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The effect of heat treatment on the toughness, hardness and microstructure of low carbon white cast irons

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The effect of destabilisation and subcritical heat treatment on the impact toughness, hardness, and the amount and mechanical stability of retained austenite in a low carbon white cast iron have been investigated. The experimental results show that the impact energy constantly increases when the destabilisation temperature is raised from 950°C to 1200°C. Although the hardness decreases, the heat-treated hardness is still greater than the as-cast state. After destabilisation treatment at 1130°C, tempering at 200 to 250°C for 3 hours leads to the highest impact toughness, and secondary hardening was observed when tempering over 400°C. The amount of retained austenite increased with the increase in the destabilisation temperature, and the treatment significantly improves the mechanical stability of the retained austenite compared with the as-cast state. Tempering below 400°C does not affect the amount of retained austenite and its mechanical stability. But the amount of retained austenite is dramatically reduced when tempered above 400°C. The relationship between the mechanical properties and the microstructure changes was discussed.

1. Introduction

High chromium white cast irons have been widely used in the mining and minerals industry because of their excellent abrasion resistance [1–4]. Normally it is considered that the eutectic carbides in a hypoeutectic white irons are responsible for the good abrasion resistance, and the role of the matrix, including austenite, martensite or a mixture of the two, provides sufficient mechanical support to prevent the carbide from cracking and spalling [1, 5]. Previous work [6, 7] has shown that increasing the volume fraction of eutectic carbides improves the abrasion resistance. However, within the range of chromium content used in the Cr-Mo white cast irons, the main carbide is M_7C_3 [1], which is hard and brittle and can provide an easy path for crack propagation. This leads to the brittleness of the material and therefore limits its applications, particularly in conditions, which involve considerable impact. As it is difficult to modify the shape of the eutectic carbide [1], an alternative method to improve the toughness of a white cast iron with a particular chemical composition is to alter the matrix. Sare [8] has indicated that the matrix plays a critical role in determining the fracture toughness of white cast irons through its ability to stop brittle cracks propagating from one carbide particle to another. A number of researchers have also found that alloys with an austenite matrix possess higher fracture toughness, than those with a martensitic matrix and that, as the volume fraction of austenite in the matrix increases, so did the fracture toughness [9–12].

It was long believed that the bulk hardness of materials determined its wear performance – the harder the material, the higher the wear resistance. After much research on this type of materials over the past half-century, it is now understand that the pearlite or ferrite matrix of white irons does dramatically reduce the abrasion resistance of materials, due to the poor support of carbides, but the tough and soft austenite in the matrix plays a different role. It has been shown that the presence of austenite in the matrix can positively contribute to abrasion resistance, due to work hardening and stress-induced martensitic transformation, which will provide good support to the carbide [8, 12, 13–15]. Some research shows that the presence of 25 to 30% retained austenite in the matrix results in the best abrasion resistance [13]. Other workers [15] suggested that 30 to 50% retained austenite is the optimum. Tabrett *et al.* [1] have reviewed previous work and concluded that with hard abrasives (SiC) in low stress abrasion, the abrasion resistance of austenite and martensite are similar. The abrasion resistance of an austenite matrix is better than martensite for high stress abrasion, because the hard abrasive particle work hardens the austenite via stress induced transformation. With softer abrasive, such as garnet, the martensitic matrix has higher abrasion resistance than austenite for both low and high stress abrasions, because of the absence of transformation induced by the softer particle. From previous work it can be seen that whether or not stress-induced martensitic transformation occurs within the austenite matrix of white cast irons can directly and significantly affect the abrasion resistance of this type of materials. The occurrence of the stress-induced martensitic transformation is controlled by the mechanical stability of the retained austenite. Retained austenite with high mechanical stability is difficulty to transform by the application of external stress, and lower mechanical stability austenite can transform at lower external stresses. Thus, it is possible to improve the abrasion resistance with softer abrasive by reducing the mechanical stability of the retained austenite in the matrix of white cast irons. However, there is still limited reported research on the mechanical stability of retained austenite in white cast irons. One of the aims of the present work is to investigate the influence of heat treatment on the mechanical stability of retained austenite in a white cast iron.

For most of the Cr-Mo white cast irons, the matrix in the as-cast state is stable austenite. Hence, a destabilisation heat treatment is normally applied to the castings to reduce the high alloy content of the austenite resulted via secondary carbide precipitation within the matrix, so that on cooling the retained austenite matrix can fully or partially transform to martensite. This secondary carbide can also improve the strength of the austenite matrix, so that it provides a better support for the eutectic carbide. Much work [2, 5, 15–17] has been done to investigate the effect of heat treatment on the properties and microstructures of white cast irons. Normally, increasing the austenitizing temperature, increases the amount of retained austenite and improves the fracture toughness [15], but reduces the hardness. The optimal destabilisation temperature varies with the chemical composition of the alloy [1]. Overview the past work, none has studied the effect of heat treatment on the mechanical stability of retained austenite. The tempering or subcritical heat treatment following the destabilisation treatment is designed to minimise the internal stress. If low retained austenite contents are required, tempering is performed at higher temperatures. When the alloy contains Mo, secondary hardening can be observed when tempering temperature is over 400°C [1, 15]. But, the influence of tempering treatment on the retained austenite is still not fully understood. This forms another aim of the present work.

Because of the excellent abrasion resistance, white cast irons have been increasingly applied in an environment involving considerable impact, such as large-scale mills [18]. In addition, white cast irons have been gradually introduced into areas formally the exclusive domain of the much tougher steels [8]. Thus, higher toughness white cast irons are required. Bereza [18] suggested that for severe impact loading conditions, high chromium irons with the lowest possible carbon content should be used. Although the abrasion resistance will be lowered, it is still much better than any other material. In the last few years, a lower carbon white cast irons series has been developed [11, 19]. By reducing the carbon content and applying a high temperature heat treatment, the lower carbon white iron can achieve a fracture toughness of 40 MNm$^{-3/2}$. Compared with the fracture toughness of 20–30 MNm$^{-3/2}$ for the conventional white cast irons, the lower carbon iron has effectively double the fracture toughness. Moreover, the volume fraction of the eutectic carbide in this lower carbon white iron is only reduced to 21% from 27% [20]. The latter figure is the amount of carbide in conventional white cast irons. Thus, the lower carbon white iron still has a reasonable good abrasion resistance, according to Zum Gahr's work [21]. Further studies done by Hann and Gates [22] have indicated that transformation toughening of austenite within the matrix is responsible for the higher fracture toughness. The fracture toughness determined at higher temperatures, which there is no stress-induced transformation occurred, is much lower than that determined at lower temperature where the stress-induced martensitic transformation occurred. To date the research on the lower carbon white cast irons has concentrated on fracture toughness. As argued by some researchers [1, 8, 23], the fracture toughness tests only measure the resistance of a material to crack propagation, while the fracture of white cast iron components in service is often controlled by the resistance to crack initiation. In brittle materials like white cast irons, once the crack formed, it will quickly grow and cause fracture. On the other hand, the material is often used in an environment involving impact. Hence, investigating impact toughness is more significant for practical applications. The third aim of the present work is to determine whether there is transformation toughening under impact conditions and to study the effect of heat treatment on the impact toughness.

