

FRACTURE PROCESSES AND FRACTURE TOUGHNESS IN
POWDER FORGED STEELS

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INTRODUCTION

The concept of fracture mechanics has been applied to selected powder forged steels in an attempt to correlate fracture toughness, K_{IC} , with micro-structural and fracture characteristics of these materials. The second phase inclusions, either dispersed within the lattice or found at the prior powder particle boundaries, act as internal defects with associated stress concentration. Predominantly non-coherent, non-metallic inclusions are considered in this paper only, since they are expected to have a significant effect on fracture toughness. In some powder forged materials a few regions of bainite, fine pearlite and ferrite mixture were occasionally observed. These regions originated from iron-powder contamination as a result of powder processing practice; they do not, however, seem to have any effect on K_{IC} value [1]. This observation is in agreement with the Charpy V-notch impact test results [2].

The steels used in this investigation were low alloy Cr-Mn and Ni-Mo steels, made by powder metallurgy techniques, subsequently hot forged to full density and then subjected to various heat treatments. The conventional notch impact test data have been shown to be of such low sensitivity as to make this method extremely unreliable in relating properties to structures. Therefore an evaluation on the basis of plane strain fracture toughness was made. Full density materials are required in order to obtain meaningful K_{IC} values. At present, the fracture toughness test seems to be the most reliable test in assessing the integrity of powder forged parts subjected to stress applications.

MATERIALS AND PARAMETERS

The two types of low alloy steel compositions studied, i.e. Cr-Mn and Ni-Mo steel were the same as previously reported [3 - 7]. Cr-Mn steel contained approximately 1.5% Cr, 0.8% Mn and 0.33% C whereas Ni-Mo alloy contained 1.7% Ni, 0.5% Mo and 0.5% C. In some experiments, however, a Ni-Mo alloy steel with higher manganese (0.42%) and lower nickel (0.49%) content was used. A major effort to produce a high strength alloy powder steel has concentrated on these two alloy systems. It is known, that more stable oxide phases form in Cr-Mn steels, whereas they are largely absent in Ni-Mo steels, because of the ease with which they can be reduced. In higher manganese (0.42%) Ni-Mo steels, however, larger numbers of oxide inclusions were observed after forging as compared with lower manganese (0.20%) Ni-Mo steels [6]. Although these two types of steels were used in this study, the conclusions relating the K_{IC} values and the inclusion characteristics should be valid in general. The Cr-Mn type steel re-

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presents the material, in which oxide inclusions play a dominant role in fracture; the interparticle, (i.e. along prior powder particle boundaries), type of fracture is expected to prevail. The Ni-Mo type steel represents material in which the fracture of the matrix, i.e. transparticle fracture, should be a common fracture feature.

As demonstrated before [5, 6] the total oxygen content in the form of various oxides is the most significant single contributing factor in determining the K_{IC} value. The oxygen content was varied from 100 to >1000 ppm, with the value of 300 ppm taken arbitrarily as a line between low and high oxygen content.

The compact tension fracture toughness specimens were cut as shown in Figure 1. Most of the work in determining K_{IC} done previously was on compact tension specimens with the notch perpendicular to the forging plane and forging direction, orientation C, Figure 1. Only very recently work on K_{IC} anisotropy in Ni-Mo steels was reported [1], a similar study on Cr-Mn steels has not been done yet. All tests were valid fracture toughness tests according to ASTM E-399. Specimens 12 mm in thickness, B, were used. The ultimate tensile strength was in the order of 1600 MPa. All tests were performed at room temperature.

