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THE FEM ANALYSIS OF STRESS DISTRIBUTION IN FRONT OF THE CRACK TIP AND FRACTURE PROCESS IN THE ELEMENTS OF MODIFIED AND UNMODIFIED CAST STEEL G17CrMo5-5

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Abstract: The article presents influence of modification of the low-alloy cast steel G17CrMo5-5 by rare earth metals on stress distribution in front of the crack at the initial moment of the crack extension. Experimental studies include determination of strength and fracture toughness characteristics for unmodified (UM) and modified (M) cast steel. In the numerical computations, experimentally tested specimens SEN(B) were modelled. The true stress–strain curves for the UM and M cast steel are used in the calculation. The stress distributions in front of the crack were calculated at the initial moment of the crack extension. On the basis of data on the particle size inclusions in the UM and M cast steel, and the calculated stress distributions was performed an assessment of the possibility of the occurrence of cleavage fracture. The analysis results indicate that at room temperature for the UM cast steel, there is a possibility of cleavage fracture, while for the M cast steel occurrence of cleavage fracture is negligible.

Keywords: Fracture Toughness, Stress Distributions in Front of the Crack, Cast Steel, Fracture Mechanisms

1. INTRODUCTION

Elements made of low-alloy cast steel are widely used in different branches of industry, especially in power industry. One main problem observed during utilization of these elements was occurence of a sudden destruction. In the studies (Bolanowski, 2005; Gajewski and Kasińska, 2009; Heon et al., 2006; Luniov, 2002) were received wide scatter intervals of the impact energy data. The modification of cast steels by rare earth metals (REM) leads to an increase of mechanical properties (Gajewski and Kasińska, 2009; Kasińska, 2014). These changes were caused by microstructure transformations, which were occurred because of adding the REM. For low-alloy cast steel G17CrMo5-5, especially a significant increase was obtained for the fracture toughness characteristics (Dzioba et al., 2015).

According to the local approach to fracture, the fracture process begins if the level of stresses (or strains) in front of the crack, exceeds the critical value on the critical distance (Beremin, 1983; McClintok, 1968; Ritchie et al., 1973; Seweryn, 1994). By Ritchie-Knott-Rice's modified criterion, the fracture process occurs if the tensile (opening) stresses in front of the crack exceed the critical value at the critical distance (Dzioba et al., 2010; Neimitz et al., 2010).

In the present study, the authors focused on the analysis of the process of cast steel cracking G17CrMo5-5 in an original condition (UM) and after modification of the REM (M). Main objective of the analysis is to evaluate the possibility of the occurrence of cleavage fracture in the tested types of steel. The analysis was based on the approach taking into account stress values, that arised in front of the crack tip, and microstructural constituents of the material - particle sizes, the particle size of the inclusions (Dzioba, 2011; 2012).

2. TEST METHODS AND MECHANICAL PROPERTIES OF G17CrMo5-5 CAST STEEL

Experimental studies including determination of strength and fracture toughness characteristics were carried out on two melts of the low-alloy cast steel G17CrMo5-5 (Tab. 1) (EN–10213–2:1999). The difference between the two melts based on a modification of one of them with the addition of rare earth metals (REM), introduced in the form of mischmetals, having the following composition: 49.8% Ce, 21.8% La, 17.1% Nd, 5.5% Pr, 5.35% the remainder of REM. Heat treatment after casting included normalizing (940 ^{0}C) for 1 hour and tempering (710 ^{0}C) for 2 hours (Gajewski and Kasińska, 2009; Kasińska, 2014).

Tab. 1. Chemical composition of the low-alloy cast steel G17CrMo5-5

C	Si	Mn	Cr	Mo	Ni	Al	S	P
0.17	0.4	0.6	1.2	0.53	0.1	0.034	0.012	0.018

Modified and unmodified cast steel after a heat treatment has a ferritic-pearlitic-bainitic microstructure. An addition of REM to alloy caused a reduction of an average grain size. The modification also caused changes in the morphology of nonmetallic inclusions. Irregular shape of nonmetallic inclusions of the UM cast steel changed to spherical (Fig. 1) (Gajewski and Kasińska, 2009; Kasińska, 2014).The sizes of the spherical particles are smaller (about twice) and they are uniformly dispersed in the metal matrix for the M cast steel (Fig. 2) (Gajewski and Kasińska, 2009; Kasińska, 2014).

