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# Austempered ductile iron: an alternative material for earth moving components

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**Abstract**

Traditionally steels have enjoyed some kind of monopoly in earth movement applications like ripper tips and grader blades. Earth movement demands that the material possesses both wear resistance and toughness. Ironically, the limitation of steels is that it is difficult to get a good combination of these properties. Recent research efforts in earth movement have focused on austempered ductile iron (ADI) as an alternative material, which exhibits both these properties. ADI is obtained when ductile cast iron is accorded a special heat treatment known as austempering. Before the usage of ADI can flourish, there is a need to thoroughly understand its mechanical and tribological behaviour. This paper details the heat treatment of ductile iron to yield ADI and also examines its mechanical and abrasive wear properties. These properties are compared with those of a proprietary quenched and tempered (Q&T) steel used in applications requiring wear resistance. Typically, when a load of 0.25 $N\,mm^{-2}$ is used, the relative abrasion resistance (RAR) of ADI austempered at 375 °C with an initial hardness of 315 Hv is 2.01, while that of a Q&T steel, of hardness 635 Hv is 2.02. The good wear resistance exhibited by ADI despite the low initial hardness can be attributed to the surface transformation of retained austenite to martensite during abrasion. This phenomenon has been positively confirmed by XRD.
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*Keywords:* Austempered ductile iron; Quenched and tempered steel; Toughness; Abrasive wear resistance; Mechanical properties

## 1. Introduction

The dynamic engineering world, as embodied in earth movement, continues to exert enormous demands for light, durable and cost effective materials. For these reasons, there is a need to continually invent new materials and evaluate those already in service. One such material is ductile iron. Research efforts on this material, have mainly, focused on possible improvements of its mechanical properties; primarily strength, toughness and wear resistance by according it appropriate heat treatments. One such heat treatment is austempering and the resultant product is called austempered ductile iron (ADI).

The austempering process was first developed by Davenport and Bain [1] and applied to steels in the 1930s. In fact, the microstructure resulting from the austempering of steel is called bainite and is named after Bain [1]. The austempering process in ductile irons involves austenitising, quenching and isothermally transforming (or austempering) a specimen or component at a temperature in the bainitic region for an appropriate period of time. Austenitisation and austempering are often conducted in molten salt baths to avoid surface oxidation of the specimens or components after which they can either be air or water cooled.

Although austempering is done in the bainitic region, a metastable microstructure of high carbon retained austenite and ferrite—appropriately termed ausferrite is formed first. This is the ideal structure of ADI and it is different from the bainite obtained in steels, which comprises ferrite and cementite. If austempering of the ductile iron is prolonged, the ausferrite disintegrates to a typical bainitic structure [2]. This occurs with a penalty in the form of reduced toughness and ductility and should therefore be avoided.

A wide range of mechanical properties can be developed in ADI by selection of appropriate austempering temperatures and times. Several authors have investigated the mechanical properties of ADI [2–9]. There is a considerable interest in ductile irons austempered in the temperature range 325–400 °C. This family of ADIs

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exhibits high tensile strengths, toughness and wear resistance. These attractive properties render the ADI family strong candidates for ground engaging tools like ripper tips. The microstructures of these ADIs comprise acicular to feathery ferrite within a matrix of retained austenite.

The role of retained austenite in terms of wear resistance of ADI (a crucial parameter in earth movement) has been the subject of much speculation. Researchers have postulated that the retained austenite undergoes considerable strain hardening and possible transformation to martensite [10,11]. In this paper, the transformation of retained austenite to martensite during the wear of ADI is investigated for ductile iron austempered in the temperature range of 325–375 °C. Comparisons are also drawn between the tribological behaviour of ADI and that of a proprietary abrasion resistant quenched and tempered (Q&T) steel often used for earth movement applications.

## 2. Experimental procedure

### 2.1. Materials

A mainly ferritic ductile cast iron meeting the BS 2789:1973 specifications (SGI 420/12) whose analysis is shown in Table 1 was used in this study. Also included in Table 1 are the compositions of EN 24, a steel often used in areas requiring good wear resistance and that of the SAE 1020 steel which was used as the standard in the wear testing experiments.

