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Evaluation of mechanical properties of soft magnetic materials for axial flux permanent magnet synchronous machines

Abstract. *Accurate determination of real material mechanical properties is important for safe servicing of energy components. The aim of the paper is systematic experimental approach for determination of mechanical properties of high strenght low alloyed steels and mild carbon steel in the rolling, thickness and width direction.*

Streszczenie. *W artykule przedstawiono metodę eksperymentalnej i systematycznej oceny właściwości mechanicznych stali niskostopowej i niskowęglowej o wysokiej wytrzymałości. Precyzyjne określenie tych parametrów pozwala na zwiększenie bezpieczeństwa użytkowania i serwisowania elementów. (**Ocena właściwości mechanicznych miękkich materiałów magnetycznych w maszynach synchronicznych z magnesami trwałymi o strumieniu osiowym**).*

Keywords: soft magnetic materials - mechanical properties - experimental testing.
Słowa kluczowe: materiały magnetyczne miękkie, właściwości mechaniczne, test eksperymentalne.

Introduction

The high strength low alloyed steels (HSLA) grade HT50 and HT80 is widely used for construction of different modern energy components [1]. The mild steel is typically carbon steel, with a comparatively mild amount of carbon (0,16% to 0,3%) and with ferromagnetic properties. Ferromagnetic properties make it ideal for electrical machines and other electrical devices. Due to the non-laminated rotor discs the mild steel is especially applicable to axial flux permanent magnet synchronous machines. Mild steel with high amount of carbon is vulnerable to rust. Where the rust free technology is required the stainless steel over mild steel is preferred. On the other hand, stainless steel does not have ferromagnetic properties although it is composed mainly of ferromagnetic metal. Mild steel is also used in construction as structural steel. It is also widely used in the car manufacturing and energy industry.

Three different types of steels were tested due to comparison of mutual mechanical properties. The mechanical properties of the HSLA steel grade HT50 and HT80 and mild steel were evaluated using standard tensile [2], Charpy [3] and CTOD (Crack Tip Opening Displacement) test [4-5]. The specimens were taken from the steel plates in rolling, thickness and width direction.

The differences in microstructures among material regions influence on the mechanical properties [6-8]. Thus, systematic experimental determination of material mechanical properties including fractographical and metallographical investigation of fracture surfaces is necessary.

Table 1. Chemical composition of the HSLA steel grade HT50 and HT80 and mild steel

Composition (%)	HT50	HT80	Mild steel
C	0,12	0,16	0,28
Si	0,55	0,68	0,52
Mn	0,67	0,75	0,71
P	0,015	0,020	0,011
S	0,002	0,003	0,007
Cr	0,70	0,79	0,05
Ni	0,07	0,09	0,01
Mo	0,042	0,032	0,013
Cu	0,19	0,24	0,62
Al	0,001	0,002	0,001

Experimental procedure

Chemical composition of the HSLA steel grade HT50 and HT80 and mild steel, plate thickness of 40 mm are given in Table 1. All testing specimens were taken from the steel plates in rolling direction (A), thickness direction (B) and width direction (C).

The yield strength and tensile strength were obtained using round bar tensile specimens, as shown in Fig.1. Tensile testing was done at room temperature (20^{O} C).

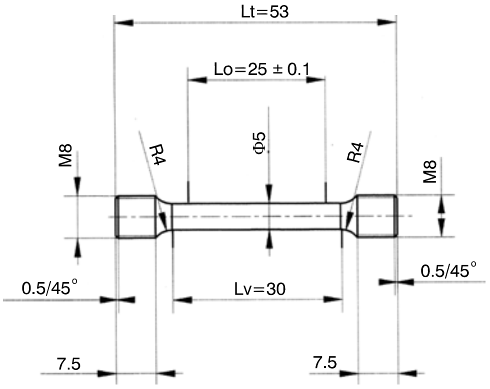

Fig. 1. Tensile round bar specimen B 5 x 25

Charpy - V testing was used to determine the impact toughness of steel plates. Shape and dimensions of standard Charpy - V specimen, mechanically notched, are shown in Fig. 2. Testing was performed at the temperature -10^{O} C. For every test temperature three specimens were fractured.