2. Experimental

Two low carbon white cast irons have been used in the present work. Their chemical compositions are listed in Table I. Both alloys were received as-cast blocks of size 15 × 60 × 170 mm. The blocks were cut into semifinished smaller blocks of size 15 × 60 × 15 mm before any heat treatment. The destabilisation heat treatment processes for the alloy LS-28 were to austenitize the semifinished smaller blocks at 950°C, 1020°C, 1080°C, 1130°C and 1190°C for 6 hours. Specimens were buried in a foundry sand and coke mixture to prevent decarburisation and oxidation. After air cooling, the specimens were ground into final size of 10 × 10 × 55 mm, and followed by tempering at 200°C for 3 hours. The specimens that were given a destabilisation treatment at 1130°C were also tempered at 250°C, 280°C, 310°C, 340°C, 500°C and 600°C for 3 hours, respectively in order to investigate the influence of tempering

TABLE I Chemical composition of the alloys used in the present work (%wt)

Alloys	C	Cr	Si	Mo	Ni	Cu	Mn
LS-28	1.89	14.6	1.22	1.86	1.47	0.53	1.04
LS-31	1.72	21.0	1.60	1.90	1.80	—	0.70

temperature on the properties and microstructures. The alloy LS-31 was only given a destabilisation heat treatment at 1190°C for 6 hours, followed by tempering at 200°C for 3 hours after cooling. The LS-28 specimens that were destabilisation treated at 1130°C and tempered at 200°C were tested over the temperature range from −80°C to 200°C to investigate the effect of transformation toughening.

Vickers hardness at 30 kg (HV30) was measured for all specimens. The toughness measured in high chromium white irons using the Charpy test is very low and it is hard to distinguish the differences in toughness for various conditions [1]. Thus, in the present work, the impact toughness was determined by using un-notched Charpy size specimens. Obviously, this is not a standard determination of toughness. But, it is suitable for the examination of the transformation toughening under impact conditions, and can be used to compare the relative toughness of the same alloy after different heat treatments.

The amount of retained austenite was determined using a recently developed technique for determination of retained austenite in heavy textured specimens [24]. A Philips X-ray generator with a Mo-target tube operated at 36 KV and 30 mA was used for X-ray diffraction. A Siemens texture goniometer and TEXTAN software were employed to undertake the determination. The mechanical stability of retained austenite was expressed using the decomposition rate ΔV_{AR} resulting from the plastic deformation. That is, if V_{AR}^1 is the amount of retained austenite after heat treatment, V_{AR}^2 is the retained austenite amount of the specimen after it has been deformed for certain percent plastic deformation, then

$$\Delta V_{\mathrm{AR}} = \left(V_{\mathrm{AR}}^1 - V_{\mathrm{AR}}^2\right)/V_{\mathrm{AR}}^1$$

Obviously, the bigger the ΔV_{AR}, the lower the mechanical stability of the retained austenite. In the present work, cylindrical specimens with a diameter of 10 and 20 mm long were heat treated together with the impact specimens using the heat treatment processed described above. Then, 1.5 mm thick plates with diameter 10 mm were cut off from the end of each the cylindrical specimens, and used to determine V_{AR}^1. Subsequently, the rest 18 mm long cylindrical specimens were compressed to have 2.0% plastic deformation and plates with the same size as above were cut off from the middle of the cylindrical specimens. These plates were used to determine V_{AR}^2. Thus, ΔV_{AR} can be obtained for each of the heat treatment process.

The amount of M_7C_3 carbide in white cast iron after different heat treatment was measured by quantitative metallography performed on a QuantiMet 570. After etching in a solution of 15 g $FeCl_3 \cdot H_2O + 450$ ml $HCl + 180$ ml H_2O, which was diluted 1 part solution to 5 parts water for use, the primary and second carbides showed good contrast that distinguished them from other phases (austenite and martensite).

The carbon content and carbon distribution in the austenite matrix of specimens having different destabilisation heat treatment were determined using a technique described in Ref. 25. In this technique, the lattice parameter a_{A} of local austenite in micro-scale was determined using Kikuchi line diffraction patterns, and the carbon content was calculated using the following equations [26]:

$$a_{\mathrm{A}} = 3.555 + 0.044\mathrm{C}_{\mathrm{A}}$$

where C_{A} is the carbon content of austenite in weight percent.

The preparation processes for TEM specimens was as follows: Thin plates of thickness of 0.6–0.8 mm were sliced from the impact specimens using a diamond cutting blade. After being mechanically thinned to 0.08 mm, specimens were jet polished in 8 pct perchloric acid and acetic acid mixture at 15°C with a voltage of 30 V and polishing stopped just before perforation. Then the specimens were ion milled to perforation at room temperature. All thin foils were examined in a JEOL 4010 TEM.

3. Results

3.1. Impact toughness

The variation of the un-notched impact energy with the destabilisation temperature and tempering temperature is shown in Fig. 1a and b, respectively. In both figures, the impact energy is represented by symbol A_{K}. It can be seen that as the destabilisation temperature is increased from 950°C to 1200°C, the A_{K} value rises constantly increased from 3.7 J to 7.5 J. All these values are higher than the value in the as-cast state, except for the 950°C treatment, where the A_{K} value is the same as in the as-cast sate. This confirms that the toughness of white cast iron can be significantly increased by the destabilisation treatment [1]. As mentioned in the experimental section, the specimens used in the present work are not standard impact specimens, but the difference in the A_{K} value at various temperatures is still significant and greater than the range of experimental errors. Hence, the varying trend of impact energy of white cast iron with destabilisation temperature shown in Fig. 1a is considered to be real. Unlike the effect of destabilisation temperature, the highest A_{K} value is obtained after tempering at temperatures between 200°C and 250°C, when compared with no tempering treatment and tempering at higher temperatures. Above 250°C tempering temperature, the A_{K} value drops. When the tempering temperature is higher than 400°C, the A_{K} value even lower than that of the un-tempered materials.

