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Influence of a 1.5 T magnetic field on the tensile properties of Eurofer-97 steel

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Abstract

Eurofer-97 is the main structural material targeted for the EU DEMO fusion tokamak and will be exposed to magnetic fields of ~6 T during operation. It is therefore necessary to understand the effect of magnetic fields on the mechanical properties of the Eurofer-97. Here we preform 30 uniaxial tensile tests with and without a 1.5 T magnetic field at room temperature. Statistical results reveal that the magnetic field has minimum effect on the ultimate tensile strength and elongation of this Eurofer-97. No change in the fracture surface is observed. The importance of performing fatigue and creep tests with magnetic fields are also discussed.

Keywords: Magnetic field, Eurofer-97, tensile properties, fracture surface

Eurofer-97 is the main structural material considered for the in-vessel components of the EU DEMO fusion reactors such as the breeding blanket and divertor cassette [1]. These components are exposed to magnetic fields up to ~6 T [2, 3] during their service life. Any degradation to the engineering properties of Eurofer-97 under a magnetic field will affect the engineering design allowable in EU DEMO design. Thus, it is important to understand the effect of an applied magnetic field on the mechanical performance of Eurofer-97 during the conceptual design phase, so any effects can be considered during selection of component designs.

The effect of magnetic fields on fracture toughness [4, 5], fatigue [6], elastic modulus and ductility [7] of paramagnetic [4] or ferromagnetic [5] materials have been investigated in the last five decades. Murase et al [4] found that 8 T magnetic fields decreased the fracture toughness of austenitic 304 and 316LN steels by approximately 20% at 4.2 K compared with the results at 0 T. This is attributed to a transformation to the martensitic structure induced by the magnetic field through decreasing the austenite stability. The fracture toughness is decreased because the martensite phase is more brittle than the austenite phase.

It was generally expected that ferromagnetic steels would also show some magnetic field effect on materials' Young's module due to magneto-elasticity [8] and on plastic deformation due to magneto-plasticity [9]. However, existing literature provides conflicting evidence. Clatterbuck et al [5] found that the mechanical properties of phase stable ferromagnetic Incoloy 908 are not affected by high magnetic fields (14 T) at 4.2 K. In contrast, in an early study conducted by Bose, [6] a saturating magnetic field was shown to reduce the fatigue cycle life of pure iron at room temperature. Bose et al [6] suggested that the possible reasons for this are that the presence of a magnetic field (i) increases the mobility of dislocations, due to most of the domain walls vanishing, and (ii) accelerates the strain ageing ability of the materials. However, no further microscopy examinations have been performed to support these assumptions. Sidhom et al. [7] demonstrated that a saturating magnetic field slightly decreased the room temperature modulus of elasticity and ductility of plain carbon steel by affecting the volume percent of the ferrite phase. However, the results in Ref. [7] were relatively inconclusive, as the impact of magnetic field on the elastic modulus, ductility and volume percent of ferrite were smaller than ~6%. A more rigorous statistical analysis therefore required to draw firm conclusions.

Despite a thorough search, no literature was found by the authors for the mechanical performance of Eurofer-97 under magnetic field and there is no clear mechanistic understanding that would allow a full evaluation of its effect. The purpose of this study was to statistically investigate the tensile behaviour of Eurofer-97 under a saturated 1.5 T magnetic field [10] at room temperature. The ultimate tensile strength, elongation and fracture morphology of the samples tested with and without a magnetic field were compared.

A reduced activation ferrite-martensite Eurofer-97 steel was employed for this study. The composition of the steel is given in Table 1 [11]. This material was provided by Karlsruhe Institute of Technology (KIT) in the form of plate with ~6 mm thickness. The as-received Eurofer-97 steel was normalized at 980 °C for 0.5 h, followed by air cooling and then tempered at 760 °C for 1.5 h.

