TWINNING EFFECT ON CLEAVAGE FRACTURE STRESS

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The relationships between twinning process and fracture of ferritic steels have been investigated. The twinning process during loading at various temperatures was tested with the help of the acoustic emission technique. The effect of temperature was manifested by different twins configurations above and below the transition temperature. The high stress concentration, equal to the theoretical strength in the vicinity of the terminated twin has been observed and the mechanisms of the stress relaxation at the twin tip have been discussed. It has been shown that in ferritic steel both the twins generated fracture and fracture without twinning can be observed. The importance of the cross-slip during the fracture process is also underlined.

INTRODUCTION

During the last 30 years a number of investigations to determine the relationship between the twinning and brittle fracture of the BCC metals have been performed. It is well recognized that twins can be observed in a brittle fractured metals, however there is no widely accepted theory under which circumstances the brittle fracture is initiated by twins. Moreover the existing theories cannot explain the role of twinning in the ductile - brittle transition of metals. The influence of twins on the strength of materials is not understood also.

In this paper the relationship between twinning and mechanical behaviour of the BCC metals below and above the brittle - ductile transition temperature has been analysed.

Samples that had been loaded by tensile stress were examined by means of the metallographic and fractographic techniques. These observations were compared with the stress distribution at the twin matrix boundary.

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EXPERIMENTAL METHOD

The tests were performed on silicon iron (3,05% Si). The grain oriented and the random grain oriented samples were tested. The grain oriented samples were loaded in the [001] direction. To supplement the analysis the brittle fracture stress for the manganese cast steel was measured using the Griffith - Owen method. For most of the BCC metals the twinning is not distinctly monitored on the stress - strain curve. Therefore, to detect the twinning process the acoustic emission method has been utilized. In these tests the acoustic emission produced during the twinning process has been indicated as a RMS voltage. A signal processor (Model 204, Acoustic Emission Technology Corporation) was used together with a sensor with the nominal resonance frequency of 175 kHz.

The results of the strength tests for the silicon iron with the random grain orientation are shown in Fig. 1. The twinning could be observed below and above the ductile brittle transition temperatures (T_{DB}) up to 300 K. At the temperatures $T > T_{DB}$ the twinning occurred below yielding. Some scatter in the critical twinning stress has been observed and a number of the twin bursts could he observed below the yield stress. For the temperatures $T < T_{DB}$ the twinning stress and the fracture stress coincided.

A similar behaviour for the grain oriented silicon iron has been observed. The difference in results obtained was in lower value of T_{DB} and larger degree of scatter of the twinning stress. At the temperature above T_{DB} the twins were uniformly distributed on the surface of the sample while at $T < T_{DB}$ the twins were situated in the vicinity of the fracture surfaces. Twinning below the yielding did not influence the yield stress however the plasticity of the sample was more pronounced. As can be seen in Fig. 2. the intensive and low stress twinning promote the plastic deformation.

The configurations of the twins change suddenly at the transition temperature. Above the T_{DB} temperature the twins in the twinning systems predicted by theory are observed. The twins can extend across the grain or can be arrested at the existing twin. The stress concentration at the twin - twin intersection is relaxed by the local deformation. Wavy slip lines (Fig. 3) show the contribution of the cross-slip into stress relaxation.

Below the T_{DB} temperature the twins arrested inside the grains can be seen. At the twin tip one can observe the slip lines and the twins a in such systems which cannot be initiated by the external loading (Fig. 4). This plastic deformation at the vicinity of the twin tip could have taken place as a result of the stress concentration only.

To evaluate the stress concentration at the twin tip the stress distribution at the twin matrix boundary was examined. The calculations were performed utilizing Eshelby (1) and Mura and Cheng (2) theory. The twin was considered as an ellipsoidal elastic inclusion located within elastic matrix. Both isotropic and anisotropic models were used and it was concluded that for the thin twins the results are equivalent. More details concerning the applied method are given elsewhere (3). The results of computation are shown in Fig.5. As can be seen, if there is no stress relaxation, the stress concentration at the twin tip is equal to the theoretical cohesive strength. This high stress cannot be sustained by the material and the stress relaxation must occur. This may take place as a result of the local plastic deformation by slip and twinning or by micro-crack nucleation.