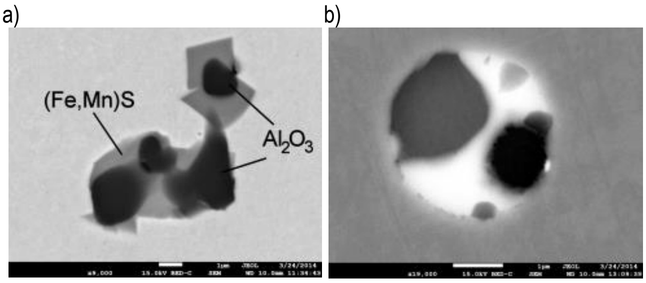

Fig. 1. Shape of nonmetallic inclusions in cast steel G17CrMo5-5: a) irregular – for UM; b) spheroidal – for M (Gajewski and Kasińska, 2009)

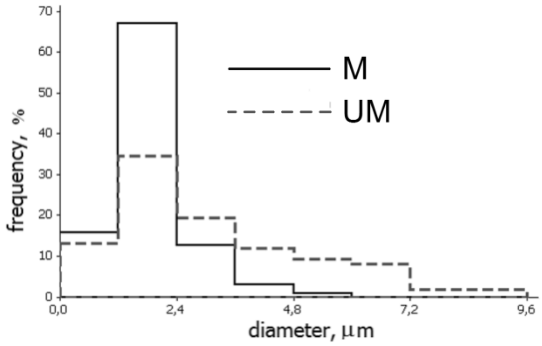

Fig. 2. The size distributions of the inclusions, d_i, in UM and M cast steel

All tests were performed at temperature T_{test} =+20 ^{0}C. Strength characteristics were determined in the uniaxial tensile test on the standard, 5-times round specimens on the testing machine UTS/Zwick-100, which is equipped with an automated control and data recording system. The tensile specimens were cut-out directly from the tested SEN(B) specimens. The results are shown in Tab. 2, where σ_0 is a yield strength, σ_u is an ultimate strength, n is a power exponent in the Ramberg-Osgood law, A_5 is an elongation, Z is an area reduction. We can observe that modification by REM of the cast steel caused an increase of strength characteristics and plasticity.

Tab. 2. Strength characteristics of the UM and M cast steel G17CrMo5-5

Specimens	σ_0 MPa	σ_u MPa	n	A_5 %	Z %
UM_1	444	587	12.08	19	52
UM_2	442	595	11.47	19	62
UM_3	441	596	11.47	20	59
Average	**442**	**593**	**11.67**	**19.7**	**58**
M_2	468	620	12.45	22	69
M_3	457	618	11	22	56
Average	**463**	**619**	**11.73**	**22**	**63**

Fracture toughness was determined on the SEN(B) specimens: B=12 mm, W=24 mm, S=96 mm. Fatigue cracks were derived from the notches. During derivation of the fatigue cracks, loading was performed on the testing machine MTS-250 under conditions of controlled force and at a frequency of 20 Hz. In accordance with the requirements of the standard (ASTM E1820-09), the length of the fatigue crack was about 1.5 mm, and the total dimension of the notch and the fatigue crack was about $a_0/W\approx0.5$. The method of a potential drop changing was used to measure the growth of the crack length during the test (ASTM E1737-96). In case of the specimens made of the UM cast steel after ductile crack growth, occurred a brittle fracture. However a ductile extension of the crack was large (Fig. 3), so that it enabled to determine the J_R curve (Fig. 4). For the M cast steel was observed a fully ductile increment of the crack extension, in the whole range of loading (Fig. 3). The J_R resistance curves for the M cast steel are placed higher than the J_R resistance curves for the UM (Fig. 4). The critical values of J integral, J_C, and values at the initial moment of the crack extension, J_i, for the tested specimens are presented in Tab. 3.

