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THE INFLUENCE OF THE RARE EARTH METALS MODIFICATION ON THE FRACTURE TOUGHNESS OF G17CrMo5-5 CAST STEEL AT LOW TEMPERATURES

WPŁYW MODYFIKACJI METALAMI ZIEM RZADKICH NA ODPORNOŚĆ NA PĘKANIE STALIWA G17CrMo5-5 W OBNIŻONYCH TEMPERATURACH

This paper presents the influence of the rare earth metals (REM) modification on mechanical properties and fracture toughness of G17CrMo5-5 cast steel at low temperatures. The REM was in the form of mishmetal. The research has been performed on serial (several) industrial melts. The fracture toughness values of unmodified and modified cast steel at the temperature range from -80°C to 20°C were tested. The reference temperatures of the brittle-to-ductile transition, T_Q, for both unmodified and modified cast steel were determined. The positive influence of the modification by REM on the fracture toughness and the reference temperature T_Q are shown.

Keywords: modification, rare earth metals (REM), fracture toughness, master curve, temperature of brittle-to-ductile transition

Artykuł przedstawia wpływ modyfikacji metalami ziem rzadkich na własności mechaniczne i odporność na pękanie staliwa G17CrMo5-5 w obniżonych temperaturach. Metale ziem rzadkich wprowadzano w postaci mischmetalu. Badania prowadzone były na wytopach przemysłowych. Odporność na pękanie była badana na staliwie niemodyfikowanym i modyfikowanym metalami ziem rzadkich w zakresie temperatur od -80°C do +20°C. Została wyznaczona temperatura przejścia w stan kruchyT_Q dla obu wytopów tj. modyfikowanego i niemodyfikowanego. Przedstawiono pozytywny wpływ modyfikacji na odporność na pękanie oraz temperaturę T_Q.

1. Introduction

The REM advantageous influence depends on the method of adding them into the liquid metal and on the amount of mishmetal. It was noticed that exceeding the amount of REM over a certain limit does not improve the alloys properties in any significant way [1]. The REM actively react with sulphur, nitrogen, carbon, and other impurities in steel which are in the form oxides, sulphides and polysulphides [2]. Therefore, they are used for reducing the amount of these elements in metal alloys. The addition, the REM changes the shape and distribution of nonmetallic inclusions also [3-5].

Information contained in the literature on this subject concerns mostly the REM influence on steel properties [6]. Previous studies have shown a significant effect of the REM on the microstructure [7], tensile properties and on the impact strength of the cast steel [8].

The aim of this report is to show the influence of the REM on the fracture toughness of the G17CrMo5-5 cast steel at the wide range of low temperatures. The tests were carried out on specimens machined from the industrial melts.

2. Materials and experiment

The chemical composition of the G17CrMo5-5 cast carbon steel received from the series of industrial melts was as follows: 0.17% C, 0.4% Si, 0.6% Mn, 1.2% Cr, 0.53% Mo, 0.1% Ni, 0.034% Al, 0.012% S, 0.018% P. It agrees with the EN-10213-2:1999 standard.

The G17CrMo5-5 cast steels were melted in the electric induction furnace, of 2000 kg capacity and with a standard lining in the crucible. The deoxidation and desulphurisation baths were received in the furnace by means of metallic Mn, ferromanganese FeMn80C01, ferrosilicium FeSi75Al1.5 and calcium silicon SiCa20-3. The final deoxidation of Aluminium A5 was done directly before the tapping of the cast steel out of the furnace. The cast steel modification was done by means of the mishmetal consisting of 49.8% Ce, 21.8% La, 17.1% Nd, 5.5% Pr, 5.35% and the rest of the REM. After casting and refining the cast, a heat treatment was performed: normalizetion at 940°C, 1h/air, and tempering of 710°C, 2h/air.

Experiments were carried out on specimens from two melts of G17CrMo5-5 cast steel: unmodified, denoted as 1 and modified by REM, denoted as 2.