### 2.2. Preparation of specimens

Tensile test bars of diameter 7.98 mm and gauge length of 54 mm were machined from the ductile iron. For toughness determination, un-notched impact test pieces of dimensions 10 mm × 10 mm × 55 mm were machined from the same material. To establish the relative abrasive wear resistance of the ductile iron, EN24 steel and SAE 1020 steel, test pieces of dimensions 10 × 10 × 15 mm were used.

For each intended test, a set of ductile iron specimens was heat-treated to produce ADI. The heat treatment, which was similar for the tensile, impact toughness and wear test pieces, consisted of austenitising at 900 °C for 60 min in a salt bath followed by quenching and isothermally holding the samples for 50 min in another salt bath maintained at either 325, 340, 350, 360 or 375 °C. The time duration of 50 min ensured that the specimens were in the heat treatment processing window where the optimum combination of mechanical properties of ADI can be expected [12].

The EN 24 steel samples for abrasive wear testing were austenitised at 850 °C for 45 min and quenched in oil. They were subsequently tempered at 250 °C, (Q&T1), 350 °C (Q&T2) and 450 °C (Q&T3). An annealed EN 24 specimen was also tested for abrasive wear resistance.

### 2.3. Optical microscopy

Following standard metallographic procedures, all the specimens were etched using 3% nital and examined under a Nikon optical microscope equipped with a 35 mm camera. The latter was used to obtain all the micrographs reported in this work.

### 2.4. Mechanical tests

The tensile tests were conducted on a Denison Mayes tensile testing machine using a load of 100 kN. All the toughness tests were conducted at room temperature using an Izod machine with a 325 Joules capacity hammer and a striking velocity of 4.5 $ms^{-1}$. Both the as cast and austempered specimens had their Vickers macrohardness tested on a Universal hardness tester using a load of 20 Kg. The Q&T steels were also tested for hardness using the same machine and load.

### 2.5. Abrasive wear testing

A modified Rockwell belt sanding machine, tailored to function as a semi-automatic abrasion testing rig was used. During the test, a dead loaded specimen (implying that weights are put on top of the sample) of dimensions 10 mm × 10 mm × 15 mm was made to abrade against the surface of a bonded alumina abrasive belt. In this setup, the specimen traverses normal to the horizontal movement of the belt such that it is always abrading against unworn particles at all times.

Prior to the actual tests, each sample was *run in* on an old alumina abrasive belt until the abraded surface was flat and uniform. The leading edge of each sample was marked so that in the subsequent test, the sample always

Table 1
Chemical composition of the SGI, EN24 and SAE 1020 in wt.%

| Material | C | Si | Mn | S | P | Ni | Cr | Mo | Mg |
|---|---|---|---|---|---|---|---|---|---|
| SGI 420/12 | 3.44 | 2.61 | 0.16 | 0.01 | 0.024 | 0.03 | 0.04 | Trace | 0.052 |
| EN 24 | 0.41 | 0.20 | 0.61 | 0.04 | 0.03 | 1.37 | 0.99 | 0.25 | – |
| SAE 1020 | 0.21 | 0.01 | 0.43 | 0.03 | 0.01 | – | – | – | – |

assumed the same alignment. In order to ensure accurate weight measurements, after running in, sticking abrading particles and wear debris were ultrasonically cleaned before the specimen was dried and the initial mass recorded. The samples were then abraded on new alumina belts after which they were ultrasonically cleaned, dried and re-weighed. The mean diameter of the abrasive alumina particles was 300 μm while the linear speed of the belt was 0.288 $ms^{-1}$. Two compressive stress, namely, 0.25 and 0.33 $N\,mm^{-2}$ were applied to the specimens over an abrasion distance of 4.2 m. A meaningful wear test must be reproducible. In the presently described test runs, the weight loss was within ±4% of each other. This was deemed satisfactory, as the results were consistent with other pin on disc testing equipment [13]. The weight loss was averaged and converted to volume loss with the wear resistance being defined as shown in Eq. (1).

$$\text{Relative abrasion resistance (RAR)} = \frac{\text{Volume loss of mild steel (SAE1020)}}{\text{Volume loss of specimen}} \qquad (1)$$

