

EFFECT OF SPRAY FORMING ON THE FRACTURE PROPERTIES OF HIGH-CHROMIUM WHITE IRON

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Abstract

The application of high chromium white iron for wear resistant purposes is often limited by its brittle behaviour, caused by the coarse network of chromium carbides present in conventionally cast iron. In this work the fracture properties are investigated of white iron produced by spray forming, an alternative production route yielding a much finer structure. Different heat treatment conditions are considered. The energies required for crack initiation and propagation and the fracture toughness are determined by performing low-velocity tests with an instrumented drop-weight impact tower using Charpy-like specimens with a sharp notch. It is found that spray-formed iron has favourable initiation properties as long as it is not heat treated. However, a drastic deterioration of the fracture properties material is found after applying a de-stabilising heat treatment. As a spin off, it is found that the properties of conventionally cast iron can be improved considerably by performing a high-temperature heat treatment.

Introduction

Hypo-eutectic high-chromium white cast irons is a composite material containing a substantial volume fraction of eutectic chromium carbides embedded in what could be described as a high-alloy steel matrix. The eutectic carbides provide the material with an excellent wear resistance, but due to their brittleness the fracture toughness of the material is only limited.

In conventionally cast material the chromium carbides form a relatively coarse network. The development of this carbide network is inherently linked to the conventional casting technique. It is thought that this network morphology is a major reason for the poor fracture properties, see Tabrett *et al.* [1]. It has been attempted to increase the material toughness by modifying the microstructure through alloying or through heat treatments, *e.g.* Janssen *et al.* [2]. Such attempts have only shown limited success, mainly because the eutectic carbide network is not significantly affected. However, by using an alternative production route for high chromium white cast iron, the so-called spray forming technique,

the carbides become more finely distributed and more globular. Preliminary research indicates that this production technique may lead to a drastic improvement of both the fracture toughness and also of the wear resistance, *e.g.* Hanlon *et al.* [3, 4].

The objective of this research is to assess and explain the effects on fracture properties that are brought about by these drastic changes in microstructure. Primarily these changes refer to the morphology of the chromium carbides. However, it turns out that the matrix structure is also significantly affected by spray forming.

Experimental

Material and Production

In this work hypo-eutectic high chromium white irons are considered that are produced by conventional sand casting and by spray forming. By conventional sand casting ingots are produced with dimensions $250 \times (80-89) \times 125$ mm. Table 1 shows the chemical composition as determined afterwards. The volume fraction of eutectic carbides is estimated to be in the range of 14 - 17 vol.%.

TABLE 1. Composition of the white cast iron [wt. %].

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

Spray forming is performed by remelting part of the conventionally-cast white iron. Previous research showed that the composition is not significantly affected during the spray forming [3, 4], so a good comparison of the properties is possible. In figure 1 three different stages are shown of the spray forming process. A gas flow containing small, initially liquid droplets of white iron (coming from the upper left corner in the figures) hits a rotating substrate (bottom). Doing so a billet is formed in the height direction in the course of a few minutes. The ultimate dimensions of the billet are $\text{Ø}140 \times 160$ mm.



FIGURE 1. Three subsequent stages during spray forming of the billet.

The ingots of the material after conventional sand casting shows the usual columnar macrostructure near the surface and equi-axed macrostructure in the centre. All specimens for subsequent tests were taken from the equi-axed zone. Less than 1 vol.% of pores are found to be present, all smaller than 20 μm in size. Figure 2a shows the microstructure of the material. The eutectic carbides can be recognised as the white plate-shaped phases. The white phases adjacent to the carbides are ferrite and retained austenite. Martensite was found between the eutectic carbides (not visible). The dark parts in the matrix consist of pearlite.

