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EFFECTIVE GRAIN SIZE FOR CLEAVAGE FRACTURE IN PEARLITIC EUTECTOID STEEL

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INTRODUCTION

The prior-austenite grain size has been established as the dominant microstructural factor controlling the fracture toughness in pearlitic eutectoid steel; the finer the austenite grain size, the greater the toughness, with this behaviour relatively independent of pearlite spacing and colony size [1]. However, not only are austenite grain boundaries no longer present after the completion of austenite/pearlite transformation, it is often observed that pearlite colonies can cross austenite grain boundaries [2, 3]. Therefore, the effect of prior-austenite grain size on toughness cannot be a direct one, but must instead have a controlling influence on some aspect of the interpearlitic colony structure which does control the fracture process.

In order to clarify the role of austenite grain size on toughness, direct correlations between fracture surface and microstructure have been carried out. This includes measurements of the average cleavage facet size, and direct determination of the orientation relationships among ferrites in adjoining pearlite colonies by thin-foil transmission electron microscopy (TEM) techniques, specifically the microdiffraction capability of the scanning mode of the TEM.

MATERIALS

The eutectoid steel studied is the basic rail composition used in the United States, containing 0.81% C, 0.87% Mn, 0.17% Si, 0.02% P and 0.01% S. After austenitization in the temperature range from 800° C (1073° K) to 1200° C (1473° K), specimens were isothermally transformed in salt pots for various times and temperatures in the range of 550° to 675° C (823° K to 948° K) to produce a fully-pearlitic microstructure. Pearlitic spacings ranged from 1000 Å to 3000 Å, and prior-austenite grain sizes from 15 - 150 µm were attained. These isothermal heat treatments produced no significant changes in colony size, which were in the range of 4.3 - 7.1 µm. Fracture surfaces of fatigue pre-cracked Charpy specimens, which were fully transgranular cleavage even at room temperature, were characterized by optical, SEM and TEM studies. More detailed heat treatment and mechanical testing procedures have been previously documented [1].

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EXPERIMENTAL RESULTS AND DISCUSSIONS

Direct Correlations Between Fracture Surface and Microstructure

In order to clarify the roles of pearlite colony and prior-austenite grain boundaries in the process of brittle transgranular fracture, the nature of the fracture surface has been directly correlated to the microstructure.

By direct etching of the fracture surface with saturated Picral, it was revealed that the majority of individual cleavage facets consisted of a number of pearlite colonies (Figure 1). In addition to the direct etching technique, a modified Almond et al's [4] method has been used to examine the fracture surface and microstructure simultaneously. A fractured specimen is mounted in a thermally plastic lucite and sectioned at an angle to the fracture surface. The surface that makes an obtuse angle with the fracture surface is then polished and etched by normal metallographic procedures, and the lucite is dissolved away with acetone. The edge between the fracture surface and etched surface is then examined by scanning electron microscopy (SEM). While in some cases it was observed that cleavage cracks could be obstructed at pearlite colony boundaries, more often the crack traverses several pearlite colonies (Figure 2), in agreement with the direct etching technique. This observation is consistent with that of Turkalo [5].

These techniques could not reliably differentiate between prior-austenite and pearlite colony boundaries. In an attempt to investigate the direct role of prior-austenite grain boundaries in crack propagation, thermal etching [6] in vacuum has been used to reveal the prior austenite structure. After the thermally-etched specimens were fractured by hammer impact at -45° C (228° K), the edge between fracture surface and thermally-etched surface was examined by SEM. It was found that while a crack often changed direction at a prior austenite grain boundary, a single cleavage facet could sometimes cover more than one austenite grain.