Round-shape uniaxial tensile specimens (Fig. 1a) with 2 mm gauge diameter and 7.6 mm gauge length were made from the steel plate perpendicular to its rolling direction. A servohydraulic machine was used to conduct uniaxial tensile tests at room temperature. A cylindrical in-shape permanent magnet with an in-bored diameter of 30mm, out-bored diameter of 90mm and height of 30mm (Fig. 1b) was adapted to this machine. This magnet can provide a uniform magnetic field of ~1.5 T to samples perpendicular to loading direction. For each test, the sample was assembled (Fig. 1b) first which was followed by lifting up the magnet to a pre-designed height which allows the samples align to the centre of the magnet (Fig. 1c). The samples were then soaked in 1.5 T magnetic fields for 2 hours before loading up with a cross-head displacement rate of 0.02 mm/min. A total of 30 tensile tests with and without (15 samples each condition) magnetic field were tested.

Fig. 2a shows a typical engineering stress-strain curve of the Eurofer-97 tensile sample deformed to fracture at room temperature. Results showed that there is a non-linear behaviour at applied stresses in the range of 0 to ~200MPa. This is because only the displacements between cross-heads of the machine were measured during each tensile test, rather than the displacements on the gauge length of the samples (extensometry was not able to be placed on the samples). In order to obtain more accurate elongations, the non-linear region was replaced by the extrapolation of the later linear region at the applied stresses in the range of ~ 200-500 MPa, as shown in Fig.2a. The data before (black circle) and after (blue line) the correction are shown in Fig. 2a. The loading-up curve of each test with and without applied a magnetic field is plotted in Fig. 2b and 2c. Notably, all of the loading-up curves were identical to each other, this proving the tests are repeatable. It should also be noted that only the slope of elastic region for each test can be obtained, which reflects the corresponding Young’s modulus.

Fig. 3 compares the slopes, ultimate tensile strengthens and elongations of the tests with and without applied the 1.5 T magnetic field. The corresponding average value with error bars represents a standard deviation of 2. This result shows that the differences in average ultimate tensile strengthen and elongation with and without applied a magnetic field were less than 1%. This difference is likely due to experimental errors arising from the measurement error of the sample dimension (~10 um), the changing of the load cell off-set value (~2 MPa) and changing laboratory temperature (~10℃). The average ultimate tensile strength and elongation agreed well with the results present in [12].

The fracture surface of the tested samples (ID 13 and 31) were examined using a Tescan FEG-SEM operated at a voltage of 20 kV. Fig. 4 shows the relative low (4a and 4c) and high (4b and 4d) magnification of the typical SEM fracture morphologies of samples tested without (a and b) and with (c and d) an applied magnetic field. The results demonstrate that both the tested samples manifest a ductile dimpled fracture surface. The applied magnetic field therefore has no effect on the fracture mechanisms of the Eurofer-97 steel.

Magnetic fields often affects the mechanical properties of materials significantly through affecting (i) the phase transformation [4], (ii) precipitation kinetics [13], and (iii) the interaction behaviour between the microstructure and applied magnetic fields [6, 14]. As tempered Eurofer-97 steel has a very stable phase and microstructure during the tensile deformation at room temperature; the effects of applied magnetic fields may therefore be limited. However, Giordana et al [15, 16] indicated that the microstructural (such as the growth of subgrain size, the decrease of the free dislocation density and friction stress) of Eurofer-97 changed significantly during fatigue tests at room temperature. Hence, the applied external magnetic fields might have a significant effect on the fatigue properties of Eurofer-97.

Magnetic fields have also been found to affect the creep rate of a wide range of materials, including paramagnetic titanium, aluminium alloys, diamagnetic copper and ferromagnetic cobalt nickel and carbon steel [17]. Immediate changes of creep rates were observed once a pulsed magnetic field was switched on and off during the primary or secondary creep stage. This instant effect can likely be attributed to the magnetic field, which directly alters the electron structure of the atoms composing the metallic material. However, there are very few theoretical, experimental or microscopy studies to further elucidate the behind mechanisms.

In conclusion, analysis of the statistical results show that a 1.5 T applied magnetic field has no discerbible effect on the ultimate tensile strengthen, elongation and fracture mechanisms of Eurofer-97 steel at room temperature. Further studies to evaluate the effect of applied magnetic fields on fatigue and high temperature creep behaviour of Eurofer-97 steel are of crucial importance for fusion power plant design.

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Tab. 1: Composition specification of Eurofer-97rolled plate (wt%).