Before and after abrasion, the ADI specimens were analysed for retained austenite and ferrite using the X-ray diffraction technique. This was necessary to ascertain if there was a transformation of retained austenite to martensite during abrasion. Before abrasion, an X-Ray analysis was performed on specimens that had been polished using a 6 μm diamond paste, ultrasonically cleaned in alchol and then dried. After abrasion, the specimens were ultrasonically cleaned in alcohol and dried prior to the X-ray analysis. All the X-ray analysis work was conducted on a Mac Science machine with monochromated CuKα radiation. The voltage and current settings were 30 kV and 20 mA. The $2\theta$ scan angles ranged from 20° and 105° and the data was captured as a computer file. A Difftech computer software, which utilises the integrated areas of both the austenite (2 2 0) and (3 1 1) and ferrite (2 0 0) and (2 1 1) peaks was used in the determination of the volume fractions of retained austenite and ferrite before and after abrasion.

## 3. Results and discussions

### 3.1. Metallography

Although metallographic investigations were carried out for all samples, for brevity, only representative

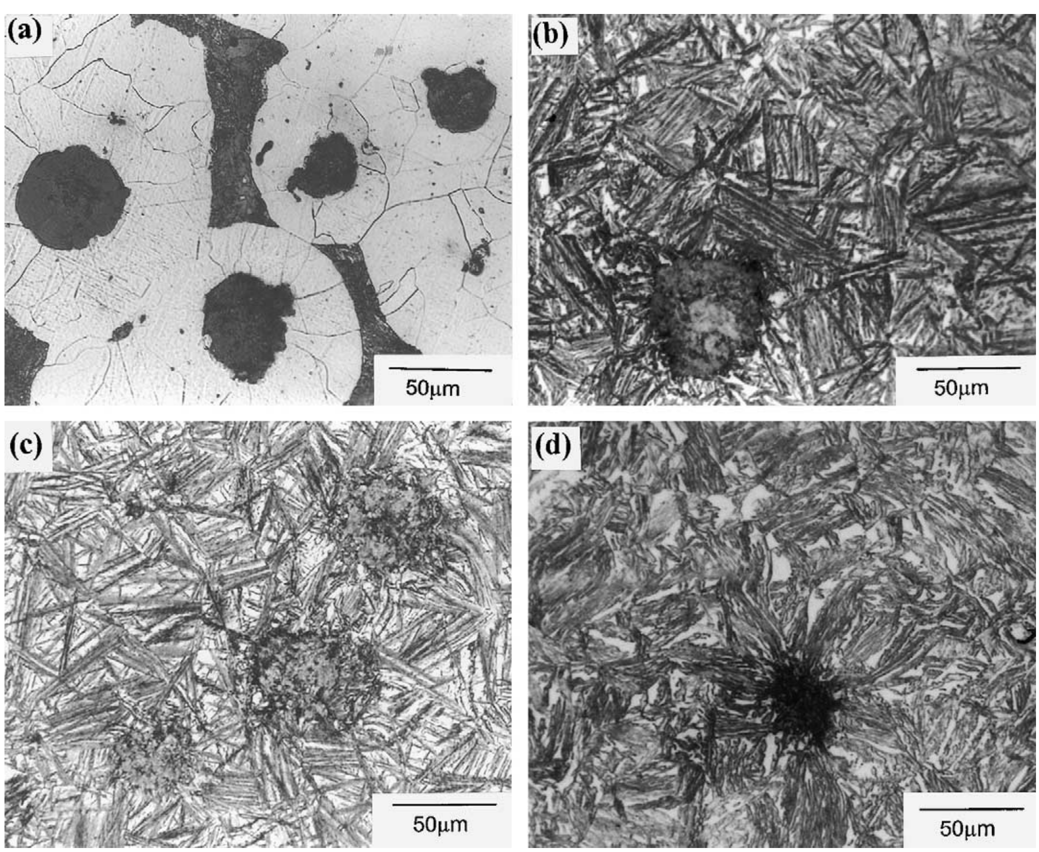


Fig. 1. Microstructure of (a) as cast ductile iron showing ferrite and islands of pearlite, (b) ductile iron austempered at 325 °C showing acicular ferrite and retained austenite, (c) ductile iron austempered at 350 °C and (d) ductile iron austempered at 375 °C, notice that the ferrite has become more feathery. Magnification ×500.

results are presented and discussed. Fig. 1a shows the as cast structure which is predominantly ferritic. Islands of pearlite are also evident. In Fig. 1b–c, the microstructures of ADI are depicted for austempering temperatures of 325, 350 and 375 °C. The structure after austempering at low temperatures (Fig. 1b) is finer and the ferrite is more acicular. Higher austempering temperatures yield a coarser feathery structure as evidenced by Fig. 1d. It is also apparent from these results that as the austempering temperature increases, so does the ferrite lath spacing and the volume fraction of retained austenite.

