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An Investigation on the Suitability of Surface Engineered Austempered Ductile Iron as a Gear Material

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AN INVESTIGATION ON THE SUITABILITY OF SURFACE ENGINEERED AUSTEMPERED DUCTILE IRON AS A GEAR MATERIAL.

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ABSTRACT.

This preliminary study demonstrates that surface engineered austempered ductile iron is a valid alternative gear material to carburised steel.
The impact energy of ductile cast iron samples in various conditions, including as – cast, austempered at 240°C and austempered and shot peened using both 0.7mm and 1.4mm steel balls, was measured.
As expected the as-cast material exhibited nominal impact energy. This has been attributed mainly to the pearlitic matrix structure.
Austempering generally increases the impact energy. The extent of the improvement is however dependent on the austempering temperature and the resulting microstructure. It was shown that the structure following austempering at 240°C consists of fine acicular ferrite needles with high aspect ratio and relatively small quantities of retained austenite. These two features account for the comparatively low impact energy and high hardness values. Increasing the austempering temperature to 375°C leads to structures containing coarser ferrite needled and up to 40% retained austenite. Various investigators have shown that the high impact energy of irons austempered in this temperature range is dependent on the percentage retained austenite content[1, 2] and stability of the latter[3].
It can be seen that a reduction in size of shot used for peening has the effect of moving the maximum subsurface compressive stress closer to the surface. This increases the surface stress, but results in a shallower compressive surface layer. High surface compressive stresses make it more difficult to initiate surface cracks and thus properties such as fatigue and impact energy are bound to improve[4]. In the case of high surface compressive stresses, the sub-surface becomes critical and thus the advantage of having a deeper affected zone. This may suggest that in order to obtain maximum benefit from peening duplex size shot should be used.
Samples austempered at 240°C and shot peened have higher impact energy values than as cast samples. This may suggest that the fatigue behaviour of gears austempered at the higher temperatures may be superior to those treated at lower temperatures whilst the tribological characteristics may be inferior. This is however not necessarily the case and needs to be investigated further.

Keywords: Gears, Austempered ductile iron, impact energy, shot peening, surface engineering**.**

INTRODUCTION.

Gears are required to have a tough core, capable of withstanding the shock loads experienced during transmission and a hard wear resistant case that can endure the high compressive stresses between the interlocking gear teeth. Case carburized steel gears satisfy these service requirements but the former are relatively expensive to manufacture. Furthermore, steel has relatively poor damping characteristics and a comparatively high coefficient of friction, implying, noisy gear trains and the requirement for lubricants, if heavy material loss is to be avoided.

The primary purpose of this study is to find an alternative gear material to carburised steel. Austempered ductile iron (ADI) is a commendable contestant, in the first instant because it lends itself to casting which is a direct near net shape process. Finish machining of cast iron gears requires therefore minimal material removal, thus curtailing material wastage and machining costs. Secondly austempering is a much shorter thermal process than carburising and therefore is comparatively cheaper. Finally the graphite found within the cast iron matrix serves not only as a solid lubricant which reduces friction but also helps to dampen shocks and vibration. As a result the cost of austempered ductile iron gears is only a fraction that of the corresponding carburised steel counterparts[5] .

Austempered ductile iron gears may have mechanical properties that are comparable to those of the carburised steel counterparts but their performance under contact fatigue is still somewhat inferior[6,]. The performance of ADI gears can however be improved by applying surface engineering techniques. In such cases the object is to create a "composite" with properties that are superior to either the austempered ductile iron base material or the coating / modified surface.

The immediate effect of bombarding high velocity shots onto a metallic target is the creation of a thin layer of high magnitude compressive residual stress at or near the metal surface[7]. Shot peening is used to increase the resistance of metal parts to fatigue failure in a variety of industries, including aerospace, automobile, heavy equipment and power generation. Residual compressive stresses introduced by the peening process have a major beneficial effect upon metal fatigue and combating tensile stress related modes of failures such as corrosion cracking, corrosion fatigue, thermal fatigue and fretting fatigue[8]. This is of considerable importance to gear design and manufacture.

