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CHARACTERIZING FRACTURES BY ELECTRON FRACTOGRAPHY

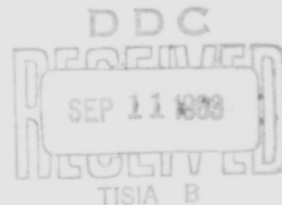
PART XII ILLUSTRATED GLOSSARY, SECTION I: QUASI-CLEAVAGE

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ABSTRACT

This report is one of a series intended to illustrate and explain the terminology used in describing the features in high magnification fractographs.

Quasi-cleavage is one of several fracture modes possible in the mechanical rupturing of quenched and tempered (martensitic) steels. The high magnification surface topography in this fracture mode resembles true cleavage in that the fracture facets are relatively flat with markings which often, though weakly, resemble river patterns in true crystallographic cleavage. In addition to the steps which produce these markings, there are also "tongues" (cleavage on secondary planes) which strongly resemble true cleavage. But in addition there are, in quasi-cleavage, ridges produced by plastic deformation and rupture of thin webs of metal between two growing submerged crack fronts; these markings do not resemble true cleavage. These fractures are discussed and illustrated.

PROBLEM STATUS

This is an interim report; work on this problem is continuing.

AUTHORIZATION

NRL Problem Number: M01-08

Bureau Problem Number: RRMA 02 091/652 1/R007 06 01

INTRODUCTION

The relation of high magnification fracture surface topography to the microstructure through which the fracture passes is a portion of a broad program aimed at understanding the micro-mechanisms of the various fracturing processes and the application of this knowledge to improving alloys and facilitating failure analyses.

Electron fractography, where the electron microscope is used to observe fracture surfaces, is still in its infancy. The state of development has been compared to that of light-microscope metallography in the 1880's. Many thousands of fracture surfaces, in diverse metal systems, created under diverse conditions, will have to be critically analysed before the science and art of electron fractography can be fully developed and its usefulness fully delineated.

It is hardly feasible to report and catalog all the necessary encyclopedic quantities of information about the topography of fractures by individual fractographs, and resort must therefore be made to terms describing the significant features of the fractures. To ensure that the meaning of the nomenclature used in the NRL program is clear, a series of reports discussing the various fracture modes in detail is being prepared. It is inevitable that names often must be

given to features before a full understanding of the genesis of these features is achieved, and hence the names, if they imply mechanisms are subject to possible outdating.

The present report is the first of a series. It treats a fracture mode which is not yet fully understood.

True crystallographic cleavage is reasonably well understood from the standpoint of fractography. To a more limited degree, the coalescence of voids in plastically strained crystals to form "dimpled rupture" is also understood (1-3). However, when tempered martensite "cleaves" the mechanics and the crystallography of the separation are poorly understood. In contrast to the case of a pure metal or a simple solid solution, where with x-rays one can prove the crystal orientation, tempered martensite is a highly complex and highly useful conglomerate of various carbides, ferrite, martensite and retained austenite, all so finely divided that their orientation with respect to the fracture surface has not yet been determined. Each "cleavage" facet on the fracture surface of a piece of tempered carbon steel is probably associated with thousands of fine particles, and the experimental difficulties have to date discouraged attempts to determine whether the fracture passed through or around these particles, or what their orientations are. Therefore, the flat surfaces seen at high magnification in the replicas of

steel fracture surfaces are called "quasi-cleavage" facets, instead of cleavage facets. The prefix "quasi" rightly introduces uncertainty into the descriptive term "cleavage", and until someone determines the mechanism (or mechanisms) by which this type of fracture occurs, descriptive terms concerning the fracturing process and the resulting fracture surfaces should remain non-specific; it is hoped that future work will provide the necessary information to permit more specific terminology .

RESEMBLANCES BETWEEN TRUE CLEAVAGE AND QUASI-CLEAVAGE

The prefix quasi means "seemingly" or "resembling". Quasi-cleavage resembles cleavage because the fracturing process is essentially low-energy or "brittle", occurs most frequently at low temperatures, and the high magnification fracture surface topography is composed of flat areas which are frequently separated from one another by cleavage-like steps (which intersect one another to form river patterns). In addition, quasi-cleavage fracture surfaces often contain "tongues" similar to those seen in true cleavage (where the fracture path momentarily follows a secondary plane). Steps and tongues in quasi-cleavage may be seen in Figure 1. Good examples of true cleavage markings (including steps and tongues) may be found in References 4 and 5.

