Effect of Heat Treatment on Fracture Properties of High-Chromium White Cast Iron

M. Janssen[1], M.B. van Leeuwen[2] and M.F. Mendes de Leon[3]

[1] Department of Materials Science, Delft University of Technology, Rotterdamseweg 137, 2628 AL Delft, The Netherlands
[2] Stork FDO B.V., PO box 379, 1000 AJ Amsterdam, The Netherlands
[3] IHC Parts & Services, PO box 50, 2960 AA Kinderdijk, The Netherlands

ABSTRACT: *High-chromium white cast iron contains chromium carbides that provide excellent wear resistance, but also cause poor fracture properties. Heat treatments are applied in an attempt to decrease the angularity of the eutectic carbides and to improve the toughness of the matrix by intentionally creating a high fraction of retained austenite, while minimizing the formation of secondary carbides. It is found that the austenitising temperature hardly affects the carbide morphology. However a large effect is found on the shape and size of the secondary carbides formed and on the relative fractions of austenite and martensite. Measurements are performed with an instrumented drop-weight impact tower on Charpy-like specimens containing electric-discharge-machined notches. Results show that austenitising at high temperature (1100 °C) leads to a significantly larger total fracture energy compared to the as-cast condition. However, the energy absorbed at crack initiation and the* K_{Ic} *value seem not to be affected. SEM observations of the fracture surfaces clearly indicate that the crack propagates along the interfaces of or through the eutectic carbides. A ductile fracture appearance is found around secondary carbides.*

INTRODUCTION

High-chromium white irons are often applied in applications where wear-resistance is essential. Actually this material is a composite since it contains a considerable volume fraction of chromium carbides, providing the excellent wear resistance, embedded in a matrix of high alloy steel. The usual production route is casting. In hypo-eutectic iron a coarse network of eutectic chromium carbides of the M_7C_3 type is formed during solidification. This brittle network promotes crack initiation and provides a low energy route for cracks to propagate, leading to poor fracture properties, *e.g.* [1].

The eutectic carbides are very stable and the morphology of the network formed during solidification cannot be significantly affected through heat treatments [2]. However heat treatments do affect the structure of the matrix and so can have some effect on the fracture properties of as-cast material.

As-cast material is usually heat treated. One reason is to eliminate pearlite formed during cooling down after solidification, since this has a bad effect on wear resistance. Another reason is to control the relative fractions of martensite and retained austenite. A high fraction of retained austenite is promoted by a so-called *stabilising heat treatment*. At temperatures of 1100 °C and higher all secondary carbides will gradually dissolve, leading to an increased carbon and chromium content in the austenite. If subsequent cooling is fast enough to prevent these elements to form secondary carbides, the M_s temperature is lowered and a high fraction of retained austenite results.

On the other hand in a *destabilising heat treatment* austenitising is around 1000 °C, causing secondary carbides to precipitate. This lowers the alloy content and thus promotes the martensitic transformation at low temperatures. Cooling must be fast enough to prevent pearlite formation.

Compared to martensite, austenite has a higher intrinsic fracture toughness [3] and strain induced martensite formation may further enhance this. Therefore, from a fracture mechanical point of view it seems advantageous to aim at a predominantly austenitic matrix. Secondary carbides formed in an austenitic matrix are reported to negatively affect fracture properties. Note that the effect of retained austenite and martensite on wear resistance is quit complex and depends strongly on the type of wear.

In the present work a conventionally cast hypo-eutectic white iron is investigated. To clarify the effect of the retained austenite and martensite content and the role of secondary carbides on fracture behaviour several heat treatments are applied. The effect is monitored by testing the heat-treated material with an instrumented drop-weight tower. Note that although in this work the focus is not on dynamic fracture properties, a drop-weight test does provide a relatively simple way of characterising crack initiation and propagation. Furthermore, an additional advantage is the fact that the (slightly modified) Charpy specimens which are used are relatively easy to prepare.