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3. Results

3.1. Microstructure, tensile properties and impact strength

After the heat treatment, the G17CrMo5-5 cast steel exhibited ferrite + bainite microstructure. The result of modification was significant in decreasing the grain size of the G17CrMo5-5 cast steel (Fig. 1a, 1b). The nonmetallic inclusions occurring in the unmodified cast steel were mostly heterogeneous. This can be seen on a scanning electron microscope images of the polished surface of the metallographic specimens, that were not etched as well as by the microanalysis of the chemical composition. The (Mn,Fe)S sulphides crystallize on pads that are most often the Al_2O_3 particles of a large dispersion. The Al_2O_3 oxides occurred in larger clusters and they were accompanied by the (Mn,Fe)S sulphides (Fig. 2). The modification caused a change in the morphology of nonmetallic inclusions. Adding the REM into the liquid metal resulted in the shape and size of nonmetallic inclusions changes. They assumed mostly the spherical shape (Fig. 3) and they were more evenly arranged in the metallic matrix in comparison with the unmodified cast steel [7,8].

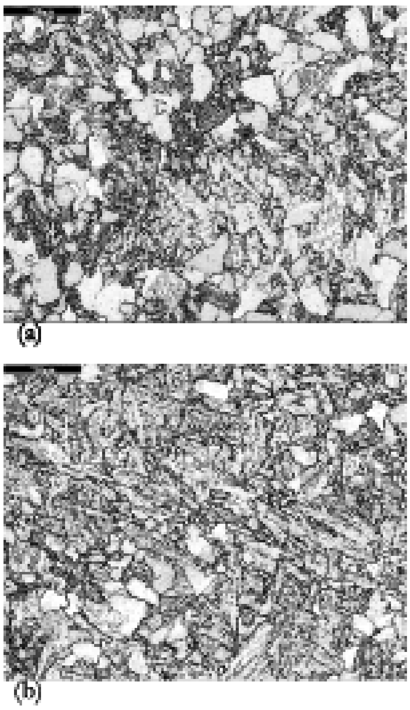

Fig. 1. Unmodified (a) and modified (b) microstructure of the G17CrMo5-5 cast steel

Average values of the tensile properties and impact strength for unmodified and modified cast steels, which were obtained before and were published in the previous articles [1, 7, 8], are presented in Table 1. The modification by REM resulted in increasing both the tensile properties and the impact strength of tested specimens. The tensile properties increased slightly, but the rise of impact strength was significant.

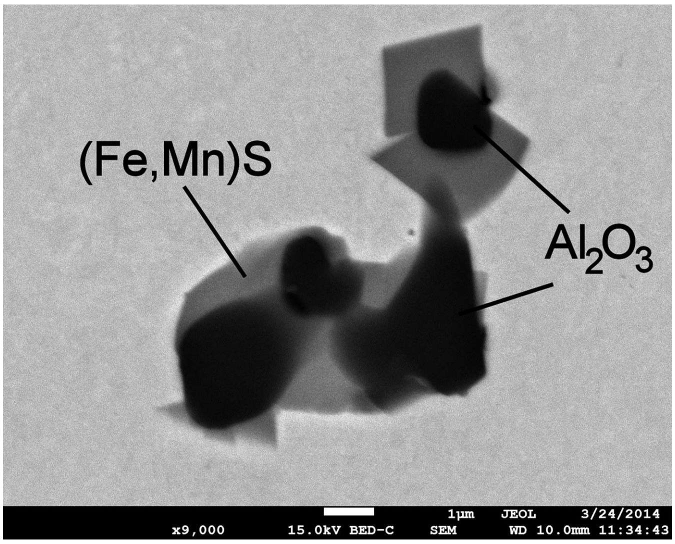

Fig. 2. The shape of nonmetallic inclusions in the unmodified G17CrMo5-5 cast steel

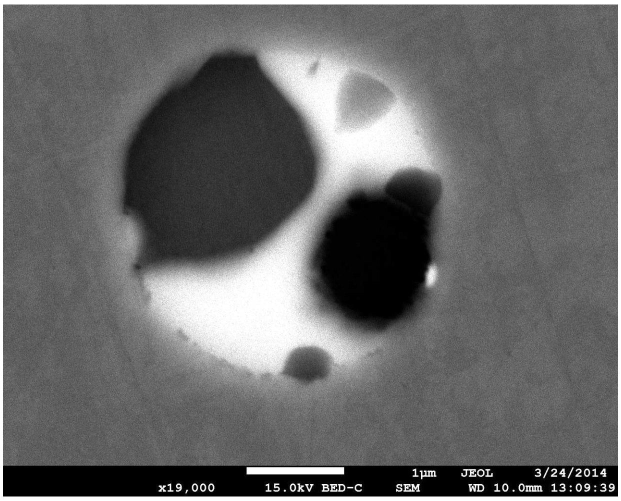

Fig. 3. The spherical shape of nonmetallic inclusions in the modified G17CrMo5-5 cast steel