DIFFERENCES BETWEEN TRUE CLEAVAGE AND QUASI-CLEAVAGE

One difference in these two fracture modes which is easily recognizable in the electron microscope is that the origin of the fracture of each quasi-cleavage facet is frequently contained within the facet, whereas in true cleavage the initiation point is almost always at the edge of each facet. Since quasi-cleavage facets often have their origins within the facets (as contrasted to the edge of the facets) it is assumed that quasi-cleavage cracks extend at least partially by the growth of individual, completely submerged, facets ahead of the main crack. This is not often seen in true cleavage. When the stress concentration at the tip of the main crack causes nucleation of submerged cracks ahead of the main crack, the process is called satellite nucleation.

Another distinct difference between the two fracture modes is the amount of plastic deformation associated with fracture. Quasi-cleavage topographical features are largely formed by plastic flow at the edges of the growing, submerged, quasi-cleavage cracks. For this reason, a large proportion of quasi-cleavage facets are seen to be slightly concave, and tear ridges (formed by the plastic rupture of material between two or more growing quasi-cleavage openings) are often seen within and between facets. Tear ridges are shown in

Figure 1, and sketched in Figures 2 and 3.

STUDIES OF PRECISELY MATED QUASI-CLEAVAGE SURFACES

Figure 1 shows precisely matched regions from replicas of two mating fracture surfaces. A piece of type 410 stainless steel wire was quenched, tempered at 900°F, notched, and broken at 50°F. Cellulose acetate replicas were made of both fracture surfaces, shadowed with palladium and backed with carbon to form the two-stage carbon replicas seen in Figure 1.

One replica was positioned in the microscope with the objects which cast shadows sticking up while the other was mounted with the objects sticking down. This made the resulting pictures appear to be taken from "outside the specimen" (viewing the fracture surface from outside the specimen) in the pictures of one replica, while they appeared to be taken from "inside the specimen" for the other replica. This particular arrangement of replicas in the microscope produces pictures with matching details arranged the same way in the two sets of pictures, which explains why the two pictures in Figure 1 do not have to be folded face-to-face to make the details match*. Stereo pictures of selected regions were taken to permit the most critical analysis.

* This arrangement is almost a necessity in precision-matching experiments. If one forgets to mount the replicas in the microscope with the proper orientation to produce this effect he may achieve the same effect by printing the pictures from one replica with the emulsion side down and the other with the emulsion side up.

Figure 2 is a sketch of some of the features observed in quasi-cleavage and exhibited in Figure 1. Figure 2 is an idealized section of a volume of tempered martensite which has failed by quasi-cleavage. The tongues and steps mate like a hand in a glove, while the tear ridges are a result of local plastic deformation similar to the necking down of a tensile specimen to a chisel point. In Figure 1, examples of steps are seen as lines between the numbers 1 and between the numbers 2. Examples of tear ridges are shown between the numbers 3 and between the numbers 4. Tear ridges shown between the numbers 5 are thought to be formed when three sub-merged cracks grew together as illustrated in Figure 3. Examples of tongues can be seen in Figure 1 in the regions bounded by the numbers 6.

The exact nature of the steps and tongues exhibited in quasi-cleavage has not been established. Stereo viewing shows the steps to be more deformed than shown in the sketch in Figure 2. The steps are also sometimes observed to blend in with tear ridges as illustrated in Figure 4, and exhibited between the numbers 7 in Figure 1.

FURTHER EXAMPLES OF QUASI-CLEAVAGE

A good illustration of a single quasi-cleavage facet may be seen in Figure 5. The facet is bounded by the four large

arrows. This fractograph shows the initiation region just above and to the left of center. River patterns leading away from the center are indicated by the small arrows.

Figures 6 and 7 are cellulose acetate replicas of hardened and tempered AMS 6434 fractured at -320°F . Examples of facets are found between the arrows in Figure 6. Each facet is distinctly flat and has an orientation different from its neighbor. Both Figures 6 and 7 show many more tear ridges than steps.

In very brittle materials, secondary cracking, or branching away from the plane of the main fracture is sometimes observed. This is shown in the fractograph of a high strength die steel broken at room temperature, Figure 8. The secondary cracks are replicated as thin films of cellulose acetate and are finally exhibited as thin films of carbon which appear as wandering black bands with jagged edges. The magnification of this fractograph is too low to show the fine scale details of quasi-cleavage, but they consist almost entirely of tear ridges. The mechanism of the formation of these ridges greatly resembles the mechanisms of dimpled rupture.