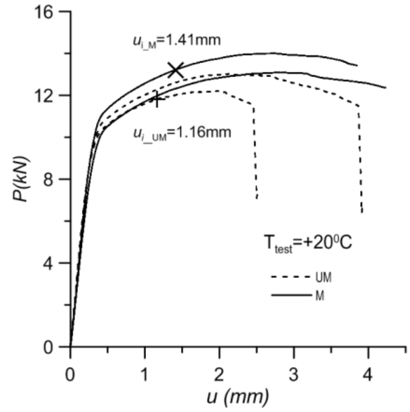

Fig. 3. Load-displacement curves of the M and UM cast steel and points coresponding to the J_i values

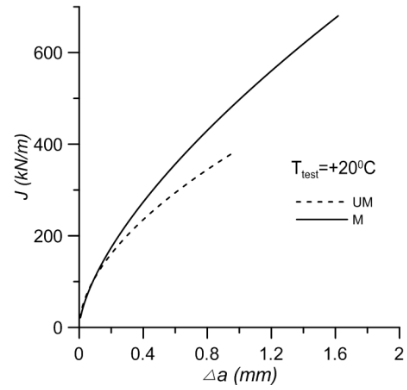

Fig. 4. J_R curves for the M and UM cast steel for the specimens analyzed in FEM

Tab. 3. J_i and J_C values for the M and UM cast steel (* - the spesimen analyzed in FEM)

Specimens	J_i kN/m	J_C kN/m	Type of crack extension, length of crack extantion
UM_17	194	299	Ductile-Brittle; Δa_D=1.80mm
UM_18*	160	246	Ductile-Brittle; Δa_D=0.87mm
Average UM	**177**	**273**	
M_16	210	317	Fully Ductile
M_18*	207	312	Fully Ductile
Average M	**209**	**315**	

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3. NUMERICAL ANALYSIS OF STRESS DISTRIBUTIONS IN FRONT OF THE CRACK

Numerical analysis was performed on SEN(B) specimens. Computations were carried out in Adina 8.9. The ¼ part of the three-dimensional specimen was modeled, because two symmetry planes exist. The specimen in thickness direction was divided into ten layers. The layers became thinner in the direction of the free surface. This was caused by a greater gradient of the component stress changes near the side surface of the specimen. Tip of the crack was modeled as a quarter of an arc of a radius 10 μm. The finite element mesh size was reduced in the radial direction to the crack tip. In the computations there were used 20-nodal three-dimensional finite elements. The load in calculation was defined by a displacement of the loading roll of the testing machine at the moment, which corresponded to the J-integral value, at the initiation of crack extension. Those moments are points on the load-displacement curves for the UM (u_{i_UM}) and M (u_{i_M}) cast steel (Fig. 3). In computation the load increased linearly to reach a certain value. The real σ-ε curves derived on the basis of the plots obtained during uniaxial tensile tests for the UM and M cast steel (Fig. 5), which were used in FEM calculation. The model of a large strain was adopted.

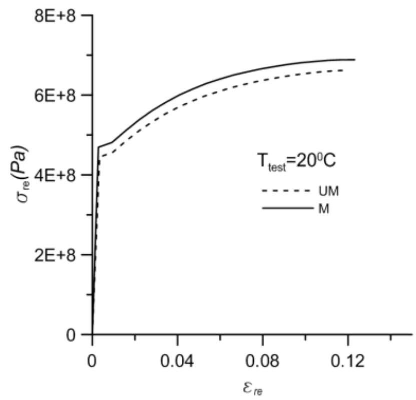

Fig. 5. Plot of modeled materials used in numerical computations – true σ-ε curves

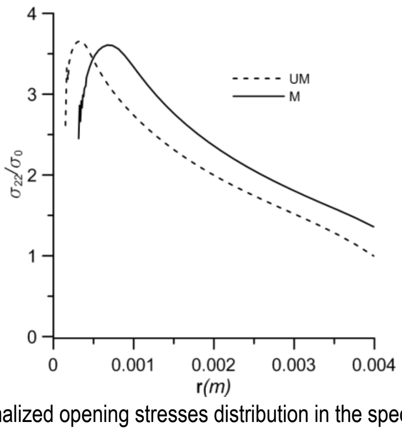

Fig. 6. Normalized opening stresses distribution in the specimen axis

The stress distributions in front of the crack tip σ_{11}, σ_{22}, σ_{33} in the particular layers were obtained. The value of the maximum opening stresses, σ_{22}, for the UM and M cast steel reaches the highest level ~3.6σ_0 in the axis of the specimen (Fig. 6). The maximum opening stresses decrease with a distance in a direction to a free surface of the specimens (Figs. 6-9). However, a lower max levels of the opening stresses in the thickness direction obtained for the SEN(B) specimens made of the M cast steel (Figs. 6-9).