NATURE OF INCLUSIONS AND FRACTURE SURFACE ANALYSIS IN Cr-Mn STEELS

The matrix produced from nitrogen atomized Cr-Mn alloy steel powder forgings consisted of tempered martensite, after various thermo-mechanical treatments. The original powder particles were compressed during hot forging into lens shaped grains. Assuming that some oxidation cannot be prevented during processing of powder and taking into consideration the high stability of oxides in Cr-Mn steels, the predominantly interparticle fracture following the oxide inclusion path along prior powder particle surfaces, is expected to prevail in specimens of all three directions, mixed with some transparticle fracture. The lower degree of interparticle fracture is obviously expected in lower oxygen specimens. The fracture surfaces of specimens of either A or C orientation should not differ substantially in spite of somewhat different fracture paths corresponding to crack arrester and crack divider geometry. The specimens of orientation B, easy crack propagation direction, would, however, result in fracture surfaces parallel to the forge plane. A SEM fractograph of a specimen of Cr-Mn steel in orientation C is shown in Figure 2 at low magnification (X160). The interparticle fracture, typical of Cr-Mn steels, is observed with some regions of transparticle fracture. The forging direction is perpendicular to the apparent longitudinal particle axis. The interparticle fracture area is seen in Figure 3 at high magnification (X9400). There is no question that the oxides on the surface of the original powder particles have been broken during forging and later modified in shape by solid state reactions. Their very fine, uniform distribution is in part responsible for the observed fine dimple distribution. The inclusions, approximately 1 μ m in diameter, are seen within the dimples and were identified by electron diffraction and X-ray techniques as oxide spinels, and manganese-alumina-silicates. The transparticle fracture is the matrix type fracture and has a coarse dimpled structure, with the average size of a dimple many times larger than the average size in the interparticle fracture zone. The inclusions associated with these transparticle dimples originate from common steel making processes and sulphides and silicates are to be expected.

The energy required for fracturing the specimen, and subsequently the K_{IC} values can be assessed on the basis of dimple size. Transparticle fracture, characterized by the coarse dimpled structure, is associated with a larger amount of plastic work than the interparticle fracture shown in Figure 3, which consists of small, shallow dimples. Taken to the extreme, a further decrease in dimple size would lead to a featureless fracture surface approaching a cleavage type of fracture. Some isolated cleavage type fractures were also observed which were associated with large inclusions not broken in the forging process.

The dimple size was introduced in the term, λ_c , in the equation: $K_{IC} \approx \sqrt{2\sigma_y E \lambda_c}$ [8], where λ_c is interdimple spacing. The more general equation should include the plastically deformed zone area. From this relation the K_{IC} value for transparticle fracture (larger λ_c) is expected to be higher than for interparticle fracture (smaller λ_c). In practice, correlation of interdimple spacings to K_{IC} is very difficult, although video tape was used and the total fracture surface was scanned. It should be noted, that experimentally both types of fracture occur in the same specimen, Figure 2, and the actual value of K_{IC} reflects the mixture of interparticle and transparticle modes of fracture. An accurate estimate of an effective λ_c is difficult.

NATURE OF INCLUSIONS AND FRACTURE SURFACE ANALYSIS IN Ni-Mo STEELS

The effect of higher manganese (0.42%) content in some of the Ni-Mo steels used on oxide formation was reported earlier. A larger number of oxide inclusions was observed as compared to lower manganese (0.20%) steel [6]. As in Cr-Mn steels, the resulting structure consisted essentially of tempered martensite.

The fracture typical for Cr-Mn steels, Figure 2, is not found in Ni-Mo steels. The fracture for the lower oxygen (<300 ppm) samples is mostly transparticle. The dimple network is seen in Figure 4 at X4200 magnification. Within some dimples inclusions were observed. The fewer inclusions in the low oxygen steel indicate that the inclusions affecting properties are largely oxide phases.

The higher oxygen containing samples (>1000 ppm) also fractured in a manner very different from that observed in Cr-Mn steels in Figure 2. The typical pattern of interparticle fracture in Cr-Mn steels exposing the original particle morphology was absent in Ni-Mo steels. The fracture was largely transparticle, (similar to Figure 4), mixed with interparticle delamination. The interparticle fracture was found to be affected by orientation. Orientation B, the easy crack propagation direction, was characterized by fracture surfaces associated with oxide inclusions lying in the plane of the fracture. These were sometimes relatively large. In Figure 5 such an area is shown at X1000 magnification. The inclusion of this size is atypical. However, its chemistry is typical for small inclusions which are the product of fractured large inclusions. This particularly large inclusion is a complex silicon, calcium, magnesium and iron oxide. The detail of the same area at higher magnification (X2000), Figure 6, revealed a large spherical inclusion and a great number of smaller, somewhat irregular inclusions. The spherical inclusion was identified as containing manganese and silicon. Smaller, irregular inclusions are the fragments of large complex oxide particles and are also of a more or less complex nature. The forging direction in Figures 5 and 6 is perpendicular to the plane of the photograph. This area clearly

shows the variety of shapes and compositions of inclusions, although the dimpled structure resembles strongly the fracture structure in Figure 4, except for a large number of small inclusions within the dimples.