Dimples between quasi-cleavage facets are often observed. Several patches of dimples are indicated by large arrows in Figure 9. All steels examined to date that fail by quasi-

cleavage at one temperature fail by dimpled rupture at some higher temperature, and the presence of dimples at intermediate temperatures is to be expected. The small arrows of Figure 9 indicate abrupt changes in elevation where individual facets, which do not lie on the same plane, are connected. Quasi-cleavage facets, then, occur at various elevations and orientations relative to the macroscopic plane of the crack, and are joined in some instances by abrupt changes in elevation, and in other cases by dimpled rupture. At low temperatures, however, neighboring facets usually intersect one another without the existence of such borders.

Figure 10 shows another room temperature high strength die steel fracture with a few quasi-cleavage facets. Here the main failure mode is seen to be dimpled rupture.

SUMMARY

Though quasi-cleavage occurs frequently in tempered martensitic carbon steels, it is one of the least understood fracture modes. The term quasi-cleavage is used in describing this low energy fracture mode because the mode resembles cleavage. When the mechanisms of quasi-cleavage become known (there may be several, depending upon the material and fracture conditions) more precise descriptive terminology will be used. On the one hand, due to the formation of steps and

tongues, quasi-cleavage mechanisms are thought to be closely resembling those of true cleavage. On the other hand, due to the plastic deformation frequently observed (formation of tear ridges, dimples and concave facets) there are strong indications in some cases that quasi-cleavage mechanisms are similar to those of dimpled rupture (plastic nucleation, growth, and coalescence of voids). It may be that in tempered carbon martensitic steels one has the possibility of a spectrum of available fracture modes varying from 100% dimpled rupture with one extreme set of conditions to 100% quasi-cleavage with the other extreme set of conditions. Steels may, of course, also fail by a grain boundary separation (intergranular decohesion) with or without plastic deformation, and the tear ridges seen on quasi-cleavage facets are sometimes also seen on these intergranular fractures. The presence of tear ridges, then, is not sufficient to characterize a fracture as quasi-cleavage.

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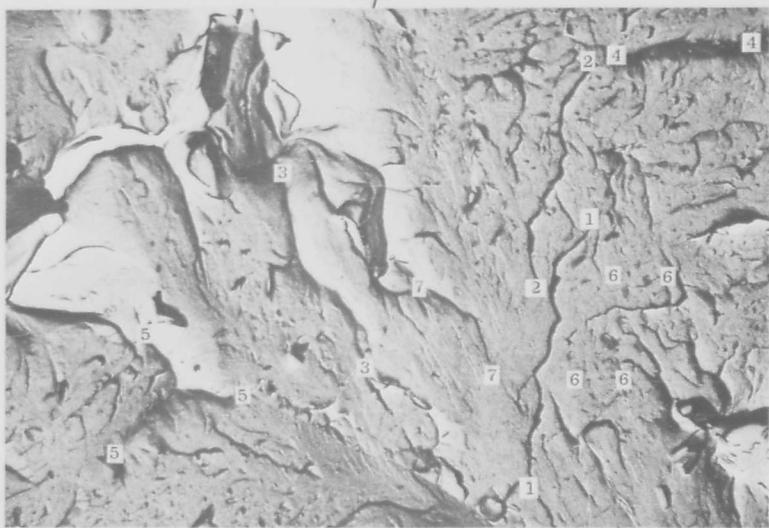


Fig. 1 - Precisely mated quasi-cleavage facets from the two halves of a hardened and tempered AISI 410 stainless steel wire broken in tension at 50 °F. Stereo viewing showed three features of quasi-cleavage which are indicated between numbers. Between numbers 1 and between numbers 2 are steps - similar to those in true cleavage - seen as dark lines. The numbers 3 and 4 indicate examples of tear ridges and 5 shows where three tear ridges converge. Tongues, similar to those found in true cleavage are seen in the regions bounded by 6's. Between the numbers 7 is an example of where a step merges with a tear ridge. Cellulose acetate replica technique. 15,000X.

