THE CAUSE OF SEPARATIONS AND ITS EFFECTS ON FRACTURE BEHAVIOUR

B. Engl, A. Fuchs*

In controlled rolled steels sometimes a fracture phenomenon referred to as separation is observed. A distinction can be made between two main types of separations: inclusion- and structure-type. The separations of the structure-type can be more of grain boundary-type or more of cleavage-type depending on processing conditions. The microstructural mechanisms are described. Separations do not affect the properties in the tensile test. Their influence on the notched bar impact test can be explained with a lamination model. The separations have no negative influence on the crack arrest behaviour in pipelines.

INTRODUCTION

Controlled rolling has proved to be an economic process in the production of HSLA-steels with excellent strength/toughness combinations for line pipes. Fractured tensile or impact test pieces of these steels sometimes show a special fracture phenomenon known as "separation", "delamination" or "splitting" (1)-(7).

These separations are located near the fracture region and are perpendicular to the main fracture and parallel to the rolling plane, fig. 1. Tensile test pieces normally show a larger separation in the centre, while impact test pieces frequently show a system of parallel separations of different order: The deepest separation in the midthickness devides the volume near the fracture in two parts. These are devided furtheron by separations of second order which are only of about half the depth of the midthickness separation. The new developed segments are again devided by shorter splits. Separations are formed by constraint stresses perpendicular to the main stress, (8).

Under dynamic conditions, where a larger crack propagation than in CVN-specimens is possible, for instance in DWTT-specimens or burst tests of pipes, the separations often show a periodic arrowhead-like pattern, fig. 2. An explanation of this pattern has been proposed associated with a stress gradient in the thickness direction and a periodic stress relief during crack propagation, (9).

* Hoesch Hüttenwerke AG, Dortmund

THE DIFFERENT KINDS OF SEPARATIONS AND THEIR MICROSTRUCTURAL CAUSES

The results of detailed microscopic investigations of the microstructural features of the separated surfaces allow to differ between two main kinds of separations: Inclusion-type and structure-type, (10).

Separations of the inclusion-type occur at the interface between the inclusions, for instance elongated MnS, and the matrix. The tendency to the inclusion-type of separation is more associated with the cleanliness of the steel than with thermomechanical treatment and can be reduced by lowering the inclusion content by special metallurgical procedures. Therefore the inclusion-type is of minor importance in modern clean steels.

Detailed scanning-electronmicroscopic investigations of the separations of the structure-type revealed that they can run transcrystalline, intercrystalline or mixed.

Fig. 3 shows separations in a CVN-specimen which are mainly of the transcrystalline cleavage-type. One can see the typical cleavage facets, with the cleavage lines and steps in the form of "river lines". The main fracture surface shows a shear fracture with the usual dimpled appearance. The occurence of cleavage separations mainly depends on texture. Since cleavage fracture in iron and ferritic steels occurs on crystallographic {200} planes, an orientation of these planes parallel to the rolling plane favours the occurrence of the cleavage-type. In the presented example a very high proportion of {200} planes parallel to the rolling plane was achieved due to heavy rolling in the $\gamma + \alpha$ -region between 750°C and 600°C.

Fig. 4 shows a separation in a tensile specimen which is mainly of the intercrystalline grain boundary-type. The tensile specimen had been deloaded just before the main fracture. It can be seen that the separations form shortly before the main fracture after a considerable reduction of area. Due to the high degree of cold deformation, the surfaces of the separations reveal elongated grains with a lined structure on the grain boundaries in the highly necked region, left SEM photo. These lines can be explained by slip planes which have formed steps at the grain boundaries. Near the end of the separation, right SEM photo, the grain boundary mode of the separation surface is clearly visible because of less deformation and the absence of glide steps. Detailed investigations by light- and electron microscopy revealed that in connection with grain boundary separations, carbides were found at the grain boundaries, which had a more or less film-like morphology. By electron diffraction they were identified as cementite, (10). There was no evidence for the existance of film-like precipitated Nb-carbonitrides, which have been reported in the literature in connection with separations, (11).

The main reason for the occurrence of grain boundary-type separations is attributed to severe thermomechanical rolling procedures in the lower austenite region where recrystallization is retarded and austenite grain elongated. Further it can be assumend that the thermomechanical treatment promotes the film-like precipitation of grain boundary cementite during cooling.