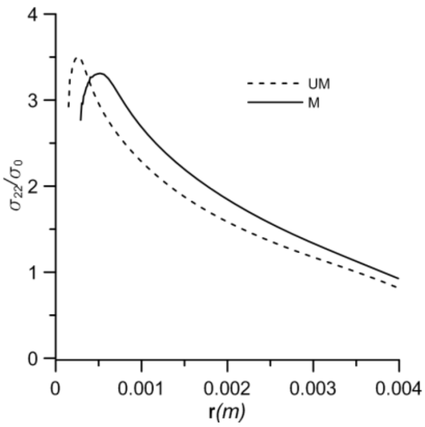

Fig. 7. Normalized opening stresses distribution in the 5th layer

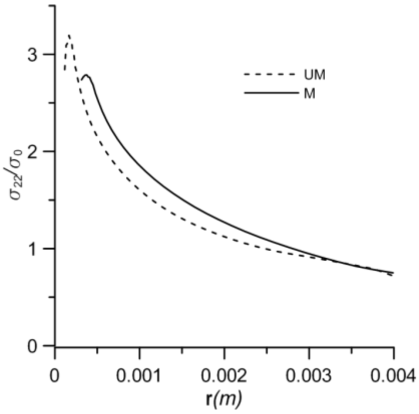

Fig. 8. Normalized opening stresses distribution in the 8th layer

Parameters of the triaxiality stress state in front of the crack at the critical moment for the UM and M cast steel were calculated. The parameters T_z (Guo, 1993) and $3R$ (Rice and Tracey, 1969) are used in fracture mechanics to evaluate the triaxiality stress state level. The weighted average value of T_z – T_m, and the weighted average value of $3R$ – $3R_m$ were proposed to evaluate the triaxiality stress state in the paper (Neimitz et al., 2015). These parameters take into account the specimen thickness.

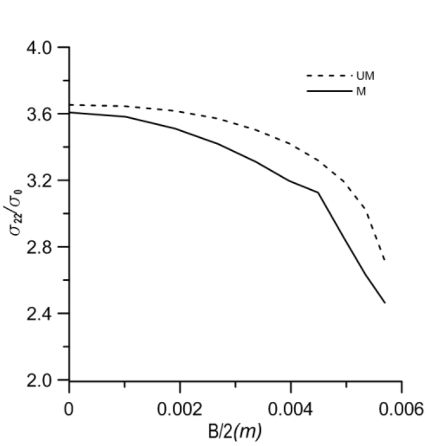

Fig. 9. Distribution of the maximum values of the normalized opening stresses in thickness direction

$$T_z = \frac{\sigma_{33}}{\sigma_{11}+\sigma_{22}}, \quad (1)$$

$$T_m = \frac{2}{B}\sum_{i=1}^{10} T_{zi}B_i, \quad (2)$$

$$3R = \frac{(\sigma_{11}+\sigma_{22}+\sigma_{33})/3}{\sigma_0}, \quad (3)$$

$$3R_m = \frac{2}{B}\sum_{i=1}^{10} 3R_iB_i, \quad (4)$$

where: σ_{11}, σ_{22}, σ_{33} are stress components in the stress plane, opening and in the thickness direction, respectively; σ_0 is a yield stress; *i* is a layer number; *B* is a layer thickness.

