REASONS FOR THE APPEARANCE OF SEPARATIONS IN HSLA-STEELS

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The present study deals with the question whether the formation of cleavage separations in HSLA-steels follows a critical cleavage fracture stress criterion and analyses the influence of a {100}texture on this type of fracture. Cleavage fracture stresses in 3 plate directions were determined. These results and texture analysis led to the conclusion that delamination fracture is probably not only controlled by a stress criterion, but also strongly influenced by plastic anisotropy resulting from a {100}texture.

The mechanical properties of high-strength low alloy steels (HSLA) have been improved considerably by controlled rolling. When testing controlled rolled sheets in certain temperature ranges, additional fracture planes often appear perpendicular to the main fracture plane. This fracture phenomenon called separation, delamination or splitting is classified in inclusion type, grain boundary type and cleavage type (1) according to microscopic features and typical causes for appearing. A stress acting in through-thickness direction of a plate is commonly seen as a prerequisite for delamination fracture. Baldi and Buzzichelli (2) found that separations obey a critical cleavage fracture stress criterion in through-thickness direction. It is remarkable though that this stress criterion was first fulfilled after having taken plastic anisotropy into account.

Cleavage type separations are often associated with the presence of a {100}texture. Crystallographic {100}-planes alligned parallel to the rolling-plane are supposed to favour cleavage separations, because cleavage fracture proceeds along these planes in ferritic steels. In the present study an attempt was made to determine whether the appearance of cleavage type separations results from a stress in through-thickness direction exceeding the critical cleavage stress for a controlled rolled HSLA-steel with the help of double-notched tensile tests and two-dimensional finite-element calculations. It was furthermore hoped to learn more about the significance of a {100}texture in reference to delamination fracture.

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EXPERIMENTAL

The specimens investigated originate from controlled rolled and normalized (920 °C/20'/air-cooled) sheets with chemical compositions as listed in Table I.

TABLE I - Steel compositions of the investigated sheets in wt-%

	C	Si	Mn	P	S	V	Al	Nb	ppm N
X70 II	0,14	0,33	1,74	0,013	0,013	0,054	0,061	0,063	93
X70 III	0,11	0,46	1,70	0,013	0,003	0,063	0,055	0,050	61

In the following main emphasis will be laid on X70 III, because X70 II failed to develop separations in double-notched tensile specimens.

Cylindrical unnotched and rectangular double-notched tensile specimens in longitudinal (L) and transverse (T) direction and miniature tensile specimens, notched and unnotched, in through-thickness (TT) direction were tested on a 20 t-tensile machine between 77 K and 293 K.

Several fracture planes caused by delamination were examined with a scanning electron microscope and identified as cleavage type.

Specimens for texture analysis were taken from the mid-thickness planes of both steels X70 II and X70 III in controlled rolled and normalized condition. {100}pole figures were obtained with an automatic X-ray texture goniometer (3), (4).

RESULTS AND DISCUSSION

Tensile Tests

The results received by testing cylindrical unnotched specimens were of main interest for finite-element calculations which will be discussed later. Separations appeared in almost all unnotched specimens of steel X70 III in controlled rolled condition. Fracture stress was markedly influenced by testing direction with highest values in longitudinal and lowest in short transverse direction. Yield stress showed only little dependence of testing direction with highest values found in short transverse direction. The values for fracture stress and yield stress and the influence of testing direction were reduced by normalizing.

Fig. 1a and 1b show fracture stress σ_f and general yield stress σ_{gy} of double-notched specimens as a function of the testing temperature. The transition temperature, here defined as the temperature at which fracture stress reaches its highest value when proceeding from lowest temperatures, is identical for L- and T-specimens and hardly influenced by normalizing. The transition temperature of TT-specimens though, lies considerably higher and was reduced about 50 K by normalizing. Separations were observed in longitudinal and transverse specimens of X70 III in rolled condition between 123 K and 293 K.

