FRACTURE TOUGHNESS VARIATION IN A CrMoV STEEL ROTOR FORGING AT 120°C

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The performance reliability of massive steam turbine rotor forgings made out of CrMoV steel is governed by the fracture toughness of the material which in turn is influenced by the microstructural variation. The present investigation was undertaken to determine the fracture toughness of the surface material and the core material at 120°C. A J-integral route using multiple specimen technique was resorted to for this purpose. It was found that presence of about 20 per cent ferrite in bainitic matrix had a detrimental effect on toughness.

INTRODUCTION

Low alloy steel turbine generator rotor forgings used in power generation industry are heat treated to obtain a bainitic structure. The present day advanced manufacturing technologies ensure chemical and microstructural homogeneity to a large extent, however, in these massive rotor forgings certain amounts of ferrite is often observed in the core material. The resultant microstructures are a completely bainitic structure at the near surface regions and a mixer of bainite and ferrite in the core material. A structural integrity analysis, therefore, must consider fracture toughness of the appropriate microstructural condition.

The study related to the influence of microstructural phases on fracture toughness has received considerable attention in the recent years. However, the influence of mixed microstructures has been explored

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only in a few studies. Dolby and Knott (1) have demonstrated that the introduction of upper-bainite into a martensitic structure progressively lowers the fracture toughness. Recently, Hagiwara and Knott (2) have determined fracture toughness for mixed martensitic-bainitic structures in HY80 steel. These authors varied the amounts of upper bainite phase in a systematic manner and found a decrease in cleavage fracture resistance of the material with increasing bainite contents. On the other hand, retained austenite is known to be beneficial to fracture toughness property, acting as crack arrester. The effect of acicular ferrite in a weldment is also favourable to an increase in fracture toughness. While the influence of pro-eutectoid ferrite is generally known to have a detrimental influence on fracture toughness, Stenbacka (3), on the contrary, Cane and Dolby (4) have shown a beneficial effect of proeutectoid ferrite on fracture toughness in a C-Mn steel.

In the present study, the influence ferrite content in a bainitic microstructure in a Cr-Mo-V steel has been investigated on the fracture toughness. The tempered bainitic structure is a complex structure with bainite packet as the effective grain size. On the other hand, the effective grain size of the ferritic phase is apparent from the microstructure. Thus, mixed microstructural phases present a situation of duplex grains. The other microstructural considerations are the carbide precipitates in the bainitic phase which control the fracture strength. Ritchie et.al.(5) have shown that austenite grain size also controls the fracture toughness in bainitic structures. It is, however, not the objective of this study to isolate the individual effects of various microstructural parameters. The influence of ferrite phase has been examined by maintaining other parameters such as inclusion level and prior austenite grain size constant.

EXPERIMENTAL PROCEDURE

A Cr-Mo-V steel investigated in the present study had the chemical composition shown in Table 1. The representative mechanical properties for an oil quenched and tempered rotor forging material are given in Table 2. The material received for investigation was in form of a radial trepan of 26 mm in diameter. The microstructures of the near surface and core materials were examined and are shown in Fig.1.

The fracture toughness of the CrMoV steel in each microstructural condition was determined by utilizing elastic-plastic J-integral fracture criterion keeping in view the large size of specimen required for a valid K_{Ic} value in accordance with ASTM Test Method E-399 for plane strain fracture toughness. Round compact tension specimens were prepared from the trepan as per ASTM standard E-399 and multiple specimen J-integral tests were carried out in accordance with ASTM Test Method E-813. The tests were conducted on a MTS servohydraulic testing machine at 120°C. The specimens were pre-cracked to a crack depth ratio of 0.6. Heat tinting, to mark the area of crack extension during loading the specimens to various magnitudes, was carried out at 300°C for 15 minutes. The specimens were fractured by pulling at liquid nitrogen temperature. A test temperature of 120°C was selected as it falls above the upper shelf temperature and the component in service experiences elevated temperature. The material showed appreciable stable crack growth during J-integral tests at this temperature.

TABLE 1 - Chemical Composition of Turbine Rotor Steel Investigated (Weight %).

C	Si	Mn	S	P	Ni	Cr	Mo	V
0.28	0.18	0.61	.005	.005	0.54	1.17	1.01	0.25

TABLE 2 - Mechanical Properties of Turbine Rotor Forging Material Investigated.