Material	**C**	**Si**	**Mn**	**Cr**	**Ni**	**Mo**	**Al**	**W**	**V**	**Ti**	**Co**
Eurofer-97	0.11	0.03	0.55	8.95	0.013	<0.005	0.009	1.06	0.202	<0.003	0.004

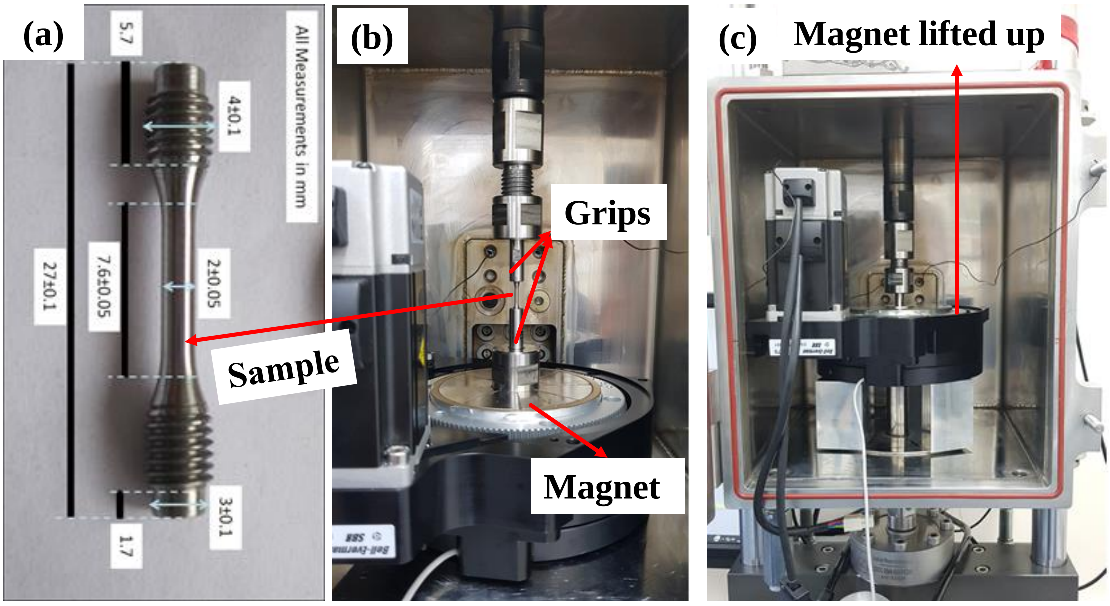

Fig. 1 (a) Geometry the tensile specimens, (b) the sample, grips and overall set-up of the tensile test with applied magnetic field and (c) the permanent magnet was lifted up to a pre-designed height which allows the samples was in the centre of the magnet.