Cleavage Facet Size

The results from the direct correlation studies suggested that both the pearlite colony and prior-austenite grain boundaries, and especially the latter, can act as effective obstacles to crack propagation. However, the fact that the crack can often be continuous across these boundaries strongly suggests that another parameter, i.e., the cleavage facet size, is the more critical microstructural unit. By establishing the origin of this unit, a clearer picture of the fracture process should emerge. On a qualitative basis, since most of the energy-absorbing processes for a propagating crack are associated with boundaries where the crack changes direction [7], one would expect that the finer the facet size, the more difficult would be the process of crack propagation.

In fractured, pre-cracked, Charpy specimens of rail steels, the average cleavage facet size was measured from stereo pairs of microfractographs by the linear intercept method. The average facet size was found to be a strong function of the prior-austenite grain size, in agreement with previous results [1] showing that the fracture toughness in the fully-pearlitic steel was primarily dependent on the prior-austenite grain size. However, the facet size was always somewhat less, particularly for the larger prior-austenite grain size materials (Figure 3), implying that the facet size is controlled by, but is not identical to the prior-austenite grain size.

Orientation Relationships Among Ferrites in Adjoining Pearlite Colonies

It is well established that ferrite usually cleaves on {100} crystallographic planes [8]. In pearlitic steels as well, the cleavage cracks apparently follow specific cleavage planes in the ferrite lamellae [5, 9]. One recent investigation, using an etch pit technique and goniomicroscope, measured a {100} cleavage plane for ferrite in pearlitic steel [10]. If we adopt the hypothesis that a single cleavage facet corresponds to fracture along closely aligned cleavage planes (say {100}), then, the fact that a crack can propagate across a number of pearlite colonies, requires that the {100} planes in the interlamellar ferrite in these colonies be essentially continuous. In order to investigate this possibility, the ferrite/ferrite orientation relationships in neighbouring colonies were studied by selected-area electron diffraction. Three diffraction patterns were usually taken for a given pair of pearlite colonies; two from each colony and one encompassing both regions and the colony boundary. The diffraction patterns obtained were often quite complicated mainly because of the numerous diffraction spots from the cementite. In such cases, micro-diffraction by scanning transmission electron microscope (STEM), permitted the unique and simple determination of individual ferrite laths in the lamella. For even though the width of ferrite lamella is on the order of 1000 Å, this is well within the resolution of micro-diffraction.

Figure 4 illustrates an example of this, where in this case four colonies have a common $\{100\}_\alpha$ zone axis. Their misorientations, determined from both the selected-area diffraction and micro-diffraction patterns, vary from 3° to 19°. The relatively large misorientation of 19° between grains 3 and 4, does not obviate a common cleavage plane for this grain pair since they have essentially the same $\{100\}_\alpha$ zone axis. Thus, the boundary between each of the grain pairs is close to a symmetric tilt boundary. The $\{100\}_\alpha$ rotation axis varied by less than 5° in this case.

Other diffraction pairs yielded non-equivalent zone axes, and for these cases standard stereographic projections for cubic crystals were used to ascertain the angle between possible common $\{100\}_\alpha$ planes in the adjoining colonies. Nineteen individual pairs of colonies were analyzed for each of two specimens chosen; one was for a large prior-austenite grain size, and the other was for a small prior-austenite grain size. In both cases, the pearlite colony size was similar. Results are summarized in Table 1. For sample 1, it is of interest to note that in almost 65% of random colony pairs examined, misorientation between $\{100\}_\alpha$ in the adjacent colonies is less than about 5°. If an orientation difference of about 10° is included and assumed to still produce a single facet, about 90% of colony pairs of sample 1 and about 65% of sample 2 can generate macroscopically flat fracture facet. Such large percentages are consistent with the fact that facet sizes are many times larger than the colony sizes. Techniques are currently being developed to determine, by the same method, orientation within an identified fracture facet, which should yield more definitive results.

The results to date demonstrate that {100} cleavage planes of ferrites can be closely aligned across a number of pearlite colonies. Since a running cleavage crack must alter direction at mismatch boundaries, these orientation units describe an individual facet. As we have discussed, toughness can be related to the number of these mismatch boundaries in a microstructure. Then, if the prior-austenite grain structure can control the resultant ferrite orientations in pearlite, the influence of austenite grain size on toughness is explainable.

