Fracture behaviour of notched and un-notched powder metallurgical (P/M) green compacts

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In previous work by the authors, a simple method of introducing a sharp V-notch into green powder compacts without inducing any damage to the locality of the notch tip was forwarded [1]. In this work, extremely sharp notches were made by compacting powder around a razor blade rather than using the blade to cut notches, as is the general practice.

The present work employs single-edge V-notched beam (SEVNB) specimens prepared by this novel technique together with conventional 3-point bend specimens.

Distaloy AE Densmix powder, produced by Hoganäs AB, Sweden, was used to manufacture both types of specimen. The composition and physical properties of this iron powder mixture (provided by the manufacturer) are given in Table I. A polymer-based lubricant, whose composition is the proprietary knowledge of Hoganäs AB, is also present in the powder mixture at a level of 0.5 wt.%.

Specimens (32 mm in length and 12 mm in breadth) were compacted at room temperature using a pressure of 600 MPa, which resulted in a green density of 6.95 Mg m^{-3}. The height of the pressed specimens was controlled by varying the quantity of powder in the die. In the case of the SEVNB specimens, the bottom punch had been modified to accommodate a razor blade edge [1] and pressing was aimed at producing a notch depth of approximately one-quarter of the specimen height regardless of the compaction pressure. Fig. 1 shows a typical V-notch produced in the iron powder mixture compacts by the method referred to in the figure. Cross-sectioning was performed using electro-discharge machining (EDM) to ensure no mechanical damage and hence the microstructure, to some extent, has been obscured by corrosion products. However, it can still be seen that the notch is extremely sharp with a root radius in the order of 2–3 μm.

Specimens were tested in a symmetrical 3-point bending configuration (span between outer rollers of 16 mm) using crosshead speed of 0.5 mm $\min^{-1}$ and the failure stress calculated using Equation 1:

$$\sigma_{3\text{-point}} = \frac{3PL}{2t^2b} \qquad (1)$$

where P is the maximum recorded load, L is the distance between the outer support rollers, t is the specimen thickness, and b is the specimen width.

Initially, the behavior of conventional bend specimens was compared to that of SEVNB specimens. Conventional bend specimens were pressed to thicknesses of 6 and 4 mm whilst SEVNB specimens were pressed to thicknesses of 8 and 5.34 mm. The notches in the SEVNB specimens were to a depth of a quarter of the total beam thickness, leaving the un-notched thicknesses in these specimens of 6 and 4 mm (the same thicknesses as the conventional bend specimens). Failure stress calculations were made for the notched specimens based on this reduced section thickness. The results of these strength tests are shown in Fig. 2 with each datum bar being derived from the average of six tests.

It can be seen from Fig. 2 that the presence of a notch has only a small influence on the calculated green strength. Nevertheless, it is evident that the SEVNB specimens are slightly stronger than the equivalent 3-point bend specimens (even when the error involved in these strength values is taken into account). This phenomenon can be accounted for by considering the stressed volume generated within each of the respective tests and applying a weakest-link statistical approach [2, 3]. In this case, differences in stressed volumes arise from differences in where the stress is generated. In the conventional, un-notched 3-point bend specimens tensile stresses are distributed over the volume of sample which is located above the neutral axis between the outer bending supports. However, in the SEVNB specimens, the presence of the notch concentrates the stress and reduces the volume over which it acts [4]. This results in higher strength values due to the decreased probability of the stress sampling a flaw (or in this case a pore) of critical size.

SEVNB tests were also performed with blunt notches. Notches were introduced into the specimens in the same manner as outlined in [1], but in this case the powders were compacted around an edge with a U-shaped profile. The resultant notches had radii in the order of 150 μm. Table II shows the results of strength tests performed on blunt notch iron powder mixture specimens pressed to an un-notched through thickness of 4 mm under a compaction pressure of 600 MPa.

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TABLE I Composition and physical properties of Distaloy AE powder

Chemical composition (excluding lubricant) (wt.%)	3.99 Ni, 1.53 Cu, 0.52 Mo (0.52 C admixed)
Size distribution	<22 μm = 10%, <55 μm = 50%, <106 μm = 90%
Apparent density (Mg m^{-3})	3.13
Tap density (Mg m^{-3})	4.01

TABLE II Results of 3-point bend tests performed on specimens containing blunt and sharp notches. The standard deviation is calculated from the results of six tests

Specimen	Green strength (MPa)	Standard deviation (MPa)
Blunt notch	13.08	±0.17
Sharp notch	13.71	±1.18

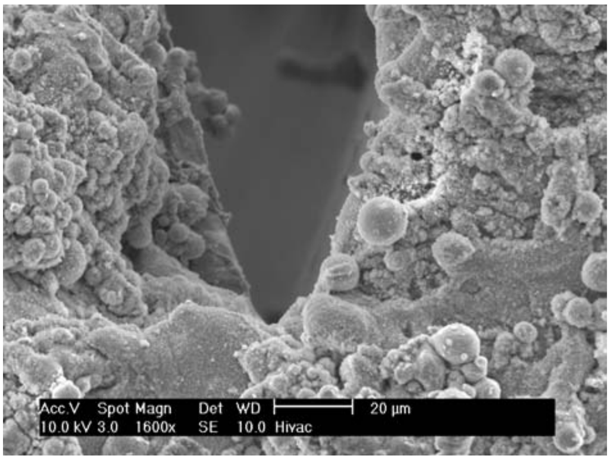

Figure 1 Electron photomicrograph of a cross-section through a typical notch generated in the iron powder mixture compact.