3.2. Hardness

Fig. 2 shows the Vickers hardness of the LS-28 white cast iron at different heat treatment conditions. From Fig. 2a it can be seen that destabilisation treatment at lower temperature (950°C) dramatically improves the hardness compared with the as-cast state. Then, as the destabilisation temperature increases, the hardness gradually decreases. But, the hardness is still higher than the as-cast state. Lower temperature

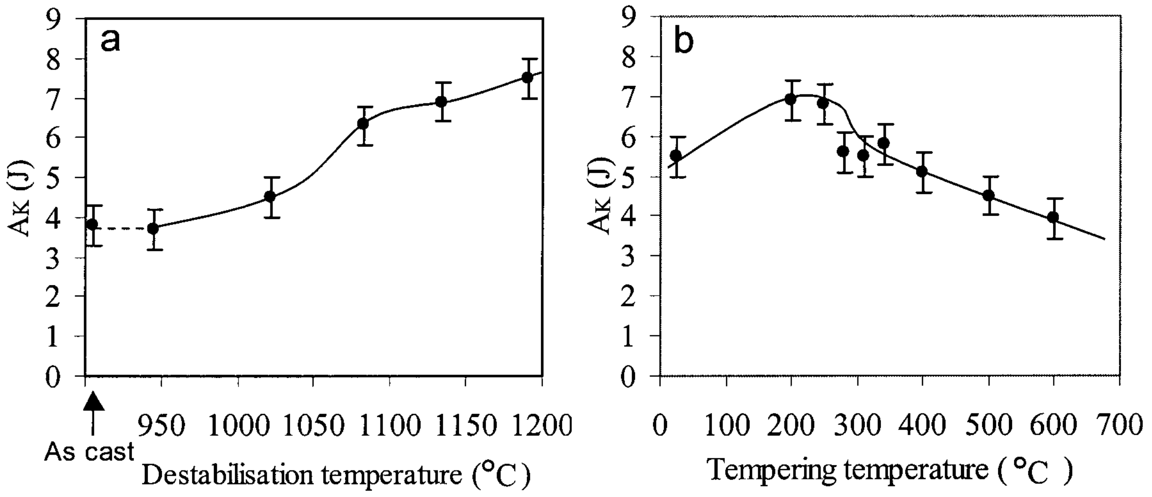

Figure 1 The variation of impact energy of LS-28 white cast iron with destabilisation temperature and with tempering temperature. (a) destabilisation treatment at various temperature for 6 hours, followed by tempering at 200°C for 3 hour after air cooling (b) destabilisation treatment at 1130°C for 6 hours and tempering at different temperature for 3 hours after air cooling.

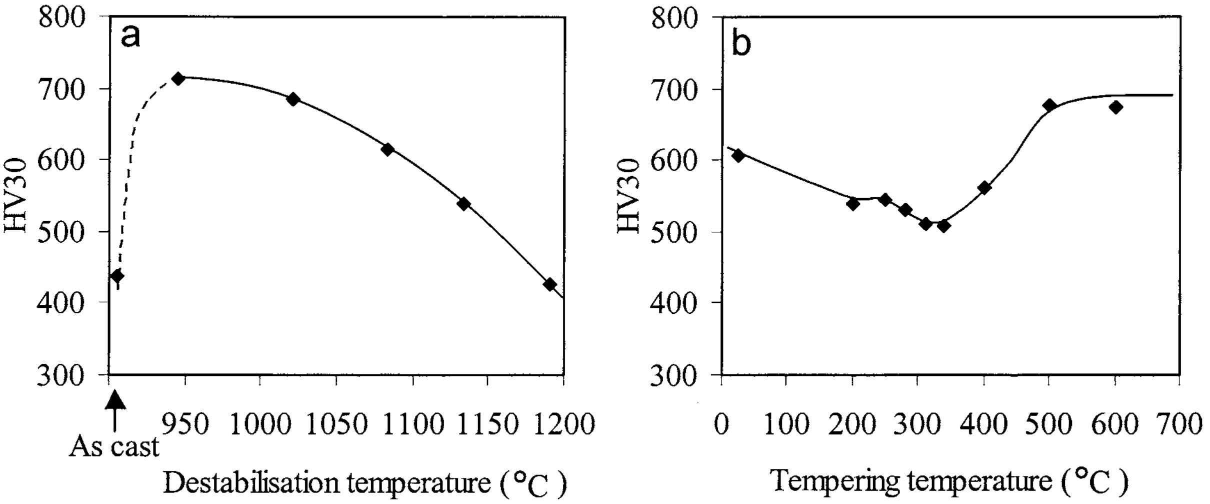

Figure 2 The variation of hardness of LS-28 white cast iron with the destabilisation temperature and tempering temperature. (a) destabilisation treatment at various temperature for 6 hours, followed by tempering at 200°C for 3 hour after air cooling (b) destabilisation treatment at 1130°C for 6 hours and tempering at different temperature for 3 hours after air cooling.

tempering slightly reduces the hardness relative to the un-tempered material (see Fig. 2b). But, when the tempering temperature is over 400°C, the hardness starts to increase again due to secondary hardening. The hardness after tempering at 500°C and 600°C is even higher than in the un-tempered condition.

3.3. Retained austenite

Fig. 3 shows the relationship between the volume fraction of carbides determined by quantitative metallography and the amount of retained austenite determined using the new technique [25] as a function of the destabilisation temperature and the tempering temperature. In the as-cast state, the white cast iron contains mainly dendritic austenite, plus eutectic austenite eutectic carbides and some martensite [1, 11, 15, 19]. During the destabilisation treatment, secondary carbides precipitate in the austenitic matrix, reducing the matrix alloy content, carbon in particular. Thus, the Ms temperature of the matrix increases and it may transform to martensite during the subsequent cooling [1]. From Fig. 3a it can be seen that the volume fraction of carbides in all destabilisation treated specimens is larger than that in the as-cast state. With increase in the destabilisation temperature, the volume fraction of carbides gets smaller. The amount of retained austenite in the destabilisation treated specimens is less than that of the as-cast material. However, the retained austenite increased as the destabilisation temperature is raised. These results are consistent with most previous work [1, 13, 20]. Tempering below 400°C does not significantly effect the volume fraction of carbides, or the amount of retained austenite. Tempering over 400°C leads to an increase in the volume fraction of carbides due to the formation of secondary carbides, and to a reduction of retained austenite as a result of the decomposition of retained austenite. Fig. 3b shows the results.

The mechanical stability of retained austenite can be expressed by the percentage of its decomposition after the specimens have been deformed plastically by 2%. This percentage decomposition is termed the decomposition rate of retained austenite and denoted by ΔV_{AR}. Fig. 4 shows the variation of ΔV_{AR} with destabilisation