This paper is the first in a series investigating the use of surface engineered austempered ductile iron as a gear material. In this preliminary study the authors measure the impact energy of nodular cast iron samples in various conditions and including as – cast, austempered at 240^{o}C and 375^{o}C and austempered and shot peened at 240^{o}C using both 0.7mm and 1.4mm steel balls. The results served to indicate conditions that merit further testing using mainly modified four pin fatigue and pin on disk tests.

1 EXPERIMENTAL PROCEDURE

1.1 Cast metal.

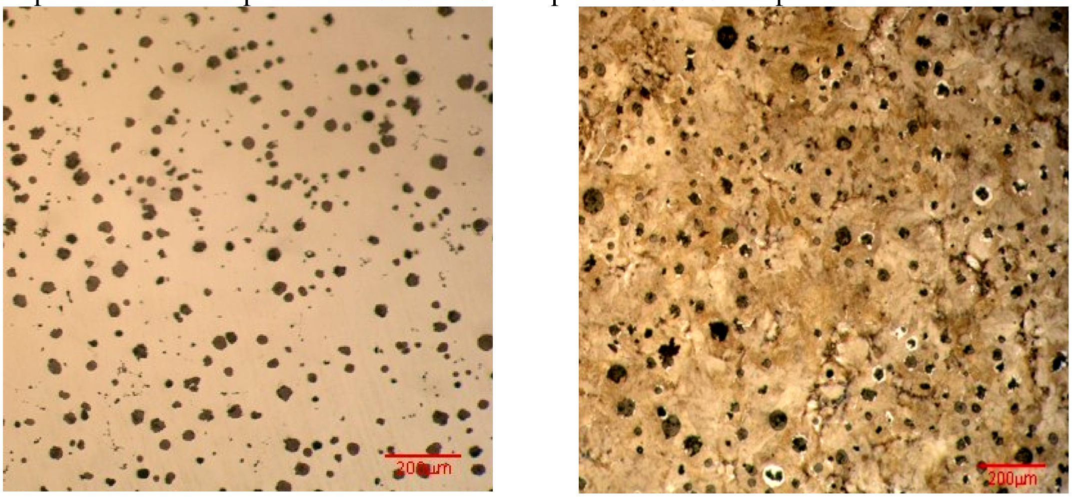
A charge of ductile iron returns, good quality steel scrap and ferrosilicon was melted in a medium frequency induction furnace. The melt was treated with 1.8% magnesium ferrosilicon alloy and inoculated with 0.67% ferrosilicon containing 75% silicon. Standard keel blocks measuring 300 x 200 x 30mm were cast in sand moulds. The composition of the iron under investigation is given in Table 1 and the resulting as-cast microstructure is shown in Figure 1.

ELEMENT	COMPOSITION (wt %)
Carbon	2.97
Silicon	2.84
Manganese	0.42
Magnesium	0.05
Copper	1.19
Sulphur	0.007
Phosphorus	0.032

Table 1. Chemical composition of the as – cast nodular iron.

1.2 Preparation of impact test samples.

Prismatic sample measuring 12 x 12 x 126mm were cut using a donkey saw and rough machined to 11 x 11 x 126mm. Two samples were set aside to be tested in the as-cast condition, 6 samples were austempered at 240°C and 6 samples at 375°C as per a heat treatment



(a) (b)

Figure 1. Microstructure of as cast ductile iron showing, (a) graphite nodules, (b) pearlitic matrix structure.

schedule shown in Table 2. A digital controlled electric furnace was used for austenitising and a gas fired salt bath for austempering. After heat treatment all samples were finished machined to the final dimensions of 10 x 10 x 126mm. This removed any decarburised skin that may have formed during austempering. Machining speed and depth of cut were kept as low as practical in order to avoid transformation of any retained austenite to martensite.

Austenitising Temperature (°C)	**Austenitising Time (hours)**	**Austempering Temperature (°C)**	**Austempering Time (hours)**
900	1	240	2
900	1	375	1

Table 2. Austempering heat treatment schedule.

