RESISTANCE TO BRITTLE FRACTURE OF DUAL-PHASE STEELS

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ABSTRACT

Two types of dual-phase steels are studied: one where ferrite is substructured,the deformation being performed in the intercritical range of the A_1-A_3 temperatures, and the other one without that substructure. Performing instrumented Charpy tests, the excellent resistance to brittle fracture of the first type has been put into evidence and the highly favourable role of the subgrains has been put forward by microfractography. Moreover,measurements of the rupture paths in the Charpy specimens clarify the complex role of the second phase as it results from the competing resistances and ductilities of ferrite and second phase in function of the temperature at which the fracture tests were realised.

KEYWORDS

Dual-phase steels, brittle fracture, intercritical rolling,sub-structure, instrumented Charpy tests, microfractography, rupture path.

INTRODUCTION

In the past fifteen years, extensive research efforts have been devoted to produce high strength steels in grades covering both structural and automotive applications (Gray,1972 ; Leslie,1975). In this latter field, an increased use of high strength steels is restricted as a consequence of formability limitations. Also,the so-called dual-phase steels (Hayami,1975, Rashid,1978), exhibiting excellent formability, have been welcome, among others, by automotive engineers.

Dual-phase steels exhibit a mixed microstructure, consisting of polygonal ferrite in which are dispersed small islands of out-of-equilibrium phases namely austenite, bainite and martensite, the latter being generally predominant. Such a result is achieved when performing a thermal treatment in the intercritical range of temperatures (between the A_1 and A_3 points) of the Fe-C phase diagram or when using a peculiar hot rolling procedure in the case of hot strips or plates.

This paper mainly deals with this last type of products, in gages above 5-6mm. The purpose of the research is the study of the resistance to brittle fracture, an aspect which has not been documented extensively up to now.

EXPERIMENTAL PROCEDURE

The steels investigated (Table 1) were rolled from 1000°C according to various procedures (Table 2) down to 12mm, and directly submitted to an accelerated cooling with the exception of plate B2 held for 30 min. at 730°C before final cooling.

Table 1 - Chemical Composition of the Steels (weight %)

	C	Mn	Si	Cr	Mo	Nb	Al_{tot}	N_{tot}
B	0,07	1,1	0,8	0,5	0,4	-	0,045	0,006
C	0,14	1,23	0,31	-	-	0,012	0,025	0,0096

Table 2 - Finish-Rolling Schedule

Plates	B 1	B 2	B 3	B 4	B 5	B 6	C
Temperature (°C) at the penultimate pass	870	790	750	750	750	780	890
Temperature (°C) at the last pass	850	730	720	720	720	760	720
Reduction (%) at the last pass	20	20	11	20	25	25	11

Tensile testing was performed on round specimens, 4mm in diameter, the gage length being 10mm. Impact tests used an instrumented Charpy testing unit (Mathy,1978) and standard Charpy specimens cut off in the rolling direction. Microstructural examinations were performed using both optical and scanning electron microscopes on polished and etched (1% nital) specimens ; also, the transmission electron microscope has been used for observations on thin foils. Moreover, scanning electron microscopy was used to examine the fracture surfaces of those specimens. The grain size and the volume fraction of the second phase were measured with a quantitative image analyser as well as the rupture paths of nickel-plated sections through broken Charpy specimens (sections perpendicular to the notch).

For that purpose, we used the roughness index R_L (Pickens, 1976),and the preferential propagation index in the second phase,Q (Shieh,1974).

RESULTS

Microstructures

The seven rolled plates examined exhibited a dual-phase microstructure, consisting of a dispersion of martensitic or bainito-martensitic islands in a ferritic matrix (the volume fraction of the former ranging from 10 to 50%). The mean ferrite grain diameter extends from 5 to 8 µm, and an increasing amount of substructure appears from B 3 to B 6 for the plates submitted to important deformation in the intercritical range and immediately cooled as described before (Fig. 1).