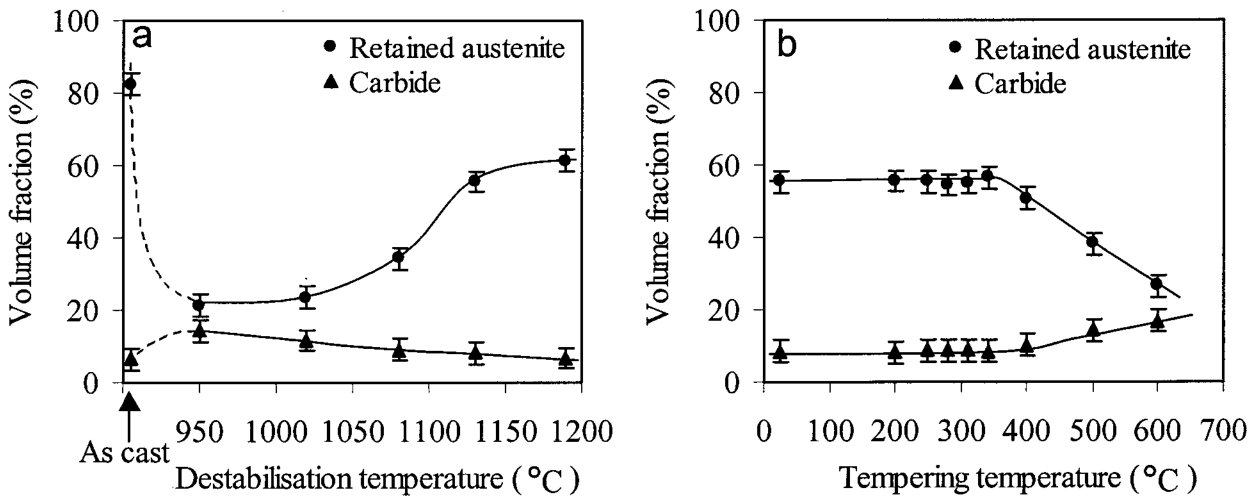

Figure 3 The variation of volume fraction of carbides and retained austenite in LS-28 white cast iron with the destabilisation and tempering temperatures. (a) destabilisation treatment at various temperature for 6 hours, followed by tempering at 200°C for 3 hour after air cooling (b) destabilisation treatment at 1130°C for 6 hours and tempering at different temperatures for 3 hours after air cooling.

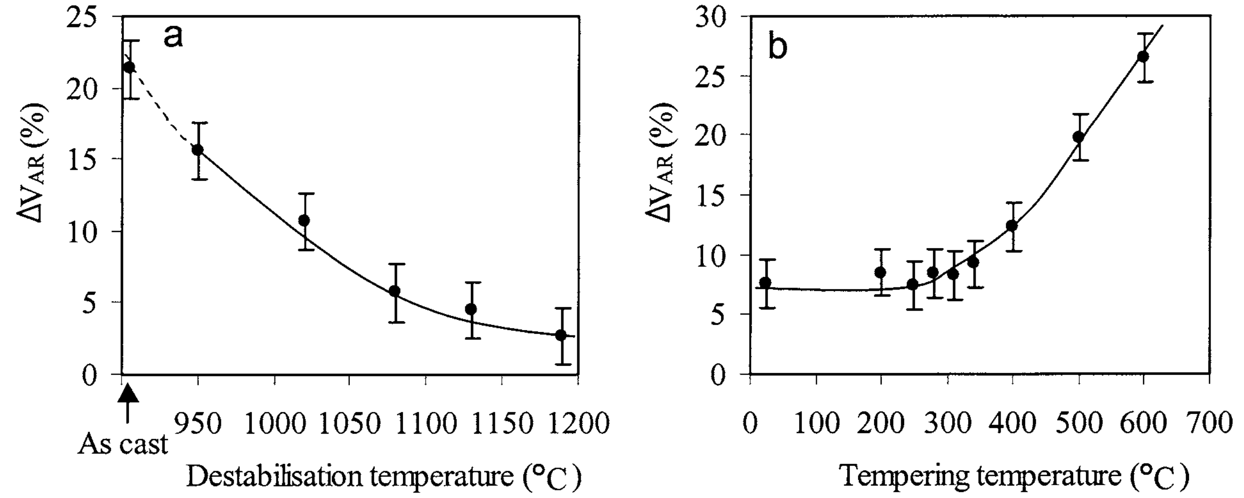

Figure 4 The variation of decomposition rate of retained austenite in LS-28 white cast iron with the destabilisation and tempering temperatures. (a) destabilisation treatment at various temperature for 6 hours, followed by tempering at 200°C for 3 hour after air cooling (b) destabilisation treatment at 1130°C for 6 hours and tempering at different temperature for 3 hours after air cooling.

temperature and tempering temperature. It can be seen that the retained austenite in as-cast white cast iron has a very high decomposition rate, – ie. its mechanical stability is low. Destabilisation treatment can efficiently improve the mechanical stability of retained austenite and as the destabilisation temperature increases, the mechanical stability also increases. Tempering below 400°C does not significantly effect the mechanical stability of retained austenite. But, when the tempering temperature is over 400°C, the mechanical stability of retained austenite in LS-28 white cast irons is significantly reduced. This is due to the precipitation of the secondary carbides, reducing the carbon and alloy content in retained austenite, and therefore, increasing the Ms and Md temperatures.

3.4. Carbon distribution in dendritic austenite

Convergent beam Kikuchi line diffraction patterns have been used to determine the lattice parameter of austenite [25, 27], and then the carbon content [27] of austenite in micro-area with 10 nm in diameter. It has been observed that the carbon content in the dendritic austenite in the as-cast sate is extremely non-uniform. Normally the carbon content is lower in the regions that are close to the eutectic carbides or the dendrite boundaries. In the middle of the austenite dendrite the carbon content is higher. Destabilisation treatment results in the homogenisation of carbon in the dendrite austenite. With the increase of the destabilisation temperature, the carbon distribution is more uniform and on average is lower than the high carbon regions in as-cast austenite dendrites. Fig. 5 shows the carbon distribution of dendritic austenite in the as-cast state and after destabilisation treatment at 1130°C. These results were obtained by randomly positioning the convergent in the austenite. In most cases the very low points in Fig. 5a are from regions close to the dendritic boundaries.

3.5. Microstructures

Like all hypoeutectic, high chromium white cast irons [1], the as-cast microstructure of low carbon white cast

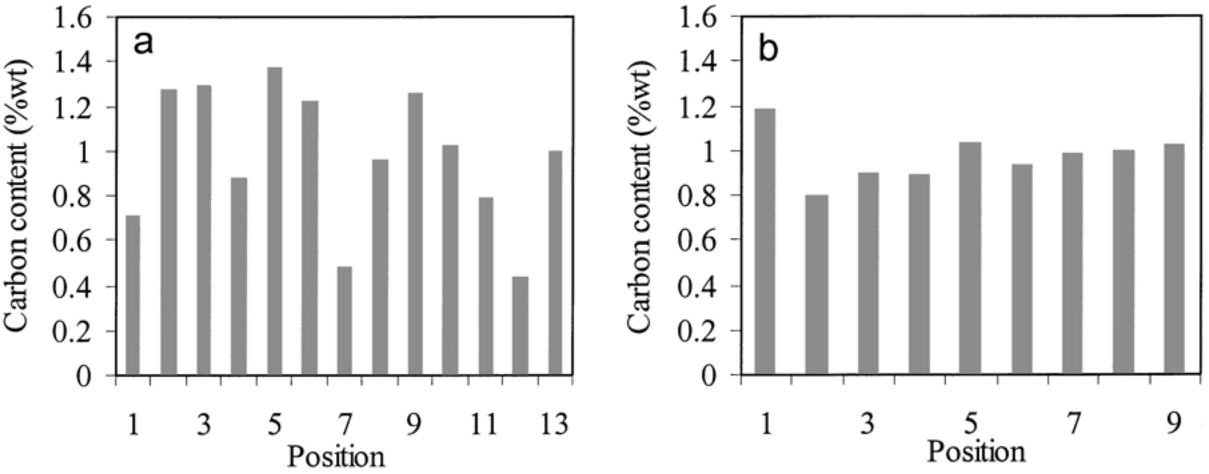

Figure 5 Random carbon distribution in dendritic austenite of LS-28 white cast iron. (a) as-cast state (b) after destabilisation treatment at 1130°C for 6 hours followed by air cooling.