Four impact samples were peened with the 0.7mm diameter shot and four samples were peened with the 1.2 - 1.4mm steel balls with specifications shown in Table 3. Impact samples were tested using an izod machine with a 325J capacity hammer and a striking velocity of 4.5m/sec. For each condition two samples were tested and each test sample gave three impact energy measurements. The results shown in Table 4 are the average of six impact measurements.

Average Shot size	1.2 to 1.4mm	0.7mm
Shot hardness	46-50 HR_c High Carbon Steel	46-50 HR_c High Carbon Steel
Shot velocity	~ 40m/s	~ 40 m/s
Peening Time (s)	330	330

Table 3. Specifications of shot peening process.

Samples for microstructural analysis and hardness measurements were taken from fractured impact sample. The amount of retained austenite present was measured using X-ray diffraction techniques. X-Ray spectra were obtained from a diffractometer with CrK_α radiation. The Bragg peaks (220) and (221) were used for the austenite and ferrite / martensite respectively. The volume fraction of graphite was measured using image analysis and unetched polished samples. Table 5 shows the percentage microconstituents of the austempered samples.

Condition	Impact Energy	Surface hardness
As cast	15 Joules	
Austempered at 240°C	40 Joules	
Austempered at 240°C and peened (0.7mm shot diameter)	62 Joules	480 HmV
Austempered at 240°C and peened (1.2-1.4mm shot diameter)	55 Joules	305 HmV

Table 4. Impact Energy and surface hardness.

2 DISCUSSION OF RESULTS.

2.1 As – cast material.

Figure 2 is a summary of the impact energy values of ductile iron samples exposed to different bulge and surface treatment conditions with values for those samples austempered to 375°C. It can be seen that the impact energy of the as-cast nodular iron is rather low even though the nodularity of the iron is better then 90 per cent, Figure 1(a). In this case the major factor determining the toughness of the iron is the matrix structure. It is well established that the impact energy of a pearlitic matrix is low compared to a ferritic counterpart[9].

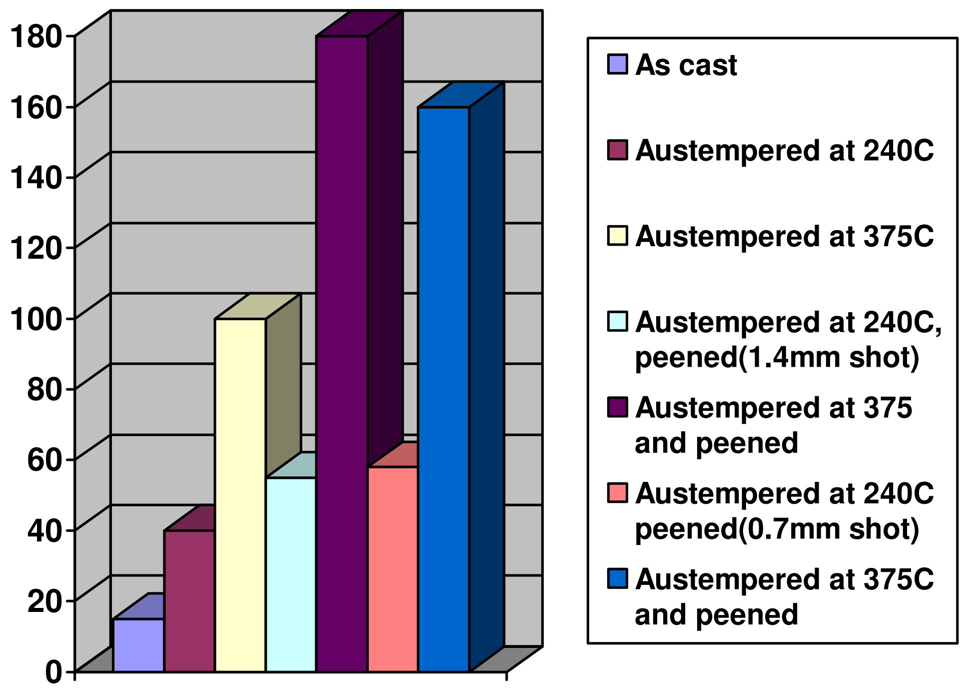


Figure 2. Impact Energy of nodular cast iron iron samples exposed to different bulge and surface treatment conditions.