This in ferrite-pearlite steels rather unusual fracture along grain boundaries suggested the assumption of a certain segregation mechanism of the grain boundaries. First hints to the rate of temper embrittlement in connection with separations were given by Kunishige (12), who demonstrated that the intensity of separations increased with the amount of phosphorus.

Because diffusion is the rate controlling process for such segregation to the grain boundary time and temperature should be interchangeable in certain ranges. To prove this some heat treatments were carried out with a conventional microalloyed HSLA-steel (13) after controlled rolling in the lower austenite region and quenching. The samples were annealed in the range of 500-650°C for 0,5 - 24 hours. The intensity of separations was investigated on tensile specimens by measuring the depth of the midthickness separation.

To verify that the grain boundary tempering is a diffusion controlled segregation process the formalism of Hollomon and Jaffe (14) was used. The results are plotted in fig. 5 and show that temperature and time can be combined in a single reaction parameter.

$$P = T (\log t + 9) \times 10^{-3} \quad (T \text{ in K, } t \text{ in s})$$

The time-temperatur interchangeability of this reaction parameter corresponds with an activation energy of about 50000 cal/mol. This value is in good agreement with newer investigations (15) of the diffusion of phosphorus in ferrite, where 52300 cal/mol were found.

The intensity of separations of the structure-type and whether they are more of the cleavage-type or of the grain boundary-type depends on the parameters of the industrial processing schedule. From the simplified schematic representation, fig. 6, it can be seen that in conventional plate rolling, with only a moderate strength/toughness combination, recrystallization takes place during or between the rolling passes due to the high rolling temperatures. Much better strength/toughness combinations are achieved with the process of controlled rolling (16). The lower rolling temperatures which lead to a very fine microstructure simultaneously enhance the tendency to the occurrence of separations. As can be seen from fig. 6 separations in controlled rolled plates usually will be more of cleavage-type due to partially rolling in austenite + ferrite region (increased texture formation) and the absence of grain boundary tempering because of the relatively fast air cooling. Separations in controlled rolled strips will be more of grain boundary-type because of less texture formation and extended grain boundary tempering during the slow cooling in heavy coils.

Normalizing completely removes the tendency to structural separations, but the good strength/toughness relation of controlled rolled steels is impaired simultaneously.

INFLUENCE OF SEPARATIONS IN TENSILE AND CHARPY TESTS

The mechanical behaviour of steel exhibiting separations of the structure-type was investigated in tensile and Charpy tests of mill produced pipe steels (VNb-steel of the grade X 65 to X 70). In tensile tests the separations form in the highly necked region just prior to main fracture (see fig. 4). Therefore the yield strength, tensile strength and elongation cannot be influenced by separations.

In through-thickness tensile specimens of steels which showed large structural separations in the longitudinal test pieces high reductions of area up to 50 % were attained. In such through-thickness specimens small separations were absverved which were consequently perpendicular to the rolling plane (10). The tendency to structural separation therefore does not mean inferior ductility in the through-thickness direction.

In fig. 7 a typical curve of the absorbed energy in CVN-tests versus temperature is shown (thick line). It can be seen that after appearing of 100 % shear fracture ($C_{V}100$) the absorbed energy still increases ("rising shelf") until it converges to a constant shelf energy at higher temperatures. This behaviour is obviously connected with the appearance of separations.

It is possible to quantify the amount of separations by measuring their depth and number in fracture profiles (17) or easier to semiquantify their intensity by a classification from weak to strong as it is shown in fig. 7. As presented in fig. 7 the amount of separations attains a maximum at temperature where for the first time 100 % shear fracture appears and decreases with further rising temperature. The slope or "rising shelf" between $C_{V}100$ and $C_{V\ max}$ is apparently caused by the decreasing amount of separations. For a hypothetical material with the same toughness at the upper shelf $C_{V\ max}$ and a comparable microstructure but without the occurence of separations the dotted curve can be assumed.

