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Fracture of brittle multiphase materials by high energy water jets

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High energy water jets are established in processing brittle, inhomogeneous materials like rocks and concrete. Despite their wide field of application, the failure mechanisms of these materials, especially the influence of inclusions, are not well known. This work examines the influence of grain inclusions on the fracture behaviour of a multiphase brittle material exposed to high energy water jet processing. The behaviour of the specimens is detected by mass removal measurements, microscopical observations and the mercury penetration technique. It is found that the failure is based on microcrack growth due to hydrostatic pressure. The fracture mechanical behaviour of the reference material changes considerably with the addition of aggregates. The addition of grains leads to a reduction of the threshold tool energy for the start of mass removal. On the other hand, the presence of inclusions permits a more reduced and controlled removal progress. The interfaces between matrix and grains are the preferred locations for crack growth and also for crack branching. The inclusions act as crack arresters and crack branchers. In the case of cracks growing through the grains, a higher amount of fracture energy is absorbed and the fracture performance is weakened.

1. Introduction

For many years, high energy water jet units have been competing regarding machining performances. They are the state-of-the-art for machining plastics and deburring metals, and they are widely used for removing concrete and cutting and drilling rocks [1].

The jets, as tools for material removal, are generated in nozzles. Inside these nozzles potential energy of high pressurized flows is transformed into kinetic energy of fast moving jets. The energy density of these jets is comparable with that of laser beams. On the surface of the machined material a stagnation pressure profile is created after the jet has hit it. This profile enables the water to penetrate into cracks, flaws and pores. Inside these instabilities the water flow generates forces on walls and flanks which results in stresses. If these stresses exceed critical values the instabilities start to grow and the material fails. General contributions to these topics were made in previous studies [2–4]. However, all these investigations did not consider the influence of inclusions and interfaces which are found in multiphase and composite materials. The importance of inclusions in conventional failure and several erosion modes was shown, among others, in earlier work [5–8]. Certainly, the interfaces between inclusion grains and the matrix where they are embedded – the grain boundaries – have a significant influence also on the material removal process in the case of water jet machining. The objective of this work is to compare the behaviour of a plain homogeneous matrix material with respect to a multiphase material which contains the matrix as one of its phases, during their cutting with pressurized water. Also of interest is the influence of the interfaces between the matrix and the embedded inclusion grains on the erosion characteristics of the brittle multiphase materials.

2. Materials and experimental methods

2.1. Materials

Two different material groups are designed and investigated. In this work they are called "matrix" and "multiphase material". The matrix is a hardened mixture of water (w) and binding agent (b) in a ratio of w/b = 0.55. As the latter, a portland cement (PZ 35 F, DIN 1164)) was used. After mixing, this composition was cured and hardened for 28 days. The same procedure was followed for the multiphase material. In this case the mixture consisted of water (w), binding agent (b) and limestone grains (g). Fig. 1 shows the size distribution of the used inclusions. The relation between water and binder was changed depending on

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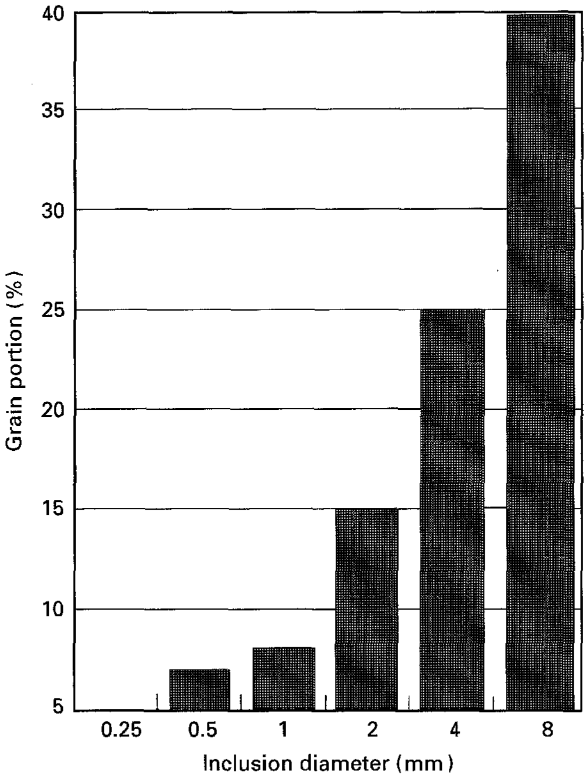

Figure 1 Grain size distribution of the used inclusions.