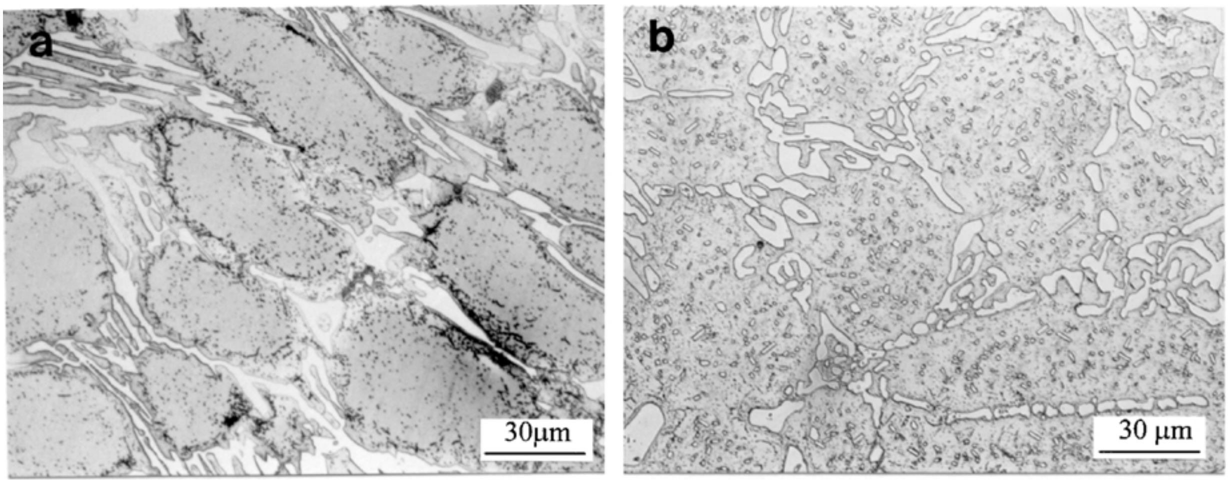

Figure 6 Optical microstructure of LS-28 white cast iron. (a) as-cast state (b) after destabilisation treatment at 1130°C for 6 hours followed by air cooling. Carbides are now clearly visible in the austenite dendrites.

iron consists of austenitic dendrites, which may partially transformed to martensite, an interdendritic eutectic carbides and partially transformed austenite. In the alloys used in the present work the transformed product is martensite [11, 19, 20, 22]. Neither bainite nor pearlite was observed. After destabilisation treatment, secondary carbide precipitation occurred in the dendritic austenite and the amount of transformed martensite is increased compared with the as-cast material. The higher the destabilisation temperature, the lower the amount of both secondary carbide and martensite. Fig. 6 shows two typical optical microstructure of LS-28 white cast iron in the as-cast state and after destabilisation treatment at 1130°C. Previous work [22, 28] has shown that both the eutectic and the secondary carbides are M_7C_3 type carbides.

Tempering does not significantly alter the optical microstructure morphology of white cast irons and the dendritic feature is preserved up to 650°C. When tempered above 400°C, secondary carbide precipitated within the dendritic structure. Fig. 7 is a typical optical microstructure of LS-28 white cast iron that has been tempered at 650°C for 3 hours after destabilisation treatment at 1130°C for 6 hours. In the present work, the source of the secondary carbides and their crystal structure and chemical composition were not investigated.

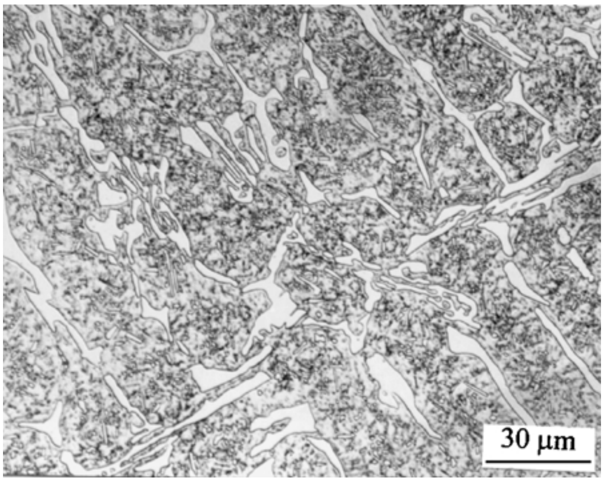

Figure 7 Optical microstructure of LS-28 white cast iron that has been tempered at 650°C for 3 hours after a destabilisation treatment at 1130°C for 6 hours.

TEM analysis has shown that the majority of the dendritic structure in the as-cast state is austenite. But twinned martensite has been frequently observed either

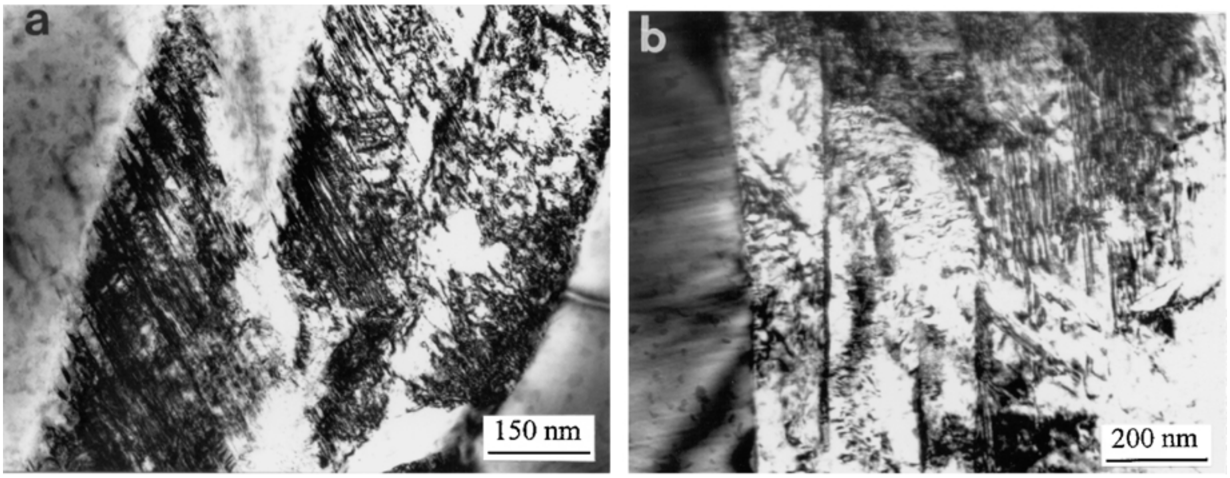

Figure 8 TEM micrographs of LS-28 white cast iron at as-cast state.