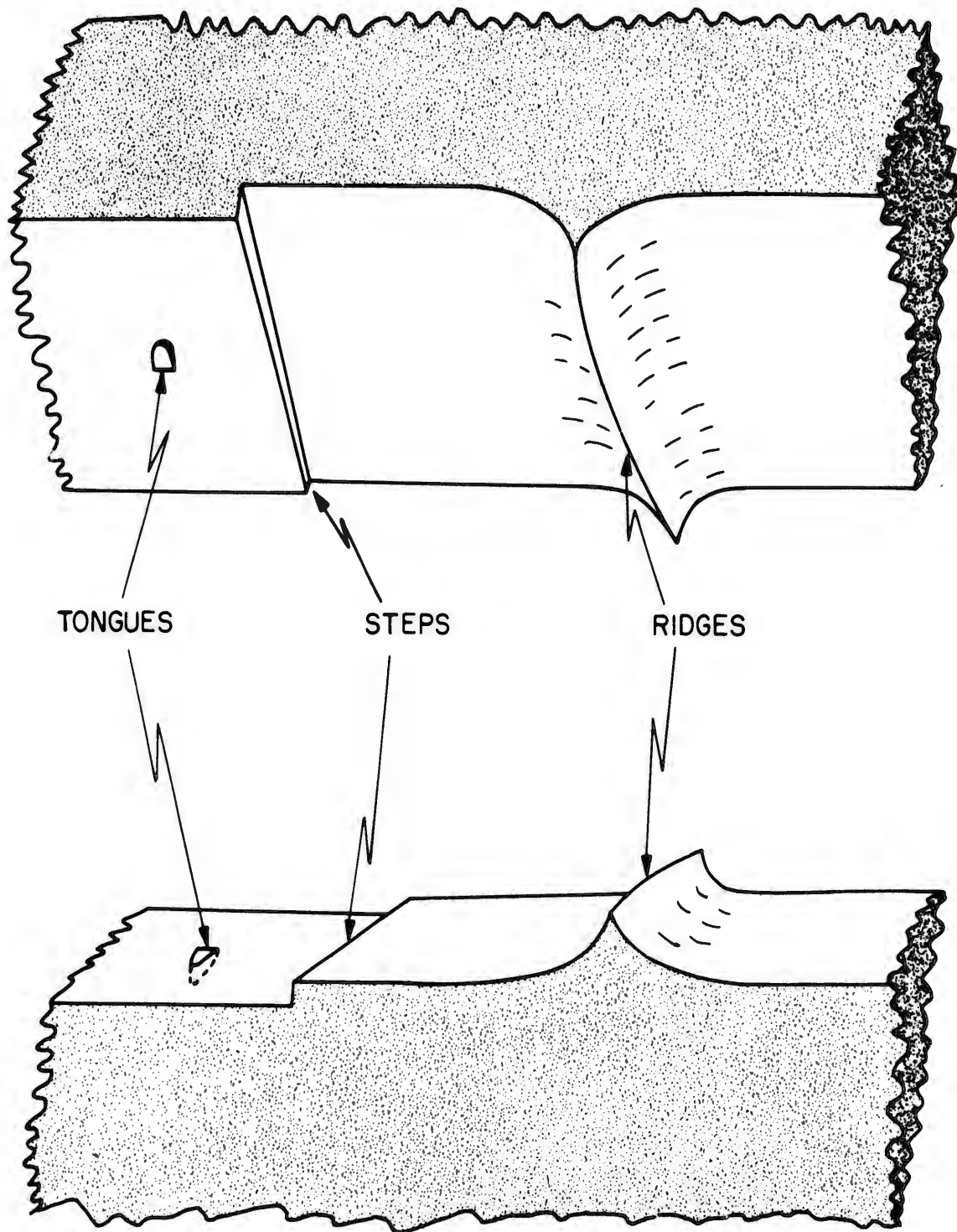


Fig. 2 - Simplified sketches of three distinctly recognizable features of quasi-cleavage. Mating fracture surfaces show steps and tongues which mate as in true cleavage, and tear ridges which stick out from both surfaces and therefore do not resemble true cleavage. Tear ridges are similar to the chisel edges that result from stretching apart very ductile tensile specimens.