Temperature, °C	0.2% Proof PStress, MPa	Tensile Strength, MPa	Elongation %
25	632	773	18.6
120	606	727	19.5

Fracture Appearance Transition Temperature was also determined for each micro-structural condition. Charpy V-notch specimens were prepared and tested in accordance with ASTM Test Method E-23. The direction of crack propagation in these specimens was maintained as axial direction similar to that in J-integral tests. The fractured specimens were examined in a Cambridge Stereoscan S-150 scanning electron microscopes.

RESULTS

The microstructures of surface and core materials showed tempered bainite and tempered bainite plus ferrite structures (Fig.1). The amount of ferrite in bainitic structure in the core material was found to be around 20 per cent.

The impact energy values obtained at various test temperatures for both structures are shown in Fig.2. The impact energy versus test temperature plotted in Fig.2 indicate FATT for bainitic and mixed bainite plus ferrite structures to be 27°C and 42°C respectively.

Load-displacement curves obtained in J-integral tests are shown in Fig.3 for the bainitic structure and in Fig.4 for the mixed bainite-ferrite structure. Typical fractured round compact specimens are shown in Fig.5. Crack blunting line and crack growth resistance curves are plotted in Fig.6 and Fig.7 based on post fracture crack extension measurements, for the two microstructural conditions. Fracture toughness values for bainite and bainite-ferrite structures were estimated to be 200 $\mathrm{MPa.m}^{\frac{1}{2}}$ and 150 $\mathrm{MPa.m}^{\frac{1}{2}}$ respectively. The impact fracture morphology for lower shelf, transition range and upper shelf temperatures is shown in Fig.8 and Fig.9 for the bainite and bainite-ferrite structures. The characteristic fractographic features of J-integral test specimens in two microstructural conditions are shown in Fig.10 and Fig.11.

DISCUSSION

The microstructural features in the CrMoV steel investigated for two microstructural conditions are:

i) prior austenite grain size,
ii) bainitic lath packets,
iii) carbide precipitates, and
iv) ferrite grains in a bainitic matrix.

The prior austenite grain size is divided into bainite lath packets, formed by parallel laths, which are the smallest microstructural units representing effective grain size. The carbides precipitated during tempering at bainite lath boundaries and prior austenite boundaries are primarily M_3C followed by M_2C and traces of MC, Viswanathan and Beck (6). Since the austenitizing and tempering temperatures are same for both bainite and bainite-ferrite structures, the above microstructural features are identical in these structures. The observed difference in fracture behaviour, therefore, has resulted due to the presence of ferrite phase in one of structures considered.

The observed difference in fracture appearance transition temperature for the surface material and the core material is in conformity with values reported by other authors. A difference of 22 pct in these values has been reported and the values obtained, in the present study indicate a difference of 25 pct. However, the FATT value of 42°C obtained for core material is indicative of high quality of rotor forging. It may, however, be mentioned here that this value may not be a true representative of the core since only one Charpy specimen could be obtained from the trepan diameter. Thus, four Charpy specimens were obtained from a length of about 235 mm starting from the core end of the trepan. One of the characteristic fractographic feature noted in the impact specimens tested at 95°C was the presence of small pebbles within each dimple as shown in Fig.8 and Fig.9. Another feature of interest is the presence of small size dimples along the boundaries joining large dimples. These small dimples are free of any pebbles. The large size dimples initiated at the inclusion - matrix interface and as the adjoining dimples coalesced together small voids initiated at the carbide particles resulting in a net work of small dimples surrounding large dimples. The larger size of dimples in the bainitic structure indicate to a larger toughness in comparison to bainite-ferrite structure as is observed in the upper shelf energy values.

The influence of ferrite phase on the ductile fracture behaviour of a bainitic structure at 120°C is obvious from the values obtained. The stable crack growth initiation is ductile in dimple mode in both structures, thus, satisfying one of the essential requirements of the J-integral test validity. Further crack propagation is in transgranular cleavage mode. Cleavage fracture took over as mechanisms of crack propagation at the characteristic distance where applied stress exceeded critical stress for cleavage fracture. The distinct features noted from fractographs in Fig.10 and Fig.11 are:

i) the width of stretched zone in two structures is different, being larger for the bainite,
ii) the cleavage fracture facets are smaller in size in bainite and steps are observed on many adjoining facets, and
iii) the cleavage facets are of mixed size in bainite-ferrite structure. Apparently the ferrite fracture facets are of large size.

