The Evaluation of the Influence of Ambient Temperature on the Values of Measured Absorbed Energy and Failure Mechanisms of Materials Utilised for the Means of Containerization

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Abstract

The paper evaluates, with the help of a fracture surface fractographic analysis, changes in failure mechanism depending on the test temperature of ultra-hard low alloy steels ARMOX 500T and ARMOX 600T, which are used for the means of containerization. The evaluation is based on experimentally determined values of absorbed energy measured by means of an impact test. Experimental investigation temperatures ranged from –80 °C to +100 °C, where the occurrence of a limit state in material is highly probable.

Keywords: ARMOX 500T steel, ARMOX 600T steel, Ultra-hard low alloy steel, Transcrystalline ductile failure, Transcrystalline quasi-cleavage failure, Fractographic analysis

1. Introduction

Brittle fracture can be characterized, in terms of macroscopy, as a failure of cohesion, at which no macroscopic deformation occurs in the area of the fracture process. The fracture occurs at nominal stresses lower than the macroscopic yield point of the material. Macroscopic yield point can, in certain situations, be the stress at which plastic deformation can be measured by ordinary devices. Similarly, "macroscopic yield point" in a component (e.g. a machine component) with structural notches is the stress at which plastic deformation spreads to the entire bearing cross-section at the point of the notch. As far as failure mechanism is concerned, the fracture surface of a brittle failure is, as a rule, created by cleavage, i.e. by breaking interatomic bonds in cleavage planes of individual grains (transcrystalline fracture) or by segregating individual grains by breaking interatomic bonds on grain boundaries (intercrystalline fracture). A fracture considered to be a degradation process occurs upon reaching critical values of quantities controlling the course of the action. The paper presents the results of an experiment carried out with ARMOX 500T and 600T steels, aiming to evaluate the effects of test temperature on the occurrence and development of a brittle failure in the steels studied. The goal of the experiment was to carry out impact tests in the temperature range specified, allowing to evaluate how the material is prone to brittle fracture and to measure the values of absorbed energy. The steels specified are employed (among others) in the manufacturing of technical means of containerization that can be utilised in climatic zones with considerable temperature differences. Such extreme temperature differences may lead to the occurrence of degradation processes in materials, and consequently to the occurrence of a limit state. The limit state in a material can be defined as a limit situation of balance between the effects of external conditions and material response. The causes of degradation processes include mechanical stress and temperature. ARMOX 500T and ARMOX 600T steels are ultra-hard low-alloy steels employed to meet specific needs of individual military and civil industrial branches. (Mentl, 2009, p293-298; Polak, 2009, p204-211)

2. Experimental

The experimental programme of the work concentrated on the evaluation of the influence of test temperatures on fracture surface failure mechanisms and the course of absorbed energy *KV* values.

2.1 Materials

Ultra-hard low alloy steel ARMOX 500T (PLATE ID NO 074218-445917) and steel ARMOX 600T (PLATE ID NO 073335-399106) were used for the experiment. The steel was supplied finally treated (after heat treatment) by the producer. Basic mechanical properties and chemical composition of the above-specified steels as per the certificate are stated in Table 1, 2.

2.2 Impact Test

Toughness is characterised by the ability of a material to absorb supplied mechanical energy and transform it to plastic deformation prior to the occurrence of a failure. Hence, in practice, the toughness of a material refers to its resistance to the occurrence of a brittle failure. Based on measured absorbed energy, a value corresponding to the work required to fracture a specimen is calculated per unit of area of the narrowest cross-section of the specimen. The experiment was carried out as an impact test by means of instrumented pendulum WOLPERT PW 30/15 with nominal energy 300 J as per ISO 148-1, and absorbed energy was determined in the test temperature range –80 °C to +100 °C on the measuring device mentioned. Prior to the impact test, specimens sized (10x5x55)mm were manufactured and fitted with a V-notch 2mm deep, 45 degree in angle and radius of the notch root ρ=0.25 mm (Figure 1). (Yu, 2009, p41-51; Yu, 2010, p54-62; Bayraktar, 2008, p313-326)

2.3 Fractographic Analysis

In order to identify the failure mechanisms on fracture surfaces after an impact test, a fractographic analysis of fracture surfaces was carried out by means of a scanning electron microscope JSM 840 (JEOL). The goal of the fractographic analysis was to evaluate the effects of test temperature on the character of fracture surfaces in the distance approx. 1/3 in the axis of the fracture perpendicular to the notch. For the purpose of evaluation, 1000x zoom was used. Also, the greatest depth ***d*** of a ductile fracture under the notch was measured (Figure 5). (Holzmann, 2007, 13-28; Baser, 2010, 1490-1495).

