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DETERMINATION OF FRACTURE PROPERTIES OF HIGH-CHROMIUM WHITE CAST IRON

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ABSTRACT

High-chromium white cast iron essentially consists of chromium carbides embedded in a matrix of high alloy steel. The carbides yield an excellent wear resistance, but also bring about a very low fracture toughness. The work described here concerns the experimental determination of the dynamic fracture properties of hypo-eutectic cast iron and the specific experimental problems that arise from its brittleness. Research is performed on how a sufficiently discriminative and reproducible measure for the fracture toughness of the cast iron can be obtained using Charpy-like specimens in combination with an instrumented drop-weight impact tower. It is found that a compliant tup causes the least load oscillations and that at low impact velocities, the measured K_{Id} values correspond well with those measured with a static test. However energy measurements with a compliant tup are troublesome: the total fracture energy is overestimated due to the kinetic energy attained by the specimen. Furthermore, to calculate the energy at fracture initiation the elastic compression of the tup should be taken into account. The results seem not to be affected by using a notch instead of a crack.

KEYWORDS

High-chromium white cast iron, Fracture toughness, Charpy impact test, Instrumented drop-weight test, Fracture energy, Notch geometry, Brittle material

INTRODUCTION

High-chromium white cast iron is a composite material which in the hypo-eutectic form consists of a network of eutectic carbides embedded in a martensitic or austenitic matrix [1]. The material is primarily used because of the excellent wear resistance provided by the eutectic carbides. This type of white cast iron has poor fracture properties, both static and dynamic. This is mainly attributed to the network of eutectic carbides, providing a low energy route for cracks to extend.

The long-term objective of this research is to gain insight in the factors that determine the dynamic fracture properties of this material in order to be able to control these to a certain extent. In the first instance the research is aimed at the use of an instrumented drop-weight impact tower using Charpy-like specimens as a discriminative, reproducible and easy technique for determining the low (dynamic) fracture toughness of high-chromium white cast iron.

In this paper experiments are described on a hypo-eutectic high-chromium white cast iron. The development is outlined of a drop-weight test suitable for this material, with an emphasis on the experimental obstacles and the considerations which led to the final set-up.

MATERIAL

Table 1 summarizes the approximate chemical composition of the high-chromium white cast iron investigated. This composition represents a hypo-eutectic alloy. The material was cast in ingots of which the dimensions, i.e. length × width × height, are 250 × (80-89) × 125 mm. Using electric discharge machining, slabs were taken from the middle of these ingots normal to the length direction with a thickness of 10 mm. The macrostructure in these slabs depends on the distance to the ingot surface. Since solidification starts at this surface a columnar structure is present in the outer region of the slab with an orientation normal to the surface. In the center no obvious orientation is visible, a structure known as equi-axed. All specimens are taken from the center part of the ingot.

TABLE 1
CHEMICAL COMPOSITION OF THE WHITE CAST IRON [WEIGHT %]

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

Figure 1 shows the as-cast microstructure of the material as it is tested. The white phases are the eutectic carbides. In-between the carbides martensite is found, while in the remaining matrix pearlite (black), ferrite and retained austenite are present.

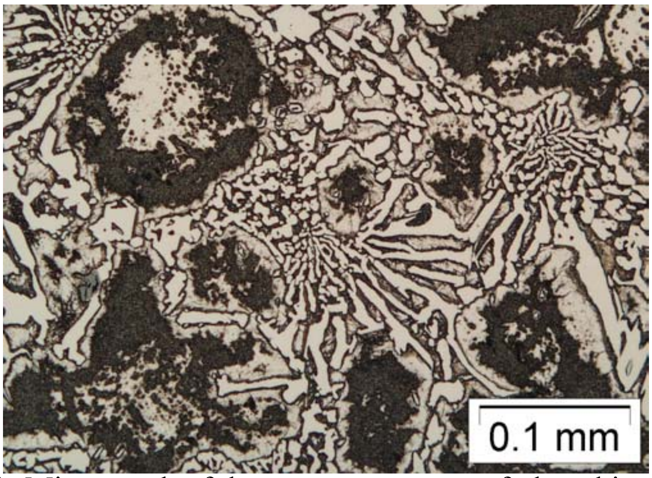

Figure 1: Micrograph of the as-cast structure of the white cast iron

EXPERIMENTAL SET-UP

The static fracture properties of a material with the brittleness of high-chromium white cast iron can be obtained by measuring the plane strain fracture toughness, K_{Ic} according to ASTM E399 [2]. This well-defined test method does, however, involve the costly and time-consuming preparation of suitable specimens, including the introduction of pre-fatigue cracks. To determine dynamic properties the standardized Charpy impact test [3] is available, which only uses a notched bar of 10×10×55 mm dynamically loaded in 3-point bending and therefore is much less expensive and faster to perform. However, from a fracture mechanics point of view, the standard Charpy test has a number of disadvantages.