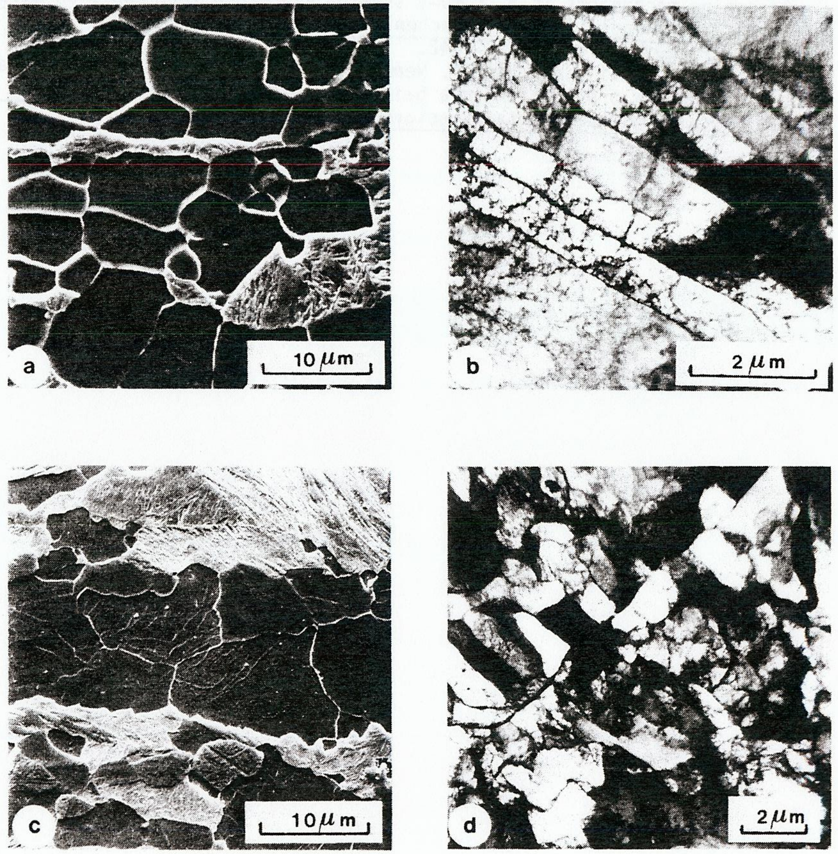

Fig. 1 - Microstructural features of substructured steels
a and b :plate B 3
c and d :plate B 6

Mechanical Properties

Tensile : Plate B 1 has yield and tensile strengths of respectively 290 and 635 MPa, its total elongation being 31%. The six other plates range from 480 to 580 MPa for yield strength, from 780 to 870MPa for tensile strength, and from 19 to 24% for total elongation.

Impact : Plates B 1 to B 6 have shelf energies between 100 and 120 J/cm^2,and this energy does not fall under a level of 35J/cm^2, even with temperature as low as -50°C. The situation is deteriorated for plate C : shelf energy 60J/cm^2,and temperature T_{K35} at which 35J/cm^2 are obtained 40°C.

A significant improvement of all the transition temperatures is obtained for all plates B when the substructure density increases (Fig.2) This concerns as well the temperature at which the plastic hinges develop entirely across the specimen before brittle fracture propagates (general yielding temperature,Te), as the arrest temperature Ta (at which the propagating brittle crack is arrested) or the ductile initiation temperature Tm .

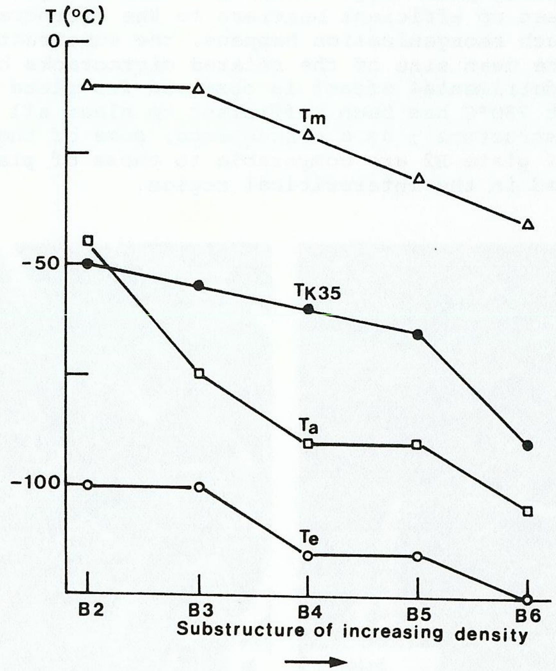

Fig.2 - Influence of substructure on transition temperatures.