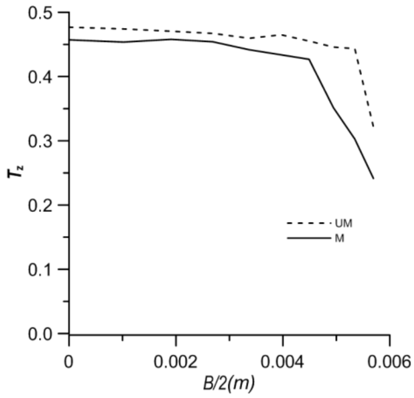

Fig. 10. Distributions of the T_z parameter in a direction of the specimen thickness

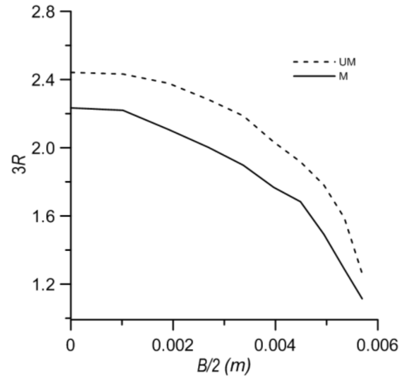

Fig. 11. Distributions of the 3*R* parameter in a direction of the specimen thickness

The parameters T_m and $3R_m$ were calculated for specimens made of the UM and M cast steel. A higher level of these parameters was obtained for the UM cast steel G17CrMo5-5 (Tab. 4).The higher level of stress triaxiality indicates higher restrictions on the growth of a plastic zone in front of the crack, reducing the amount of energy stored, and, as a result, decreasing the fracture toughness characteristics. The derived experimental results confirmed that increase of the triaxiality stress state in the specimen indicates a reduction of fracture toughness (Tab. 4).

Tab. 4. The weighted average parameters T_m and $3R_m$ for UM and M cast steel

	T_m	$3R_m$	J_i (kN/m)
UM	0.46	2.16	160
M	0.42	1.91	207

4. EFFECT OF MICROSTRUCTURE ON FRACTURE PROCESS OF G17CrMo5-5 CAST STEEL

The results of numerical calculations indicate more favourable conditions for the implementation of cleavage fracture in the unmodified cast steel, which quantitatively expressed at higher values of the triaxiality parameters, especially *3R* parameter. Detailed studies of microstructure revealed some differences in the microstructure of the UM and M cast steel. In both variants of steel, there is a similar microstructure of ferrite with large areas of perlite-bainite (Figs. 12a, 12b). But for the UM cast steel a characteristic feature is a larger quota of a ferritic component in the microstructure and larger size of ferrite grains (D_z =8-25 μm for UM; D_z =3-15 μm for M).

a)

b)

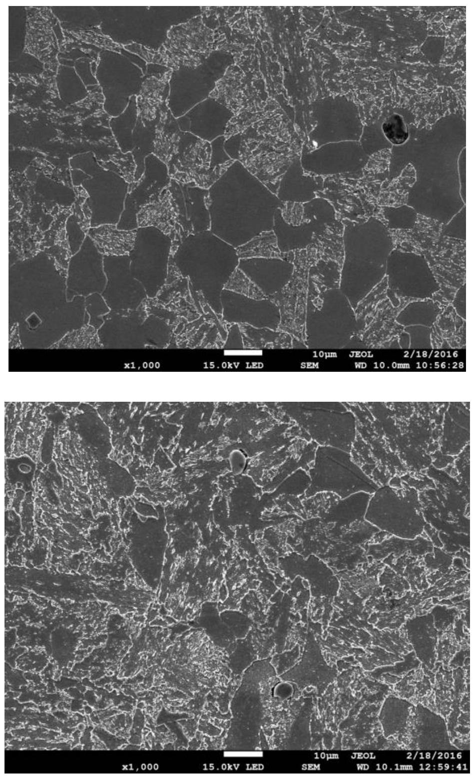

Fig. 12. Cast steel G17CrMo5-5 microstructure: a) for UM; b) for M

According to the concept of a local approach to the process of fracture, cleavage fracture will be made if the level of stress exceeds the critical levels, necessary for the development of micro-cracks inside the grain, and to overcome the grain boundary and the development of cracks in the adjacent grains (Pineau, 2006). In order to evaluate these critical levels, we may use the formulas proposed in the works of Knott et al. (Curry and Knott, 1978; Dolby and Knott, 1972; Knott, 1977). Critical level of stresses of the microcrack initiation from micro-defect can be assessed using the formula:

$$\sigma_{Ci} = \frac{\pi}{2}\left(\frac{4E\gamma_p}{\pi(1-\nu^2)d_i}\right)^{1/2}. \quad (5)$$