Method of finite elements (FEM) for stress distribution calculation

Delamination fracture surfaces exhibit a similar appearance to cleavage fracture observed on main fracture planes, which follows a critical tensile stress criterion. This leads to the assumption that separations are then initiated when the maximum stress in through-thickness direction σ_{zz}^{max} of longitudinal and transverse specimens exceeds the maximum critical fracture stress σ_{yy}^{max} in short transverse specimens. In order to solve this question it was necessary to determine and analyse the σ_{yy}- and σ_{zz}-values in the three existing plate directions.

The stress distribution in front of the notch root of double-notched tensile specimens was calculated using a 2-dimensional elastic-plastic finite-element program (5). Compared to the slip-line theory which has often been applied by other authors, FEM has proved to be more precise by considering strain-hardening.

In the present paper calculations were made with 8-node isoparametric elements assuming plane strain and isotropic material behaviour, although not quite correct, since cylindrical specimens had shown elliptical cross-sections.

The true stress-strain-curves obtained in tensile tests with cylindrical unnotched specimens were taken into account. Material behaviour in regions of plastic deformation was described sufficiently by the Ludwik-equation:

$$\sigma = k \cdot \phi^n \qquad (1).$$

Fig. 2 shows the FE-mesh used for calculations. Due to symmetry it was only necessary to calculate one quarter of a specimen.

An example for the σ_{yy}-stress distribution in front of the notch root for a longitudinal specimen tested at 123 K is given in Fig. 3. The maximum value increases with increasing load and moves towards the specimen's midplane until general yield load is reached. Combining experimental results with FE-calculations enabled the determination of the cleavage fracture stress from the load steps in which the corresponding double-notched specimen had fractured during tensile testing.

According to Ritchie, Knott, and Rice (6), cleavage fracture stress must be reached across a certain critical distance X_c to initiate cleavage fracture (Fig. 4). The actual size of X_c depends on the existing microstructure. Fig. 5 shows the temperature dependence of σ_{yy} and σ_{zz} for X_c = 0,1 mm for specimens in the diffe-rent directions. The dashed lines indicate the temperature range in which the transition temperature was exceeded because for $T = T_t$ fracture may be controlled by another fracture criterion (7). σ_{zz}^{L}-values of longitudinal specimens and σ_{zz}^{T}-values of transverse specimens are approximately 20 % lower than σ_{yy}-values of TT-specimens. An attempt was made to find a closer agreement between these values by determinating the R-values for the three testing directions (R^L = 0,36; R^T = 0,63; R^{TT} = 0,57) and applying the Hill criterion for plasticity (8). In longitudinal direction σ_{zz}^{L}-values then exceed the σ_{yy}^{TT}-values in TT-direction whereas the σ_{zz}^{T}-values in transverse direction failed to do so.

Texture Analysis

Figures 6a and 6b show pole figures for X70 III in controlled rolled and normalized state ($\phi = 75^{o}$). The relative pole intensities as marked in the diagramms are described by the ratio of the measured pole intensity of an ideal orientation to the intensity of a statistical orientated powder specimen. Steel X70 III has a well developed (100) [011] texture with (111) [211] and (112) [110] as minor components. All components were reduced considerably by normalizing.

The textures found in X70 II are extremely weak with actually no difference between rolled and normalized condition.

CONCLUSIONS

The HSLA-steel X70 was examined to determine whether the development of separations follows a critical cleavage fracture stress criterion. Tensile tests and finite-element calculations have shown that critical fracture stresses of short transverse specimens σ_{yy}^{TT} do not coincide with the critical fracture stresses measured in through-thickness direction of longitudinal σ_{zz}^{L} and transverse specimens σ_{zz}^{T}. After considering plastic anisotropy by calculating with the Hill criterion for plasticity σ_{zz}^{L} exceeded σ_{yy}^{TT} over the entire temperature range, whereas σ_{zz}^{T} remained below. These results indicate that plastic anisotropy should not be neglected when calculating although the obtained results are not very convincing. They do not agree with experimental separation behaviour by implying that separations had developed in the entire temperature range and only for longitudinal specimens. The contradicting values in longitudinal and transverse directions may be seen in connection with the rather extreme R-values measured in the corresponding specimens. According to these results further investigation will be necessary to find a definite answer to the question whether delamination fracture follows a critical cleavage stress criterion only.