TABLE 1

The tensile properties and impact strength of the G17CrMo5-5 cast steel

Cast steel	σ_y, (MPa)	σ_{UTS}, (MPa)	A_5, (%)	Z, (%)	KV, (J)
1- unmodified	443	591	21.4	56.0	42
2 - modified	446	605	24.8	65.7	110

3.2. Fracture toughness testing at low temperatures

Temperature of the brittle-to-ductile transition is an important material characteristics. Below this temperature one may expect the brittle fracture of the machine or structural components. Generally, the temperature of the brittle-ductile transition can be determined by the Charpy impact tests carried out on the series of specimens at the temperature range from -180°C to 100°C [9]. Temperature of the brittle-to-ductile transition based on the Charpy impact tests is widely used, in the engineering practice despite of the fact that it provides

TABLE 2

Fracture toughness of the unmodified and modified G17CrMo5-5 cast steel

T, (°C)	Cast steel	J_{IC}, (kN/m)	K_{JC}, (MPa·m$^{1/2}$)	Av.: K_{JC}, (MPa·m$^{1/2}$)
20	unmodfied	66.8; 298.4; 245.5	121.2; 256.1; 232.3	203.2
	modified	291.2; 311.1; 316.4	253; 261.6; 263.7	259.4
0	unmodfied	58; 141; 196	112.5; 175.9; 207.2	165.2
	modified	284.8; 315; 403	250.2; 263; 297.7	270
-20	unmodfied	38; 90; 153	91.3; 140.7; 183.4	138.5
	modified	326; 374.8; 451	267.4; 287; 315	290
-40	unmodfied	20; 30; 40	65.7; 81.3; 94	80.2
	modified	96; 146; 213	145.1; 179.2; 216.4	180.2
-60	unmodfied	20.6; 26; 34	67.3; 75.3; 86.8	76.5
	modified	53; 67; 108	108.2; 121.1; 154.3	127.9
-80	unmodfied	—; —; —	—; —; —	—
	modified	35; 48; 59	87.9; 103.1; 113.3	101.4

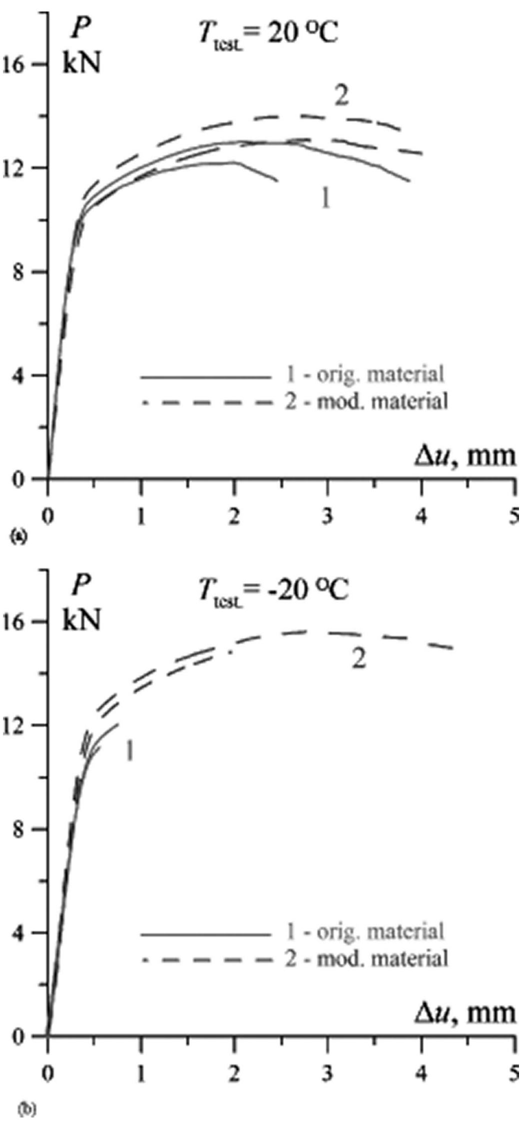

Fig. 4. Curves of loading specimens made from the unmodified and modified G17CrMo5-5 cast steel: (a) – test temperature 20°C; (b) – test temperature -20°C

only qualitative information on the mechanisms of fracture of a material. When the temperature of the brittle-to-ductile transition, T_Q, is known, the temperature dependence of the stress intensity factor (SIF) can be determined using the concept of the Master Curve [10-14].