EXPERIMENTAL

Material

This work is performed on a hypo-eutectic high-chromium white iron. Table 1 gives the approximate chemical composition. The material is cast in ingots with length × width × height = 250 × (80-89) × 125 mm. Slabs of 10 mm thick were cut from the middle of the ingots normal to the length direction. All specimens were taken from the equi-axed zone in the centre of the slabs.

Figure 1 shows the as-cast microstructure of the material. The eutectic carbides are the white phases. Between these carbides martensite is found.

TABLE 1: Chemical composition of the white iron [weight %]

C	Cr	Si	Ni	Mo	Mn	Cu
2.0	17.1	0.29	0.93	0.91	0.72	0.18

The remaining matrix consists of pearlite (black) and a mixture of ferrite and retained austenite (light). Less than 1 vol.% of pores are present, all smaller than 20 µm in size.

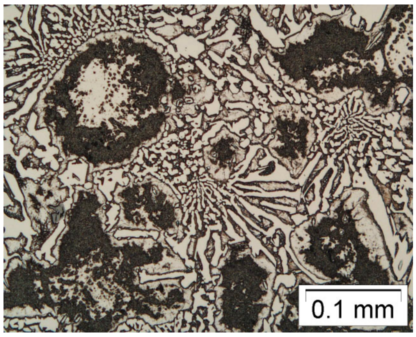


Figure 1: Micrograph of the as-cast structure

Heat Treatments

The determining parameters in stabilising/destabilising heat treatments are the austenitising temperature and the cooling conditions, *i.e.* the cooling rate and the temperature to which is cooled. Based on [2, 3] and on the hypothesis that a predominantly austenitic matrix with a minimum of secondary carbides provides the most favourable fracture properties, the ideal heat treatment is assumed to consist of the following steps:

- Austenitising at 1100 °C.
- Quenching to 300 °C. The high cooling rate minimises the formation of secondary carbides.
- Maintaining this temperature for a short while, allowing residual stresses to relax but preventing secondary carbides to precipitate.
- Cooling slowly, so no additional residual stresses develop.

In Table 2 an overview is given of the heat treatments performed on a series of Charpy specimens. Treatment 1100-2-s is the ideal treatment described above. The treatments 1100-4-s, 1100-2-w and 1040-2-s are performed to investigate the effect of austenitising time, quenching and austenitising temperature, respectively.

TABLE 2: Heat treatments applied to the as-cast high-chromium white iron

Code	Austenitising	Cooling	Holding	Cooling
1100-2-s	1100 °C/2 h	salt bath 300 °C	15 min.	air (≈30 min.)
1100-4-s	1100 °C/4 h	salt bath 300 °C	15 min.	air (≈30 min.)
1100-2-w	1100 °C/2 h	water 20 °C	15 min.	–
1040-2-s	1040 °C/2 h	salt bath 300 °C	15 min.	air (≈30 min.)

Drop Weight Tests

As already stated in the introduction the fracture properties are determined with an instrumented drop-weight impact tower (see Figure 2). A specimen is loaded in 3-point bending by dropping a mass from a specific height. The load applied to the specimen is digitally monitored through strain gauges mounted on the tup. Afterwards the load-time data is converted to load-displacement data by considering all forces acting on the drop weight and calculating the tup velocity.

The specimen resembles a Charpy specimen, *i.e.* a notched bar of 10 × 10 × 55 mm. The notch has a depth of 2 mm and a tip radius of 0.1 mm and is introduced by electric discharge machining (EDM).

From the load-displacement data the energy at crack initiation, E_i, and the total fracture energy, E_f, are calculated by integration. Initiation is assumed to occur at maximum load in this predominantly elastic material. The energies are subsequently divided by the net section area to account for small dimensional differences.