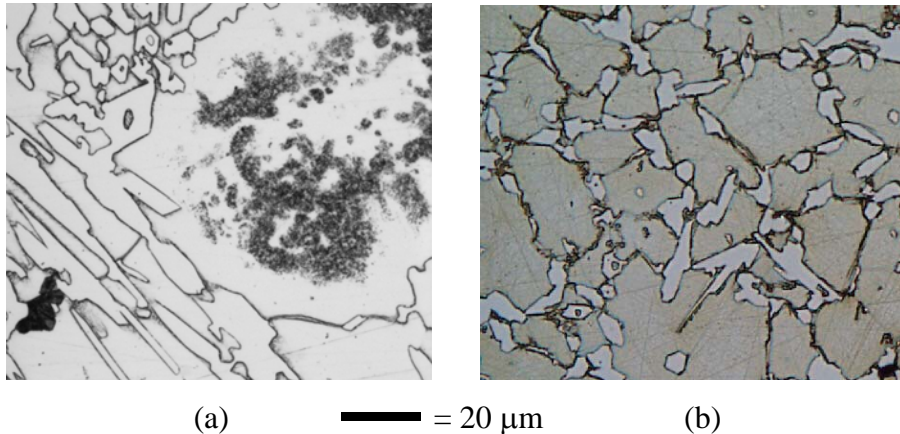
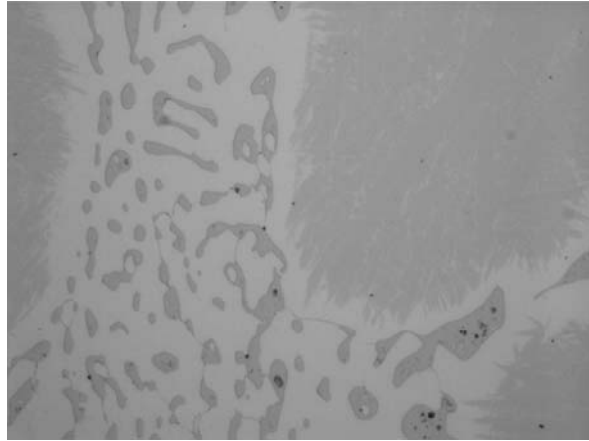


FIGURE 2. Microstructures of (a) conventionally cast and (b) spray-formed white iron.

The investigated billet of spray-formed material shows both some macroporosity and microporosity, but otherwise has a very homogeneous structure. In relation to this it should be noted that there was no opportunity to optimise the conditions for the spray forming process. From the micrograph in figure 2b it can be seen that the material has a considerably finer eutectic carbide structure (light grey). Furthermore, the matrix now consist of austenite (dark grey), with only very small amounts of martensite (not visible) close to the eutectic carbides. It is believed that this matrix structure is the result of the high cooling rate occurring in the spray forming process after solidification. This leaves insufficient time for secondary carbides to precipitate at lower temperatures, resulting in a high alloy content metastable austenite.

Heat Treatments

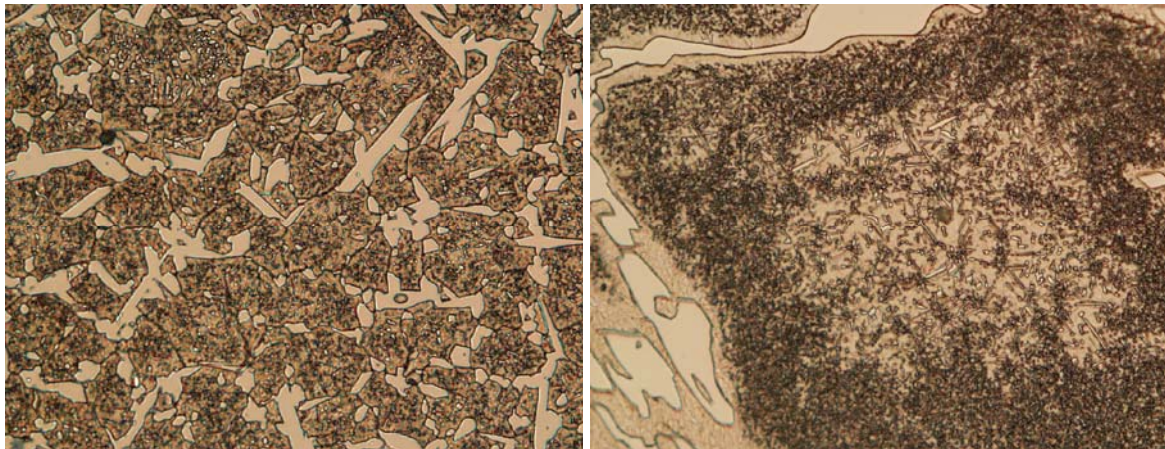
Preceding the fracture tests some heat treatments were performed with the purpose of creating more comparable matrix structures in the materials made along the two production routes. Conventional material is annealed at high temperature (7 hours at 1180 $^{\circ}\text{C}$), causing the secondary carbides to dissolve, followed by quenching. The latter step prevents the secondary carbides to precipitate as much as possible. The result is an austenitic matrix comparable with the as-spray-formed material, see the micrograph in figure 3, enabling the effect of the eutectic carbide morphology to be assessed in isolation.



————— = 50 μm

FIGURE 3. Conventionally cast white iron with an austenitic matrix obtained after high temperature annealing followed by quenching.