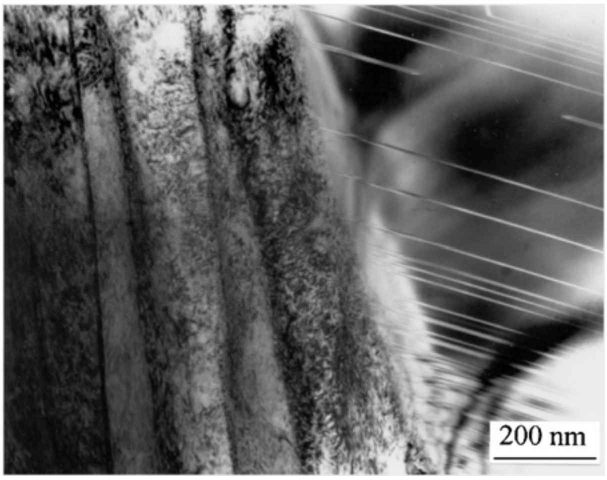

Figure 9 TEM micrographs of LS-28 white cast iron that was destabilisation treated at 1130°C for 6 hours and tempered at 200 °C for 3 hours.

in regions close to the eutectic carbides (see Fig. 8a) or other isolated areas. On occasions, lath martensite formed within about 500 nm far from the eutectic carbides, and twinned martensite formed adjacent to the lath martensite, as shown in Fig. 8b. This indicates that the chemical composition of the austenitic dendrites of white cast irons in the as-cast state is not uniform. This is consistent with the results from the determination of carbon distribution showing in Fig. 5a. Destabilisation treatment not only reduced the carbon content of the dendrite [1], lowering the stability of the austenite, but also homogenised the composition of the dendrite. After destabilisation treatment above 1130°C, twinned martensite is rarely observed. Instead the amount of lath martensite is increased. Fig. 9 shows the lath martensite formed near a eutectic carbide. Using selected area diffraction technique, it has been found that the lath martensite in LS-28 white cast iron contains quite thick retained austenite layers between the martensite laths. Fig. 10a is the bright field image and b is the dark field image of one packed of lath martensite, and c is the diffraction pattern. Research in steels [29] has shown that the austenite layer in between the martensite laths can improve the toughness of this type of martensite. This is probably one of the reasons for the higher impact toughness in the case of destabilisation treatments at higher temperatures.

3.6. Transformation toughening

In order to investigate the contribution of transformation toughening to the impact toughness of white cast irons, the impact toughness of LS-28 white cast iron was determined over a temperature range from −80°C to 200°C. The alloy was destabilisation treated at 1130°C for 6 hours and tempered at 200°C for 3 hours. Fig. 11a shows the relationship between the impact energy and the testing temperature. A peak at −20°C for LS-28 alloy can be clearly observed. However, at room temperature, the impact energy is much lower. Normally, for the alloys containing ferrite phases, the impact toughness decreases at lower testing temperatures. In this alloy, the higher impact toughness at −20°C compared with room temperature must be due to transformation toughening. Because of the difficulty of distinguishing the stress-induced martensite from the athermal martensite, one way of demonstrating the stress-induced martensitic transformation is to examine the variation of the micro-hardness with the distance from the fracture surface. Fig. 11b shows these variations. It can be seen that for the specimen that was impacted at room temperature, the micro-hardness close to the fracture surface is the same as it is far from the fracture surface. This implies that there was no stress-induced transformation during the impact process at room temperature. Therefore, there was no transformation toughening. For the specimen tested at −20°C, the micro-hardness within the region near the fracture surface is significantly higher than that of other parts of the specimen. This indicates the formation of martensite near the fracture surface during the impact process. Transformation toughening has made a contribution to the higher impact energy at this temperature. At −80°C, most of dendritic austenite has directly transformed to martensite before the impact test and, the micro-hardness is consistently high everywhere in the specimen. Fig. 11a also shows the relationship between impact energy and testing temperature for the LS-31 alloy, where the austenite is less stable than LS-28. The shape of the curve is basically the same, but the peak has shifted to a higher temperature (0°C).