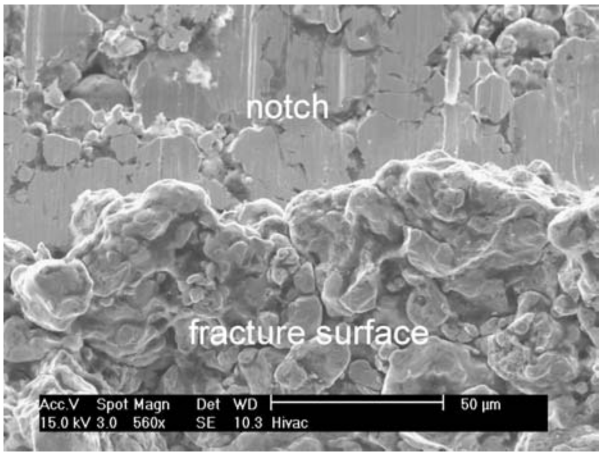

Figure 3 SEM image of the notch root region after testing a SEVNB specimen.

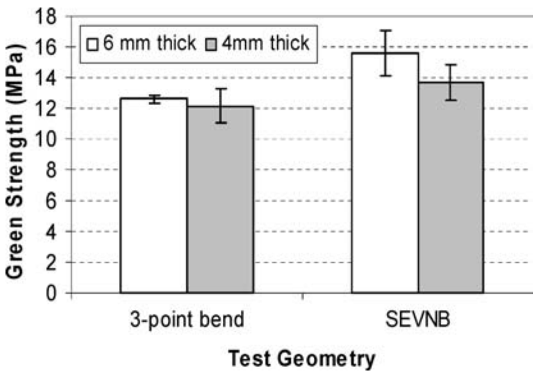

Figure 2 Results of green strength tests performed on conventional 3-point bend specimens and SEVNB specimens prepared by compacting powder around a razor blade.

Results from specimens of the same size and geometry, but with sharp notches, are also given in Table II for comparison.

From Table II it can be seen that the notch radius has no significant effect on the measured strength of the fracture toughness specimens. This lends further weight to the argument that the presence of notches in the green specimens does not affect the material property being measured: if true fracture toughness were being measured then a significant difference in the calculated values would be apparent

It is also interesting to note that the error (standard deviation) on the samples containing sharp notches is significantly larger than that on those employing blunt notches. This can, again, be related to the probability of the maximum stress sampling a pore of critical size at the notch root. In the samples where sharp notches are present, this probability is lessened (since the stress is more concentrated over a smaller volume) and the scatter is therefore increased. In the case of the blunt notches, the volume where stress is at is maximum is larger and there is a greater probability of sampling the critical pore size. Accordingly, the measured strength is seen to decrease slightly and the scatter in the data becomes smaller.

Visual examination of the fracture surfaces revealed them to be largely featureless with no striations (the presence of which may serve to indicate the point at which fracture initiated) being visible. Scanning electron microscopy of the region directly below the SEVNB notch root revealed only intergranular fracture along the interfaces where powder particles were once in contact. Fig. 3 is typical of the microstructure located directly beneath the notch tip and shows that crack propagation from the root of the notch has not occurred in a transgranular manner, but instead has followed a path around the powder particles in the immediate vicinity. The powder particles themselves are observed to be wholly intact reinforcing the assertion that crack growth has occurred through the interface between particles in intimate contact. Regions located several millimeters away from the notch root exhibit identical fractography which serves to further demonstrate that the fracture mechanism acting at the notch root is analogous to that occurring in the bulk of the specimen. Examination of the un-notched specimens, ruptured by pure bending, revealed the same mode of fracture.

These preliminary investigations suggest that the use of single-edge V-notch fracture specimens is ineffective in the direct measurement of the fracture toughness of green compacts formed from the iron powder mixture. In green materials such as these, it is unrealistic to expect that a notch, however sharp, will negate the influence of the large amount of porosity and weakly bonded particle–particle interfaces present in the microstructure and act as the singular source of crack propagation and growth. The notch tip will always have porosity either directly below it or touching it and consequently fracture is always likely to initiate from these sites and not from the notch tip. The sharpness of the notch is somewhat irrelevant since, along the entire notch length, a wide range of pore sizes are likely to be sampled. Once a crack is initiated at a pore, it will demonstrate "pop in" instability and propagate rapidly through the weak powder particle interfaces, whose primary source of strength is through particle asperity interlocking [5], causing complete sample failure.

The same failure mechanism can, with some justification, be extended to the type of fracture that occurs during conventional bend strength tests on green samples [6]. Open porosity at the surface opposite the bending fulcrum will be subject to tensile stress and as such behave in the same manner as porosity at a notch tip. The only difference is that the stressed volume in these specimens will be greater than in the notched specimens due to the notches acting as stress concentrators. This, in turn, leads to a greater likelihood of sampling any unusually large pores present, a corresponding decrease in measured strength and a decrease in scatter.

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