Furthermore, both the conventional and the spray-formed material are subjected to a so-called de-stabilising heat treatment, which is commonly applied to conventionally cast white iron before actual use. The treatment consists of annealing at 950 °C for 7 hours followed by furnace cooling. Secondary carbides get ample opportunity to precipitate, depriving the austenite of carbon and chromium and so leading to a martensitic matrix, see figure 4.



(a) ————— = 50 μm (b)

FIGURE 4. A martensitic matrix containing secondary carbides obtained after a de-stabilising heat treatment in (a) spray-formed and (b) conventionally cast white iron.

Drop Weight Tests

The fracture properties are determined with an instrumented drop-weight impact tower. A Charpy-like specimen (10×10×55 mm) is used in which, by electric discharge machining

(EDM), a 2 mm deep notch is introduced with a tip radius of 0.05 mm. The test consists of loading the specimen in 3-point bending by dropping the weight from a small height, leading to a relatively low impact velocity of 1 m/s.

Load versus time data are recorded and converted afterwards to load versus displacement data. Due to the relatively stiff and brittle nature of the white irons it was necessary to correct the calculated displacements for the elastic compression of the tup during loading. This was done by subtracting the load divided by the tup stiffness, see Janssen *et al.* [6].

Subsequently, the energy at crack initiation, E_i , and the total fracture energy, E_f , are calculated by integration of the load-displacement data, where initiation is assumed to occur at maximum load in this predominantly elastic material. The calculated energies are divided by the net section area (approximately 80 mm²) to account for small dimensional differences. Although these energy values will be geometry dependent, they do give qualitative information.

Additionally, using the measured maximum load, the plane-strain fracture toughness, K_{Ic} , is calculated using the expression given in ASTM standard E399 [5] 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 identical results, [6].

Results

The results of the drop weight tests on the conventional and the spray-formed material, each in two different heat treatment conditions, are summarised in Table 1. Each value, the average of 4 tests, is followed by the 95% reliability interval according to the student-t test. The difference between the initiation and total fracture energy is also included in the table and designated the crack propagation energy, E_p .

TABLE 2. Results of drop-weight impact tests.

Heat treatment	Conventionally cast iron		Spray-formed iron	
	1180 °C / 7 h quenching	950 °C / 7 h slow cooling	as spray formed	950 °C / 7 h slow cooling
Initiation energy E_i [kJ/m ²]	6.2 ± 1.2	4.9 ± 0.4	6.3 ± 0.6	3.9 ± 0.4
Propagation energy E_p [kJ/m ²]	10.5 ± 3.9	3.1 ± 0.3	1.5 ± 0.1	1.0 ± 0.3
Fracture energy E_f [kJ/m ²]	16.7 ± 4.5	7.9 ± 0.7	7.9 ± 0.6	4.9 ± 0.3
Fracture toughness K_{Ic} [MPa√m]	27.1 ± 6.0	29.3 ± 1.7	27.9 ± 2.0	21.0 ± 2.2

Visual observation reveals that the fracture surfaces of the spray-formed specimens are considerably smoother than those of the conventional material. Furthermore, the materials with an austenitic matrix, *i.e.* the as-spray-formed material and the conventional material after an 1180° treatment, exhibit a slightly rougher surface than their martensitic counterparts. In the latter material there even was slant crack growth, *i.e.* the nominal crack plane clearly deviated from the notch plane.

Discussion

Conventionally cast white iron

The results for the conventional material give some new viewpoints on the relation between fracture properties and microstructure in this relatively coarse material. Therefore these will be discussed first. For a complete interpretation of the results, table 3 gives some previously obtained drop weight test data for conventionally cast white iron.

TABLE 3. Some previously obtained results for conventionally cast iron [2].

Heat treatment	as-cast	1040 °C / 2 h quenching	1100 °C / 4 h quenching
Initiation energy E_i [kJ/m ²]	5.0 ± 0.4	4.5 ± 0.3	5.0 ± 1.9
Propagation energy E_p [kJ/m ²]	3.4 ± 1.0	3.0 ± 1.6	5.1 ± 1.5
Fracture energy E_f [kJ/m ²]	8.4 ± 1.0	7.5 ± 1.9	10.1 ± 0.4
Fracture toughness K_{Ic} [MPa√m]	28.7 ± 0.9	26.2 ± 1.8	26.8 ± 3.9

First of all, the energy and toughness values after the 950° treatment are more or less comparable with those found previously both for the as-cast condition and for iron subjected to a heat treatment at 1040 °C. It should be realised that the microstructural differences between these materials only relate to the matrix and that the network of eutectic carbides formed during solidification is not affected by these heat treatments. This network is believed to determine fracture properties to a large extent. It has been observed for example that crack propagation preferentially takes place along the eutectic carbides [2].