1. For materials that exhibit a distinct amount of plastic deformation a plane strain condition at the notch tip is not guaranteed. This, however, will not be a problem for the white cast iron considered here, since plasticity is limited.
2. In the standard Charpy test only the total energy needed to fracture the specimen is determined. Therefore no information about crack initiation is obtained. This can be overcome by using an instrumented test set-up capable of monitoring the load.
4. The effect of the loading rate cannot be investigated in a pendulum set-up. However, a drop-weight test set-up does provide this versatility.

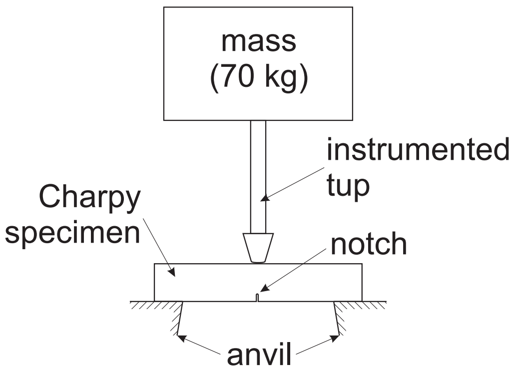

Figure 2: Set-up of instrumented drop-weight impact test

These considerations led to the use of an instrumented drop-weight impact tower for performing the test (see Figure 2). It consists of a mass of approximately 70 kg that loads the specimen by dropping it from a certain height. The load is transferred to the specimen by means of a tup and is digitally monitored as a function of time through a set of strain gauges mounted on the tup.

The dynamic fracture toughness, K_{Id}, is derived from the load at which crack extension initiates. For the brittle cast iron this is assumed to be the maximum load, P_{max}. Thus, from [4],

$$K_{Id} = \frac{P_{max} S}{B W^{3/2}} \cdot \frac{3\sqrt{\frac{a}{W}}\left[1.99 - \frac{a}{W}\left(1 - \frac{a}{W}\right)\left\{2.15 - 3.93\left(\frac{a}{W}\right) + 2.7\left(\frac{a}{W}\right)^2\right\}\right]}{2\left(1 + 2\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)^{3/2}}, \quad (1)$$

where S = specimen span,
B = specimen thickness,
W = specimen height,
a = notch length.

In order to calculate energy values, the load versus time record is converted to load versus displacement data, a conversion which is based on the velocity during the test. In turn this velocity is calculated using the initial impact velocity and by considering the forces acting on the drop weight, i.e. gravity and the specimen load. Note that for the brittle material tested here and the relatively high impact energy of the drop weight, the velocity during the test will typically only drop slightly below the initial velocity.

Two energy values are assessed: the energy needed to initiate crack growth, E_i, and the total energy to fracture the specimen, E_f. These are calculated by integrating the area under the load-displacement curve until maximum force and under the whole curve respectively. To account for small differences in specimen dimensions the energies are divided by the area of the net section.

EXPERIMENTS TO EVALUATE IMPACT TEST

There are a number of experimental aspects that need to be clarified before reliable impact tests on the white cast iron can be performed:
1. The energy involved in the fracture of a material as brittle as white cast iron is very low. The question arises whether the test set-up is capable of determining such low values accurately.
2. Impact testing brittle material involves a relatively short time to fracture. Immediately after impact the load signal will inevitably oscillate. Also because plasticity in the specimen is only limited, it will take some time before these are damped. This can possibly mask crack initiation, thereby disabling the measurement of K_{Id} en E_i.
3. In standard Charpy specimens a V-notch (0.25 mm tip radius) or a U-notch (1 mm tip radius) is introduced. The workmanship with which this notch is machined will vary and it is uncertain whether the tip radius is small enough to simulate a natural crack. Introducing a fatigue crack would be preferable, but this is cumbersome in the white cast iron considered here and also contrary to the objective in this research, i.e. the development of an easy test method.

These aspects are assessed by performing the tests described below.

Tup Capacity

Tests are performed at a velocity of 3.4 m/s using a small-capacity tup (15 kN) and a high-capacity tup (220 kN). Specimens were prepared with a notch with 0.2 mm tip radius (see below). The resulting load-displacement curves, shown in Figure 3, differ considerably. The high-capacity tup causes the load to increase more rapidly and to a considerably higher value, resulting in a displacement at maximum force that is much smaller. Furthermore, the load oscillations are significantly larger and take longer to damp.