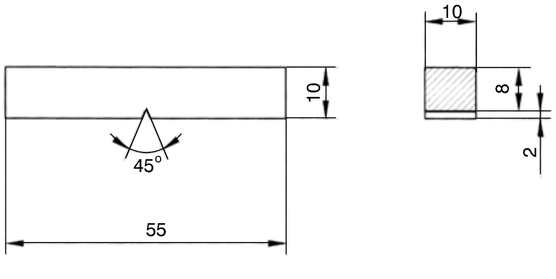

Fig. 2. Shape and dimensions of Charpy – V notch specimen

CTOD Fracture toughness of the HSLA steel grade HT50 and HT80 and mild steel was evaluated using standard static CTOD test [4-5]. Specimen loading was carried out with constant crosshead speed v = 0.5 mm/min. The test temperature was -10^{O} C according to the recommendation of the OMAE (Offshore Mechanics and Artic Engineering) association. For CTOD testing the single specimen method was used [1]. To evaluate fracture toughness of steels standard fracture mechanics tensile specimens with shallow notches were used, as shown in Fig. 3.

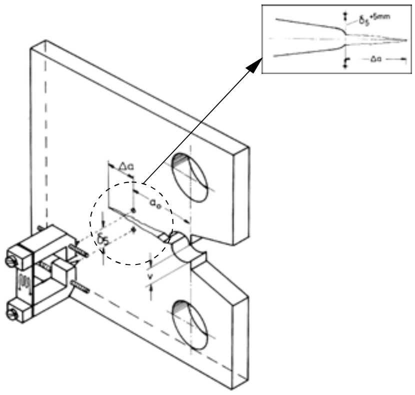

Fig.3. Direct measurement of CTOD values at crack tip of fracture mechanics specimen

For all specimens the fatique precracking was carried out with the Step-Wise High R ratio (SHR) method procedure [4]. During the CTOD tests the potential drop technique was used for monitoring stable crack growth [5]. The CTOD values were directly measured by special clip gauge [5] on the specimen side surfaces at the fatique crack tip over a gauge length of 5 mm (see Fig.3).

Discussion of results

Mechanical properties of HSLA steel HT80 and HT50 and mild steel plate in the rolling direction (A), thickness direction (B) and width direction (C) are presented in Table 2. The basic values of yield strain and tensile strain of testing steels, given in Table 2, were obtained from engineering stress (R) - strain (e) diagrams. It is known that engineering material curves can not be used for analysis of material deformation characteristics and finite element calculations in the range of high plastic deformations.

Average Charpy-V testing values of three fractured specimens are represented in Table 2.

Table 2. Mechanical properties of HSLA steel HT80 and HT50 and mild steel plate in the rolling direction (A), thickness direction (B) and width direction (C)

Steel grade	Measured direction	Yield strain (MPa)	Tensile strain (MPa)	CTOD (mm)	Charpy V (J) at –10^{O} C
HT50	A	542	591	0.390	47, 68, 71 Av=62
HT80	A	693	830	0.401	69, 78, 64 Av=70
Mild steel	A	452	497	0.423	42, 55, 62 Av=53
HT50	B	501	562	0.240	39, 41, 55 Av=45
HT80	B	657	799	0.253	53, 68, 66 Av=62
Mild steel	B	439	471	0.231	39, 44, 61 Av=48
HT50	C	531	587	0.416	42, 76, 69 Av=62
HT80	C	665	811	0.478	67, 71, 63 Av=67
Mild steel	C	447	478	0.443	40, 51, 65 Av=52

The lowest Charpy toughness was measured in the specimens taken from the steel plates in thickness direction (B). The cause for low toughness was appearance of inconvenient ferritic microstructure with distributed brittle martensite – avstenite (M-A) constituents (Fig. 4).