There have been two different approaches to account for the orientation relationships between the ferrite of pearlitic structure and the parent austenite. Smith and Mehl [11] proposed that the orientation of the pearlitic ferrite is related to the prior-austenite grain in which it is contained. In this model, the pearlitic ferrite from a single austenite grain has a preferred orientation, such that cleavage planes in adjacent pearlite colonies are continuous or closely aligned. Thus, a finer prior-austenite grain size would lead to smaller units of preferred ferrite orientation and a higher fracture toughness. The size and number of such units should correspond closely to the austenite grain size.

An alternative explanation, originally hypothesized by Smith [12], is that the ferrite lamellae of a given transformed austenite grain should bear a specific orientation relationship to a neighbouring grain of austenite; this adjacent grain being the true parent grain for the crystal of ferrite. In such a model, the effect of prior-austenite grain size on toughness might then be explained by relating austenite grain size to the size of orientation units in the pearlite. Each unit is made up of adjacent pearlite colonies of common parentage and therefore common ferrite orientation. In a structure that has a large prior-austenite grain size, there may be many colonies, nucleated on a given grain side, and therefore of the same parentage. These colonies would make up one unit. In a fine grained structure, however, far fewer colonies would have common parentage. This would also mean that for an equal pearlite colony size, the fine grained structure would have considerably more orientation units and therefore would present more resistance to crack propagation. In support of this hypothesis, Dippenaar and Honeycombe [13] recently found in a high manganese steel that the pearlitic ferrite and cementite are related to the austenite grain into which they are not growing.

Both approaches satisfactorily rationalize the dependence of toughness on grain size. However, the lack of direct correspondence between prior-austenite grain size and facet size in this study tends to support the approach of Smith, and Dippenaar and Honeycombe, although considerably more work is needed to establish the origin of these pearlite colony units. Such studies are underway using partially transformed specimens of eutectoid steel.

CONCLUSIONS

(1) The average cleavage facet size in this pearlitic eutectoid steel is a strong function of the prior-austenite grain size, but it is always somewhat less, particularly for the larger grain size materials.

(2) {100} cleavage planes of ferrites are often closely aligned across a number of pearlite colonies.

(3) The size of these orientation "units" can be considered as the average cleavage facet size.

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Table 1 Angles Between $\{100\}_\alpha$ Planes in Neighbouring Colony Pairs

Sample No.	Austenite Grain Size, µm	Cleavage Facet Size, µm	Pearlite Colony Size, µm	Number of Colony Pairs of a Given Misorientation		
				0 - 5°	5 - 10°	> 10°
1	147	96	5.7	12	5	2
2	25	25	5.9	5	7	7