A fractograph of a sample with a fatigue precrack in orientation C, Figure 7, shows a large crack associated with oxide inclusions with small inclusion fragments within the dimples, (forging direction is perpendicular to the crack). The depth of the field is remarkable and the dimpled structure is particularly clearly seen at the lower crack interface.

K_{Ic} VALUES

A quantitative correlation of K_{Ic} values with fracture processes as deduced from SEM fractographs is not possible at present. However, the qualitative correlation exists. As mentioned before, the total oxygen content largely in the form of various oxides is the most important factor in determining K_{Ic} values [5, 6]. At 300 ppm of oxygen, K_{Ic} for Cr-Mn steel was found to be in the range of $40 \text{ MPa}\cdot\text{m}^{1/2}$, and for Ni-Mo steel, $55 \text{ MPa}\cdot\text{m}^{1/2}$. At lower oxygen level (<100 ppm) the difference in K_{Ic} for Cr-Mn and Ni-Mo steel should diminish; K_{Ic} values of over $60 \text{ MPa}\cdot\text{m}^{1/2}$ were determined for both steels. The very recent data suggests that the difference in fracture toughness for Cr-Mn and Ni-Mo steels at the same oxygen level might not be very significant. An attempt was made to plot all available K_{Ic} data for the orientation C test samples versus oxygen content and it appears that a single curve could be drawn regardless of steel composition (Cr-Mn versus Ni-Mo).

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REFERENCES

- BRATINA, W. J., FOSSEN, W. F., HOLLINGBERY, D. R. and PILLIAR, R. M., Modern Developments in Powder Metallurgy, 9, MPIF, Princeton, N.J., 1977.
- STEED, J. A., Powder Metallurgy, 18, 1975, 201.
- PILLIAR, R. M., BRATINA, W. J. and McGRATH, J. T., Modern Developments in Powder Metallurgy, 7, MPIF, Princeton, N.J., 1974, 51.
- PILLIAR, R. M., LADANYI, T. J., MEYERS, G. A. and WEATHERLY, G. C., Proc. Fourth Conf. on Powder Metallurgy, Vysoke-Tatry, Czechoslovakia, Part I, 1974, 233.
- LADANYI, T. J., MEYERS, G. A., PILLIAR, R. M. and WEATHERLY, G. C., Met. Trans. A, 6A, 1975, 2037.
- PILLIAR, R. M., HOLLINGBERY, D. R. and FOSSEN, W. F., Int. J. of Powder Metallurgy and Powder Technology, (to be published).
- BRATINA, W. J. and GIBBON, W. M., Fourth European Symp. for Powder Metallurgy, Grenoble, France, 1975, paper 7-7-1.
- HAHN, G. T. and ROSENFELD, A. R., Met. Trans. A, 6A, 1975, 653.

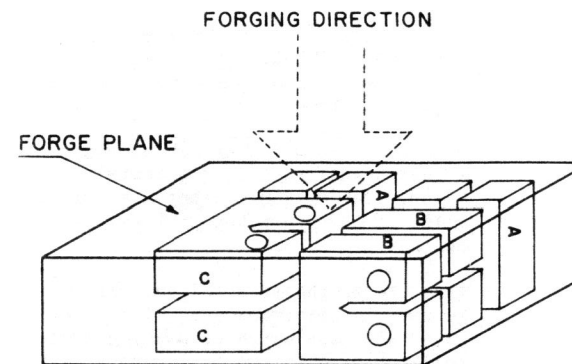


Figure 1 Schematic diagram showing three orientations of CT fracture toughness specimens



Figure 2 Fracture surface characteristic for Cr-Mn steel. Interparticle fracture with a few areas of transparticle fracture is noted. X160