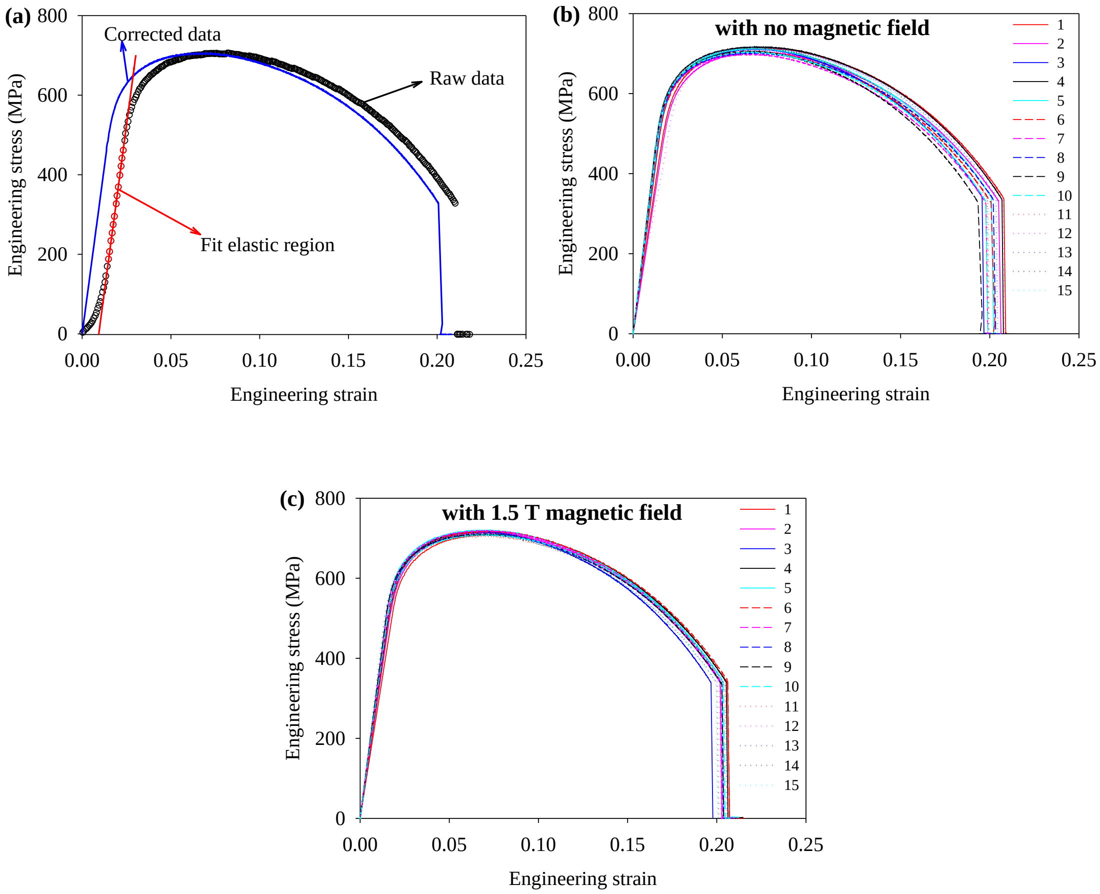

Fig. 2. (a) Data correction method of a typical loading-up curve. Corrected engineering stress versus engineering strain curves (b) without and (c) with 1.5 T magnetic field.