2.2 As - austempered iron.

2.2.1 Microstructure

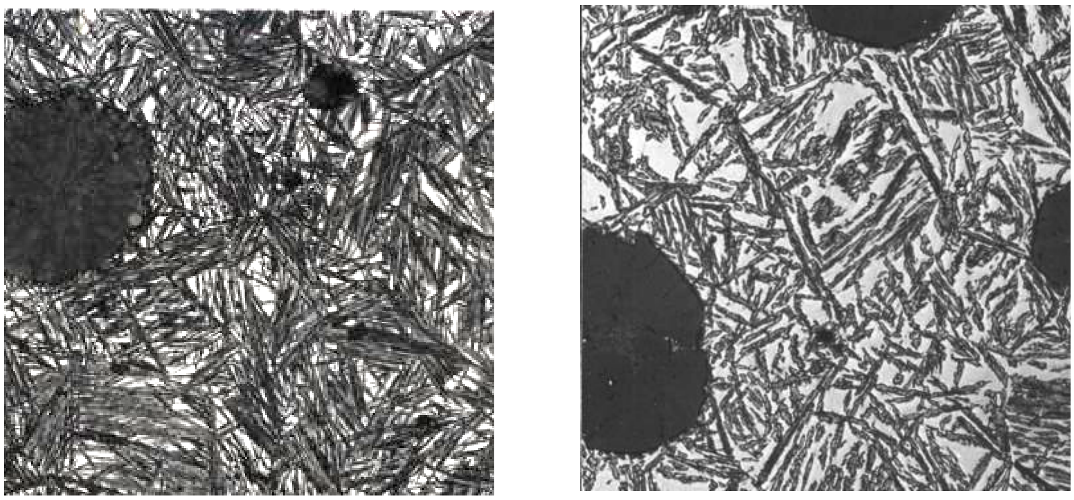
Figure 3(a) and (b) show the microstructure of samples austempered at 240 and 375^{o}C respectively. The specimen austempered at 240^{o}C has an acicular structure characteristic of martensite in steel. Image analysis and XRD measurement showed that these structures contain 10.5% carbon and 16% austenite. At this temperature the austenite occurs mainly in the form of slivers between adjacent ferrite plates. In comparison structures austempered at 375^{o}C have a coarser structure. In this case the ferrite needles are short and have a smaller aspect ratio. The austenite content increases to 40% and is in a more equiaxed form. Neither of the two structures showed signs of martensite.

Condition	Graphite (% vol.)	Retained austenite (% vol)	Martensite (% vol.)
Austempered at 240^{o}C	10	17	None
Austempered at 375^{o}C	10	40	None

Table 5. Percentage microconstituents in austempered samples.

The metallographic structure subsequent to isothermal transformation is strongly dependent on the austempering temperature (T_A). A low T_A results in a large undercooling of the austenite and a slower carbon diffusion rate. Thus at low isothermal temperature the nucleation of ferrite platelets rather than their growth is favoured. As a result the austenite transformation produces a highly acicular structure.

As the T_A increases to 375^{o}C the ferrite-austenite spacing increases markedly while the number of ferrite plates decreases, figure 3(b). These structural changes suggest that now kinetically, growth is favoured to nucleation.



(a) (b)