Fig. 2a shows the microstructure of an annealed EN24 steel, which is predominantly pearlitic, the white phase is ferrite. Fig. 2b depicts the microstructure of Q&T1. This structure of tempered martensite is typical in steels subjected to the quench and temper heat treatment process.

### 3.2. Mechanical properties of ductile iron and ADI

Table 2 shows the properties of as cast ductile iron and that of specimens austempered in the range 325–375 °C accordingly designated as ADI 325, ADI 340, ADI 350, ADI 360 and ADI 375. The mechanical properties of ADI can be discussed within two contexts. Firstly, a comparison can be drawn between the properties of the parent ductile iron and that of ADI. Secondly, they can also be discussed in terms of their (that is mechanical properties) evolution with austempering temperature.

The significant improvements in the properties of ductile iron brought about by austempering are apparent. For example, when austempered at 375 °C, the hardness and tensile strength are nearly doubled although the toughness and elongation decrease marginally (Table 2). The relatively high toughness and elongation values obtained do confirm that the specimens were austempered for an appropriate time (which ensured that they were in the heat treatment processing window) and were free from embrittling carbides.

The dependence of tensile strength, hardness, toughness and elongation on the austempering temperature is conspicuous in Table 2. The trends are such that the tensile strength and hardness decrease with austempering temperature while the elongation and impact toughness indicate significant increases as the austempering temperature is raised. These trends are to a large extend associated with the morphology of the ausferrite matrix which in turn is, strongly influenced by the austempering temperature (Fig. 1b–d). As the austempering temperature increases, so does the amount of retained austenite. The face centred cubic (FCC) structure of austenite with its large number of slip planes and directions has greater ductility than the body centred cubic (BCC) matrices of ferrite. Consequently, as the

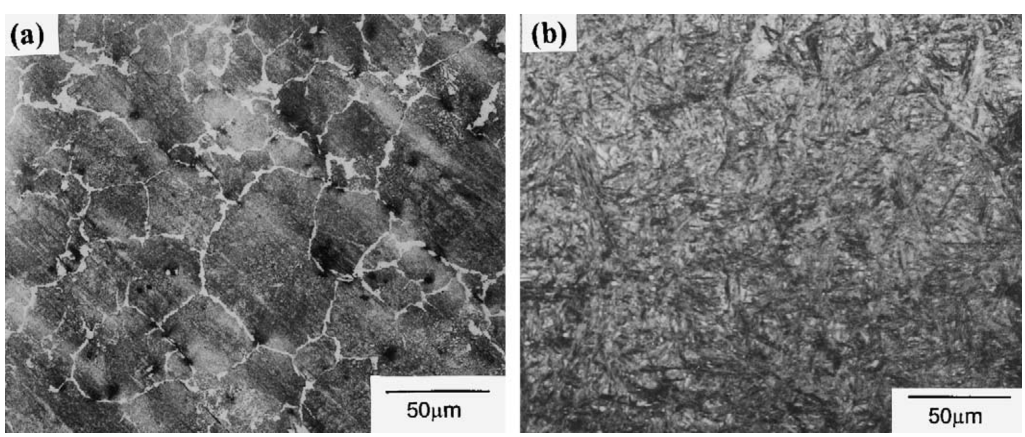


Fig. 2. Microstructure of (a) annealed EN 24, showing pearlite and ferrite and (b) Q&T EN 24 steel (Q&T1), showing tempered martensite. Magnification ×500.