Contrary to the bainite, the effective grain size in the ferrite phase is the size of ferrite grains distinctly observed in the microstructure. These ferrite grains are much larger than bainite packets. Larger grain size and the resultant large cleavage facets have an effect in reducing fracture toughness. Cleavage fracture in ferrite phase resulting in large flat facets is a lower energy fracture process in comparison to cleavage fracture in bainite which has higher energy step formation process during fracture of packets in different orientations, Torronen et.al.(9).

CONCLUSIONS

Microstructural variation in a CrMoV steel forging influenced its fracture behaviour at 120°C. Introduction of about 20 pct ferrite in a bainite matrix resulted in an increase of FATT from 27°C to 42°C and a decrease in fracture toughness from 200 $\mathrm{MPa.m^{\frac{1}{2}}}$ to 150 $\mathrm{MPa.m^{\frac{1}{2}}}$. This difference in fracture properties has been attributed to larger grain size of ferrite phase and low energy fracture process in ferrite in comparison to bainite.

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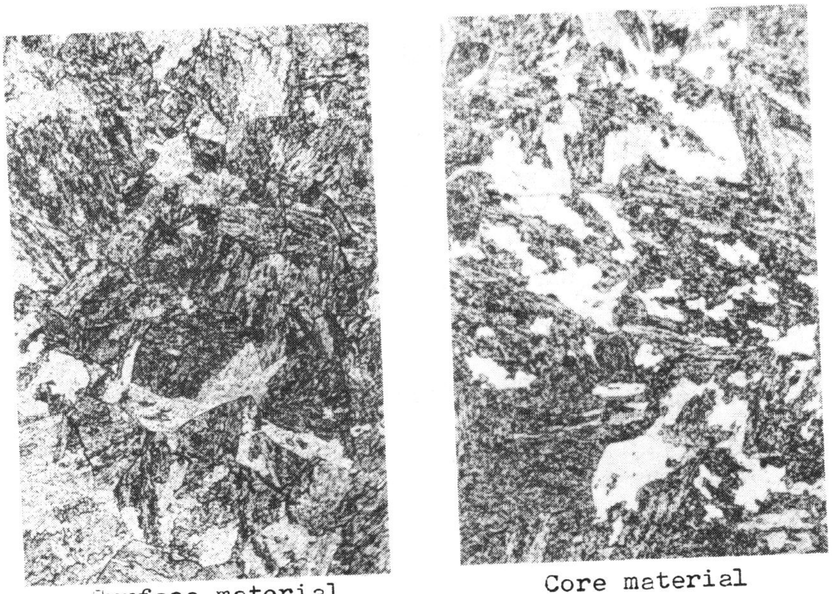