Texture analysis definitely supports the assumption that a strong (100) [011] texture causes cleavage type separations because only X70 III in controlled rolled condition showing the sharpest texture did also exhibit separations. Such a preferred orientation where ferrite cleavage planes are preferentially alligned parallel to the rolling plane, is therefore likely to promote delamination fracture by providing easy planes for cleavage.

SYMBOLS USED

k = flow stress at 100 % plastic strain (N/mm^2)
L;T;TT = longitudinal, transverse, and through-thickness direction of a rolled sheet
n = strain-hardening exponent
R = strain ration defined as ϕ_1/ϕ_2
T = temperature (Kelvin)
T_t = transition temperature (Kelvin)
X_c = critical distance below the notch root (mm)
σ = tensile stress (N/mm^2)
σ_f = fracture stress (N/mm^2)
σ_{yy} = cleavage fracture stress in y-direction of a specimen (N/mm^2)

σ_{zz} = cleavage fracture stress in z-direction of a specimen (N/mm^2)
σ_{gy} = general yield stress (N/mm^2)
ϕ = true strain
Φ = radial angle in a pole figure

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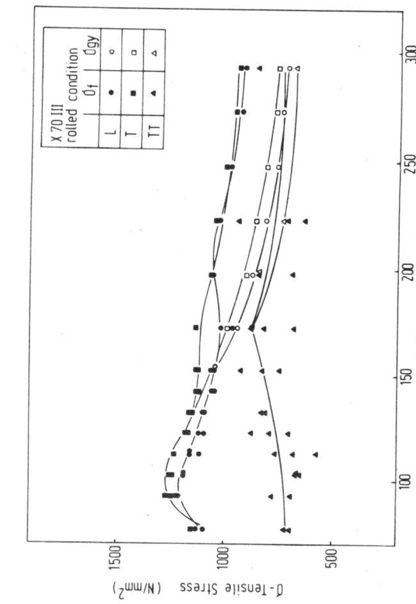