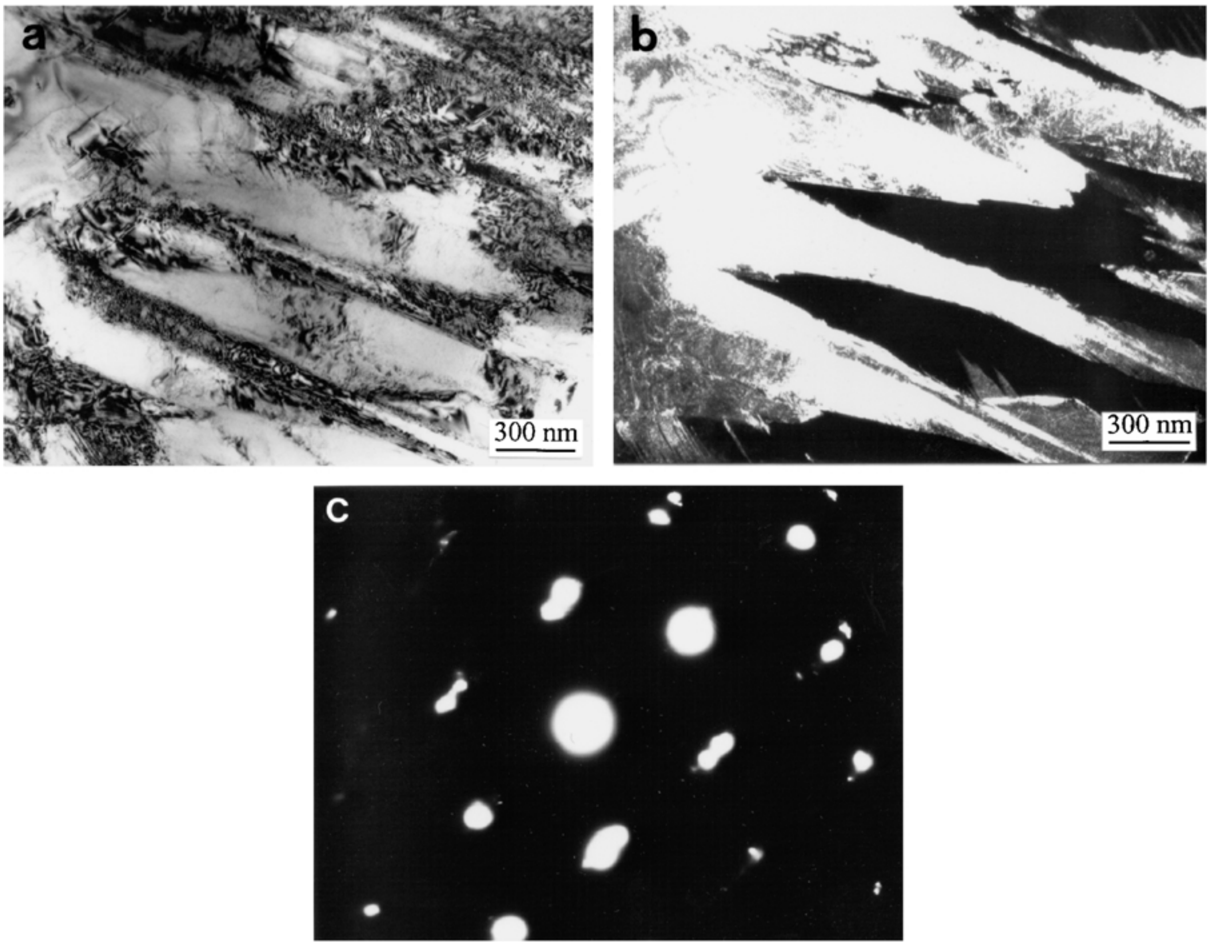

Figure 10 Bright and dark field image showing the retained austenite layer in between the martensite laths. (a) bright field (b) dark field from austenite (c) selected area diffraction pattern.

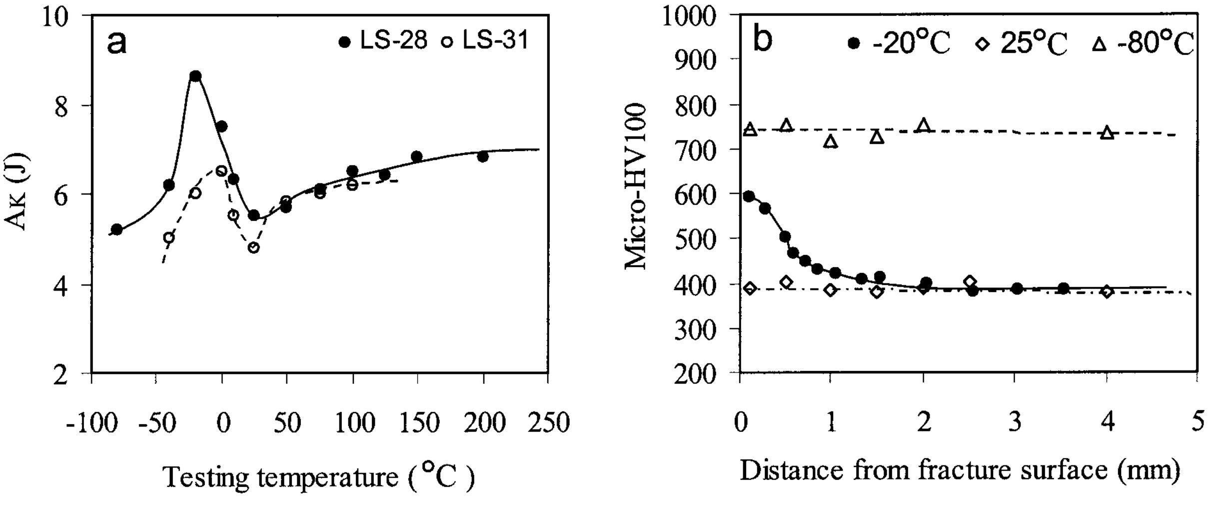

Figure 11 Variation of impact energy of LS-28 and LS-31 and micro-hardness distributions in LS-28 white cast irons with the testing temperature. (a) A_K value of LS-28 and LS-31 alloys at different testing temperature. (b) variation of micro-hardness of LS-28 with distance from the fracture surface of the impact specimens tested at different temperatures.

4. Discussion

4.1. Impact toughness

White cast irons are good for the applications involving abrasion environment, such as in mining and minerals industry, and the large amounts of carbides in these white cast irons are responsible for the good abrasion assistance. The majority of the carbide in high chromium white cast irons are M_7C_3 type carbides, which are very hard and brittle. Hence, white cast irons have very low toughness, and do not find wide application in the conditions that involve considerable impact. Improvement of the toughness of white cast irons would significantly increase the service life of components made of the white cast irons. Previous work [8–10, 17] has shown that an austenitic matrix is associated with higher fracture toughness, and as the amount of retained austenite increases, the fracture toughness is improved. The reasons for improvement of toughness by retained austenite is considered to be either the reduction of crack propagation rate [8, 29] or the dissipation of energy resulting from the stress-induced martensitic transformation [9, 29] or a combination of these two mechanisms [29]. When the first mechanism dominates, the greater the amount of retained austenite, the higher the resulting toughness. But, the second mechanism depends on both the amount of retained austenite and on its mechanical stability. If the mechanical stability of retained austenite is too high, no transformation occurs and, the toughness is not improved. Similarly, if there were little retained austenite, the dissipated energy resulting from the transformation would be small and would not make any significant contribution to the toughness. In addition, the present authors also believe that the alloy distribution, – carbon distribution in particular, has a significant effect on toughness. For the as-cast LS-28 white iron, although the amount of retained austenite is over 80%, the impact toughness in this state is still very low. This is due to the carbon segregation shown in Fig. 5a. From Fig. 8 it can be seen that untempered twinned martensite is formed next to the eutectic carbides. The proximity of these two hard and brittle phases provides an ideal path for crack propagation. In addition, cracks may be induced in the carbides by the transformation stresses resulting from the formation of twinned martensite next to the carbide. The formation of this type of martensite can be explained as follows: During the solidification process, lower carbon regions form in the austenite close to the eutectic carbide that formed earlier. If the cooling rate was fast enough to prevent the carbon from diffusing to this low carbon region, then the Ms temperature of this region may be higher than room temperature. Hence, martensite forms on cooling. Because of the high overall carbon content of the alloy, the martensite formed next to the eutectic carbides is twinned martensite. This segregation of carbon can be effectively eliminated by a subsequent destabilisation treatment.

The primary aim of the destabilisation treatment is to destabilise the high alloy content austenite, so that the matrix can transform to martensite on cooling, therefore improving the hardness [1]. Some studies [30, 31] have shown that increase the amount of retained austenite by increasing the destabilisation treatment temperature had little, or even a detrimental, effect on fracture toughness. Tabrett *et al.* [1] thought that this was a consequence of the toughness determination technique used in these studies, namely the dynamic Charpy test. However, Sare and Arnold [15] reported that the fracture toughness can be significantly improved by increasing the destabilisation treatment temperature. The present result in Fig. 1a is consistent with Sare and Arnold's results, even though the un-notched Charpy test is employed in this case. Obviously, the improvement of impact toughness is due to the increase in the amount of retained austenite. But, as the amount of retained austenite increases with the increase of destabilisation temperature, the mechanical stability of retained austenite is also increased (see Fig. 4a). From Fig. 11 it is clear that the LS-28 white cast iron that was destabilisation treated at 1130°C for 6 hours exhibited transformation toughening at −20°C where the mechanical stability of retained austenite was lower. But, at room temperature, no stress-induced transformation occurred, and therefore, no transformation toughening was observed. Hence, it is believed that the increase of room temperature impact toughness with increasing destabilisation temperature is through impeding crack propagation by retained austenite. Transformation toughening mechanism made no contribution to the impact toughness at room temperature and above.

