MECHANISMS AND MECHANICS OF FERRITIC PEARLITIC STEEL DELAMINATION

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Cleavage delaminations, parallel to the rolling plane, appear on fracture surfaces of CT and axisymetric failed specimens of gas tube ferritic-pearlitic laminated steel. Delamination is present only in the center of the thickness, as a crack normal to the main crack. The purpose of this paper is to explain from metallurgical and mechanical features of the delamination zone why it is a preferential splitting path.

INTRODUCTION

Different delamination mechanisms including transgranular or intergranular brittle fracture have been previously studied on different rolled steels :

- for Inagaki (1), Hero (2) or De Ardo (3) the delamination source was a second phase (networks of cementite surrounding ferrite grain or carbide aggregates).
- for Baldi (4) or Bramfitt (5) the dimensional anisotropy of grains caused delamination.
- Bourell (6) proposed delamination induced by deformation texture.

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In our case, the material structure consists of alternate bands of ferrite and pearlite, parallel to the tube length and to the rolling direction. A thin segregated zone (0 to 100 µm), at about half the thickness was observed. Chemical composition and mechanical features of the gas tube steel are given in table 1.

Metallurgical features of the delamination zone.

Four types of inclusions are found in the segregated zone: 1) elongated manganese sulphides longer and more numerous in the segregated zone (50 to 200 µm) , 2) aluminates (some µm) evenly distributed in the thickness or associated with sulphides, 3) small square unanalysed inclusions (<1µm), 4) niobium inclusions specific to the segregated zone, perhaps carbonitrides of niobium.

The delamination zone shows Si, Mn, P and Ni segregation contents. Linear analysis are made in a zone without sulphide. Shivaiva (7) has shown that in ingot steel making plate, a segregated zone existed in the center of the thickness. Its structure was bainite, transformed at low temperatures, for Mn > 1.8 % and P< 0.3 %. In the segregated zone of the gas tube, P % = 0.16 and Mn % = 2.4. So the quenching effect of manganese and phosphorus can produce a bainitic structure during the casting of the bloom.

Microhardness measurements (HV 0.3) are done through the thickness of the tube. Hardness increases from 200 to 360 in the segregated zone. Microhardness measurements (HV 0.025) through the thickness, only in the ferrite range, reveal no increase.

Toughness of the delamination plane.

The setting of a special specimen and the reason for its modelling. Due to the low tube thickness (about 10 mm), the determination of the delamination toughness requires the setting of a special specimen. Usual flat specimens, DCB (double cantilever beam) couldn't have been produced. The loading mode characterizes our specimen (figures 1 and 2) : on it, edge rails allow the loading by clevises. This special loading mode requires a modelling of the specimen and its clevises to calculate the stresses at the crack tip and so the specific stress intensity factor.

During tests, the displacement, $2V_m$, on the load line and the strength P are measured. To validate the model, a comparison is made between experimental compliance $2V_m/P$ and model one.

Finite element modelling with an elastic behavior. We chose an elastic behavior model because specimens fail in small scale yielding. With a 2-D modelling of the upper clevis and one half of the specimen, the compliance is six times weaker than the experimental one. This result shows that with 2-D analysis, it is not possible to model the loading by side rails.

3-D Modelling. One quarter of the specimen and one quarter of the upper clevis are discretize by twenty node isoparametric bricks (figure 3). The mesh consists of 6501 degrees of freedom and 348 brick elements. To model the loading by rails, the contact exists only between rails of the specimen and the clevis.

For a = 24 mm, the model compliance value is 33.10^{-6} mm/N with nodes 50 µm apart around the crack tip and the experimental one is 55.10^{-6} mm/N. A three-dimensional model gives the result with 40% higher stiffness. A recrystalization treatment (700°C, 6H) allows to measure the plastic zone at the crack tip. Crack tip plastic zone value at the specimen center is about 50 µm. This weak value seems to indicate that the choice of an elastic behaviour is a good one. In the 3-D model, the calculator possibilities limit the number of elements. Then we have only three elements in the width : this fact can explain partly the gap between test and model. By an other way, due to the loading mode by rails, the limit conditions aren't perfectly known.

Determination of the rupture strength. Rupture strength values are scattered. This scattering is the result perhaps of the discontinuity of the delamination plane. Fracture surfaces of specimens show a ductile step between fatigue crack and rupture : the higher the step (from some µm to some 100 µm), the greater the fracture strength value. In first approximation, we chose the strengths of specimens with little ductile steps. Their average gives the following value : $P_{rupt.} = 6000 \pm 1000$ N . On the fracture surface, two different facies are discernible : one is cleavage type, the other is flat with a high niobium inclusions content. The knowledge of the delamination rupture mechanism will help us to determine more precisely the rupture strength value.