3. Results and Discussion

3.1 Absorbed Energy

Based on experimentally determined values of absorbed energy *KV* in the range of test temperatures –80 °C to +100 °C (Figure 2) in ARMOX 500T steel, test temperature range –80 °C to 0 °C can be identified as a zone with high probability of occurrence of degradation processes leading to the occurrence of a limit state in the material. The values of the absorbed energy determined in this test temperature range were lower at the temperature –40 °C (by approx. 17.6%), –60 °C (by approx. 25.5%), and –80 °C (by approx. 32.7%) if compared to the value of absorbed energy *KV* determined at the temperature +20 °C. In ARMOX 600T steel, the values *KV* were lower at the temperature –20 °C (by approx. 7.1%), –40 °C (by approx. 8.2%), –60 °C (by approx. 12.9%), –80 °C (by approx. 23.5%) if compared to the value determined at the temperature +20 °C. In ARMOX 600T, lower values of absorbed energy were measured if compared to ARMOX 500T steel, and the curve of *KV* values

(Figure 2) is not as steep, which may be the consequence of more brittle basic matrix of ARMOX 600T steel having higher content of carbon and being more prone to brittle failure.

3.2 Fractographic Analysis

Changes in failure mechanisms in the specimens studied were researched by means of a fractographic analysis of fracture surfaces, and the relation between the test temperature and changes in failure mechanism of the steels studied was assessed. In ARMOX 500T and ARMOX 600T steels, considerable decrease in the *KV* value determined by approx. 32.7%, or 23.5% was identified at the temperature –80 °C, if compared to the value determined at the temperature +20 °C. (Man, 2010, 1625-1633; Polak, 2010, 883-892; Hornikova, 2010, 321-324; Leinenbach, 2010, 672-682)

The structure of the steels is martensite with certain portion of bainite. ARMOX 600T steel has a higher content of carbon, chromium and nickel if compared to ARMOX 500T steel (Table 1.), and the values of hardness and strength are thus higher than in ARMOX 500T steel (Table 2), as opposed to the values of absorbed energy required to fracture a test specimen. Higher content of carbon in ARMOX 600T steel enhances hardenability, but also reduces ductility of the material tested; brittle failure occurs in the material, and less absorbed energy is required to fracture a test specimen than in ARMOX 500T (Figure 2). The requirement for higher value of absorbed energy to fracture a test specimen of ARMOX 500T (Figure 3) was also confirmed by the results of a fractographic analysis of fracture surfaces, as the failure mechanism was transcrystalline ductile at higher temperatures as against ARMOX 600T steel (Figure 4), where the failure mechanism was transcrystalline quasi-cleavage and lower energy supply was required to fracture a pecimen.

In ARMOX 600T steel, value *d* (Figure 5), measured at low temperatures –80 °C to 0 °C, was lower if compared to values determined at test temperatures +40 °C to +100 °C, and at the temperature +80 °C, where the failure mechanism was transcrystalline quasi-cleavage, and there was smaller portion of ductile failure. Value *d*, measured at low temperatures –80 °C, –40 °C in ARMOX 500T steel, is higher if compared to values measured at test temperatures +80 °C and +100 °C. However, it was proved, based on the photographs taken, that larger structural formations of ductile failure occur at elevated test temperatures than at negative temperatures. An interesting phenomenon occurs at the test temperature +80 °C, as there are larger areas of ductile failure than at the test temperature +100 °C, and value *d* is generally higher. The original hypothesis assumed that value *d* will grow in direct proportion with growing temperature, but the measurements made disproved this hypothesis.

4. Conclusion

The paper was concerned with the effects of test temperatures on the values of measured absorbed energy and the evaluation of the influence of the quantity on the occurrence of degradation processes that may cause the occurrence of a limit state in the material studied in the test temperature range specified. Part of the experiment was also a fractographic analysis of fracture surfaces carried out with specimens after an impact test, where the relation between the test temperature and changes in the failure mechanism of low-alloy steels ARMOX 500T and ARMOX 600T was assessed. In the set of experimental data obtained, following findings can be highlighted:

- in ARMOX 500T steel, the failure mechanism was transcrystalline ductile in the temperature range –80 °C to +100 °C, whereas in ARMOX 600T steel, the failure mechanism was transcrystalline quasi-cleavage in the temperature range set.
- based on the comparison of results of the fractographic analysis of fracture surfaces carried out with both steels, higher probability of occurrence of degradation processes leading to the occurrence of a limit state in the material tested can be assumed in the test temperature range –80 °C to +0 °C.
- it follows from experimentally determined *KV* values that the values decrease considerably in both steels if tests are carried out at low temperatures (0 °C to –80 °C). In ARMOX 500T steel specimens, it is by approx. 32.7%; in ARMOX 600T steel specimens by approx. 23.5%. Thus, the limit of possible occurrence of a limit state was qualified for the temperature range –80 °C to –40 °C;
- higher determined values of absorbed energy in steel ARMOX 500T as against values measured in ARMOX 600T steel probably result from lower content of carbon, chromium and nickel, which causes better ductility of ARMOX 500T steel and, as a consequence, better ability of the material to absorb the energy supplied.

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Table 1. Chemical composition (weight %) of the studied steels

Steel/Element	C	Mn	Si	Cr	Ni	Mo	P	S	Al	B
ARMOX 600T	0.41	0.69	0.26	0.47	1.97	0.337	0.007	0.002	-	0.002
ARMOX 500T	0.28	0.85	0.26	0.49	0.88	0.345	0.008	0.001	0.057	0.002

Table 2. Values of basic mechanical properties of ARMOX steels

Steel	$R_p0.2$ [MPa]	R_m [MPa]	A_5 [%]	A_{50} [%]	*HBW* [Brinell]	$KC^{*)}$ *-40 °C* [J]
ARMOX 500T	1.399	1.634	min. 10	min. 32	533	min. 23
ARMOX 600T	**)	**)	**)	—	632	min. 9

*) Impact test (Charpy) EN 10 045-1, test specimen 5 x 10 mm

**) Value is not specified in the test certificate.

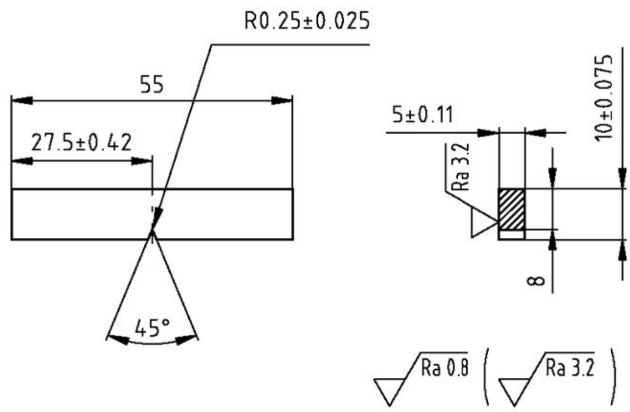


Figure 1. Basic dimensions of a test rod (specimen)

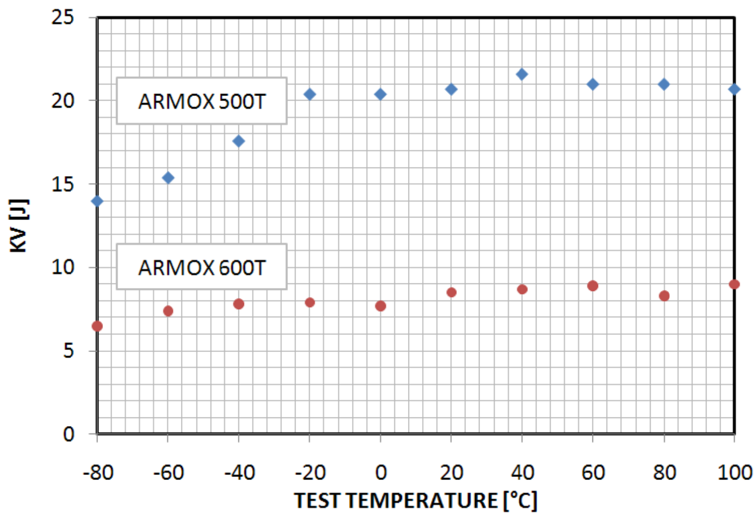
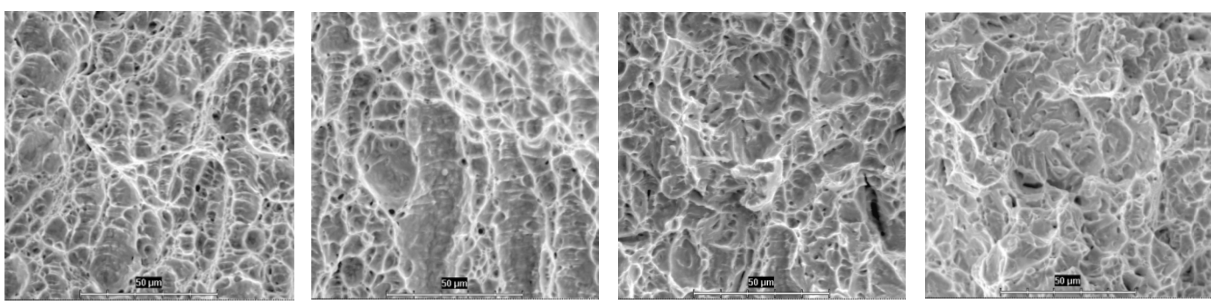