Hann and Gates' previous work [20, 22] did show a significant room temperature transformation toughening for fracture toughness in a similar alloy that was treated at 1130°C for 6 hours. This may be a consequence of the different toughness measurement method used. Fracture toughness represents the resistance of a material to crack propagation. While, the fracture of white cast iron components, which are used under impact condition, is often controlled by the resistance to crack initiation [8]. From the present experimental results in Figs 1a and 11, components made of LS-28 alloy may have longer life at −20°C than at room temperature. The lower impact toughness at room temperature is due to the high stability of the austenite. Thus, there is the potential to further improve the room temperature impact toughness of this alloy by reducing the stability of the retained austenite, – possibly by reducing the amount of the austenite forming elements Mn, Cu and Ni. When combined with a high temperature destabilisation treatment, it may be possible to develop a higher toughness white cast iron.

It is easy to understand the effect of tempering temperature on the impact toughness and hardness. Tempering at 200°C to 250°C can significantly relieve the residual stresses, and therefore, improve the toughness. When the tempering temperature is over 400°C, the formation of secondary carbides and decomposition of retained austenite, leads to a decrease in toughness accompanied by a slight increase in hardness.

4.2. Wear resistance

It may be argued that high temperature destabilisation treatment can reduce the hardness, and that this is undesirable. From Fig. 2 it can be seen that the hardness after high temperature treatment still higher than that of the as-cast state. On the other hand, the requirement for high hardness is to ensure good abrasion resistance for this material. Research in the last few years has shown that the presence of austenite in the matrix can positively contribute to abrasion resistance [8, 12]. In the 1980s, it was postulated that austenite is deleterious to the properties of white cast irons, and leads to spalling when it transforms to martensite under impact loading condition, due to the accompanying expansion [18]. With the improved understanding of the mechanism of the good abrasion resistance of white cast irons and the role of the matrix in white irons, the benefit of retained austenite has been recognised. Now it is understood that the eutectic carbides in white cast irons take the main responsibility for the good abrasion resistance [1], and the role of matrix is to provide good support to the carbides. Austenite in white cast irons may also provide good support to eutectic carbide through work hardening and stress-induced martensitic transformation [13–15]. Tabrett and Sare [1] have pointed out that in the case of high stress abrasion, the abrasion resistance of austenite matrix is better than that of a martensite matrix because the hard abrasive particles work harden the austenite by stress-induced transformation. Hence, it can be seen that the key point of whether the austenite matrix can provide good support to carbides or not depends on whether the transformation can be induced by the external stress during service. If the mechanical stability of retained austenite is too high to be permit stress-induced transformation, it will be deleterious to the abrasion resistance, like the case of low stress abrasion with soft abrasive [1]. Reducing the mechanical stability of austenite through heat treatment and modification of the chemical composition of white irons, so that the stress-induced martensitic transformation can occur under low stress abrasion at room temperature may lead to improved abrasion resistance. The abrasion resistance of the austenite matrix may be expected to be better than that of the martensite matrix, even under low stress abrasion conditions.

The destabilisation treatment can not only improve the impact and fracture toughness of white cast irons, but it can also increase the abrasion resistance through the following two mechanisms: (1) Reducing the alloy content, carbon in particular, can lower the mechanical stability of retained austenite. The stress-induced transformation may occur at lower stress, therefore, providing good support to the eutectic carbides. (2) The secondary carbides precipitated in the dendritic austenite during austenitization process can harden the austenite matrix. For the LS-28 alloy examined in the present work, destabilisation treatment at high temperature results in high mechanical stability of retained austenite, which can not be induced to transform at room temperature in an impact test. In order to improve the impact toughness and abrasion resistance at room temperature, the chemical composition of this alloy should be modified to reduce the mechanical stability of retained austenite. Although the abrasion resistance was not measured, from the results of the present work it can be predicted that the room temperature impact toughness and abrasion resistance of the lower carbon white cast irons may further improved by reducing the amount of manganese or nickel. Further research will be carried out on this possibility.

The last topic to be discussed in this paper is that of the abrasion resistance of the lower carbon white cast irons. Previous work [11, 18–20, 22] has shown that lowering the carbon content of white cast irons can significantly improve the fracture toughness compared with the conventional white irons. But, no abrasion resistance results have been reported. A number of studies [1, 2, 32, 33] have concluded that as long as the presence of pearlite and bainite are avoided, high abrasion resistance would be obtained in the high chromium white cast irons. TEM and optical microscopy observations in the present work and in previous work [20, 22] have indicated that neither pearlite nor bainite were obtained in the lower carbon series white cast irons developed at the University of Queensland. This basically ensures good abrasion resistance for the alloys. On the other hand, the reduction of carbon leads to the decrease of the volume fraction of carbides, which may decrease the abrasion resistance. Gahr and Eldis' results [21] have shown that increasing the carbide volume fraction will slightly increase the abrasive wear loss for SiC abrasive. For garnet abrasive, although the abrasive wear loss dropped with the increase of carbide volume fraction, the carbide volume fraction in the low carbon white cast irons is still within the range that corresponds to low abrasive wear loss. This implies that in most cases the lower carbon white irons can satisfy with the service requirement for abrasion resistance. Finally, the results in the present work, show that by modifying the chemical composition of the current lower carbon white irons, both the impact toughness and the abrasion resistance are expected to be further improved. Hence, the low carbon white cast irons with high temperature destabilisation treatment may proved to be one of the best materials for applications in conditions involving both abrasion and impact.

5. Conclusions

1. Increasing the destabilisation treatment temperature can significantly increase the un-notched Charpy impact toughness. Although the hardness reduces with destabilisation, it is still higher than in the as-cast state.

2. After a destabilisation treatment, tempering at 200 to 250°C leads to optimum impact toughness.

3. One reason for improvement in the impact toughness of white cast irons by destabilisation treatment is the homogenisation of the alloy, – for carbon in particular.

4. With the increase of destabilisation treatment temperature, the amount of retained austenite is increased, and this is in part responsible for the improvement of impact toughness. In addition, the mechanical stability of the retained austenite is also increased.

5. Reducing the amount of manganese and nickel in the low carbon white cast irons should lower the mechanical stability of the retained austenite, and may lead to improvement in both the impact toughness and the abrasion resistance.

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