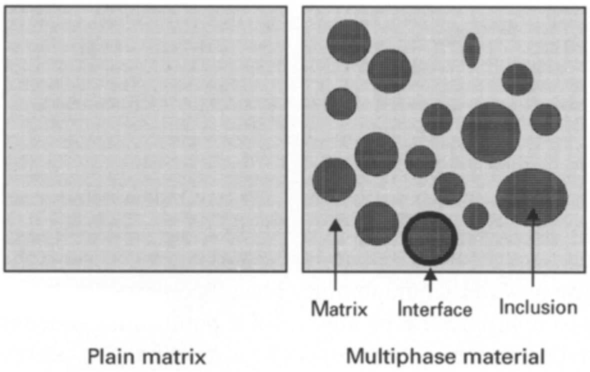

Figure 2 Structure of the plain matrix and the multiphase material.

the moisture absorbing capacity of the grain fractions. In Fig. 2 the general structures of both materials are exhibited.

2.2. Testing equipment and performance

The high energy water jet unit consists of a high pressure water pump (110 kW), hose system, nozzle holder, nozzle and rotating specimen fixturing table. The nozzle holder and specimens are located inside a closed plexiglass cell, so that it is possible to pick up the removed material and weigh it.

Non-visible structural changes inside the specimens are detected by a mercury penetration unit. Using the so called Washburn equation, one can assume a relation between the pressure which is necessary to transport mercury into the structure and the size of the transport routes (pore-crack network) [9]. The processes of preparation and handling are described in other work [9, 10]. Additionally, all samples and the removed material are observed using optical and scanning electron microscopy (SEM) microscopy. For SEM observations the particles are bonded on to aluminium specimen stubs and sputter-coated with gold.

3. Results and discussion

Fig. 3 shows the relation between jet energy and material mass removal. Some significant differences in the behaviour of the matrix and multiphase material, respectively, can be seen.

Firstly, the threshold energies of both mixtures differ from each other. The threshold energy at the point of intersection of the energy axis and the function describes the minimum energy amount for material destruction. It is found that the addition of inclusions reduces this parameter. From fracture mechanics is known that a certain amount of energy is necessary to widen a crack. This energy can be described indirectly by the material fracture toughness. Investigations by Wiedemeier [11], who found a linear relation between the stress intensity factor of different materials and their threshold water jet velocity (which is directly connected with the water jet energy), show the validity of this concept for the case of water jet processing. To explain this effect, mercury penetration measurements were carried out under different conditions. The mercury penetration measurements in Fig. 4 show that a certain amount of flaws are generated in the material due to grain addition. These flaws can be identified as interfaces between grains and matrix. In relation to Fig. 5, which shows the fracture mechanical background of the problem, one can deduce a reduced energy for crack growth if the water flow forces act on the interface between matrix and inclusion. One reason for it is the lower fracture toughness of the interfacial region. Moreover, a strong relation between flaw (crack) length and fracture stress is known from the fracture mechanics and this is also shown in Fig. 5. So the stress (which is connected with the water jet energy) for opening larger cracks, which are generated due to inclusion addition, is low compared with the stress which is neccesary to widen the smaller cracks in the plain matrix.

Based on these findings it could be concluded that the addition of inclusions to the plain matrix changes the fracture mechanical condition in such a way that a lower level of input energy is needed to introduce the destruction in the multiphase material than in the case of the plain matrix.

Secondly, Fig. 3 shows different mass removal dynamics for both materials. Whereas for the multiphase material the relation between jet energy and mass removal is linear with a steady progress, the matrix material shows a divergent behaviour. At an energy level of about 10 kJ the function shows an abrupt rise. It was observed, that the matrix specimens fail totally in this energy range. From the fracture surface shown in Fig. 3, one can deduce a brittle unrestrained fracture. Moreover, it can be seen that the roughness of the generated area increases with the

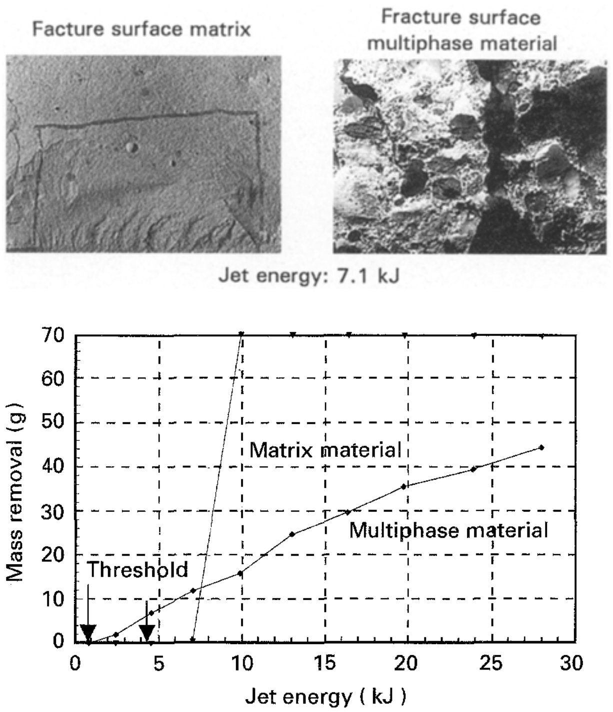

Figure 3 Relation between jet energy and material mass removal for the plain matrix and the multiphase material.