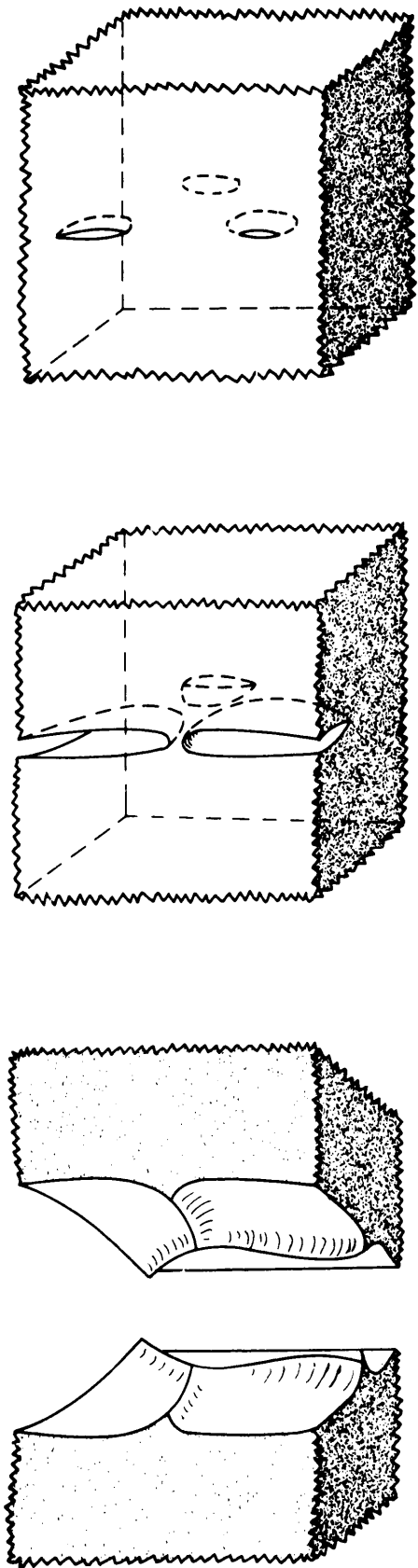


Fig. 3 - Sketch of a frequently observed feature of quasi-cleavage. Three submerged cracks, lying in approximately the same plane, grow together from top to bottom in the sketch. Plastic deformation at their tips, as they approach one another, causes the formation of tear ridges on both fracture surfaces. Though three submerged cracks are sketched - with three resultant tear ridges intersecting one another - other configurations of joined ridges develop from other combinations of submerged cracks.