The critical values of the fracture toughness, K_{JC}, were determined using the single notch three point bend specimens (SENB) of dimensions thickness, B =12 mm, width W =24 mm, the support span$S$ =4W with a notch relative length a/W ≈0.5. The tests were performed on a testing machine MTS-250 equipped with an automated control and data recording system. The specimens were tested in the temperature range from -80°C to 20°C. Low temperatures were obtained in a thermal chamber in the environment of liquid nitrogen vapours. In this temperature range different mechanisms of fracture were observed: brittle, ductile and mixed. Fracture toughness was determined using the critical value of the J integral, J_{IC}, in accordance with the procedures of ASTM standards [15, 16]. Then, the critical values of J_{IC} were converted to the SIF units, K_{JC}, by the f formula:

$$K_{\mathrm{JC}} = \sqrt{J_{\mathrm{IC}} E/(1-\nu^2)} \qquad (1)$$

where E is Young's modulus, ν is Poisson's ratio.

The critical values of fracture toughness of modified and unmodified cast steel for the measured datasets at the whole test temperature range are shown in Table 2. The selected characteristic graphs of the force and fracture toughness curves are shown in Figures 4 and 5.

Fracture toughness data shown in Table 2 indicate that the critical value of fracture toughness decreases with decreasing tests temperature. However, the fracture toughness for the modified cast steel is always higher than for unmodified material. The loading curves shown in Figure 4 indicate that the fracture process for modified cast steel was ductile and the level of the fracture toughness characteristics remained high at the low temperature, -20°C. In contrast the brittle fracture was observed, in the specimens made from the unmodified cast steel. Also a wide scatter of the critical fracture toughness values was starting from the 20°C temperature (Fig. 4, 5; Tab. 2).

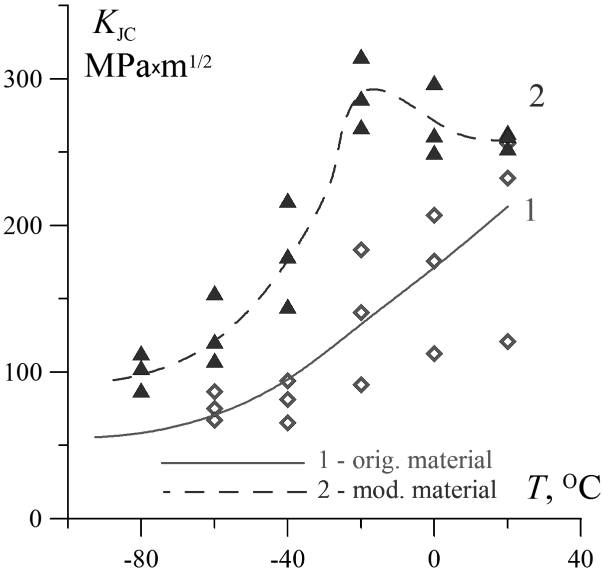

Fig. 5. Fracture toughness on tests temperature dependences for the unmodified (rhombus, line 1) and modified (triangular, line 2) G17CrMo5-5 cast steel

The results presented in Figure 5 demonstrate the beneficial influence of the REM on the G17CrMo5-5 cast steel. The fracture toughness of the modified cast steel is significantly higher than in the case of the unmodified cast steel in the whole temperature range tested. The scatter of experimental results of the cast steel fracture toughness after modification is less compared to the unmodified cast steel. Also the temperature of the brittle-to-ductile transition was shifted in the direction of low temperature.