Fig.1a Fracture and yield stress as a function of testing temperature

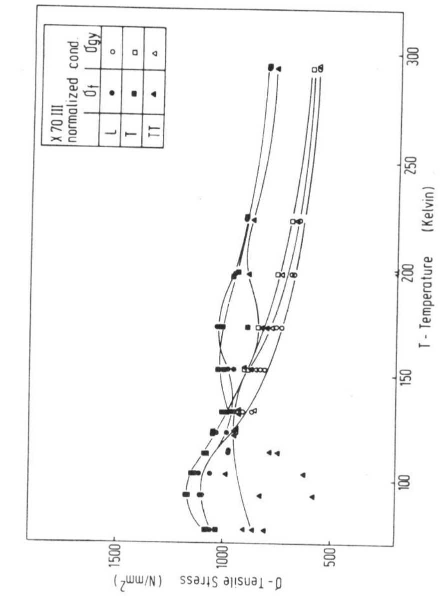

Fig.1b Fracture and yield stress as a function of testing temperature

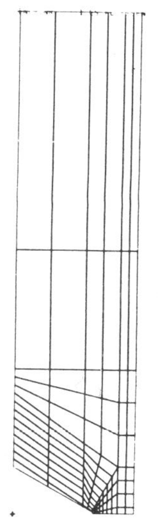

Fig.2 FE-mesh applied for stress distribution calculation

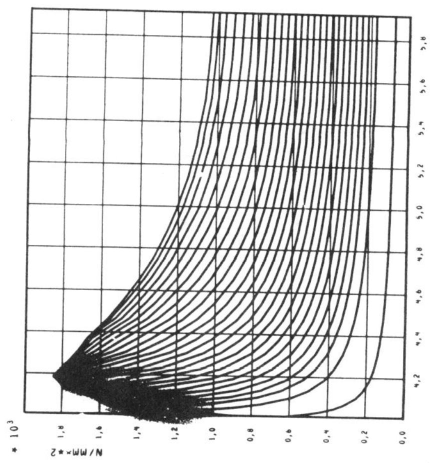

Fig.3 σ_{yy}-stress distribution below the notch root

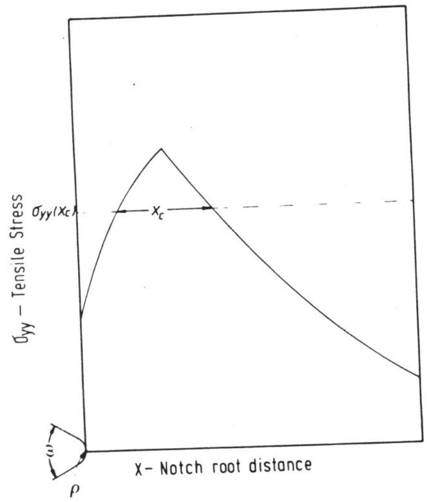

Fig.4 Illustration of the critical notch root distance X_c

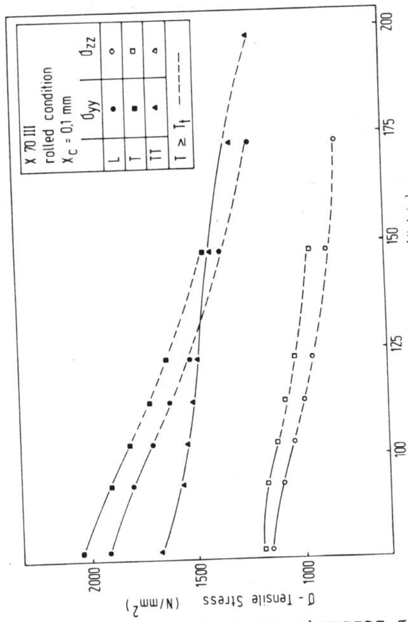

Fig.5 Cleavage fracture stresses σ_{yy} and σ_{zz} as a function of test.temp.

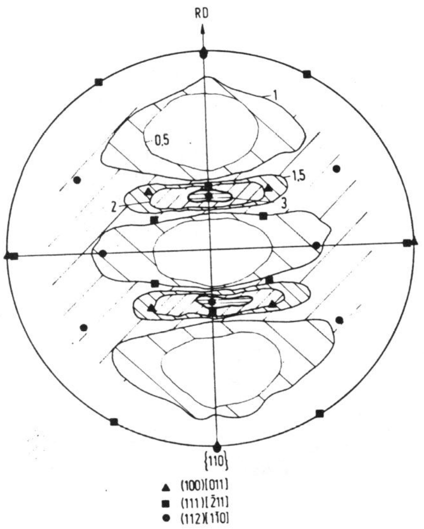

Fig.6a {110} pole figure of X70 III in controlled rolled condition

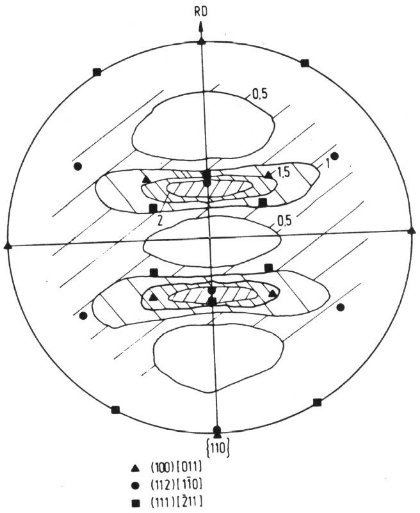

Fig.6b {110} pole figure of X70 III in normalized condition