To evaluate the possibility of the stress relaxation the shear and the normal stresses on a different crystallographic planes at the twin tip were determined. The computation was made for the terminated (112) $[\bar{1}\ \bar{1}\ \bar{1}]$twin, while the shear stress distribution on some crystalographic planes are given in Fig.6. The details concerning the stress distribution on the crystallographic planes are given elsewhere [4].

As was shown by Kumosa (5), for the silicon iron the stress on the cleavage plane of matrix at the twin tip is able to produce the micro crack ~1,5 μm long which can propagate as a Griffith crack at the stress equal to the fracture stress (~300 MPa).

High shear stresses are met in the vicinity of the twin tip (Fig.6) as well as in the vicinity of the lateral twin edge. Mechanism of the stress relaxation involves the nucleation of the twinning and slip in the systems which cannot operate under applied load . The twins and slip in the systems at the lateral edge of (112) $[\bar{1}\ \bar{1}\ \bar{1}]$ twin are shown in Fig.4. A dislocation row that can be at the twin tip relax the stress concentration. This is shown in Fig.7 where the tip of $(\bar{1}12)$ $[1\ 1\ \bar{1}]$ twin is arrested by the (112) $[\bar{1}\ \bar{1}\ 1]$ twin. The stress relaxation occurs by slip on (101), $(0\bar{1}1)$, $(\bar{1}12)$, (011) and $(\bar{1}01)$ planes on which the shear stress reaches the highest value (Fig.6). (Note: there is disagreement between crystallographic indexes in Fig.6 and Fig.7 as a result of different twins orientation).

All the above tests were performed on the silicon iron where twins can be observed easily. To get more general information some tests on manganese cast steel were made also.

The fracture stress at 77 K was determined with the help of Griffith-Owen method. To detect the twinning process, which may take place during loading the acoustic emission technique was utilized. All the samples fractured in a brittle manner and the twinning was observed in a limited samples only. The fracture stress for the samples that fractured after twinning was slightly higher (~15%) than for samples with no twins observed. On the fracture surfaces after twinning had taken place the evidences of twins that generated cracking could be seen (Fig.8).

DISCUSSION AND CONCLUSIONS.

The results presented show that twinning occurs below as well as above ductile-brittle transition temperature. However, in general, the twinning takes place at low temperatures. Twinning above transition temperature promote plasticity while twinning below T_{DB} gives rise to the higher fracture stress. These changes in the mechanical behaviour can be explained in terms of the grain fragmentation by twinning below yielding.

At the vicinity of the terminated twin a significant stress concentration takes place. The resolved shear stresses on the twinning and slip planes are equal to the theoretical shear stress while the stresses normal to the cleavage planes are equal to the theoretical cohesive strength.

Transition from the ductile to brittle fracture is associated with the sudden changes in the twins configuration. At the temperatures above transition temperature the twins extended over the whole grain both in the twin propagation and lateral directions. When the twin is arrested by a strong barrier (other twin) the stress concentration can be relaxed by a local plastic deformation including cross-slip. When the brittle fracture occurs the restriction in the twin propagation can be seen. The twins are arrested inside the grains and the stress relaxation takes place by twinning and / or slip. The local plastic deformation takes place in more than one slip systems as a result of stress concentration only. Below the T_{DB} temperature no signs of the cross slip were observed.

In the cast steel the two mechanisms of the brittle fracture initiation were observed: twin inducted fracture and fracture with no twin contribution.

The above experiments have shown that the stress concentration at the terminated twin is sufficient for crack to initiate. This stress however, can be relaxed in different modes both above and below the transition temperature. the stress relaxation below the transition temperature is less likely because no cross slip operates at this conditions. Thus, it seems that the brittle fracture of ferritic steel is rather not associated with the local stress concentration but it is controlled by by limitation of the stress relaxation.