Surface material

Core material

Mag.250X

Figure 1 Typical microstructures

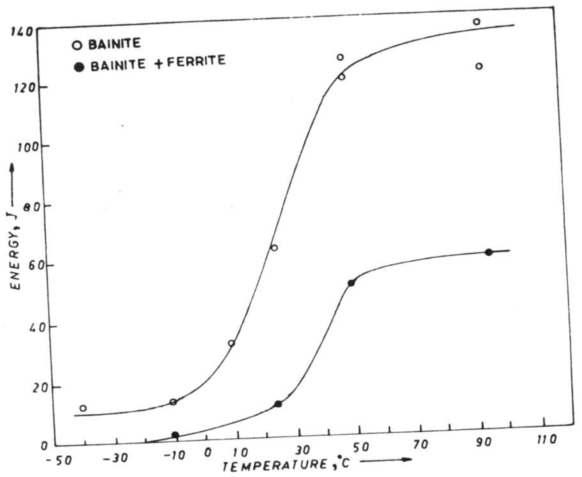


Figure 2 Variation of CVN energy versus temperature

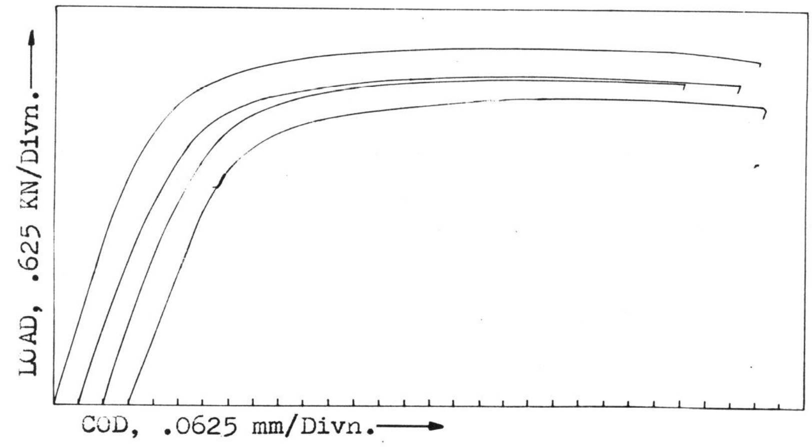


Figure 3 Load-COD curves for bainite structure

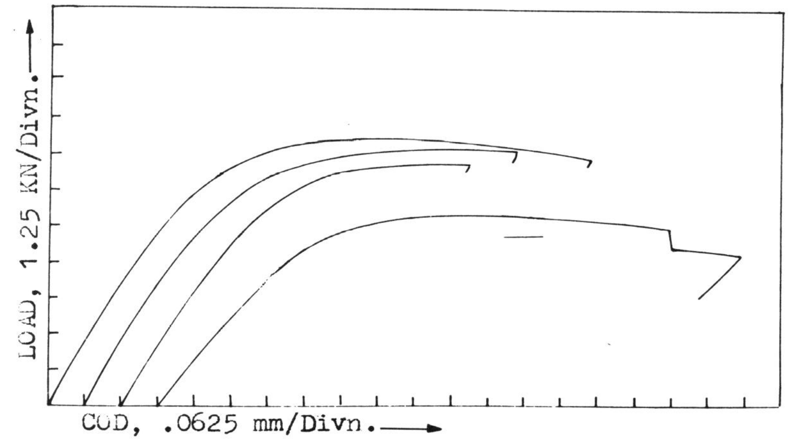
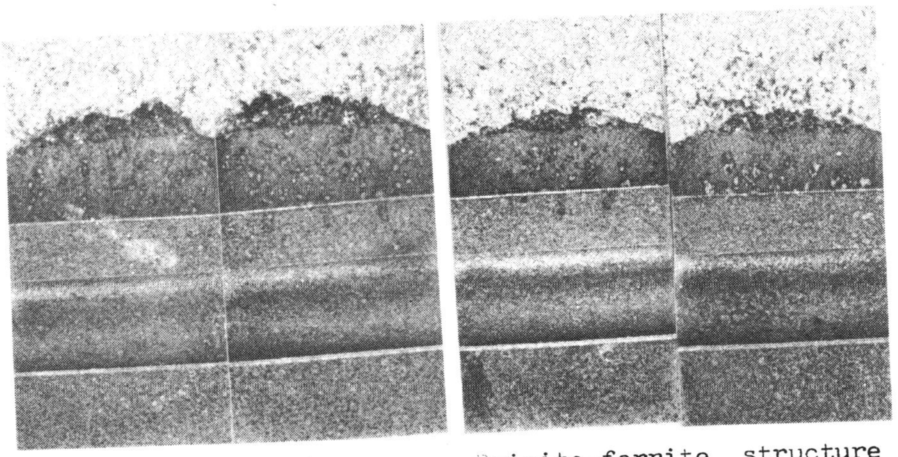