Table 2
Mechanical properties of the as cast ductile iron and ADI

| Specimen ID | Hardness (HV) | Tensile strength (MPa) | % Elongation | Un-notched Charpy values (J) |
|---|---|---|---|---|
| Ductile Iron | 178 | 487 | 15 | 142 |
| ADI 325 | 389 | 1266 | 4.3 | 88 |
| ADI 340 | 377 | 1170 | 7.2 | 124 |
| ADI 350 | 366 | 1110 | 8.1 | 132 |
| ADI 360 | 344 | 1054 | 8.6 | 138 |
| ADI 375 | 315 | 985 | 10.4 | 140 |

amount of retained austenite increases so does the ductility [14].

### 3.3. Abrasive wear behaviour and retained austenite levels of ADI

For a compressive stress of 0.33 N mm$^{-2}$, the RAR of as cast ductile iron relative to the mild steel was found to be 0.84. From Eq. (1), which defines relative abrasion resistance, an RAR value which is less that 1 implies that the volume loss of the specimen was more than that of the standard SAE 1020 steel specimen. For the same compressive stress of 0.33 N mm$^{-2}$, the RAR of ADI specimens varied between 2.00 and 2.09. This is almost a 2.5 fold increase in the wear resistance. It can, therefore, be concluded that austempering significantly improves the wear resistance of ductile iron.

The variation of the RAR with austempering temperature for two different compressive stress is shown in Fig. 3. This needs to be discussed in the light of the retained austenite levels of the specimens before and after abrasion wear testing.

Figs. 4a–b and 5a–b show the austenite peaks, labelled (2 2 0) and (3 1 1), before and after abrasion for specimens austempered at 350 and 375 °C, respectively. After the abrasive wear tests (Figs. 4b and 5b), the once prominent austenite peaks have been reduced to nearly background noise levels. This huge reduction in the size of the (2 2 0) and (3 1 1) austenite peaks coupled with some broadening of the ferrite/martensite (2 0 0) and (2 1 1) peaks in Figs. 4b and 5b after abrasion testing suggests that a transformation of the retained austenite to martensite has occurred.

In general, the RAR of specimens austempered in the temperature range 325–375 °C does not seem to vary significantly. However, the hardness decreases while the retained austenite levels increase with austempering temperature (Table 3). It would, therefore, appear that despite the fall in hardness, the increase in the amount of

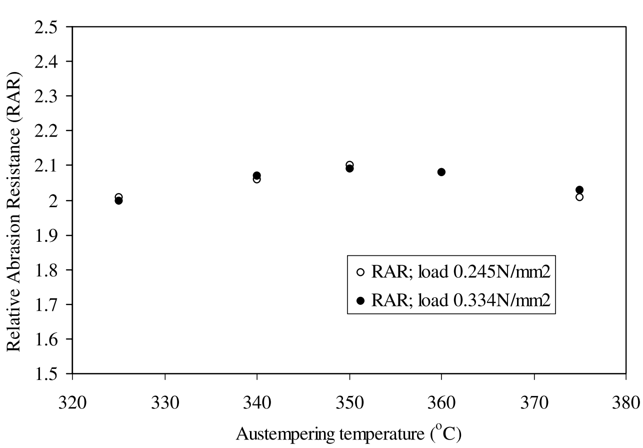


Fig. 3. Variation of RAR with austempering temperature for two different loads.

