

# Influence of the steel rolling direction on the mechanical properties and distribution of the local stress in front crack

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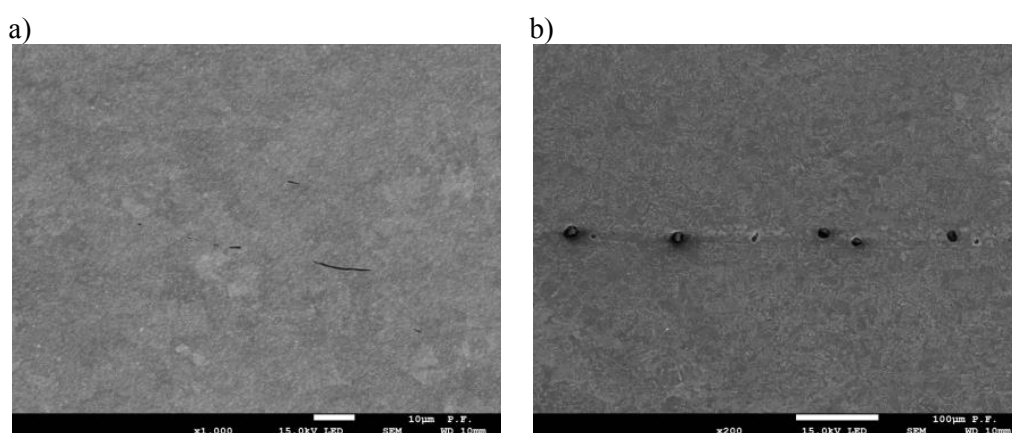
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**Abstract.** In this article presented the results of studies of strength characteristics (yield strength-  $\sigma_y$ , ultimate strength  $\sigma_{uts}$ , power exponent-  $n$ ) and fracture toughness ( $J_R$ ,  $J_{IC}$ ) determined on the specimens of steel S235 taken in the rolling and perpendicular direction. Standard strength characteristics are similar for the specimens in both directions. However, there occurs an essential difference in fracture toughness characteristics for the specimens from different directions. To determine (explain) factors that cause this phenomenon performed some metallographic studies and the analysis of local stress and strain distributions in front of the crack.

## 1 Introduction

Low-carbon structural steel is a widely used material in structural elements and in construction. The thermo-mechanical process causes the grains to elongate along the direction of rolling and the segregation of non-metallic inclusions. Increased amount of impurities and poor selection of plastic processing parameters intensifies the phenomenon of segregation, clusters of inclusions form, which cause anisotropy of mechanical properties and especially fracture toughness [1, 2, 3, 5, 6, 7]. Figures 1a and 1b show examples of microstructure pictures for specimens cut out in two perpendicular directions with visible inclusions. The specimens for fracture toughness tests were taken in the T-L and L-T directions according to the ASTM standard [4].



**Figure 1.** Steel microstructure with visible inclusions for the direction: a) T-L, b) L-T.

## 2 Experimental studies

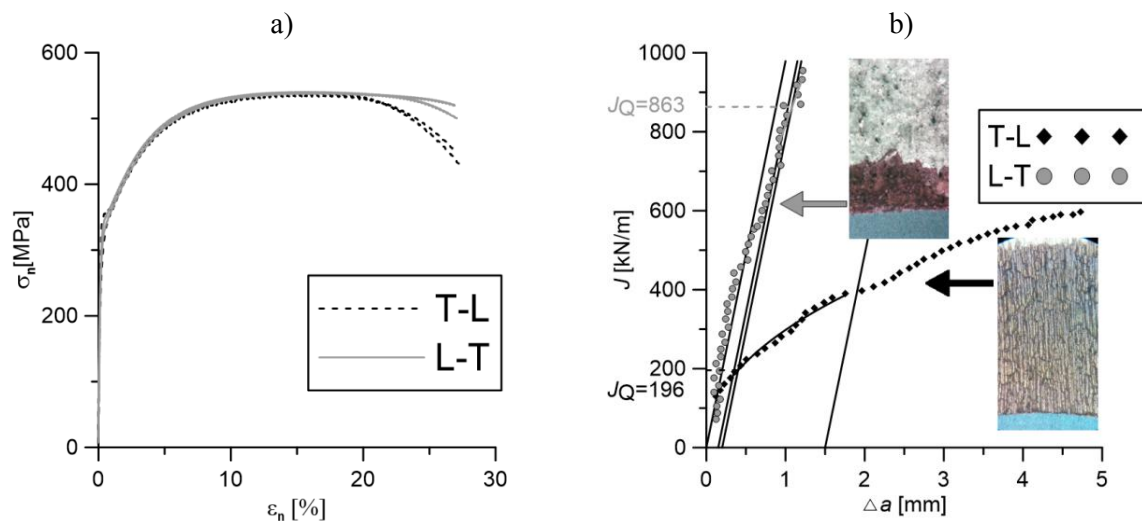
Specimens for determination of strength characteristics for a uniaxial tensile test with a diameter of 5 mm and a 25 mm extensometer base [8] were made directly from tested SENB specimens cut from a 12 mm thick plate in the T-L, L-T directions.