By an investigation of the influence of specimen thickness on the specific absorbed energy it could be estimated earlier (18) that the energy loss due to the lamination effect of separations is comparable with the difference between the dotted and thick line in fig. 7. To utilize this effect for an additional increase of absorbed energy it is necessary to reduce the amount of separations without a deterioration of the fine microstructure. This is very difficult because less severe controlled rolling generally leads to less excellent strength/toughness combinations. But in the case of strip rolling an additional possibility is given by reducing grain boundary tempering. The knowledge of the critical region, see fig. 4, was utilized in some laboratory and industrial trials with reduced coiling temperature and increased cooling rate of the coils. The expected additional increase of absorbed energy by reducing grain boundary tempering could be demonstrated (18, 19). But it should be stressed that for an industrial large scale production the necessary processing conditions are very expensive.

SEPARATIONS AND CRACK ARREST BEHAVIOUR

For the investigation of crack arrest behaviour of long range shear fractures in gas transmission line pipes large scale tests were carried out in order to establish correlations between the necessary toughness for crack arrest and the conditions of the line pipe (20). As a parameter for the material toughness the absorbed energy in CVN-test at pipe test temperature was used.

After such large scale tests of pipes which were produced from controlled rolled steels with high toughness separations were abserved and caused some uncertainty concerning their possible influence on ductile crack arrest behaviour (21, 22). A negative influence of separations would only be possible if their lamination effect in the pipes, due to different dynamic behaviour, is stronger than in the corresponding Charpy test. A quantitative evaluation of the amount of separations in fractured pipes from large scale tests of the European Pipeline Research Group (20) and in the corresponding Charpy test pieces showed in all cases a lower intensity of separations in the fractured pipes compared with the corresponding CVN-test pieces (17).

Another evaluation was made by a calculation of the plastic deformation energy of the pipe fractures from the profile of the necked fracture region. Details of this calculation which also accounts for dynamic aspects are given elsewhere (17). In fig. 8 the specific plastic deformation energy from all available pipes fractured in large scale tests are plotted versus specific absorbed energy in the CVN-test at pipe test temperature. The material with only a weak tendency to separations is characterized by dark symbols, the material with stronger tendency to separations with light symbols. It can be seen that the absorbed deformation energy in the pipe increases as expected with the absorbed energy in the CVN-test. No tendency can be seen that material with stronger separations shows lower deformation energies in the pipe compared with material with less separations.

This results demonstrate that the lamination effect of separations is already sufficiently taken into account in the value of the CVN-test and that no greater lamination effect occurs under the different dynamic conditions in large scale tests. From all this findings it can be concluded that separations cannot have a negative influence on crack arrest behaviour.

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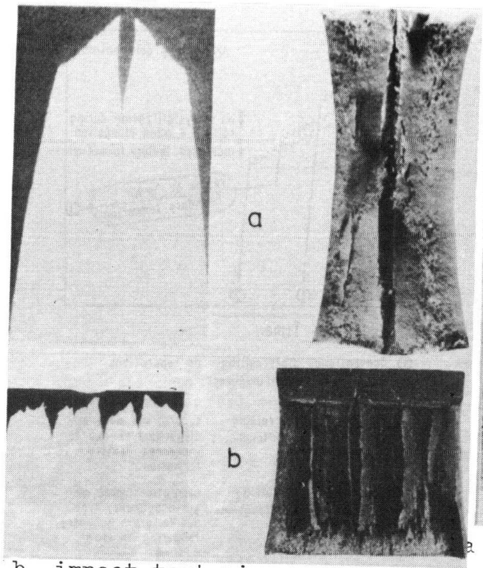
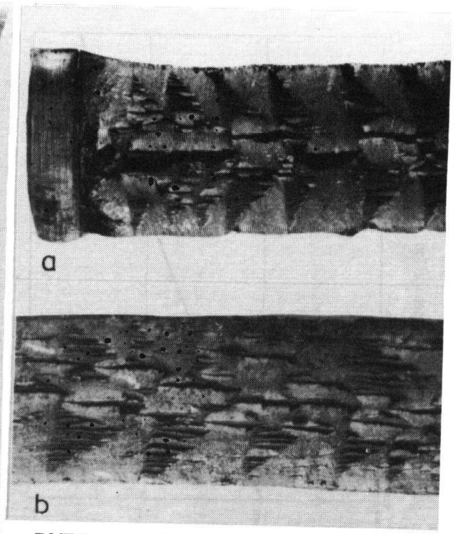