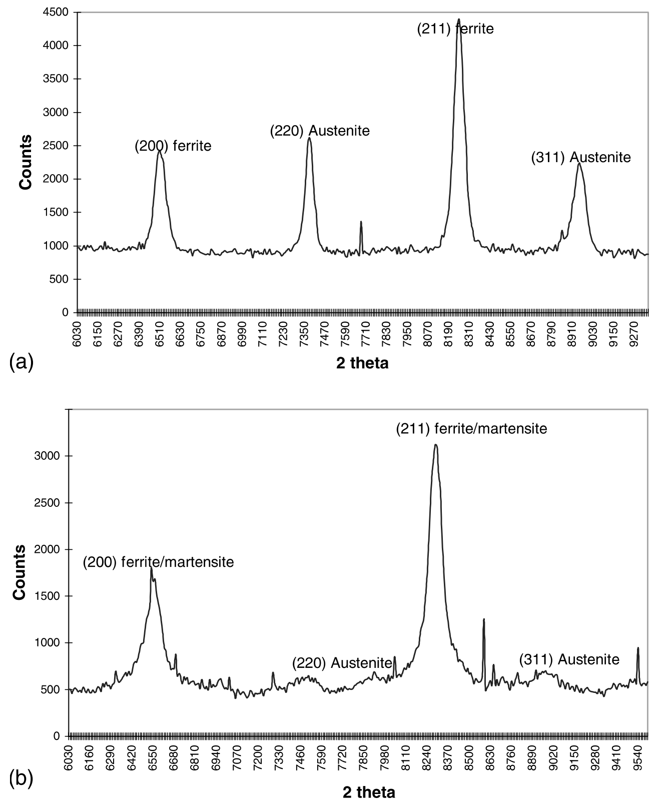


Fig. 4. (a) XRD plot of a specimen austempered at 350 °C before abrasion (b) after abrasion, note that the austenite peaks have been reduced to almost background levels.

retained austenite, which transforms to martensite, improves the wear resistance. The net result is that there is little variation of wear resistance with austempering temperature. The authors have noted that the hardness on the surface of ADI taper specimens after abrasion testing can be as high as 650 Hv [12]. These observations are consistent with the notion that retained austenite transforms to martensite during abrasion testing. The depth of the hardened layer was approximately 150 μm. This means other key bulk materials properties such as toughness and ductility are not lost due to the surface transformation.

The conclusions from the current work differ from those of Prasanna et al. [15], Ming [16] and Boutorabi et al. [17], who concluded that the wear resistance of ADI is significantly dependent on the austempering temperature and initial hardness. The results by Ming [16] can, however, be queried for two reasons; firstly the wear tests are reported as abrasion wear tests, when essentially they were sliding wear tests. Secondly the volume fractions of retained austenite reported (18.12%) and Brinell hardness (2 7 0) reported in this work seem to be low for a typical austempering temperature of 350 °C used. It may be possible that the specimens used by Ming [16] were over austempered and hence the low levels of retained austenite and hardness observed.

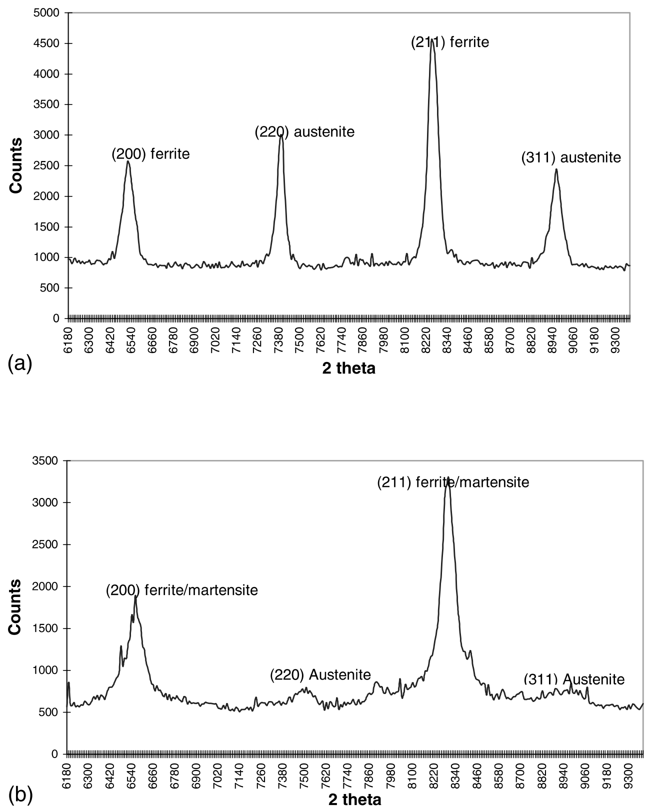


Fig. 5. (a) XRD plot of a specimen austempered at 375 °C before abrasion (b) after abrasion, note that the austenite peaks have been reduced to almost background levels.

It is also interesting to note that the conclusions by Prasanna et al. [15] are somewhat surprising considering their experimental results. For example, the difference in percent weight loss for specimens austempered at 300 and 380 °C is only 0.8% after wear testing for 24 h. For most practical purposes, this variation may be considered as negligible. Ironically this would then tend to suggest that the abrasive wear resistance of ductile iron austempered in the temperature range 325–375 °C shows little dependence on the austempering temperature as established in the present research. The major practical implication of this result is that if the service conditions demand high toughness and ductility coupled with moderate strength, high austempering temperatures can be used without much loss of wear resistance. On the other hand if high strength is of primary concern, then lower austempering temperatures are more suitable. The specific earth movement application should determine the appropriate austempering temperature to be used.