Table 2 summarizes the numerical results. The fracture toughness and the total fracture energy are strongly affected by the tup used. The initiation energy seems unaffected.

TABLE 2
RESULTS OBTAINED AT 3.4 M/S WITH TUPS WITH DIFFERENT LOAD CAPACITIES

Tup capacity [kN]	K_{Id} [MPa√m]	E_i [kJ/m^2]	E_f [kJ/m^2]
15	30.6	4.6	12.1
220	62.8	4.6	5.8

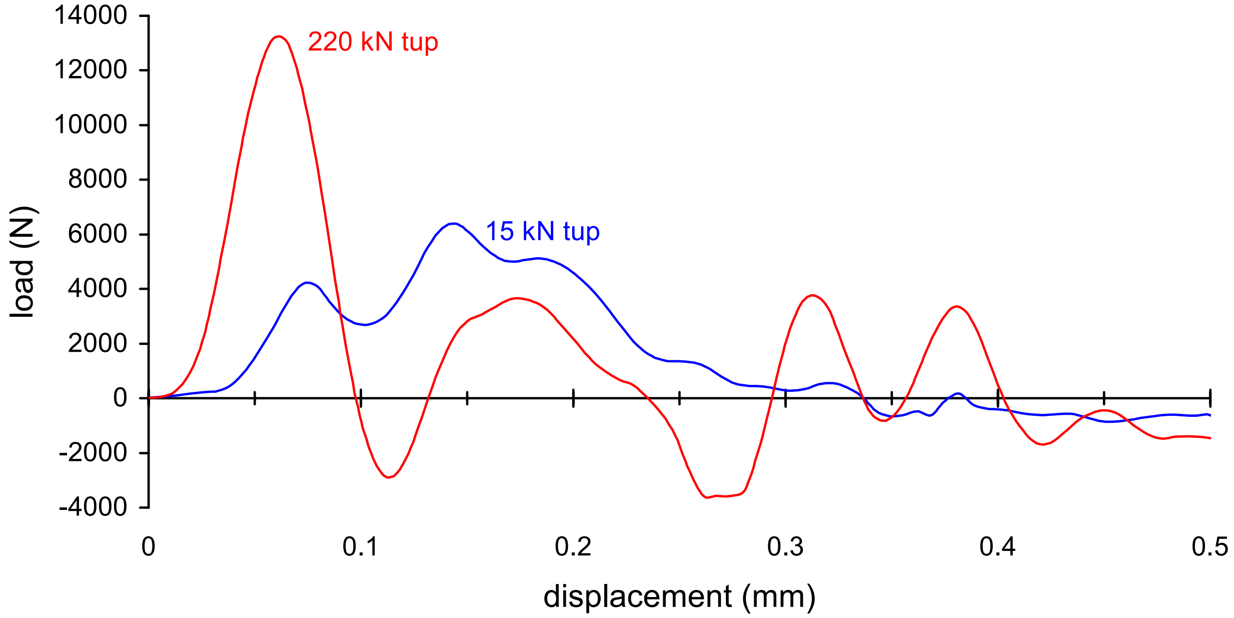

Figure 3: Load-displacement curves at an impact velocity of 3.4 m/s using different tups

Impact velocity

Using the 15 kN tup, tests are performed at different impact velocities, i.e. 1, 2, 3 and 5 m/s on specimens with a notch with 0.2 mm tip radius (see below). Furthermore, some static tests are performed using an electro-mechanical tensile machine. Figure 4 shows two examples of load-displacement curves obtained at 1, 2 and 5 m/s respectively. The values for the maximum load are affected by the velocity. Only at 1 m/s the oscillations are damped well before the maximum load is reached.