b impact test piece

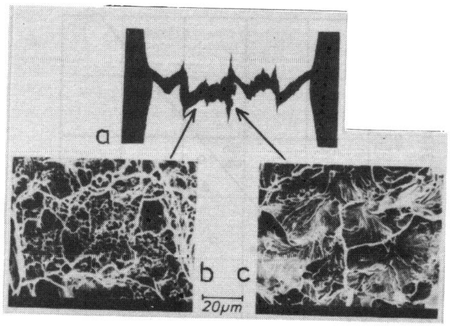
Figure 1 Macroscopic appearance of separations



a DWTT-specimen

b pipe fracture in burst test

Figure 2 Arrowhead-like arrangement of separations



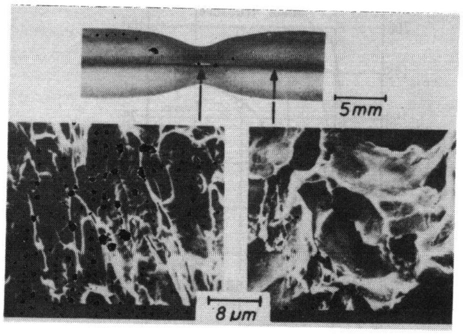
a fracture profile

b principal fracture plane

c separation surface

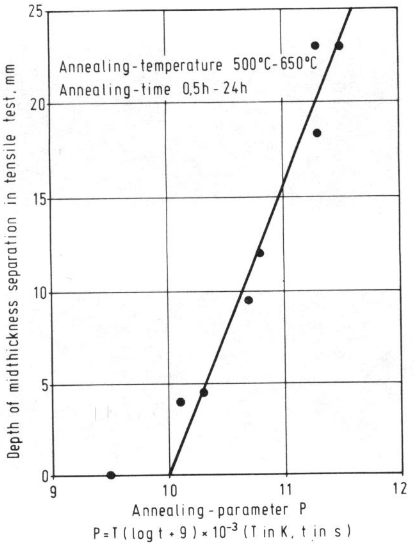
Impact test specimen

Figure 3 Separations of the cleavage-type



Tensile-specimen

Figure 4 Separation of the grain boundary-type



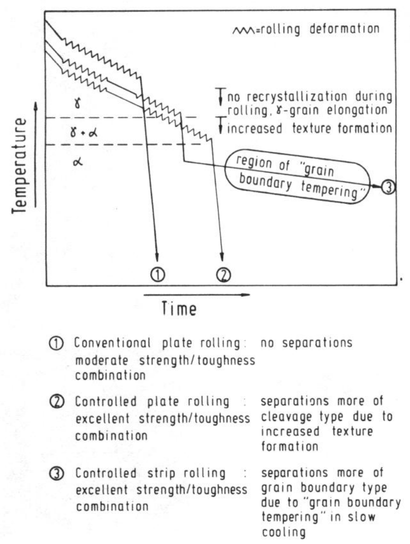
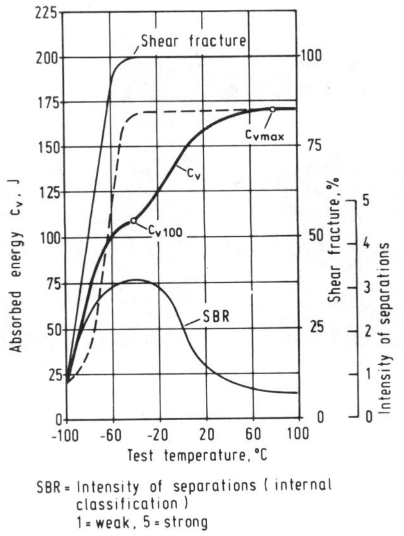


Figure 5 Interchangeability of temperature and time

Figure 6 Schematic graph of different processing schedules



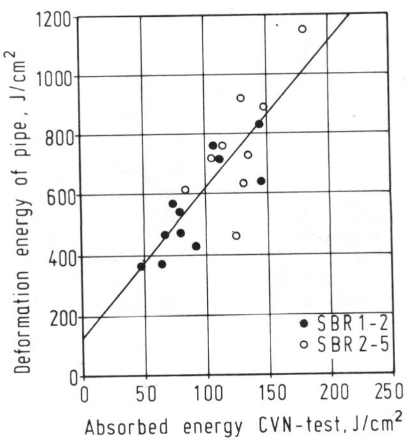


Figure 7 Influence of separations in CVN-test, long.

Figure 8 Relation between def.-energy in pipe and CVN-test