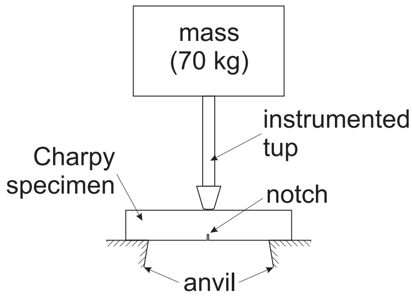


Figure 2: Set-up of instrumented drop-weight impact test

Furthermore the plane-strain fracture toughness, designated as K_{Ic}, is determined using the expression given in ASTM standard E399 [4] for 3-point bend specimens. In principal K_{Ic} should be determined using pre-fatigued specimens. However, measurements on standardised specimens have shown that for this material this specimen geometry yields similar results [5].

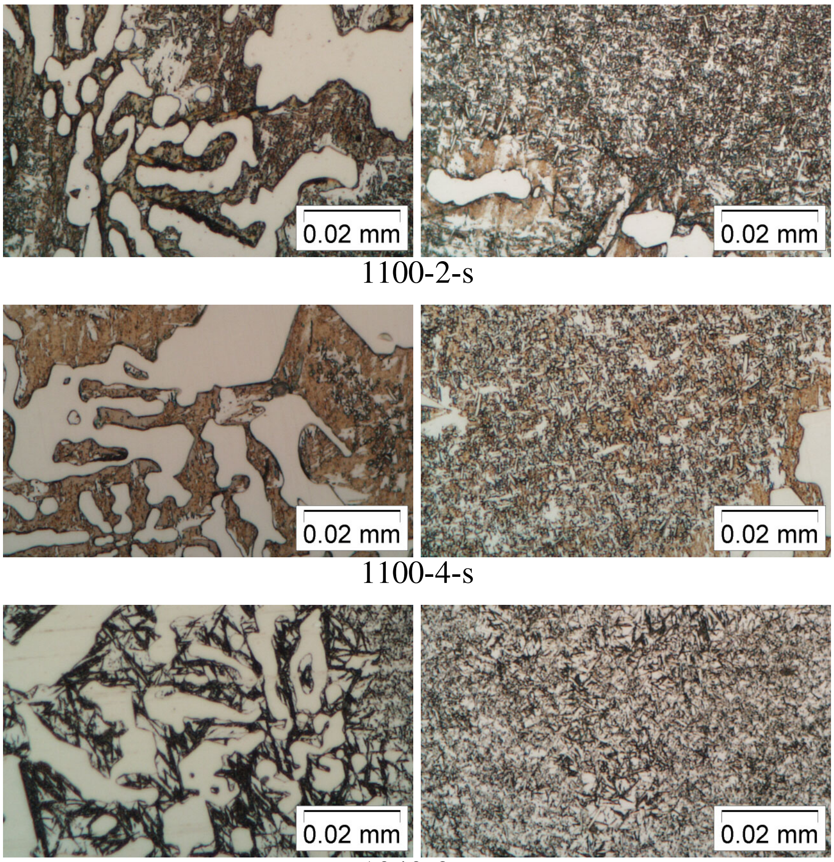
Due to the relatively stiff and brittle nature of the material it was necessary to correct the calculated displacements for the compression of the tup caused by loading. This was done by subtracting the load divided by the tup stiffness [5]. Furthermore, the impact velocity intentionally was kept low (1 m/s) to minimise load oscillations, kinetic energy involved in tossing away the broken specimen and inertia effects that disturb the linear relation between load and K_I. As mentioned in the introduction, limiting the impact velocity is not contradictory to the aims of this research.

RESULTS

Microstructure Characterisation

The structure resulting from the various heat treatments is microscopically examined and typical micrographs are shown in Figure 3.

After the 1100-2-s treatment the martensite between the eutectic carbides is replaced by retained austenite (*cf.* Figure 1). The matrix consists of a mixture of retained austenite and relatively large needle-like secondary carbides. Austenitising for 4 instead of 2 hours (*i.e.* treatment 1100-4-s) results in a lower density of secondary carbides. The morphology of the eutectic carbides might be slightly more rounded, but this is difficult to quantify exactly. Heat treatment 1100-2-w (water quenching instead of a salt bath) resulted in the same structure as treatment 1100-2-s and is therefore not shown. Finally, lowering the austenitising temperature (*i.e.* treatment 1040-2-s) leads to martensite, both between the eutectic carbides and in the matrix. The matrix now contains an increased number of more rounded secondary carbides.