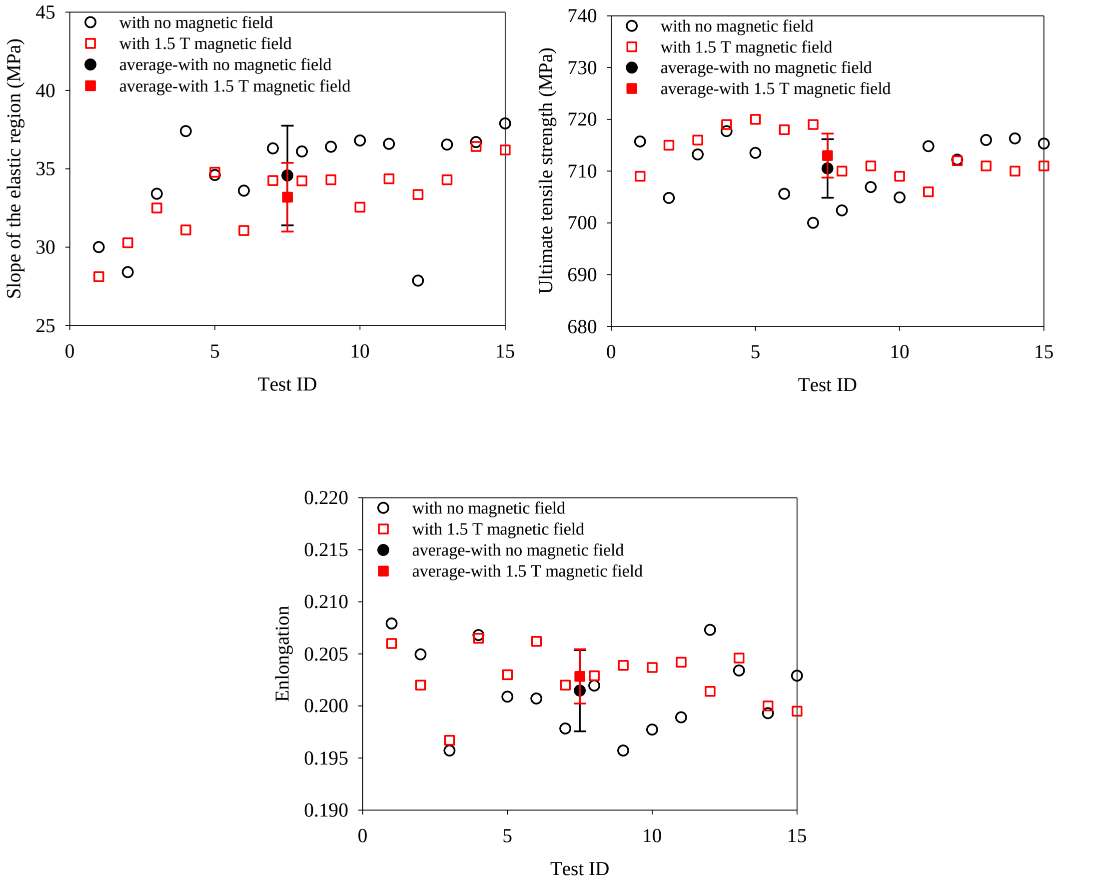

Fig 3. Comparison of (a) slope of the elastic region, (b) ultimate tensile strength and (c) elongation of Eurofer-97 with and without applied 1.5 T magnetic fields. The corresponding mean values of 15 measurements are reported and the errors are given as one standard deviation.

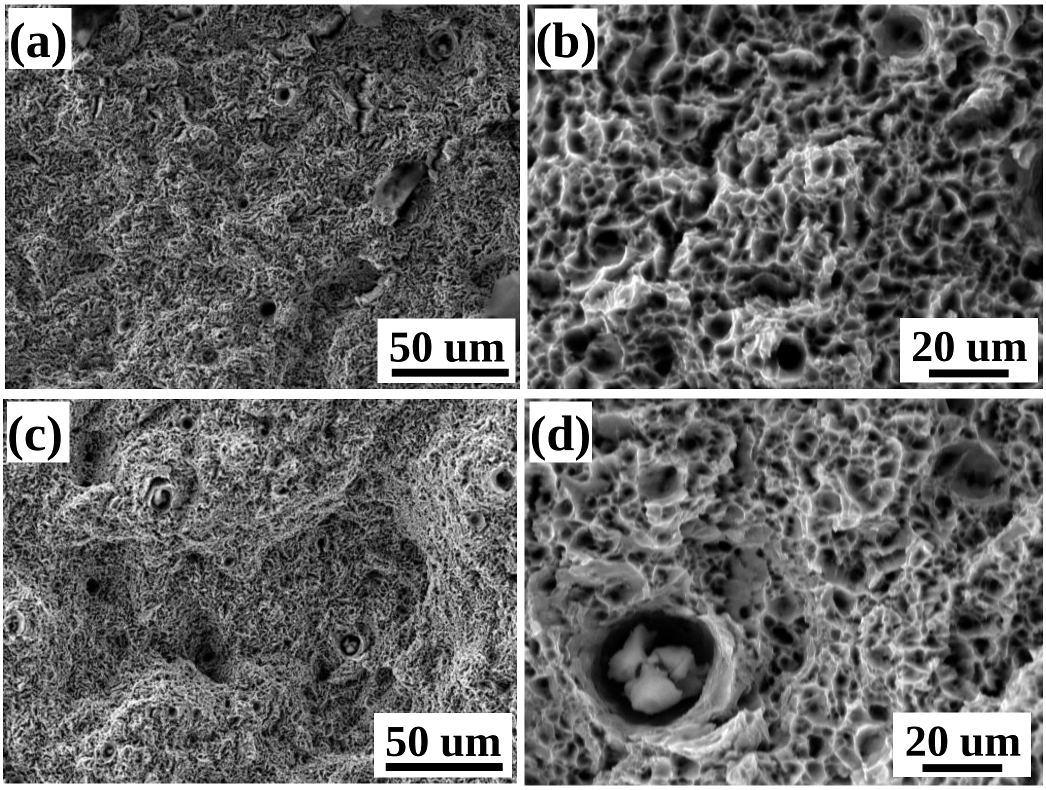

Fig. 4. Comparison between fracture surfaces of Eurofer-97 samples tested at room temperature (a-b) without and (c-d) with applied a 1.5 T magnetic field. (a) and (c) are low magnification images while (b) and (d) are relative high magnification images.

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