The determined mean values of nominal strength characteristics are similar for two directions (table 1). The nominal stress-strain diagrams ( $\sigma_n$ - $\varepsilon_n$ ), have different trend after reaching the ultimate strength value,  $\sigma_{uts}$ , (when neck is formed) (figure 2a). Differences were obtained in relative necking levels ( $Z$ ), and particular in the fracture stress values ( $\sigma_f$ ) for the two analyzed directions of specimen cutting.

**Table 1.** Nominal values of mechanical characteristics

	$\sigma_y$	$\sigma_{uts}$	$\sigma_f$	$Z$	$\underline{A}_5$
	MPa	MPa	MPa	%	%
<b>T-L</b>	336	539	1070	66	26.9
<b>L-T</b>	335	542	1300	76	27

Fracture toughness was determined on three-point bent specimens with one-edge notch, SENB, with dimensions  $B=11$  mm,  $W=22$  mm,  $a_0/W \approx 0.5$ , cut in the T-L and L-T orientation. The control and registration system made it possible to record force signals, specimen deflections at the point of load, crack opening displacement, potential changes. The obtained signals courses allowed to compute the crack growth by both the drop potential technique and unloading compliance technique.



**Figure 2.** a) diagrams  $\sigma_n$ - $\varepsilon_n$  for the analyzed directions, b)  $J_R$  curves with the views of the crack extension obtained by the change unloading compliance technique.

The resistance fracture toughness curve for the L-T direction runs significantly above the  $J_R$  curve for the T-L direction (figure 2b). Large differences in the critical values of  $J_Q$  fracture toughness were also noted. For specimens of both analyzed directions the condition for the minimum thickness  $B_c$  (equation 1) was not met, which ensures the dominance of plane strain in front of the crack (table 2). Thus, the determined critical values of  $J$  integral cannot be considered as  $J_{Ic}$ , but only as  $J_Q$  values [4]. The  $J_Q$  value was determined at the intersection of the offset line with the appropriate  $J_R$  curve.

$$B_c = 25 \frac{J_Q}{\sigma_y} \quad (1)$$

where:  $\sigma_y$  is the value of yield strength of the material at the test temperature,  $J_Q$  is the critical fracture toughness value obtained for the tested specimen.

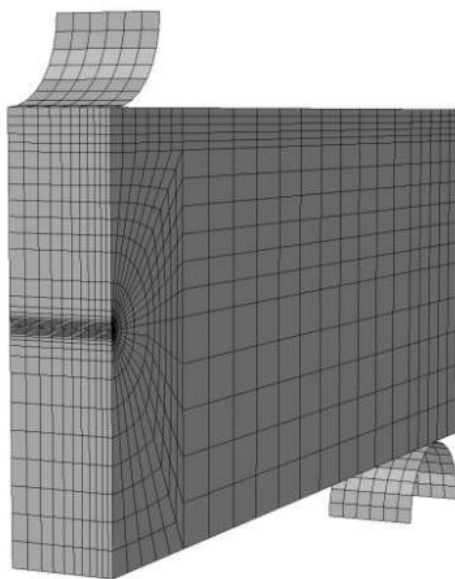
**Table 2.** Values of fracture toughness and critical thickness for plane strain domination

	$J_Q$	$\sigma_y$	$B$	$B_c$	$B > B_c$
	kN/mm	MPa	mm	Mm	-
<b>T-L</b>	863	336	11	64.4	NO
<b>L-T</b>	196	335	11	14.6	NO