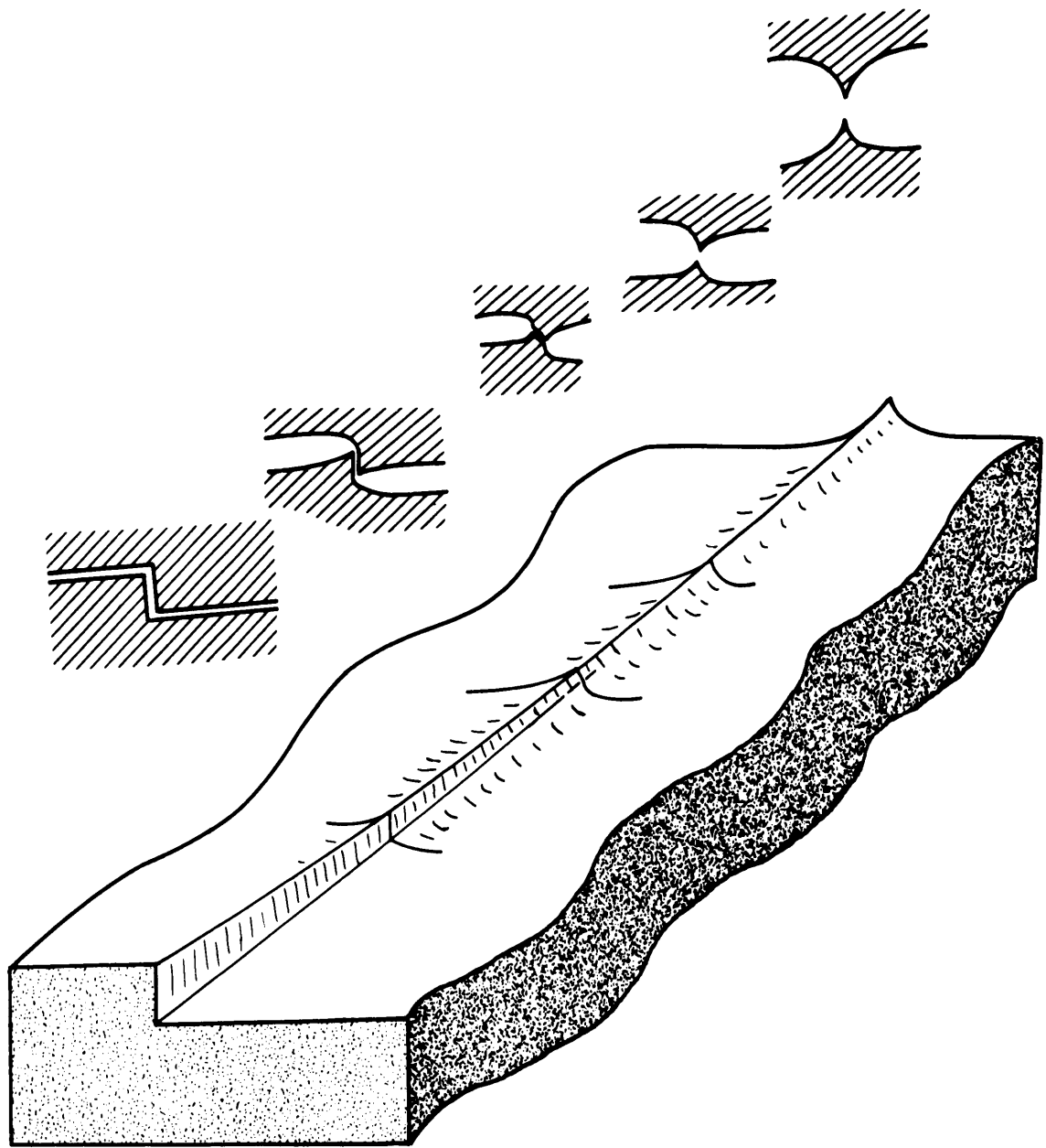


Fig. 4 - Simplified sketch of one feature of quasi-cleavage. Steps are sometimes seen blending in with tear ridges. Cross-sections of the two parted halves are sketched at the top while the bottom shows the bottom of the two fracture surfaces. The step is to the left while the ridge is to the right.



Fig. 5 - Fine scale markings on a quasi-cleavage facet in type 410 stainless steel wire broken at room temperature. The fracture initiation region for this facet is seen just to the left of center of the facet. The large arrows point out the boundaries of the facet while the small arrows indicate river patterns. Cellulose acetate replica technique. 12,000X.



Fig. 6 - Quasi-cleavage in AMS 6434. Specimen broken at liquid nitrogen temperature. Quasi-cleavage facets may be seen between the arrows. Cellulose acetate replication technique. 6,000X.