1040-2-s

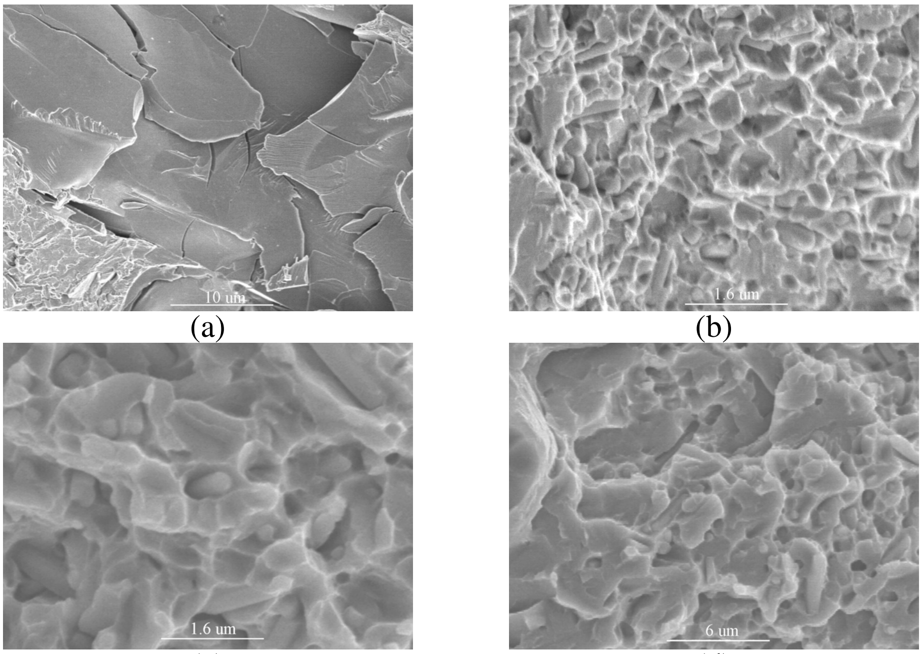
Figure 3: Micrographs of the eutectic region (left) and the matrix region (right) after different heat treatments

Drop Weight Tests and Fracture Analysis

In Table 3 an overview is given of the drop-weight test results. A 95% reliability interval, calculated according to the student-t test, is also indicated.

TABLE 3: Results of drop-weight tests for the different heat treatments

Heat treatment	No of tests	K_{Ic} [MPa√m]	E_i [kJ/m^2]	E_f [kJ/m^2]
as-cast	7	28.7 ± 0.9	5.0 ± 0.4	8.4 ± 1.0
1100-2-s	4	25.4 ± 3.6	4.9 ± 1.1	9.8 ± 1.0
1100-4-s	3	26.8 ± 3.9	5.0 ± 1.9	10.1 ± 0.4
1100-2-w	4	25.2 ± 3.1	5.0 ± 1.1	10.4 ± 2.3
1040-2-s	4	26.2 ± 1.8	4.5 ± 0.3	7.5 ± 1.9



(a) (b) (c) (d)

Figure 4: Typical fracture surfaces of (a) eutectic carbides, (b) and (c) matrix material subjected to heat treatments 1040-2-s and 1100-2-w resp., and (d) matrix material without secondary carbides

The results do not indicate significant differences in K_{Ic} and E_i values between the as-cast and the various heat-treated conditions. However an increase is found in the total fracture energy, E_f, for the heat treatments with an austenitising temperature of 1100 °C.

Observation of the fracture surfaces using a scanning electron microscope (SEM) reveals a larger fraction of eutectic carbides than is actually present in the material. The fracture surface can be divided into three types:

- The eutectic chromium carbides show cleavage fracture (Figure 4a).