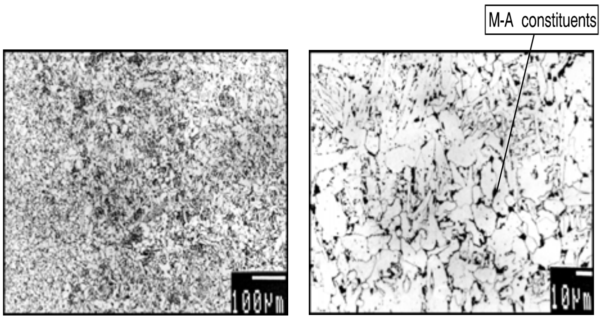

Fig.4. Ferritic microstructure with distributed brittle M-A constituents along ferrite grain boundaries

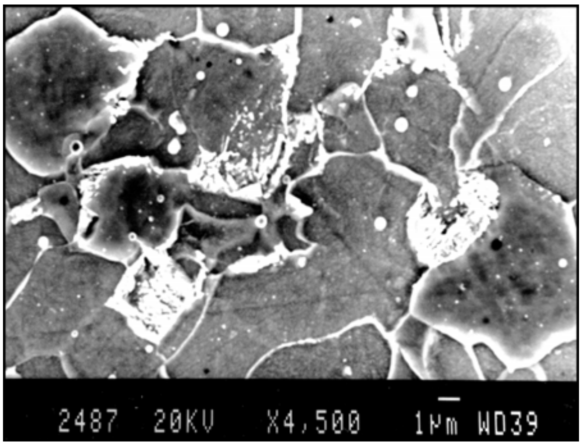

Fig. 5. Mainly ferritic microstructure with carbides (Fe_3C) precipitated at the grain boundary

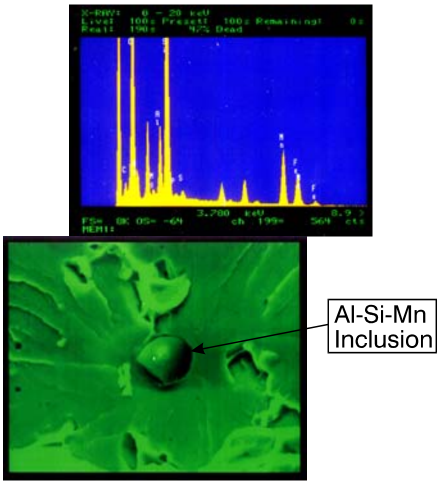

Fig. 6. Appearance and EDX analysis of brittle fracture initiation point, i.e. Al-Si-Mn inclusion

The Charpy toughness of specimens taken from the steel plates in rolling direction (A) is approximately equal to the Charpy toughness of specimens taken from the steel plates in width direction (C).

Directly measured CTOD values of fracture toughness for each type of steels are summarized in Table 2. The maximal CTOD toughness was measured in the specimens with the crack tip located in the width direction (C).

In the case of CTOD testing of specimens with the crack tip located in the thickness direction (B) the lowest CTOD was measured due to the appearance of the first brittle fracture in the mainly ferritic microstructure with carbides (Fe_3C), precipitated at the grain boundary (Fig. 5) and appearance of brittle fracture initiation point, i.e. Al-Si-Mn inclusions (Fig. 6). It should be noticed that for correct identification of brittle fracture initiation point it is of utmost importance to apply Energy Disperse X-ray (EDX) analysis to both fracture surfaces. In the opposite case it could happen that the EDX analysis detects some fictitious brittle fracture initiation point.

Conclusion

Exact evaluation of real material mechanical properties is important for safe servicing of energy components. The presence of different microstructures along pre-crack fatigue fronts has important effects on the critical crack tip opening displacement (CTOD). This value is the relevant parameter for the safe servicing of modern energy components. The mechanical properties of HSLA steels grade HT50 and HT80 and mild steel are the lowest in the thickness direction of the steel plate due to the appearance of carbides (Fe_3C) and Al-Si-Mn inclusions in the ferritic microstructure. The mechanical properties of HSLA steels grade HT50 and HT80 and mild steel are approximately equal in rolling and in width direction of the steel plates.

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