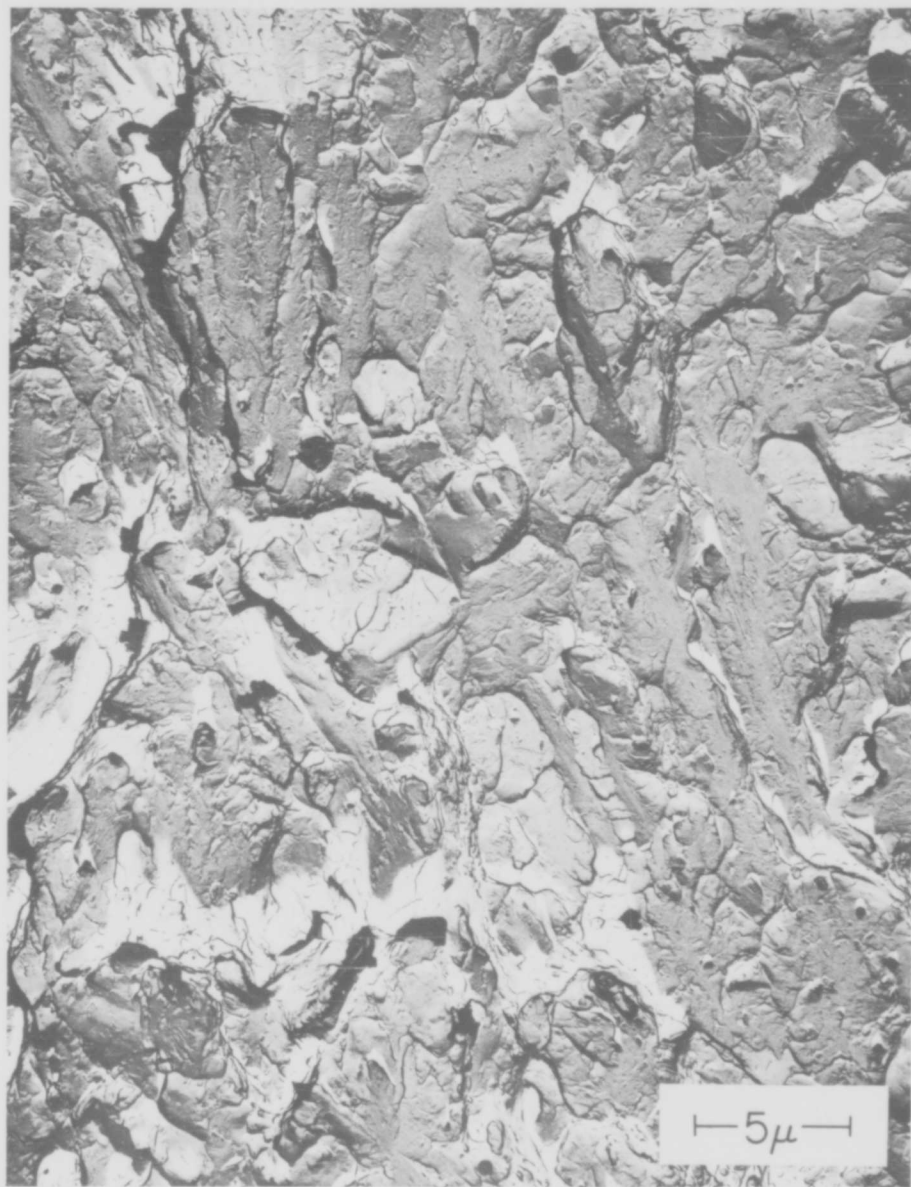


Fig. 7 - Quasi-cleavage in AMS 6434. Different region of same replica from which Figure 6 was obtained. 6,000X.

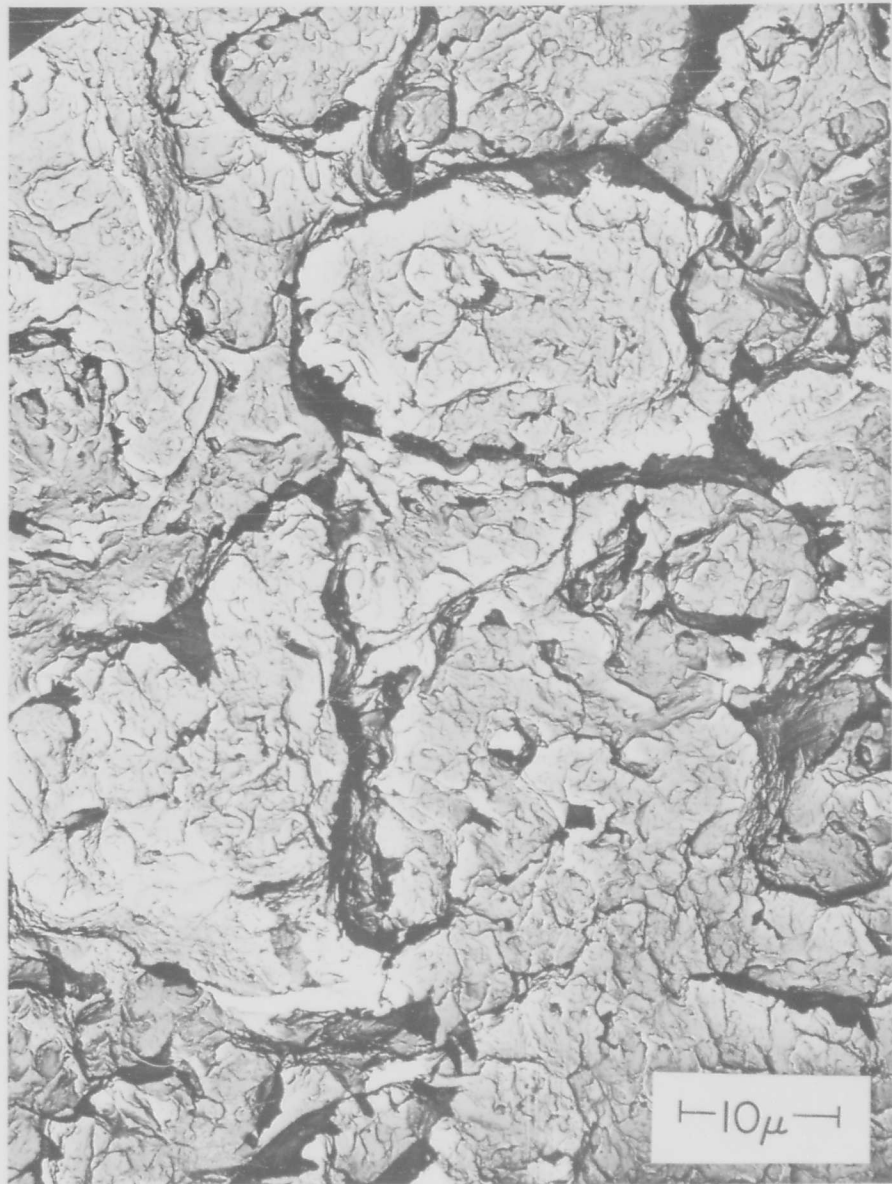


Fig. 8 - Quasi-cleavage in high strength die steel showing considerable secondary cracking. Cellulose acetate replica technique. 3,000X.