The procedure of determination of the reference temperature in the brittle-to-ductile transition region, T_Q, and the construction of the Master Curves followed the recommendations by Wallin, Gao, Dodds and Ruggeri [10-14] and they are presented in ASTM E1921-10 standard [17] and as well as in the FITNET procedures [18]. The reference temperature, T_Q, corresponds to the value of fracture toughness equal to K_{JC} = 100 MPa·m$^{1/2}$. This procedure can be applied to ferritic steels whose yield strength is in the range $285 \leqslant \sigma_y \leqslant 825$ MPa. Experimentally measured fracture toughness can be obtained either at one or at several temperatures. The procedure suggests the determining of the fracture toughness by using the specimens of thickness B =25 mm. If the thickness of the specimen is different, than 25 mm, the fracture toughness should be corrected using the formula [18]:

$$K_{\mathrm{mat}} = K_{\mathrm{min}} + (K_{\mathrm{JC}} - K_{\mathrm{min}})\left(\frac{B}{25}\right)^{0.25} \qquad (2)$$

where K_{min} is a minimum value of fracture toughness, which is assumed K_{min} =20 MPa·m$^{1/2}$ [17, 18]. In the case when the fracture toughness was measured in several different temperatures, the brittle-to ductile transition temperature, T_Q can be calculated from the equation:

$$\sum_{i=1}^{n} \frac{\delta_i \exp(0.091(T_i - T_{\mathrm{Q}}))}{\left(11 + 77\exp(0.091(T_i - T_{\mathrm{Q}}))\right)} = \sum_{i=1}^{n} \frac{(K_{\mathrm{JC}i} - 20)^4 \exp(0.091(T_i - T_{\mathrm{Q}}))}{\left(11 + 77\exp(0.019(T_i - T_{\mathrm{Q}}))\right)^5}, \qquad (3)$$

where: K_{JC_i} is the i-th value of fracture toughness determined at the temperature $T_i;n$ is a number of tested specimens; δ_i equals 1, then $K_{JC_i} < K_{cenz}$, or 0, when the inequality is opposite. The censored value K_{cenz} is calculated from the following formula: $K_{\mathrm{cenz}} = (Eb_0\sigma_y/30)^{1/2}$, where b_0 – is the uncracked width of the specimen.

If the value of the brittle-to-ductile transition temperature, T_Q, is known, the data set by the relationship $K_{mat} = f(T)$, called a Master Curve, can be received [17, 18]:

$$K_{mat} = 30 + 70\exp(0.019(T - T_{\mathrm{Q}})) \qquad (4)$$

The transition temperature, T_Q, and the master curves for G17CrMo5-5 cast steel unmodified and modified by REM are shown in Figure 6. Modification of cast steel causes a significant growth of fracture toughness. The reference temperatureT_Q moved by about 50°C in the direction of lower temperatures.

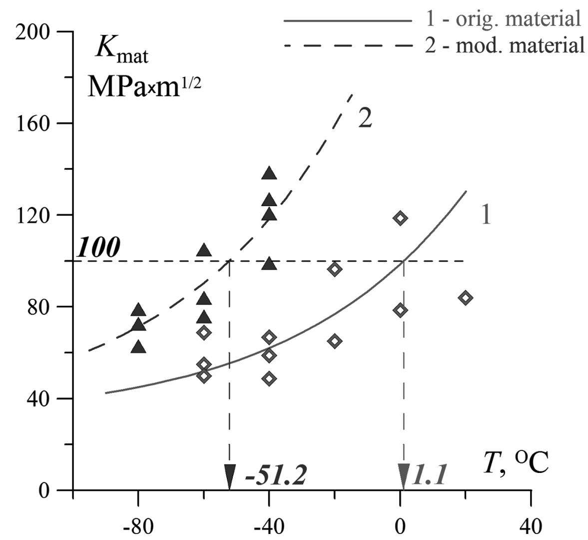

Fig. 6. Master curves and reference temperatures of the brittle-plastic transition for unmodified (line 1) and modified (line 2) G17CrMo5-5 cast steel

4. Conclusions

The modification of the G17CrMo5-5 cast steels by REM caused changes of the microstructure morphology. In comparison to the unmodified cast steel, the grains size decreased, nonmetallic inclusions transformed from the complex forms to the spherical shape, and they became more dispersed in the ferrite. This microstructure transformation stimulated an improvement of the tensile and the fracture toughness properties. In particular, a significant rise was noticed in fracture toughness in the rage of low temperature. The modification by REM of the G17CrMo5-5 cast carbon steel caused a shift of the reference temperature, T_Q by about 50°C in the direction of lower temperature. The received results confirm the results of the previous studies on the influence of the modification on the tensile characteristics and the impact toughness obtained at room temperature.

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