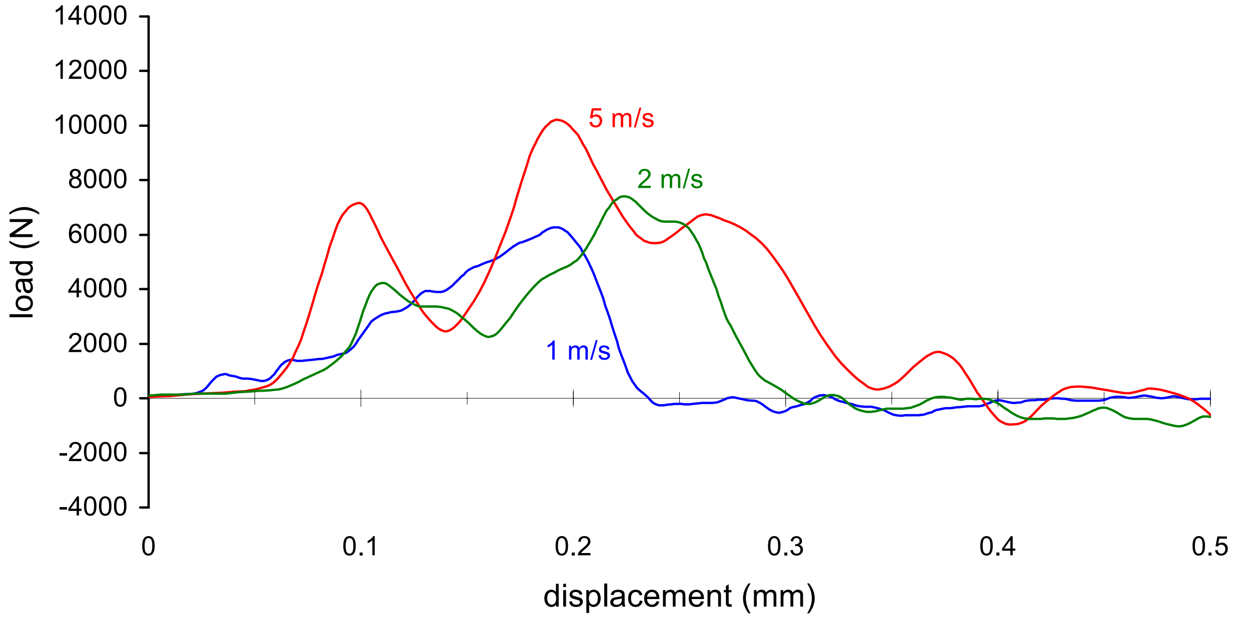

Figure 4: Load-displacement curves at different impact velocities using 15 kN tup

In Table 3 the average fracture toughness and energy values are summarized, including the number of tests and the 95% reliability interval. All measured values tend to increase with impact velocity.

TABLE 3

RESULTS OBTAINED AT DIFFERENT IMPACT VELOCITIES WITH 15 KN TUP

Velocity [m/s]	N° of tests	K_{Id} [MPa√m]	E_i [kJ/m^2]	E_f [kJ/m^2]
static	2	25± 5	7.9±2.4	–*
1	2	27±26	6.1±1.2	7.5±0.1
2	2	31± 9	7.1±1.0	10.1±6.7
3	1	29	8.3	11.4
5	1	45	9.3	–**

* specimen not completely broken
** measurement interrupted shortly after fracture

Notch geometry
Specimens are prepared with different notch geometries. Notches are introduced by electric discharge machining (EDM) using wire diameters of 0.3 mm and 0.15 mm, thus creating notch tip radii of 0.2 and 0.1 mm. Furthermore, pre-fatigue cracks are introduced in some specimens. Both static tests are performed as well as impact tests with the 15 kN tup at a velocity of 1 m/s. This velocity is chosen to be sure that K_{Id} and E_i can be measured. In Table 4 averaged results are summarized, including the number of tests and the 95% reliability interval. From these results no obvious effect of the notch geometry can be deduced.

TABLE 4
RESULTS OBTAINED FOR DIFFERENT NOTCH GEOMETRIES

Notch	N° of tests	K_{Id} [MPa√m]	E_i [kJ/m^2]	E_f [kJ/m^2]
Static test (1 μm/s)				
crack	2	22±21	6.2±5.1	–*
r = 0.1 mm	2	21± 8	6.8±3.4	–*
r = 0.2 mm	2	25± 5	7.9±2.4	–*
Impact test at 1 m/s using 15 kN tup				
crack	3	27.0±9	6.0±3.3	7.7±3.5
r = 0.1 mm	7	28.2±0.9	6.0±0.5	8.3±1.4
r = 0.2 mm	2	27.0±26	6.1±1.2	7.5±0.1

* specimen not completely broken

DISCUSSION

Tup Stiffness
The effect of the tup capacity on the load-displacement curves (Fig. 3) can be understood by considering the stiffness of the tups. For the 15 kN tup the stiffness is calculated to be 200 N/μm, while the 220 kN tup is estimated to have a stiffness that is at least 5 times higher. During loading the tups will become shorter. For example the 15 kN tup will be more than 30 μm shorter at maximum load. This means that the actual specimen displacement is the measured displacement minus the compression of the tup. Thus the actual loading rate applied to the specimen is lower for the 15 kN tup than for the 220 kN tup. This is an explanation for the smaller load oscillations and the larger displacement at maximum load found for the 15 kN tup.