- In the areas in the matrix containing secondary carbides dimples are present indicating ductile fracture (Figures 4b and 4c);
- Fracture of a less obvious nature in parts of the matrix close to the eutectic carbides which contain no secondary carbides (Figure 4d).

DISCUSSION

The drop weight results indicate that the different heat treatments only have an effect on the total fracture energy E_f, while the initiation values K_{Ic} and E_i remain unaffected. The difference between E_i and E_f corresponds to the energy needed to propagate the crack through the specimen. Apparently heat treatments are capable of affecting this growth process.

Note that both K_{Ic} and E_i are determined at maximum load. From the load-displacement curve shown in Figure 5 it may be concluded that the overall specimen behaviour is elastic. Therefore in this case K_{Ic} and E_i can be considered equivalent quantities, which explains their similar response to heat treatments.

It could be argued that crack initiation in this composite material is dominated by the presence of the brittle chromium carbides. The fact that it is found that the fracture path is mainly through and along the carbides supports this hypothesis. However, the crack is forced to cross the matrix when growing from one carbide to another. In this way, if a heat treatment changes the mechanical properties of the matrix, crack propagation is affected. Additional evidence for this is provided by rolling experiments performed previously [6] where carbides were broken by plastic deformation leading to higher E_f values but not to higher K_{Ic} values.

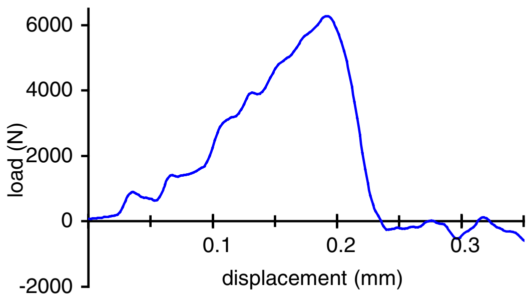


Figure 5: Typical load-displacement curve showing overall elastic behaviour of the specimen

The fracture resistance of the matrix most likely depends on:

- the relative amounts of martensite and retained austenite. Martensite, which is only present after the 1040-2-s treatment, probably lowers fracture resistance, while austenite enhances it.
- the size and interspacing of the secondary carbides. The larger secondary carbide formed during austenitising at 1100 °C have a larger interspacing than those formed at 1040 °C (Figures 4b and 4c) and also have a lower volume fraction. These factors can be shown to increase fracture resis-

tance, *e.g.* using the model of Rice and Johnson [7].

These factors are believed to explain the observed effects of heat treatment on the total fracture energy E_f. Note that since only a single heat of iron is considered, no information is obtained on the role of the volume fraction of eutectic carbides on fracture behaviour.

In the absence of secondary carbides the fracture no longer shows real dimples (Figure 4d). Perhaps this type of fracture can be associated with quasi-cleavage: a mixture of ductile and brittle fracture. However it is not clear whether this mode affects the overall fracture behaviour.

Considering the small dimensions of the specimens residual stresses are not expected on a macro level. However, since heat treatments 1100-2-s and 1100-2-w lead to identical results, there apparently is also no effect on a micro scale, *e.g.* as a result of a thermal mismatch between carbides and matrix.

In view of these results the question could be raised whether only the static properties of white cast iron are relevant to maintain mechanical integrity or if one should also consider (low cycle) fatigue behaviour.

CONCLUSIONS

From this investigation on high-chromium white cast iron it is concluded that

1. heat treatments affect crack propagation, but not crack initiation;
2. fracture toughness K_{Ic} and initiation energy E_i yield equivalent results;
3. the eutectic chromium carbides dominate the initiation of fracture;
4. fracture resistance is enhanced by avoiding martensite and/or aiming at a low volume fraction of secondary carbides with a large interspacing;
5. water quenching does not lead to residual stresses on a micro scale that significantly affect fracture behaviour.

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