Figure 1 Fracture Surface Etched by Saturated Picral

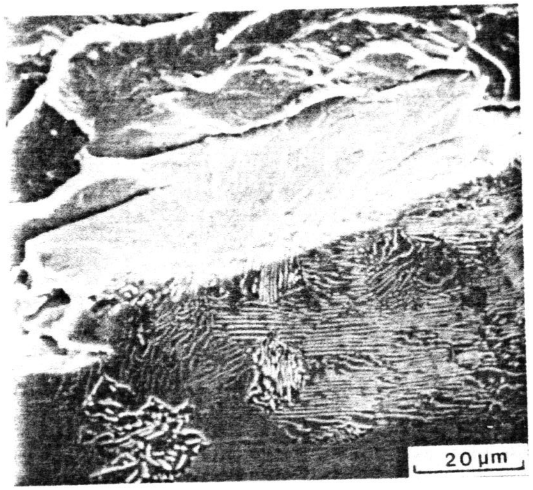


Figure 2 Direct Correlation Between the Fracture Surface and the Microstructure

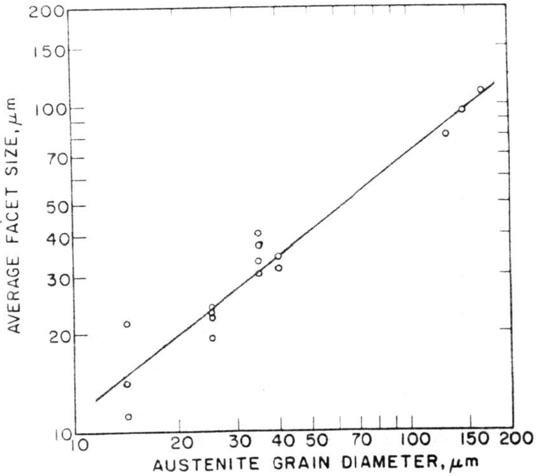
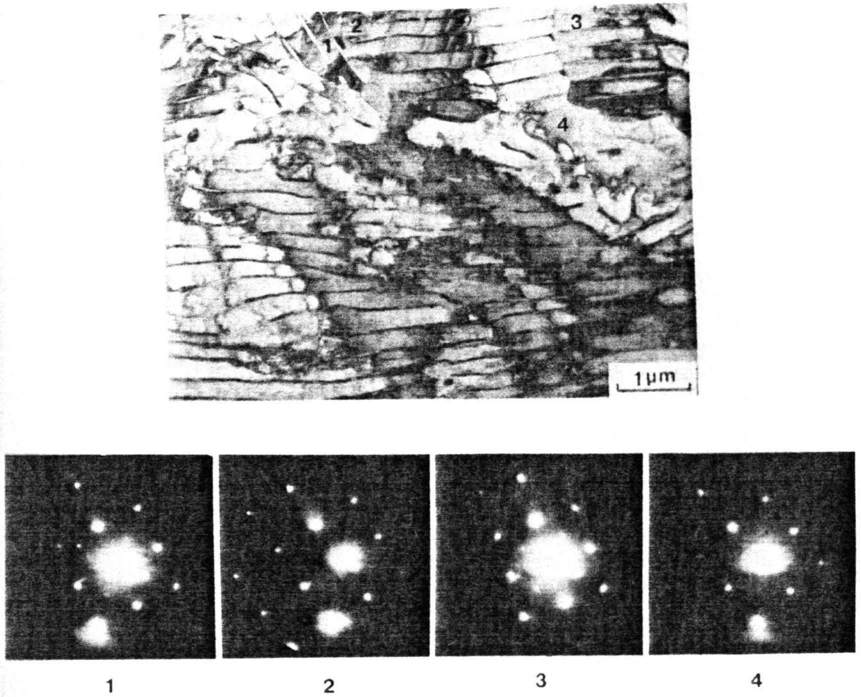


Figure 3 Dependence of the Cleavage Facet Size on the Prior-Austenite Grain Size; Slope = 0.795



(a)

Figure 4 Four Colonies with a Common $\{100\}_\alpha$ Zone Axis.

(a) Bright Field and Corresponding Micro-Diffraction Patterns; Misorientation Between Grain 1 and 2 is 6°; Grain 2 and 3, 3°: Grain 3 and 4, 19°,

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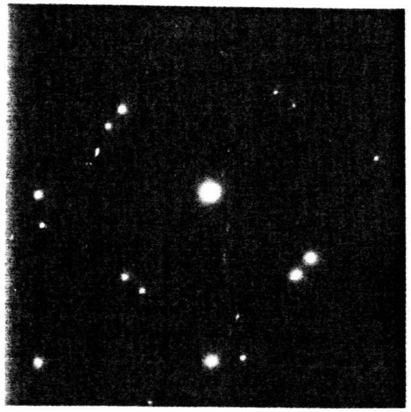

(b)

Figure 4 Four Colonies with a Common $\{100\}_{\alpha}$ Zone Axis
(b) Selected-Area Diffraction Pattern from Grain 3 and 4