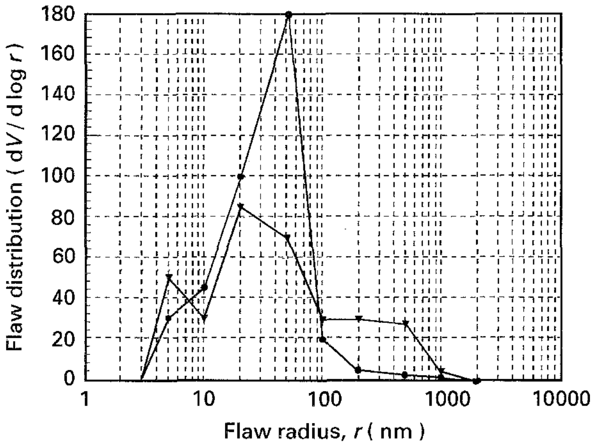

Figure 4 Flaw size distributions of the plain matrix (●) (without inclusions) and the multiphase material (▼) (with inclusions).

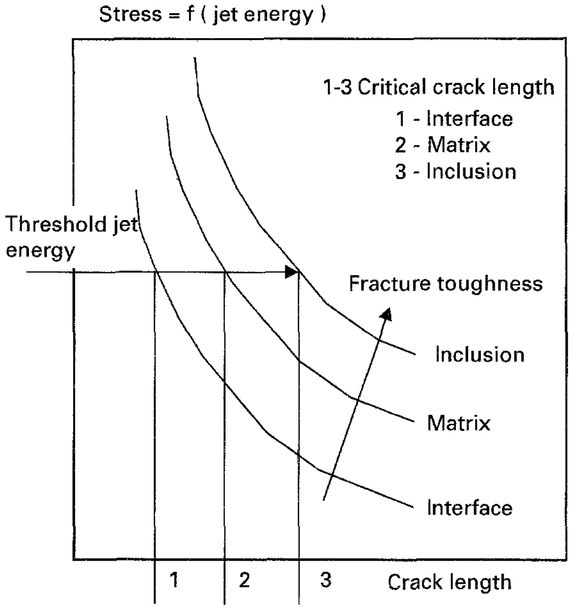

Figure 5 Fracture mechanical background of the different behaviours of the plain matrix and the multiphase material.

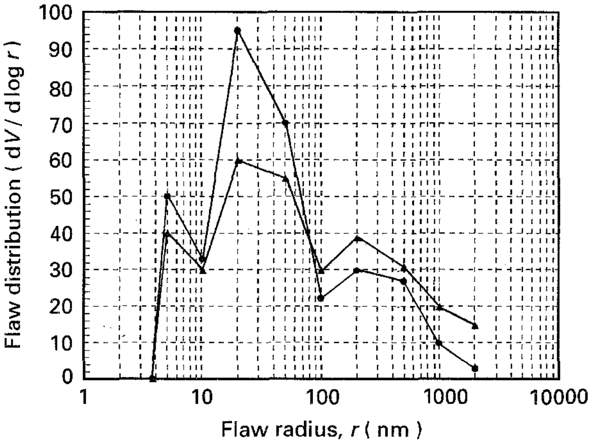

Figure 6 Flaw size distributions of the multiphase material without loading (●) and after loading (▲) by a 2.5 kJ water jet (mercury penetration measurements).

length of cracking. The reasons for this can be related to crack acceleration and secondary cracking as results of rise in supply of elastic energy. Similar effects have been observed on fractured cement pastes [12], but also on homogeneous brittle materials like glass [13]. In the present case, the crack propagation may be influenced by non-hydratized cement grains.