Figure 2. The influence of test temperature T_z on *KV* values. As follows from Figure 2, the *KV* values decrease slightly (by approx. 2.4 %) in ARMOX 600T steel at the temperature +80 °C if compared to the *KV* value determined at the temperature +20°C



Sample 2	Sample 5	Sample 23	Sample 29
T_Z = +100 °C	T_Z = +80 °C	T_Z = –40 °C	T_Z = –80 °C
transcrystalline ductile	transcrystalline ductile	transcrystalline ductile	transcrystalline ductile
d = 223 µm	d = 291 µm	d= 297 µm	d = 280 µm

Figure 3. Morphology of fracture in the distance approx. 1/3 from the notch ARMOX 500T steel

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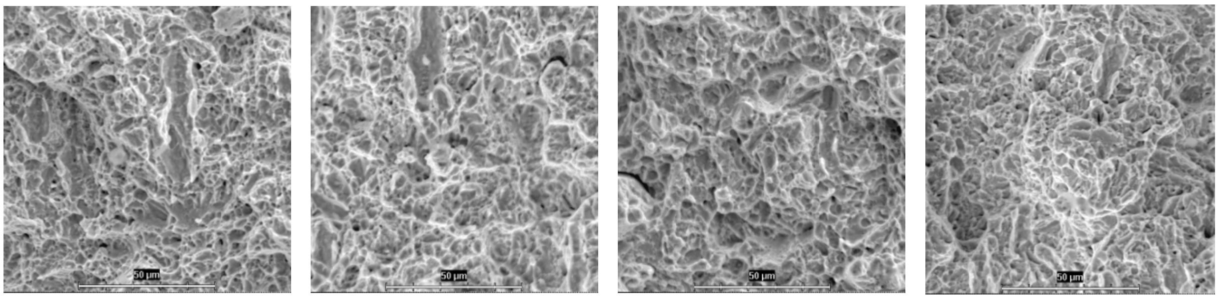

Sample 36	Sample 37	Sample 53	Sample 59
T_Z = +80 °C	T_Z = +60 °C	T_Z = –40 °C	T_Z = –80 °C
transcrystalline quasi-cleavage,	transcrystalline quasi-cleavage	transcrystalline quasi-cleavage	transcrystalline quasi-cleavage
d = 244 µm	d = 203 µm	d = 160 µm	d = 166 µm

Figure 4. Morphology of fracture in the distance approx. 1/3 from the notch ARMOX 600T steel

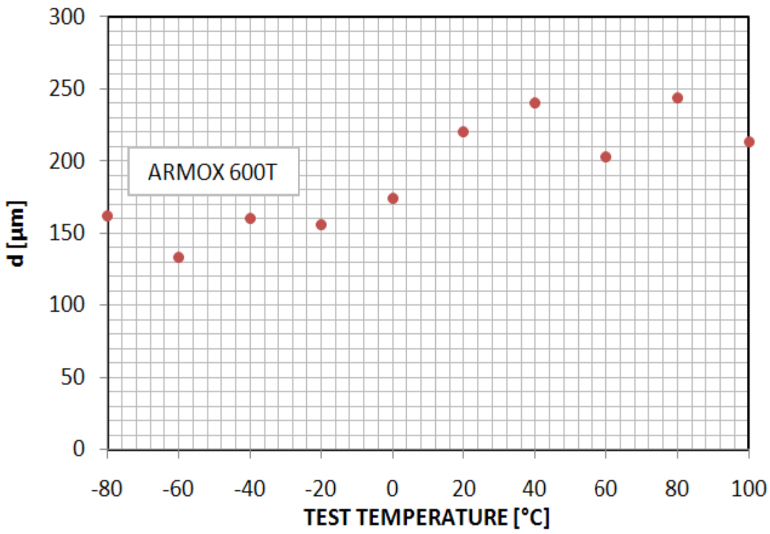

Figure 5. The influence of test temperature T_z on the greatest depth d of ductile fracture occurrence under the notch