Figure 4 Load-COD curves for bainite-ferrite structure



Bainite structure Bainite-ferrite structure

Figure 5 Typical fracture surfaces

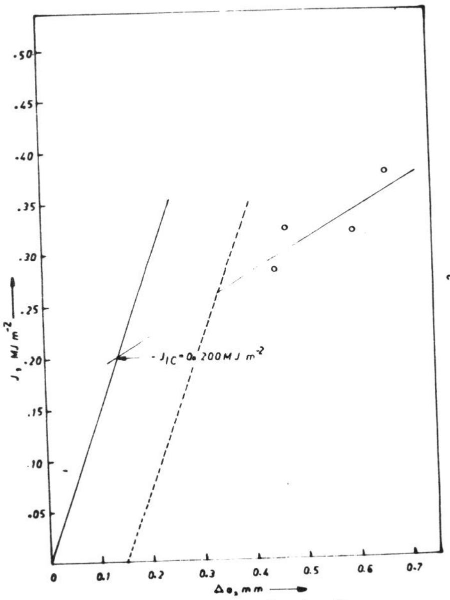


Figure 6 J-Δa plot for bainitic structure

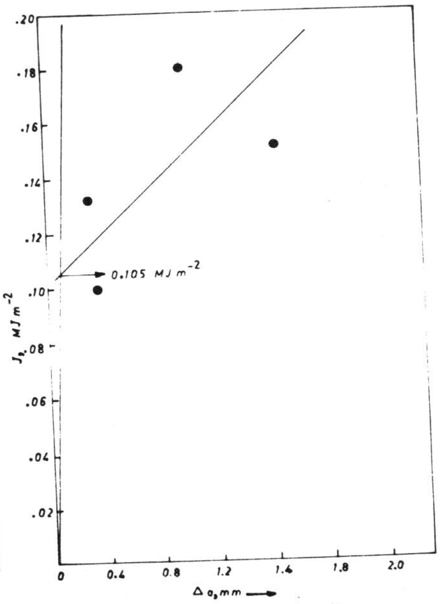


Figure 7 J-Δa plot for bainite-ferrite structure

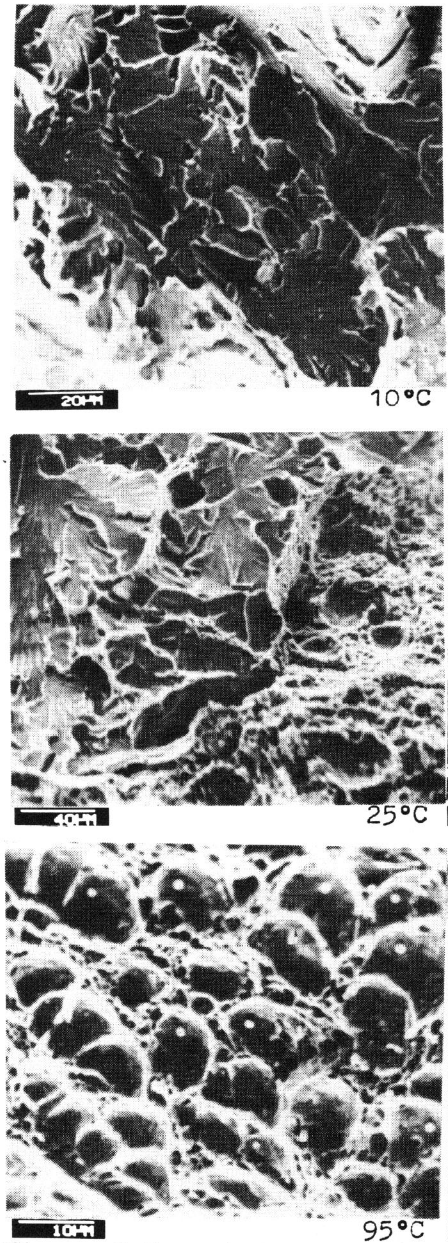