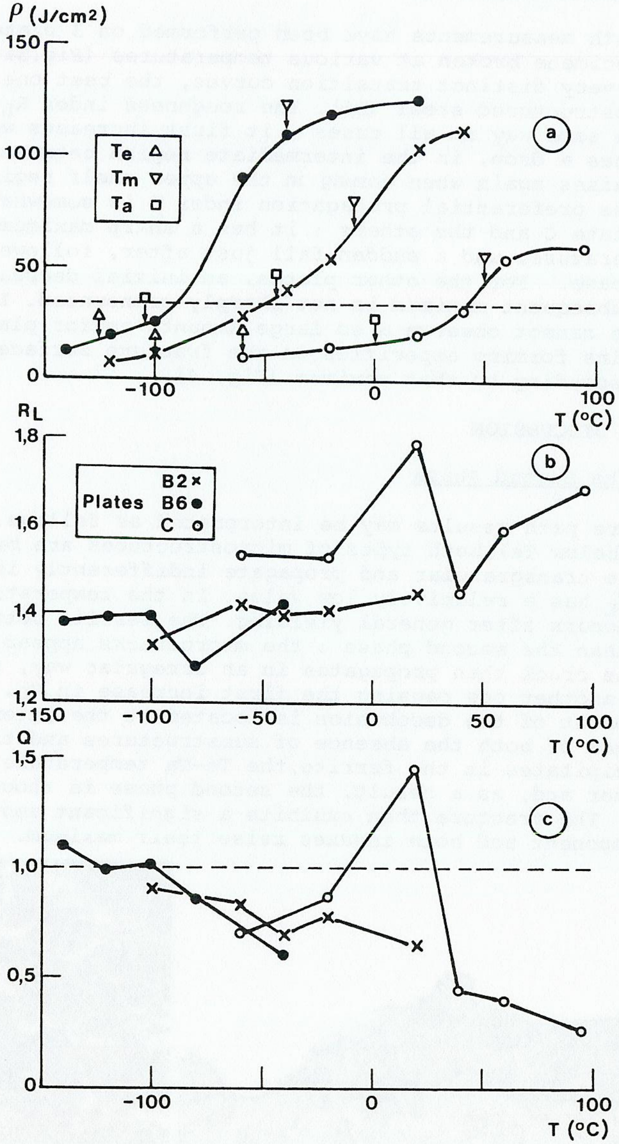

Fig. 3 - Temperature dependance, for dual-phase steels :
a. the impact strength (ρ)
b. the roughness index of the rupture path (R_L)
c. the preferential propagation index in the second phase (Q).

Rupture Path Measurements

Rupture path measurements have been performed on 3 plates (B2,B6 and C) for specimens broken at various temperatures (Fig.3a)). They exhibit three very distinct transition curves, the best one being related to the substructured steel (B6). The roughness index R_L behaves (Fig. 3b) in the same way in all cases : it first increases with temperature, then has a drop, in the intermediate region between Ta and Tm,and finally raises again when coming in the upper shelf region. The evolution of the preferential propagation index Q is somewhat different between plate C and the others : it has a sharp maximum, above 1, at room temperature, and a sudden fall just after, followed by a smoother decrease. For the other plates, an initial decrease is observed, and the subsequent maximum is not sharply pronounced. In those latter cases, one cannot observe a so large amount, as for plate C, of second phase grains forming asperities on the fracture surface at temperatures corresponding to that maximum (Fig. 4).

DISCUSSION

Role of the Second Phase

The rupture path results may be interpreted as follows. At low temperatures (below Te),both types of microstructures are brittle : the cracks are transgranular and propagate indifferently in the two phases and R_L has a relatively low value. In the temperature range Te-Ta, rupture occurs after general yielding. The ferrite better accomodates strains than the second phase : the microcracks appear at their interfaces. The crack then propagates in an irregular way, from one microcrack to another one causing the first increase in R_L. For plate C, a larger amount of the decohesion is located at the interfaces. As a consequence of both the absence of substructures and the presence of microprecipitates in the ferrite,the Te-Ta temperature range of plate C is higher and, as a result, the second phase is thougher than the ferrite. The fracture then exhibits a significant amount of intergranular component and both indexes raise their maximum.

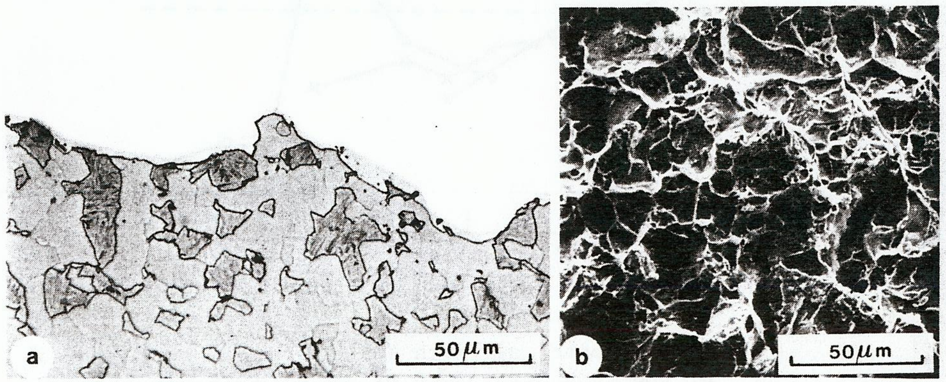

Fig. 4 - Asperities formed on the rupture surface by the second phase (Plate C - specimen broken at 20°C).