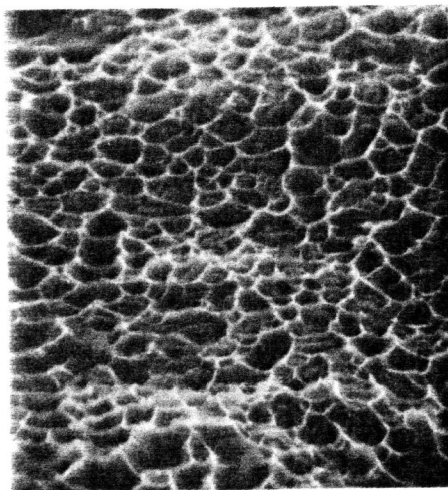


Figure 3 Interparticle fracture in Cr-Mn steel. Structure of small size dimples, many associated with fine inclusions, is seen. X9400

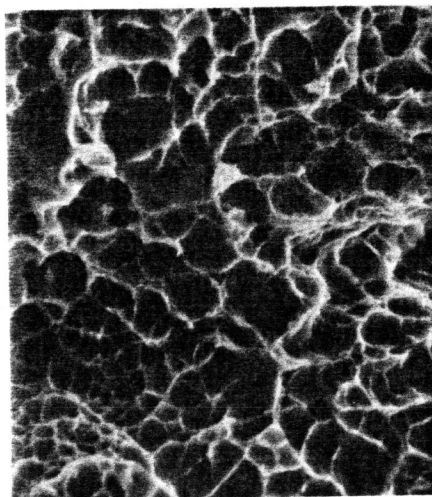


Figure 4 Transparticle fracture in Ni-Mo low oxygen steel. Note the dimple network with some inclusions. X4200

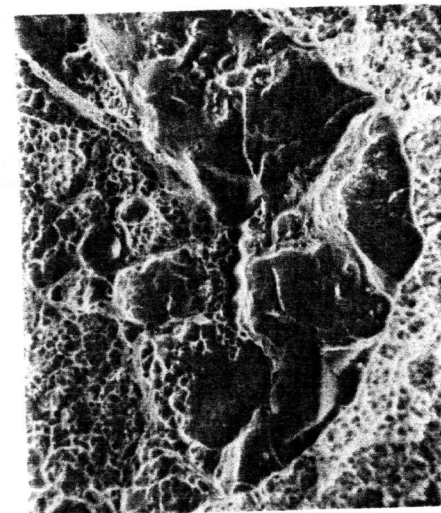


Figure 5 Fracture surface in Ni-Mo high oxygen steel with a very large atypical inclusion. Orientation B. Forging direction is perpendicular to the plane of the photograph. X1000

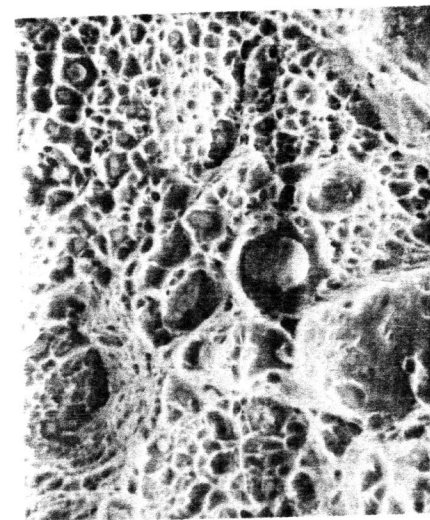


Figure 6 Detail of Figure 5. A large spherical inclusion and numerous oxide inclusions within the dimples are seen. X2000

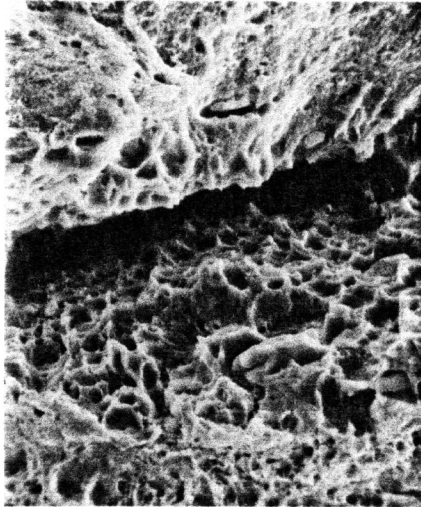


Figure 7 Fracture surface in Ni-Mo high oxygen steel with fine dimpled structure. Orientation C. Forging direction is in the plane of the photograph and perpendicular to the large crack seen in the picture. X2000