Determination of the delamination plane toughness. With a concept of a three dimensional stress intensity factor, the stress field, for mode I loading, around the crack is given by :

$$\sigma_x = K_1 / (2\pi r)^{1/2} * \cos\theta/2 * (1 - \sin\theta/2 * \sin 3\theta/2)$$

$$\sigma_z = K_1 / (2\pi r)^{1/2} * \cos\theta/2 * (1 + \sin\theta/2 * \sin 3\theta/2)$$

$$\tau_{xz} = K_1 / (2\pi r)^{1/2} * \sin\theta/2 * \cos\theta/2 * \cos 3\theta/2$$

$$\sigma_y = 2\upsilon * K_1 / (2\pi r)^{1/2} * \cos\theta/2$$

By a simple process, Chan (8) calculated the crack tip intensity factor. In the crack plane, $\theta = O$, $K_1 = (2\pi r)^{1/2} * \sigma_z$. Nodal point stresses σ_z^* in the vicinity of the crack tip, can be substituted into K_1 expression : $K_1^* = (2\pi r)^{1/2} \sigma_z^*$. From plots of K_1^* as a function of r for a fixed θ, an estimate of K_1 can be made : due to the inability of the finite element method to represent the stress singularity conditions at the crack tip, the K_1^* curve for r greater than zero must be extrapolated back to r = 0, the extrapolated value is K_1 .

Between K_1^* and applied load P, there is a relation of the type : $K_1^* = Y*P/B\,(W)^{1/2}$, Y is the compliance function. Plots of Y as a function of r/W and an extrapolation back to r/W=0 give the compliance fonction Y_0 , specific to the specimen. Then toughness is calculated from Y_0 and the rupture strength,

$P_{rupt.}$: $K_{1C} = Y_0 * P_{rupt.} / B\,(W)^{1/2}$ for $P_{rupt.} = 6000$ N , $Y_0 = 11$ and $K_{1C} = 16$ MPa$\sqrt{m}$. This value is weak, compared to the 110 kJ/m^2 value of J_{1C} of the material and can explain that the segregated zone is a delamination path.

CONCLUSION

In the delamination plane, we find numerous niobium inclusions, a notable segregation rate in Si, P, Mn and an increased hardness. So we can think that the segregated structure is bainite transformed at low temperatures and caused by the segregation of manganese and phosphorus. The delamination micromechanisms remain to be studied.

To know the segregated zone toughness, the setting and the modelling of a specimen are necessary. The main feature of this specimen is its loading by side rails. The K_{1C} value, obtained through nodal crack tip stress of a 3-D model, is weak, 16 MPa$\sqrt{m}$. Then, the segregated zone is a preferential splitting path. The use of this specimen and of this K_{1C} calculation can be generalized to other delaminated materials.

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C ±0.01	Si ±0.03	Mn ±0.05	S ±0.002	P	Nb ±0.005
0.09	0.29	1.59	0.008	<0.03	0.025

rolling direction	σ_{YS} (MPa)	σ_{TS} (MPa)	E (MPa)
longitudinal	432	585	204 000
transverse	512	622	200 000

Table 1 Chemical and mechanical features

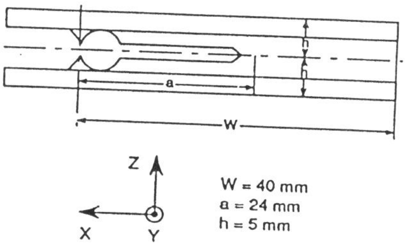

Figure 1 Side view of the specimen

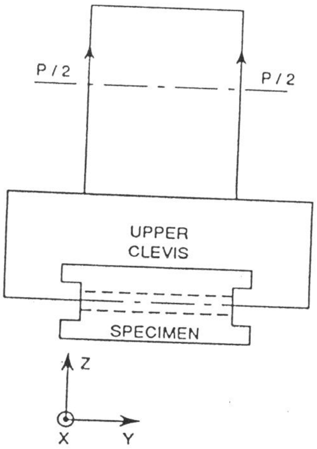

Figure 2 Loading mode of the specimen

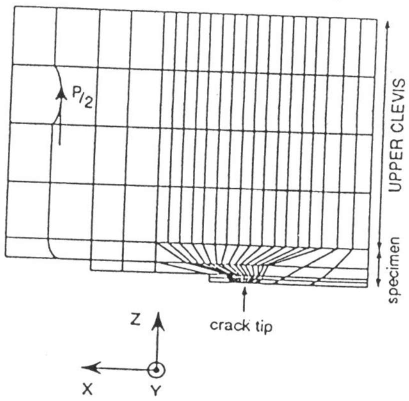

Figure 3 Projection of the 3 - D mesh