While the stress level required for the development of microcrack from the grain into neighbouring one by the formula:

$$\sigma_{Cg} = \left(\frac{\pi E \gamma_{gl}}{(1-\nu^2)D_g}\right)^{1/2}. \quad (6)$$

In the formulas (5) and (6): E is Young's modulus; ν is the Poisson's ratio; γ_p is a unit surface energy of cracks that propagates in ferrite; γ_{gl} is a unit surface energy of the crack propagating through the grain boundaries; d_i is a diameter of the inclusion particle; D_g is a diameter of the ferrite grain.

The results of the analysis of the cracking process in the UM and M cast steel G17CrMo5-5 are shown in Fig. 13. A solid line $\sigma = f(d)$ shows the dependence of critical stresses of the microcrack initiation from the micro-defect (by the formula 5). A dash line $\sigma = f(D)$ shows the dependence of the critical stresses of the microcrack growth through the grain boundary (by the formula 6). The lower horizontal dash and point line indicates the stress level, at which in the UM cast steel cleavage fracture may initiate from the particles of the largest size d_i =10 μm, (by the formula 5 and data from the Fig. 2). The upper horizontal dash and point line indicates the maximum level of the opening stresses for the UM, which were calculated numerically in the axis of the specimen (σ_C =1580 MPa). Respectively, for the M cast steel horizontal lower solid line indicates the level of the microcrack growth initiation from the particles of the maximum size, d_i =6 μm. The upper horizontal solid line corresponds to the maximum level of the opening stresses for the M cast steel (σ_C =1650 MPa). The analysis shows that in the M cast steel, cleavage fracture at the possibly highest level of loading (σ_C =1650 MPa) is likely because of microdefects nucleations and growth on the particles of inclusions d_i >3.7 μm. Also the microcrack growth through grain boundary is possible, because of the boundaries in grains of values D_g >12 μm. From the distribution of particles size presented in the Fig. 2, follows that there is about 5% inclusions of the appropriate size in the cast steel, simultaneously with a small part of ferrite grains of the appropriate size (~15%), which means that probability of the cleavage fracture occurrence is very low, less than 1%. Given that the part of the pearlite-bainite component of the microstructure construction of the M cast steel is dominant, and the growth of cleavage fracture in the microstructures of this type is difficult (Lewandowski and Thompson, 1987), the probability of realization of material cleavage fracture is negligible. Thus, the fracture process in the M cast steel will be realized by ductile mechanism. However, the probability of the cleavage fracture occurrence exists, it can be rarely realized locally in the individual ferrite grains.

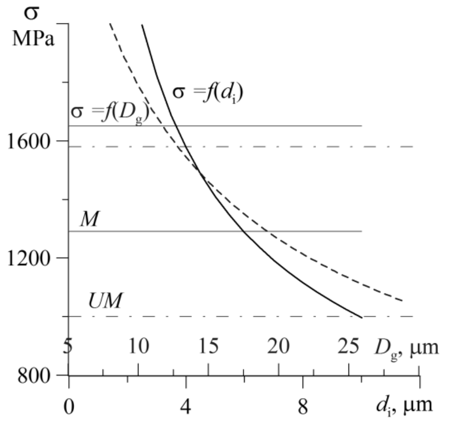

Fig. 13. Plots of the critical stresses for the M and UM cast steel

In the UM cast steel at the highest level of stresses (σ_C =1580 MPa) the initiation of cleavage fracture is possible beacuse the microcracks growths in the ferrite grain from inclusions d_i >4.0 μm. The growth of microcracks by a grain boundary is possible if D_g >13 μm. There is ~30% of the particles of the right sizes and ~40% of the ferrite grains of the right size. Taking into consideration that the ferrite grains occupy ~35% in the microstructure of the UM cast steel, the possibility of the occurrence of the global cleavage fracture is 4.2%. It is an assessment for the maximum value of stress loading. However, if we take into account the demand criteria of fracture, according to which for the realization of the cleavage fracture, stresses should reach the critical level in a material in a critical length, the probability of the occurrence of the global cleavage fracture in the UM cast steel will decrease. However, the probability of the occurrence of the cleavage fracture in the local limited areas is higher (~10%). On the basis of the conducted analysis, it can be stated that in the UM cast steel, the fracture process will be realized at the dominance of ductile mechanism. In the local areas, the occurrence of cleavage fracture is possible. In this material, there is also a low probability of the global occurrence of cleavage fracture.