By adding inclusions the situation becomes different. A lot of small particles are removed out of the specimens and the fracture surface becomes extremely rough (Fig. 3). The particles are the result of a microcrack network and they illustrate that unrestrained cracks cannot be the source of failure. Fig. 6 shows mercury penetration measurements, which are carried out on loaded but undamaged parts of the specimens. One can observe an extensive microcrack network which is formed before the material fails. An association of these microcrack networks leads to a material removal on the next higher energetic level. No total destruction of a specimen was observed, only a controlled steady removal of material. So, in contrast to the plain matrix, in the multiphase material the crack growth has been interrupted due to events of energy dissipation. Some mechanisms of crack energy absorption can be crack arresting and crack branching, respectively, due to inclusions and crack growth through inclusion grains [14]. As Fig. 7 shows, as well as crack progress through inclusions, crack progress around inclusions (crack deflection), and crack arresting by inclusions took place. Fig. 8 exhibits the fracture around an inclusion grain. Here the crack is deflected by the grain and grows along the grain boundary, a process which is described in [15]. Fig. 9 is a SEM of a damaged grain. Probably the damage on the surface is the result of a striking crack which is arrested by the grain. Fig. 10 shows another example of crack branching by an inclusion grain. Here the inclusion is removed completely.

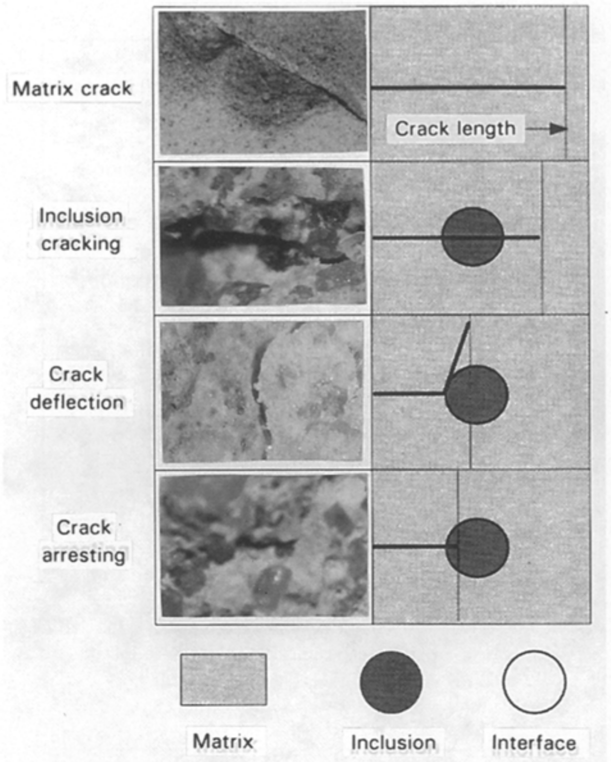

Figure 7 Mechanisms of crack energy absorption in the multiphase material: crack progress through the plain matrix (×20); crack progress through an inclusion (×11); crack progress around an inclusion (×11); crack arresting by an inclusion (×11). ▩ matrix; ● inclusion; ○ interface.

4. Conclusions

The conclusions from this investigation can be summarized as follows:

1. The addition of inclusions changes the structure and mechanical properties of the materials.
2. The interfaces between matrix and inclusions (grain boundaries) are preferred objects for attack by water jet forces because of their low mechanical properties.
3. The addition of inclusions leads to a reduction of the threshold destruction energy of the materials due to weakening by the generated interfaces.

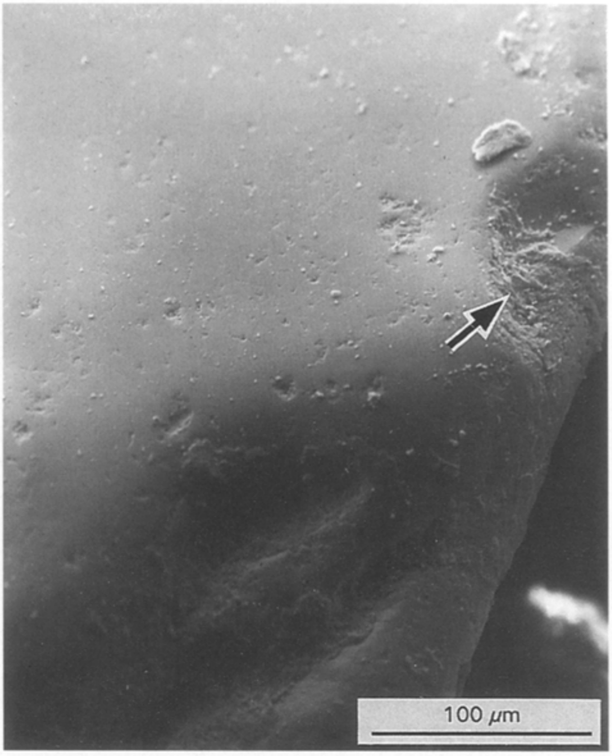

Figure 9 Crack arresting by an inclusion grain (the fracture energy was sufficient to damage the grain but it does not fail).