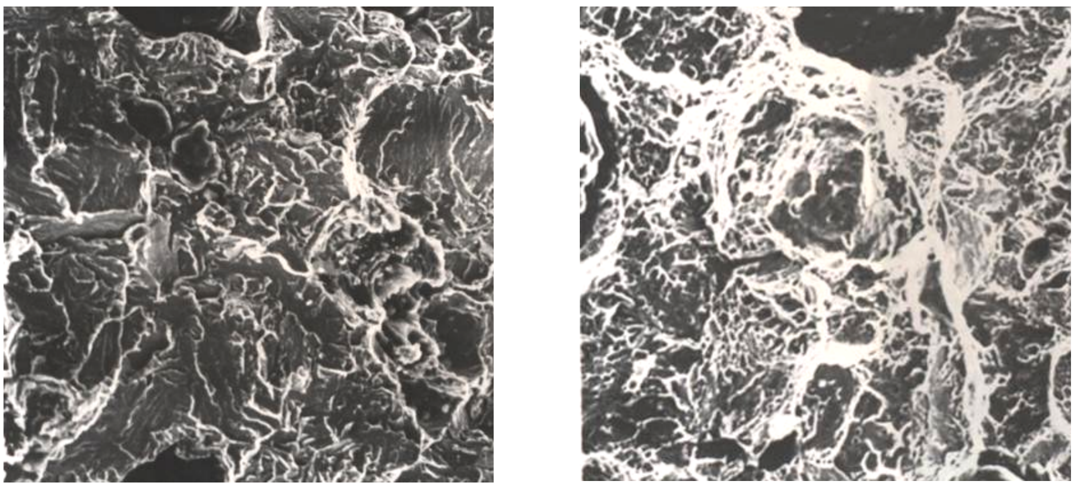
Figure 3. Microstructures of samples austempered at (a) 240^{o}C and (b) 375^{o}C. X 500.

At the lower austempering temperature the rate of nucleation of ferrite needles is high compared to the rate of carbon diffusion. A high carbon content is thus trapped within the growing ferrite needles resulting in a distorted crystal structure. At an early stage of the austempering treatment, this carbon is rejected from the ferrite and precipitates as carbide within the ferrite needles. As little carbon is transferred to the austenite, the austempering reaction can proceed continuously

such that relatively small quantities of austenite remain after austempering, Table 5. Although the ferrite nucleates more rapidly at lower temperatures, ferrite growth is slowed considerably and the completion of the austenite transformation requires longer time, particularly at temperatures as low as 240°C.
At 375°C the carbon diffusion rate is more rapid and thus most of the carbon is able to diffuse out of the growing ferrite plates. This results in austenite being enrichment with carbon, particularly between the growing ferrite plates. This in turn lowers the martensite start temperature M_s resulting in austenite being retained after cooling to ambient temperature. In fact as shown by Jonansson[(10)] austenite may be stable down to temperatures of at least -120°C. Thus the resulting structure consists of relatively coarse ferrite platelets and retained austenite, with the latter phase accounting for up to 40% of the matrix structure.

2.2.2 Impact energy, fracture toughness and hardness.

The presence of large quantities of retained austenite is considered to be responsible for the high level of impact energy of the sample austempered at the higher temperature[(2)].
Fractographs of samples austempered at 240°C and 375°C are shown in Figure 4. Samples austempered at the lower temperature show very few microvoids, in fact the fracture is mainly intergranular in nature. In comparison surfaces of samples austempered at 375°C show extensive microductility. The high fracture toughness of the latter can again be explained in terms of the large content of stable high carbon austenite. The brittle fracture of the sample treated at 240°C is related to the lower austenite content and aggregate of carbides which form around the ferrite / austenite grain boundaries at temperatures higher then 350°C[(11)].



(a) (b)

Figure 4 Fractographs of samples austenised at (a) 240°C and (b) 375°C.

The high hardness of samples austempered at 240°C can be attributed to the closely packed highly acicular ferrite needles. The slow carbon diffusion is responsible for carbon being trapped inside the fast nucleating ferrite sheaves. On cooling to room temperature carbides form within the ferrite needles. This and microstresses resulting from shear strains associated with low temperature ferrite formation, have been suggested[(11)] as a possible factor contributing to the high hardness of the samples austempered at low temperatures. Cox[(12)] suggested that long treatment times should temper the initially formed ferrite needles thus relieving stresses and decreasing hardness. However according to Harris [(13)] at these low temperatures no substantial annealing occurs. It is also possible that the low carbon austenite transforms to martensite during the application of the hardness test. This would increase the stresses within the structure

and consequently increasing the hardness still further.
The large quantity of stable high carbon austenite and coarse ferrite with practically no trapped carbon content is responsible for the low hardness of samples austempered at the higher temperature.