In the Figures 14a and 14b are shown the photos the specimens of the M and UM cast steel. In the specimen of the M cast steel was observed only ductile fracture mechanism, realized through the nucleation and growth of voids around large particles (Fig. 14a), which is confirmed by the results of the assessment presented above. Fracture mechanism in the UM cast steel is also consistent with the presented above the results of the analysis. Generally dominates ductile fracture mechanism, however we can also observe scarce local areas, where cleavage fracture occurs. It is also worth mentioning, that in the specimens of the UM cast steel after increase of the subcritical fracture (Δa > 0.8 mm), the fracture mechanism changed into cleavage type. The change may be explained that for the moving fracture, the level of stresses increases in front of the crack tip (Neimitz at al., 2010), which leads to the increase of the probability of cleavage fracture.

a)
b)

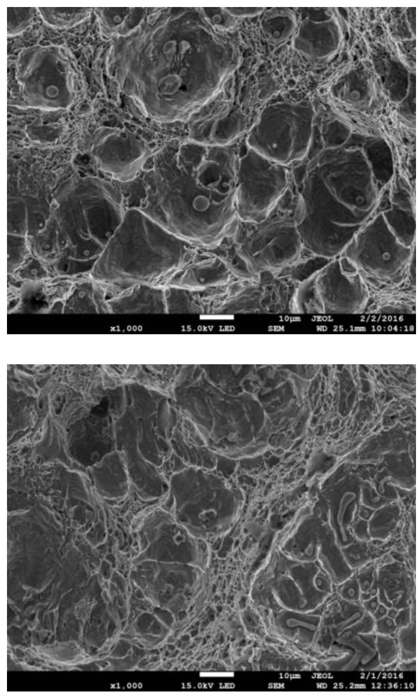

Fig. 14. The fracture surface of sub-critical crack for the cast steel G17CrMo5-5: (a) M; (b) UM

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5. CONCLUSIONS

Addition of rare earth metals to melting of the low-alloy cast steel G17CrMo5-5 increases the strength, plasticity and fracture toughness characteristics. The FEM analysis results indicate that for the initial moment of the crack extension in the modified (M) and unmodified (UM) material is required to obtain a similar level of the opening stresses in the specimen axis, $\sigma_{22} \approx 3.6\sigma_0$. However, in the M cast steel the length of the critical interval is about twice greater than in the UM cast steel. Increasing of the critical interval indicates a higher fracture toughness of a material (Luniov, 2003; Seweryn, 1994). Distributions of the main stresses and parameters of the triaxiality stresses state T_z and $3R$ in the thickness direction were presented. The weighted average values T_m and $3R_m$ were calculated. For the M cast steel, the level of triaxiality stresses state parameters are lower, that indicates lower constraint on plasticity growth and higher fracture toughness in the specimens.

Assessment of the probability of cleavage fracture was carried out, based on the numerically calculated stress distributions in front of the crack tip and the data distributions the size of non-metallic inclusions and ferrite grains. The results of assessment allowed to predicted the mechanisms of crack propagation in the UM and M cast steel, that is consistent with the results observed during specimens tests.

These results confirm the beneficial effect of the cast steel modifying by the REM, thus leading to preferred microstructure changes - to reduce the particle size of the inclusions, the reduction of grain sizes, increasing the part of the pearlite-bainite component. These changes will decrease the maximum value of the stress levels in front of the cracks, which leads to increased fracture toughness and crack growth by only safe ductile mechanism. Then, in the unmodified cast steel there is a real possibility of the brittle fracture occurrence.

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