Obviously, the calculation of energy values should in principal be based on actual specimen displacements rather than measured values. The fact that in Table 2 the energies for crack initiation, E_i, are the same, is believed to be more of a coincidence. E_i is not only influenced by using incorrect displacements, but also by the impossibility to correctly determine the moment of crack initiation. Due to load oscillations the maximum force is no longer a good measure. This also makes it impossible to determine meaningful K_{Id} values. From Figure 4 it can be concluded that at velocities of 2 m/s and above no reliable K_{Id} and E_i values can be obtained.

The total energy E_f should in principle not be affected by compression of the tup or by load oscillations, since these are elastic phenomena. The area under the measured load-displacement curve is equal to that under the actual curve if it is determined over a period that starts before impact and ends when the load signal has permanently returned to zero. The reason is that at these instants the tup is not compressed and the measured load corresponds exactly to the actual load. The fact that Table 2 suggests a large effect of the tup stiffness on E_f is explained below.

Kinetic Energy
The energy transferred from the tup to the specimen is not only used to fracture the specimen, but also to accelerate it. A fair estimate of this kinetic energy can be made if one simply assumes that the load point, i.e. the contact point between tup and specimen, has a velocity equal to the impact velocity. At 3.4 m/s this amounts to 0.17 J. Divided by the net section area, this corresponds to 2.1 kJ/m^2, a value that cannot be neglected compared to the energies measured (see Table 2).

A correction for the kinetic energy attained by the specimen during impact would be feasible. However the elastic compression of the tup causes the load-point velocity to deviate from the nominal impact velocity. Initially, due to the rising load, the load-point velocity is somewhat lower. From the moment the crack initiates and the load drops, the load-point velocity increases and rises above the nominal impact velocity. These velocity changes depend on the tup stiffness. For a stiff tup the kinetic energy the specimen ultimately attains will be close to the estimate given above, whereas for a compliant tup this value can be considerably higher. To quantify this, extensive calculations would be required, but it is believed that this effect does explain the large difference found in E_f for the two tups.

From Table 3 it can be seen that E_f increases with impact velocity. This can also be explained by the kinetic energy that the specimen ultimately acquires due to impact. It must be noted that it is impossible to establish whether in this case the material behavior is also partly responsible.

Notch geometry
The results in Table 4 indicate that an EDM notch with a tip radius of 0.2 mm simulates a real crack quite well. From Figure 1 it can be seen that the coarseness of the carbide structure of the cast iron is of the same order as this tip radius. It could be argued that in all cases there will be pores or crack-like defects close to the notch tip that become critical at approximately the same load level as a sharp pre-fatigue crack would.

Preferred Test Set-up
Because of the smaller oscillations, it seems favorable to use a low-stiffness tup. However, to obtain a more accurate value for the specimen displacement and thus for E_i, a correction is necessary. This can be done by subtracting the compression of the tup from the measured displacement. An estimate for the tup compression, discarding possible dynamic effects, follows from the load divided by the tup stiffness.

For the measurement of the total fracture energy, E_f, a high-stiffness tup is advantageous since then the kinetic energy of the specimen is only slightly enhanced after fracture. However at low velocity, e.g. 1 m/s, this effect is expected to be small. For instance the kinetic energy before fracture at 1 m/s is only 0.015 J (corresponding to 0.18 kJ/m^2). When measurements are performed at a single (low) impact velocity and they only have a comparative nature, a low-stiffness tup could be acceptable.

Clearly, to obtain K_{Id} or E_i for the cast iron, measuring at low velocities is essential. It is uncertain whether such values are also representative for the behavior of the cast iron at higher velocities. Measuring at high velocity would require alternative techniques to detect the moment of crack initiation and to account for load oscillations.

CONCLUSIONS

The following conclusions are drawn with respect to obtaining the fracture properties of high-chromium white cast iron using an instrumented drop-weight impact tower with Charpy-like specimens:
1. By using a compliant tup, the loading rate and the load oscillations are decreased, but the amount of kinetic energy transferred to the specimen is increased.
2. Values for K_{Id} or the energy involved in crack initiation, E_i, can only be measured at low velocity (≤ 1 m/s).
3. For a compliant tup E_i can only be accurately determined by accounting for compression of the tup.
4. The total energy, E_f, is strongly affected by the amount of kinetic energy transferred to the specimen.
5. The increase in E_f with impact velocity is attributed to an increase in kinetic energy that is ultimately transferred to the specimen.
6. An EDM notch with a tip radius of 0.1 or 0.2 mm yields the same results as a pre-fatigue crack.

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