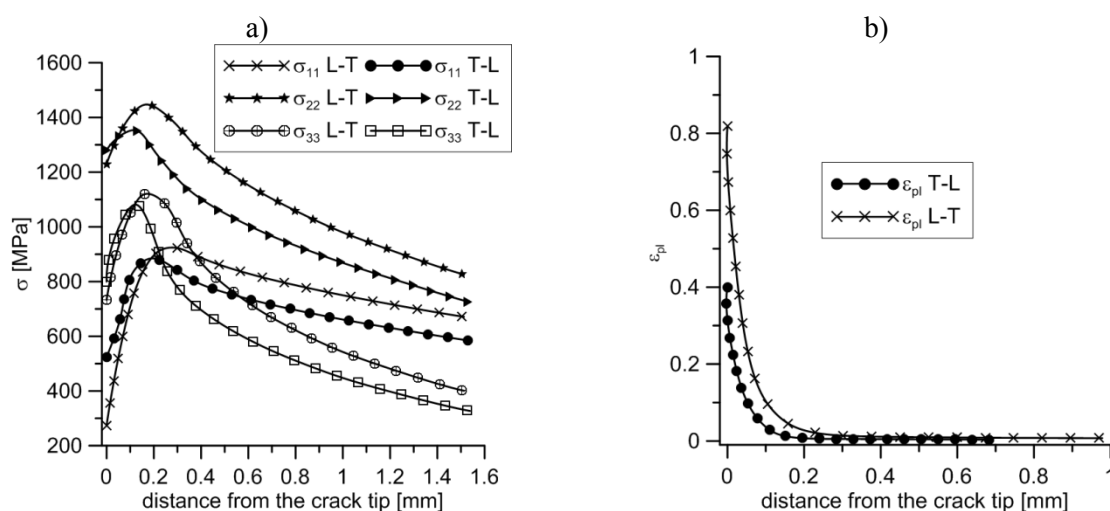
### 3 Numerical computations

The material constitutive relationships obtained as a result of the uniaxial tensile test, for the purpose of numerical computations, should be properly calibrated. This procedure was described in [12] (in print). Due to the analysis of the results in the direct proximity of the crack tip, the constitutive relationships were subjected to the calibration process [9, 10, 11, 12, 13]. As a result of numerical computations, distributions of stresses and strains in front of the crack were determined. The model of the three-point SENB specimen was used for computations, which was used during fracture toughness tests (figure 3). The computations were carried out in the Abaqus ver. 6.12-2 [14]. In the model the crack front was modeled as an arc with a radius of 0.12 mm. The specimen in the thickness direction was divided into 11 layers. In the model used 8-node three-dimensional finite elements. The arrangement of the mesh of elements was compacted as the crack front approached. In the definition of the boundary conditions of the computations, the possibility of displacement of the specimen surface to the crack front in the x direction, the area in the specimen axis from the y direction was blocked, and the lower roll was completely immobilized. In the computations the displacement of the upper roll which pressed on the specimen was controlled. The displacement value corresponded to the moment of initiation of the subcritical crack, determined as a result of experimental studies. The results presented from the axis of the numerical specimen model.

In the figure 4a presented a comparison of distributions of stress components in front of the crack, for both compared directions of specimen cutting. Higher levels of the stresses were recorded for specimen L-T direction. For the opening stresses ( $\sigma_{22}$ ), the difference in the maximum is at the level of nearly 6.5%. For the  $\sigma_{11}$  component, the difference is approx. 4%, while for the  $\sigma_{33}$  component it is 3.5%. In each case, for a material with a direction L-T, the occurrence of the local maximum of stresses is shifted from the front of the crack, in relation to the material with the direction T-L. Much larger differences in data were obtained for the distributions of effective strains in front of the crack. (figure 4b). In this case, the effective strain values for L-T direction specimen were about twice as high.



**Figure 3.** Modeled specimen type SENB.



**Figure 4.** Distributions in front of the crack: a) opening stresses -  $\sigma_{22}$ ; stresses in the thickness direction -  $\sigma_{33}$ ; stresses in the crack plane -  $\sigma_{11}$  b) of effective strains.

#### 4 Summary

In the case of low-carbon plastic steel, fracture toughness characteristics reacted very fondly on the presence and direction of non-metallic inclusions. The  $J_R$  fracture toughness curves obtained on specimens taken in different directions (T-L and L-T) are significantly different, and the differences in critical values of fracture toughness  $J_Q$  are more than fourfold. The occurrence of such significant differences in fracture toughness characteristics is difficult to predict on the basis of the results obtained in the uniaxial tensile test. The courses of nominal diagrams ( $\sigma_n$ - $\varepsilon_n$ ) are similar to the value of  $\sigma_{uts}$ . The differences are only on the section corresponding to the formation of the neck.

When the necking formed in the tensile tested specimen, the process of strengthening and damaging the material in 3D stress-strain state takes place. At the test to determine fracture toughness characteristics, the same processes take place in front of the tip during crack growth. So, comparing

the nature of the courses of tensile diagrams at the stage of neck formation, we can conclude what material has higher fracture toughness characteristics.

Quantitative analysis of stresses and strains distributions in front of the crack tip at the moment of subcritical crack initiation obtained on the basis of numerical computations of modeled SENB specimens indicates higher stress and strain values in L-T samples as compared to T-L. This means that when the subcritical crack starts, the level of J integral is higher in L-T specimens, which is consistent with the experimental results.

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