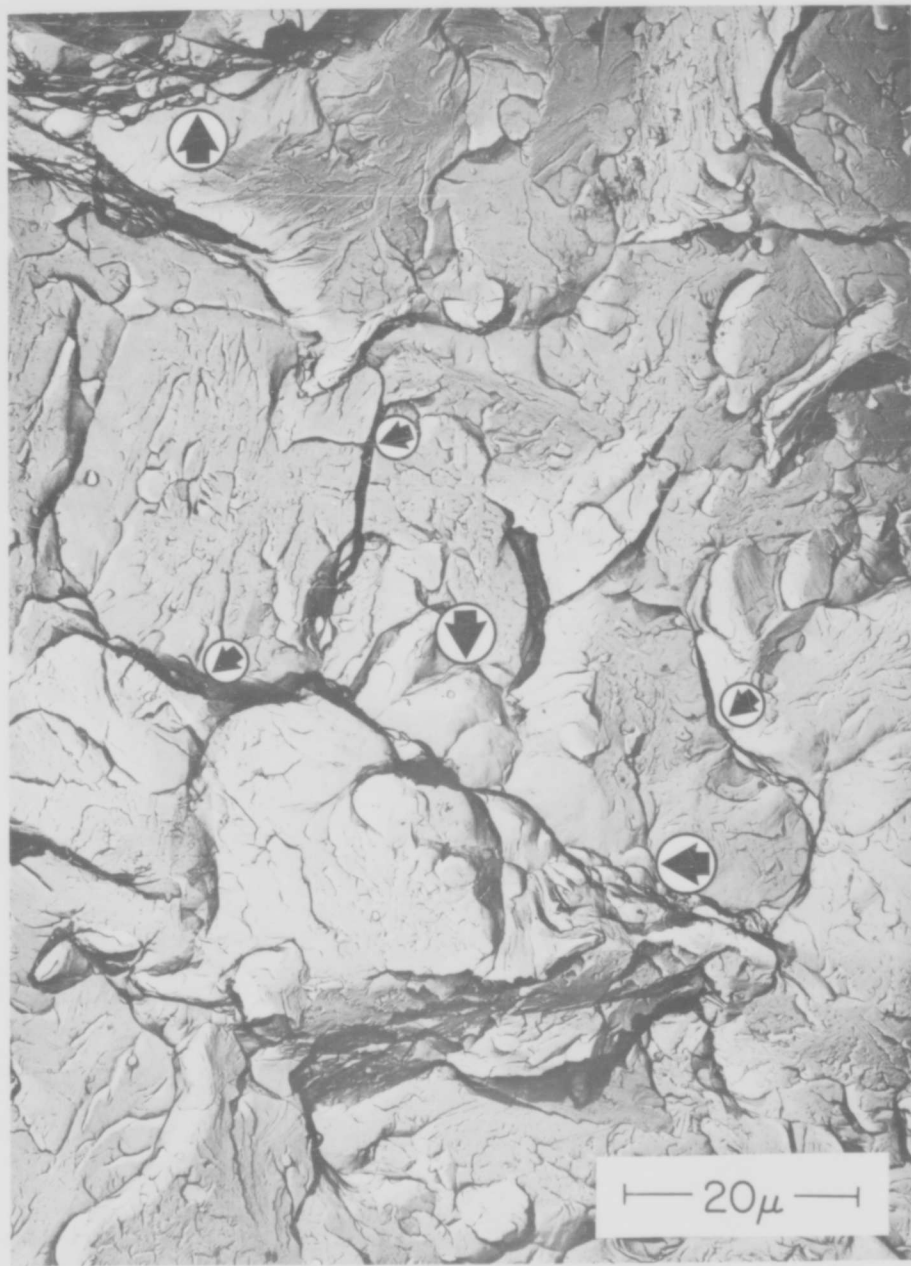


Fig. 9 - Quasi-cleavage in AISI type 410 stainless steel, quenched and tempered and broken at room temperature. The large arrows indicate dimples while the small arrows indicate abrupt changes in elevation. Palladium shadowed direct carbon replica. 2,250X.



Fig. 10 - Room temperature fracture in 5% Cr die steel showing a few quasi-cleavage facets (between arrows). The main fracture mode is dimpled rupture. Cellulose acetate replication technique. 6,000X.

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