2.3 Austempered and peened samples.

It can be seen from Figure 2 that shot peening, whether macro or micro, increases the impact energy of austempered irons. Macro peening improves the impact energy of samples austempered at 240°C from 40 Joules to 55 Joules (1.2~1.4mm shot diameter) while peening with a 0.7mm shot diameter increased the property to 58 Joules. Shot peening changes the undesirable stress patterns introduced during the manufacturing cycle. For example grinding operations introduce tensile stresses in the surface which are detrimental to fatigue. Shot peening on the other hand results in compressive stresses which improve fatigue strength and reduce notch sensitivity.
In components such as gears or aerospace parts made from higher hardness materials, notch sensitivity is even more significant. Similarly, if a part in the hardened state is knocked or scratched during subsequent manufacture or on assembly, a notch could be created that might significantly affect the fatigue strength. In such cases, shot peening is beneficial, as it has a high degree of damage tolerance as indicated in Figure 5.

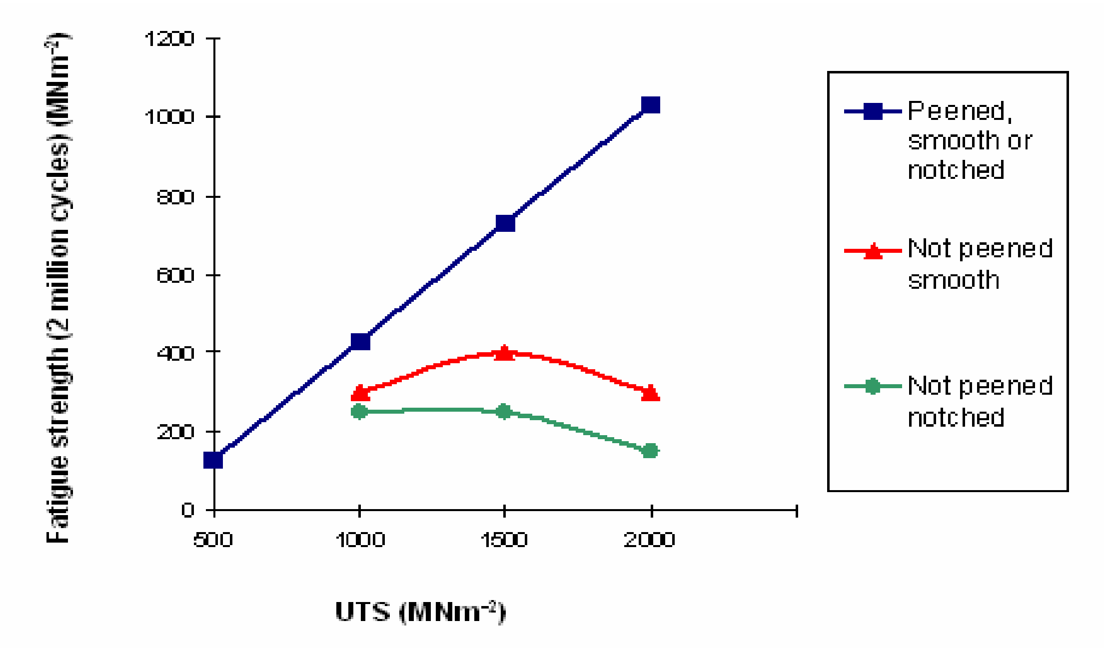


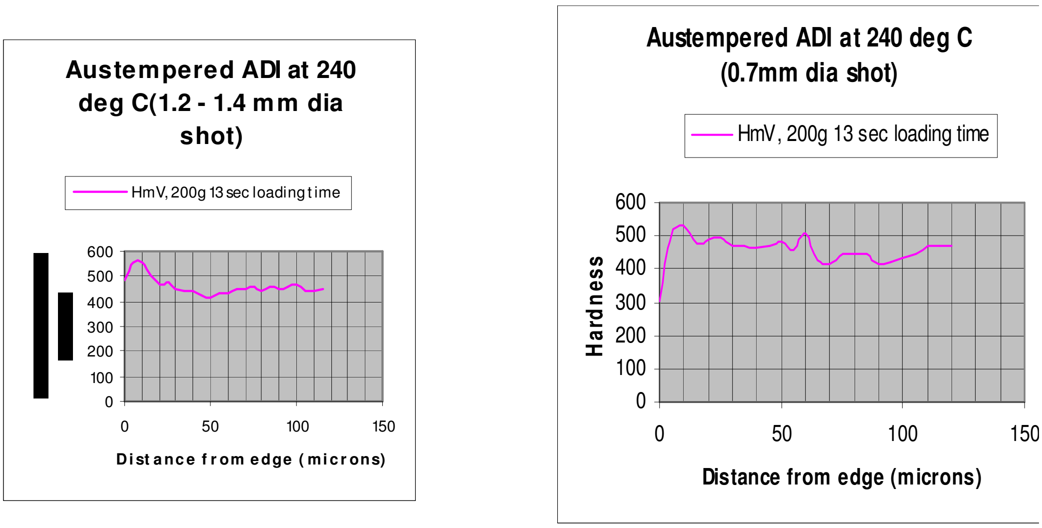
Figure 5. Comparison of peened and unpeened fatigue limits for smooth and notched specimens as a function of UTS of steel[4].

2.3.1 Comparison between macro and micro-peening.

Figure 6 compares the hardness profiles for the peened samples austempered at 240°C. It can be seen that a reduction of shot size has the effect of moving the maximum subsurface compressive stress closer to the surface. This increases the surface stress, but results in a shallower compressive surface layer. High surface stresses render it more difficult to nucleate surface cracks and therefore properties such as fatigue and impact energy are bound to improve[4]. In such cases the subsurface becomes more critical and thus the advantage of having a deeper affected zone. This may suggest that in order to obtain maximum benefit from peening duplex size shots should be used.

2.3.2 Effect of shot peening as a function of austempering temperature.