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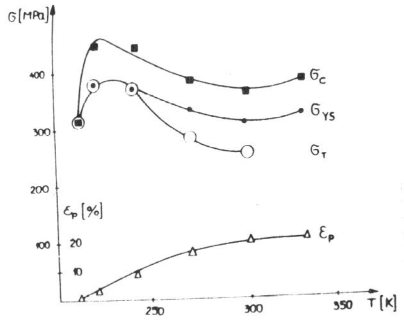

Figure 1 Fracture stress σ_c yield stress σ_{YS} , twinning stress σ_T vs. temperature for random grain oriented silicon iron

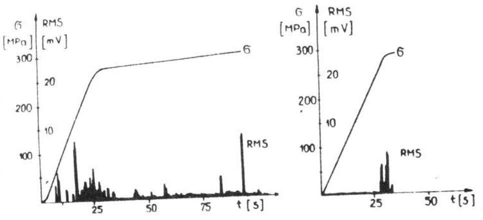

Figure 2 Acoustic emission and stress vs. time for grain oriented silicon iron tested at 213 K

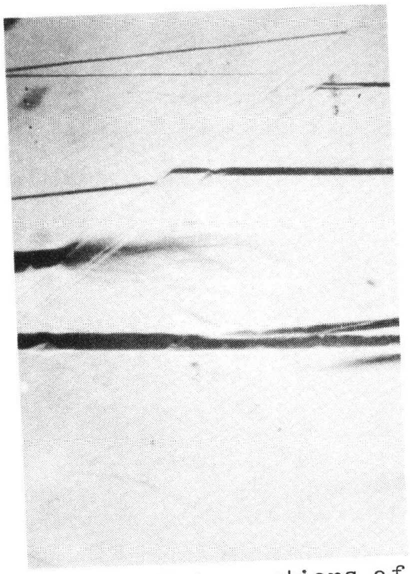

Figure 3 Intersections of twins in grain oriented silicon iron tested above transition temperature

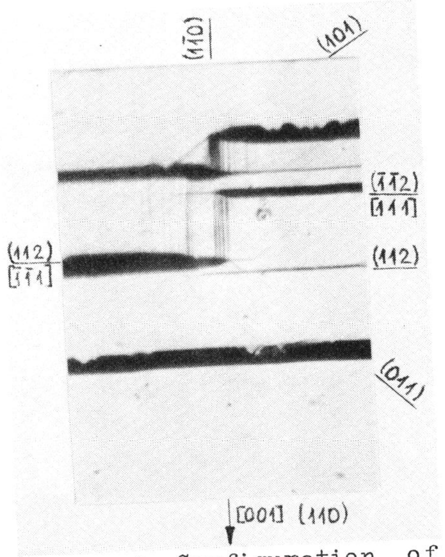

Figure 4 Configuration of twins and slip lines in grain oriented silicon iron tested at 77 K

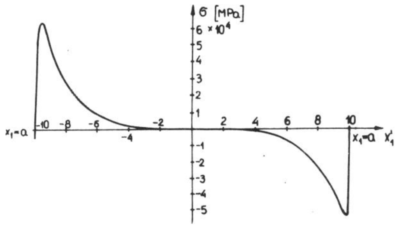

Figure 5 Stress distribution at twin matrix boundary in the direction of twin propagation

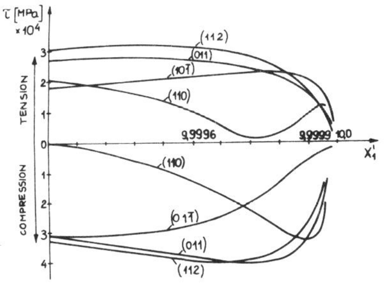

Figure 6 Shear stress on selected crystalographic planes at the twin tip

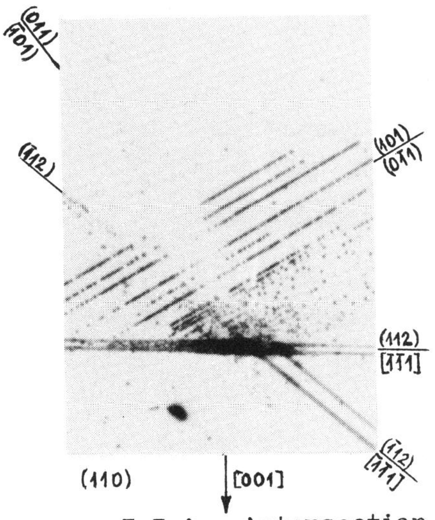

Figure 7 Twins intersection and local plastic deformation in silicon iron below the transition temperature

Figure 8 Fracture surface of cast steel tested at 77 K