4. The fracture progress, and so the machining and removal performance will be controlled by the inclusions (including size, shape and distribution) due to different mechanisms of energy absorption.
5. The destruction process is based on the generation of a crack network due to microcrack penetration and intersection.

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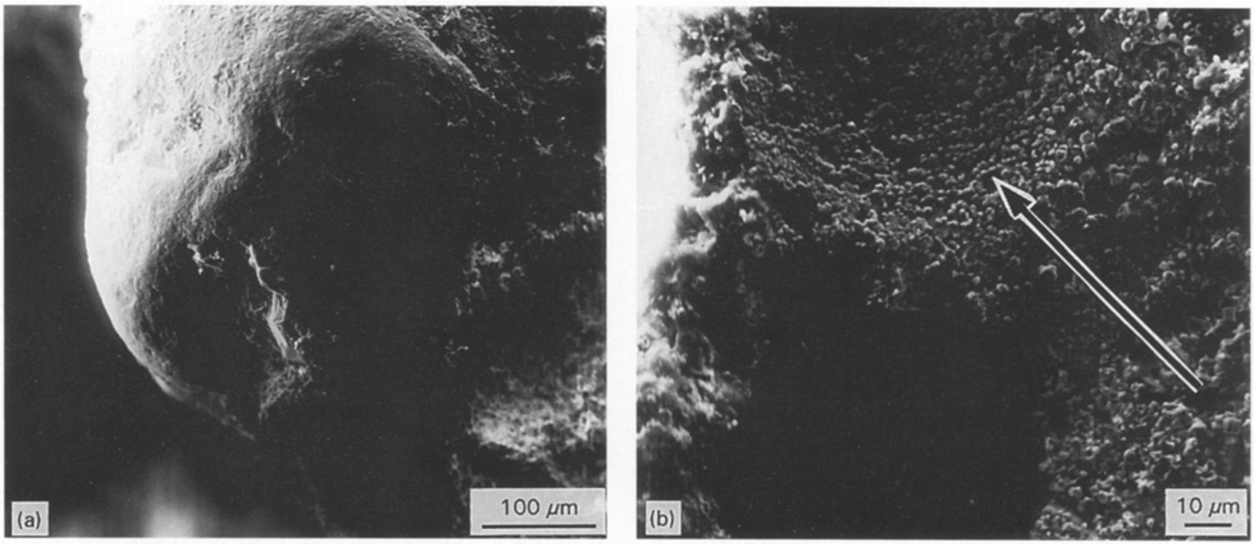

Figure 8 Fracture around an inclusion grain ((a) grain surface; (b) grain bed).

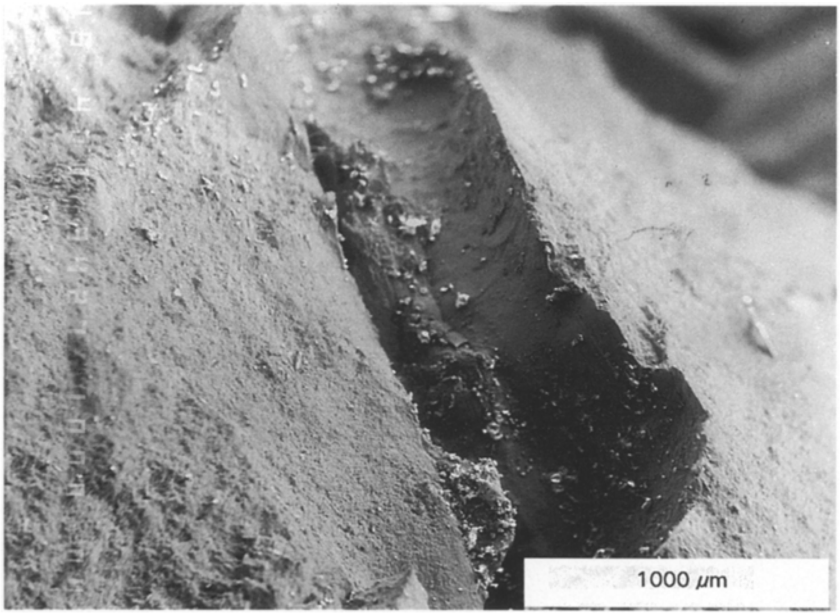

Figure 10 Crack branching by an inclusion grain (crack was deflected by the grain and progressed along the grain–matrix interface).

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