The heat treatment at 1180 °C increases the initiation energy slightly and the propagation energy significantly, while the fracture toughness does not seem to be affected. In contrast with the material referred to above, the eutectic carbide network now has slightly dissolved, causing a decrease of the volume fraction and a rounding off of sharp corners (fig. 3). The crack is forced to propagate through a relatively larger amount of matrix material, while stress concentrations at the interface between carbides and matrix are less severe. Both aspects probably contribute to a higher energy required for crack propagation. Note that this tendency was already found after annealing at 1100 °C (see table 3).

Spray-formed white iron

As-spray-formed iron, *i.e.* without a heat treatment being applied, has a fracture toughness and an initiation energy comparable to conventional material after a 1180° heat treatment. The idea exists that this is due to the similar matrices of the two materials, *i.e.* austenite without secondary carbides. Apparently the very fine eutectic-carbide structure is not of major importance here. It should be noted that the 1180° heat treatment is not typical and that the initiation energy found for conventional white iron after this treatment is already relatively high. In spray-formed iron this high value is already obtained without a heat treatment.

Clearly, the energy for crack propagation in as-spray-formed iron is considerably lower than for conventional material. Figure 5 shows a cross section of a crack emanating from the notch tip, indicating that also in spray-formed iron the crack preferentially follows the eutectic carbides. Since the structure of this carbide network is much finer, there is no need for the crack to meander as much during its growth, requiring less energy and leading to the very smooth fracture surface.

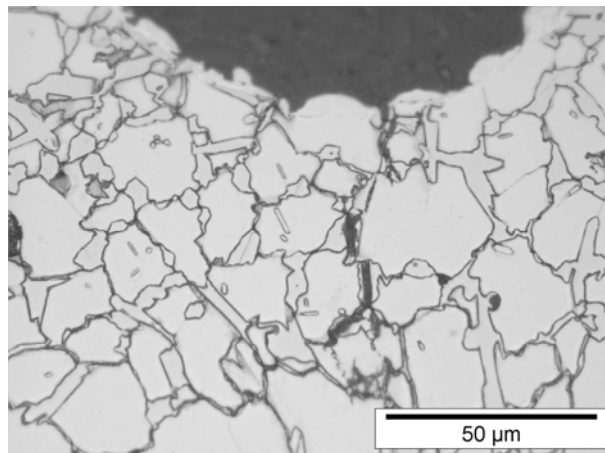


FIGURE 5. Crack propagation from the notch tip (above) in as-spray-formed iron.

The martensitic matrix with secondary carbides, obtained by applying the de-stabilising treatment at 950 °C, yields a markedly lower fracture toughness and initiation energy. This is in contrast with conventional iron after the same treatment. There is one major microstructural difference, however, which is the presence in the conventional iron of a band surrounding the eutectic carbides that is free from secondary carbides, see figure 4b. One can argue that during loading of the notched specimen the brittle carbides close to the notch tip already fail at a relatively early stage. The crack front then runs along the interfaces between eutectic carbides and the material immediately adjacent. The occurrence of crack initiation on a more macroscopic level consists of failure of this adjacent material. In spray-formed iron this is martensite containing secondary carbides, while in conventionally

cast material it probably consists of austenite, ferrite and/or martensite but in any case does not contain secondary carbides.

Crack propagation in the spray-formed iron after a 950° treatment requires even less energy and the fracture surface is even smoother. Probably the presence of a martensitic matrix containing secondary carbides plays a role in this also. Although it has not yet been experimentally verified, the smoother fracture surface suggests that relatively speaking the crack runs more through the matrix, indicating that less energy is required for this. For conventional material with a similar martensitic matrix, crack propagation is still hindered by the carbide-free band adjacent to the eutectic carbides.

Conclusions

- Conventionally cast high chromium white iron becomes tougher by annealing at 1180 °C than by heat treatments at lower temperatures. This applies for crack initiation but even to a larger extent for crack propagation.
- Spray-formed high chromium white iron without prior heat treatment has favourable crack-initiation properties, comparable to those of conventional material after a 1180° treatment. Crack growth, however, involves only a relatively small amount of energy.
- A de-stabilising heat treatment of spray-formed high chromium white iron, leading to a martensitic matrix containing secondary carbides, considerably deteriorates fracture initiation and propagation properties.

References

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