Figure 8 Impact fractographs for bainite structure

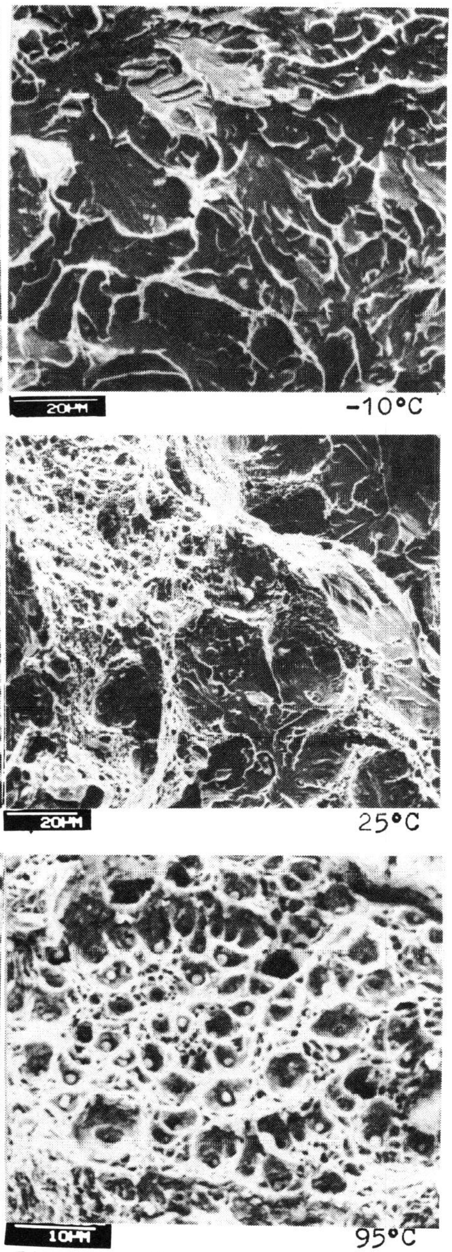


Figure 9 Impact fractographs for bainite-ferrite structure

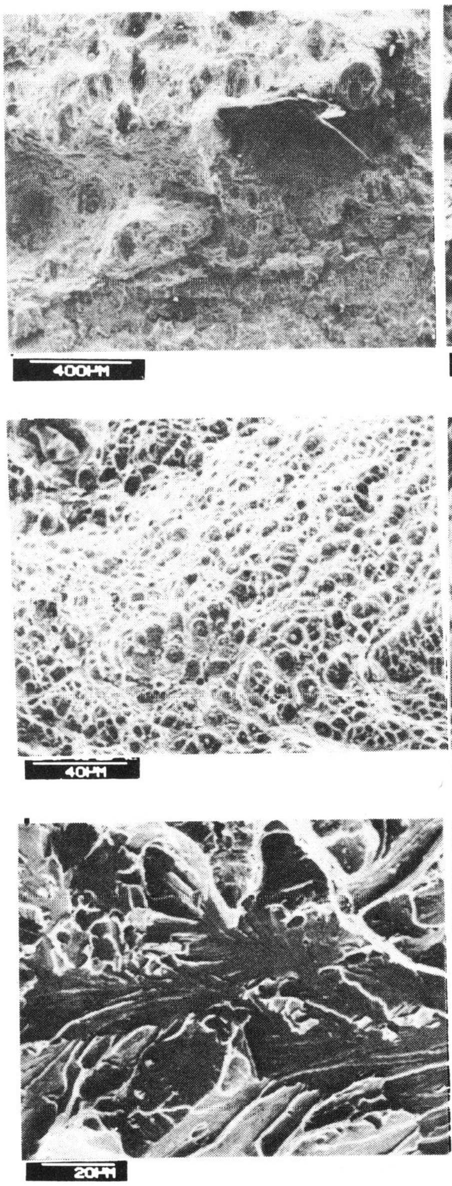


Figure 10 Fractographs for bainite structure

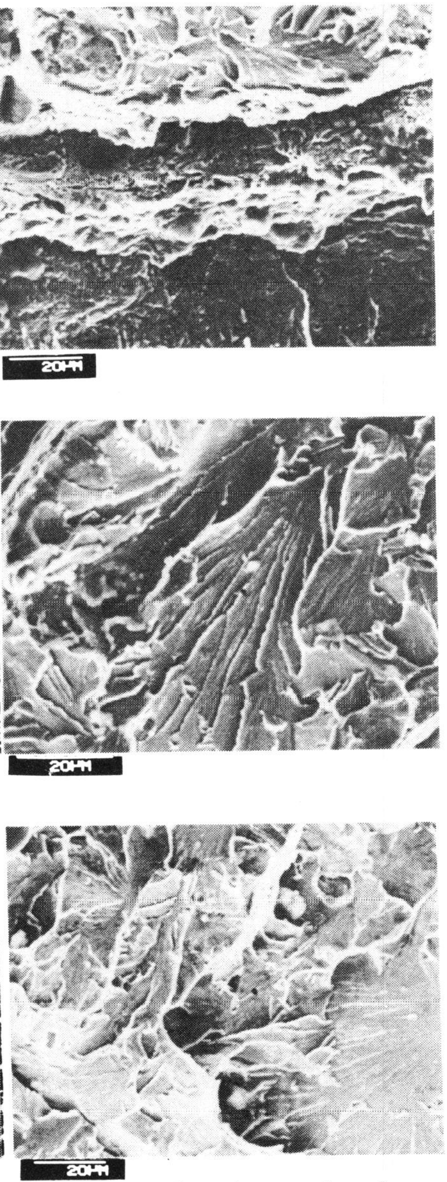


Figure 11 Fractographs for bainite-ferrite structure