure after isothermal transformation from the \((\alpha + \gamma)\) eutectoid transformation temperature range.
Then the following conclusion was drawn.

(1) Ni added ductile cast iron, which has a ferrite plus bainite duplex structure obtained by isothermal transformation from the \((\alpha + \gamma)\) range after ferritic annealing, shows much higher strength and better fracture toughness at room temperature as compared with a usual ferritic ductile cast iron. The transition temperature was comparable with that of ferritic matrix in the U-notched Charpy test, but it was lowered largely in the unnotched Charpy test. It was assumed that this phenomenon was concerned with the stability in the introduced retained austenite phase and with its TRIP effect.

(2) The reasons for the improvement of toughness in the duplex structure were considered as follows.

(i) Concerning the ferritic part: Recovery effect of toughness by high temperature annealing, lowering of carbon content and purification in the matrix.

(ii) Concerning the bainitic part: Stabilizing effect of the retained austenite by concentration of carbon and nickel, and lowering effect of average carbon content by starting from a ferritic matrix and that by quenching from low temperature. Conditions for the heat treatment in the \((\alpha + \gamma)\) range and for the isothermal transformation to satisfy the above mentioned points were clarified.

(3) In this case, it is considered that the most suitable amount of Ni addition was 4%. Although the matrix was largely strengthened by Ni addition, it changed to martensite in the as-cast condition by the addition over 6%.

(4) It was also clarified that Ni addition to the cast iron lowered the toughness in the case of the ferritic and pearlitic matrices, but it improved the toughness in the case of the martensitic, bainitic, and bainitic (or martensitic) plus ferritic duplex matrices.

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REFERENCES

(3) Metal Progress, 105 (1974), 86.
(4) P. J. Rickards: Metals & Mat., 1 (1967), 220.
(15) Y. Ueda and N. Wade: J. Japan Foundrymen’s Soc., 50 (1978), 305.