It should also be mentioned that the results obtained in the current research correlate well with some pioneering research work on the abrasion resistance of ADI conducted by Shepperson [14]. In this study, the superior wear resistance of ADI when compared to the proprietary abrasion resistance steels was noted. However, the RAR values obtained in that work are slightly lower than those in the current research. This can be attributed to differences in the load and speeds used. It may also be a result of the difference in the amount of retained austenite recorded after abrasion. In the current study, trace levels of retained austenite were detected (as shown in Figs. 4 and 5) where as Shepperson [14] detected up to 10% retained austenite.

### 3.4. Abrasive wear behaviour of SAE1020 and EN24 steels

Table 4 shows the RAR values for the steels. It is apparent that as the hardness increases so does the RAR. This is an expected phenomenon in Q&T steels. The SAE 1020 steel has an RAR value of 1 since it was used as the standard specimen.

### 3.5. Comparisons of the RAR of steels and austempered ductile iron

When comparing the RAR for steels and ADI, it can be seen that the RAR of ADI is much superior for the same hardness levels. In fact, the abrasion resistance of ADI is comparable to that of a steel with twice its hardness. For example, when a load of 0.25 $N\,mm^{-2}$ is used, the RAR of ADI austempered at 375 °C with an initial hardness of 315 Hv is 2.01, while that of a Q&T steel, of hardness 635 Hv is 2.02. This emphasises yet again that no simple mechanical property such as initial hardness appears to lend itself readily to predicting abrasive wear resistance. The superior wear resistance exhibited by ADI can be attributed to the surface

Table 3
RAR and retained austenite ($\gamma$) values for ADI

| Specimen ID | Hardness (HV) | RAR using a compressive stress of 0.25 $N\,mm^{-2}$ | RAR using a compressive stress of 0.35 $N\,mm^{-2}$ | %$\gamma$ before abrasion | %$\gamma$ after abrasion |
|---|---|---|---|---|---|
| Ductile iron | 178 | 0.8 | 0.84 | – | – |
| ADI 325 | 389 | 2.01 | 2.00 | 22 | Trace |
| ADI 340 | 377 | 2.06 | 2.07 | 30 | Trace |
| ADI 350 | 366 | 2.1 | 2.09 | 35 | Trace |
| ADI 360 | 344 | 2.08 | 2.08 | 38 | Trace |
| ADI 375 | 315 | 2.01 | 2.03 | 40 | Trace |

Table 4
RAR and Vickers hardness for steels

| Specimen ID | Hardness (HV) | RAR using a compressive stress of 0.25 $N\,mm^{-2}$ | RAR using a compressive stress of 0.35 $N\,mm^{-2}$ |
|---|---|---|---|
| SAE 1020 | 204 | 1 | 1 |
| EN 24 (annealed) | 268 | 1.14 | 1.18 |
| Q&T1 | 635 | 2.02 | 2.04 |
| Q&T2 | 520 | 1.79 | 1.81 |
| Q&T3 | 400 | 1.48 | 1.51 |

transformation of retained austenite to martensite during abrasion. This phenomenon has been positively confirmed by XRD as depicted in Figs. 4 and 5. When the surface transformation occurs, this raises the hardness to levels comparable to that of the Q&T1 steel and hence similar RAR values are obtained.

## 4. Conclusions

(a) Austempering in the temperature range 340–375 °C significantly improves the tensile strength and wear resistance of ductile irons with a marginal sacrifice of ductility and toughness.
(b) The abrasive wear resistance of ADI is much superior to that of the parent ductile iron and comparable to that of a steel whose hardness is approximately twice that of ADI.
(c) During abrasion, there is a surface transformation of retained austenite to martensite. This phenomenon raises the surface hardness of ADI and with it the wear resistance. Since this is only a surface transformation, the toughness of the material is not lost. As a result, ADIs exhibit a rare combination of high strength, toughness and wear resistance.

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