With still increasing temperatures, ferrite becomes more and more ductile, and sufficiently releases the stresses at the interfaces : microcracks appearing at those weak points become less frequent, so that rupture propagates in a smoother way, leading to reduced values of R_L and Q. As temperature approaches Tm, rupture develops into a ductile mode, so that the crack avoids more and more the harder second phase (further decrease of Q) whereas dimples formation induces the increase of roughness index R_L.

Role of the Substructure

Metallographic examinations of sections through broken specimens and microfractography of the rupture surfaces (Fig. 5) neatly put forward the highly favourable role of the subgrains. The disposition of secondary cracks (Fig. 5a), as well as the size of the cleavage facets (Fig. 5b) reveals that the subboundaries are sometimes able to stop microcracks. So, they induce a higher amount of plastic deformation at a given temperature before the crack can propagate, resulting in a larger rupture energy. For the same reason the various transition temperatures are lowered, proportionally to the number of subgrains. Also, the rolling schedule must be performed as to promote a certain rearrangment of the dislocations network: with a too weak reduction in the last rolling pass (Fig. 1a and b), this reorganization is unsufficient to set up efficient barriers to the microcracks. Inversely, when too much reorganization happens, the substructure tends to coalesce and the mean size of the related microcracks becomes then larger. This detrimental effect is observed for plate B2, which holding time at 730°C has been sufficient to clear all the grains from their substructure ; as a consequence, some of the transition temperatures of plate B2 are comparable to those of plate B1, which was not deformed in the intercritical region.

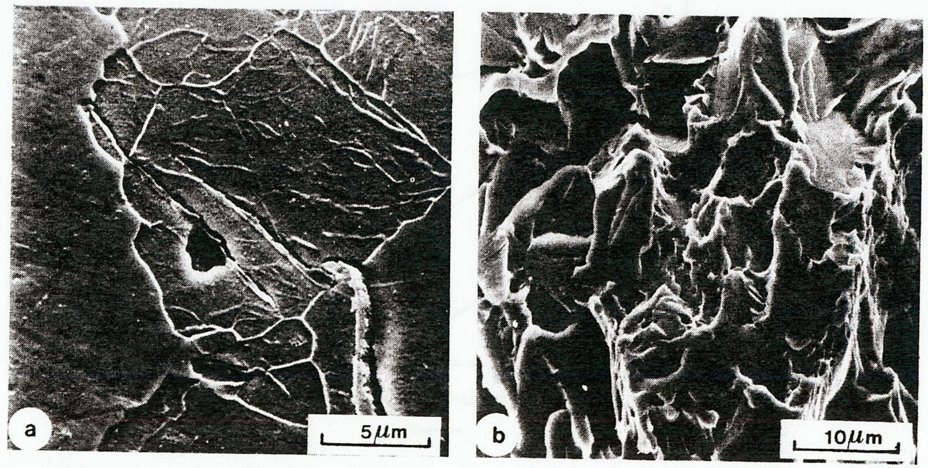

Fig. 5 - Influence of substructure on the crack propagation - Plate B6

Moreover, a somewhat higher temperature at the last pass (compare plates B5 and B6) leads, for a given reduction, to a higher substructure density, because of the reduced quantity of ferrite which undergoes most of the deformation.

CONCLUSIONS

A good resistance to brittle fracture of high strength formable dual-phase steels can be achieved by inducing in the ferrite a sufficient substructure. Indeed, that impedes large microcracks to develop easily, and so brings ferrite resistance nearer to that of the second phase.

We have combined the uses of instrumented Charpy tests and of metallographical examinations of the rupture path in Charpy specimens. This appears to be a powerful tool allowing a quantification of the rupture paths. This procedure is particularly suitable to study the physical phenomena related to the brittle rupture propagation in high strength formable dual-phase steels.

A detrimental effect of a dual-phase microstructure is the possible existence of intergranular rupture at the interfaces of the two phases, at temperatures corresponding to normal use. This study shows that this effect can be avoided when inducing in the ferrite a suitable substructure by an appropriate choice of the intercritical rolling procedure.

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