It was shown that shot peening increases the impact energy of samples austempered at 240°C.The impact energy of these samples is however still inferior to those of corresponding test pieces austempered at 375°C. Furthermore it is thought that at this temperature, the compressive stresses induced in the surface as a result of the shot hammering action would transform some of the retained austenite to martensite. The phase change is associated with an expansion which is expected to increases the compressing stresses even further than at the lower temperature. Work in progress will investigate the effect of shot peening on samples austempered at the higher temperature. It needs to be seen however whether i) martensite is actually present in the shot peened samples and ii) if present, whether it would actually improve fatigue and impact properties. The authors' experience is that the martensite found within the ADI structures prior to testing provide an easy path for crack propagation thus generally reducing mechanical properties and particularly fatigue, impact energy and ductility. On the other hand, martensite formed during crack propagation serves to induce compressive stresses at the tip of the crack, causing the crack to blunt and to stop propagating.



(a) (b)

Figure 6. Micro hardness profile of peened (a) (1.2-1.4mm shot) and (b) (0.7mm shot) samples austempered at 240°C

3 CONCLUSIONS.

- The low impact energy of the as-cast nodular iron can be improved by austempering
- Samples austempered at 375°C exhibit high impact energy. This can be attributed to the high percentage of stable high carbon austenite. Fractured surfaces show extensive microductility.
- The impact energy of samples austempered at 240°C can be accounted for by the closely packed highly acicular structure and low austenite content. Fractures of these samples show very few microvoids and are in fact mainly intergranular in nature.

- Shot peening on a micro and macro scale increases the impact energy.
- The impact energy of shot peened samples austempered at 240°C is higher then that of corresponding austempered samples.
- A reduction of shot size has the effect of moving the maximum subsurface compressive stress closer to the surface. This increases the surface stress, but results in a shallower compressive surface layer.
- It was argued that in order to obtain maximum benefit from peening duplex size shot should be used.
- This preliminary study demonstrates that surface engineered austempered ductile iron may be a valid alternative gear material to carburised steel.

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