Fusion Engineering and Design 141 (2019) 68–72

Contents lists available at ScienceDirect

Fusion Engineering and Design

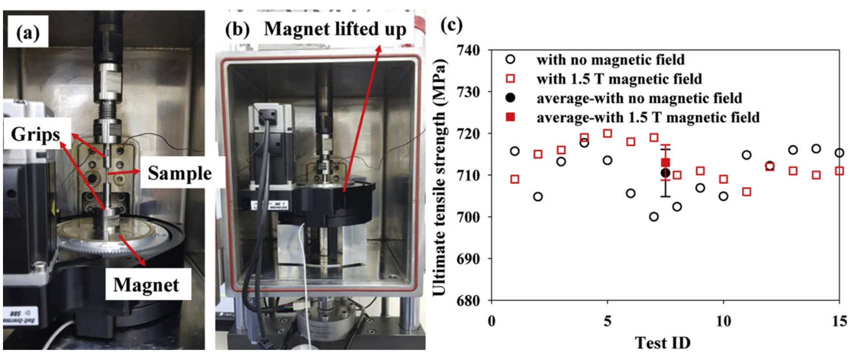
journal homepage: www.elsevier.com/locate/fusengdes

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

Y.Q. Wang[a,*], M. Gorley[a], S. Kabra[b], E. Surrey[a]

[a] United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK
[b] ISIS Facility, Rutherford Appleton Laboratory, Didcot, Oxfordshire, OX11 0QX, UK

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Magnetic field
Eurofer-97
Tensile properties
Fracture surface

ABSTRACT

Eurofer-97 is the main structural material targeted for the EU DEMO fusion tokamak and will be exposed to magnetic fields up to ˜10 T during operation. It is therefore necessary to understand the effect of magnetic fields on the mechanical properties of the Eurofer-97. We perform 30 uniaxial tensile tests with and without a transverse 1.5 T magnetic field at room temperature. Statistical results reveal that the magnetic field increases the value of proportionality limit by ˜2.6% (from 514 ± 4.5 MPa to 528 ± 10 MPa), but has minimum (< 1%) effect on the ultimate tensile strength and elongation of this Eurofer-97. No clear change in the fracture surface is observed.

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 in the range from 3.7 T to 10 T [2–4] 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 [5,6], fatigue [7], elastic modulus and ductility [8] of paramagnetic [5] or ferromagnetic [6] materials have been investigated in the last five decades. Murase et al. [5] 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

* Corresponding author.
E-mail address: yiqiang.wang@ukaea.uk (Y.Q. Wang).

https://doi.org/10.1016/j.fusengdes.2019.02.081
Received 21 June 2018; Received in revised form 10 January 2019; Accepted 20 February 2019
0920-3796/

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 Young's modulus due to magneto-elasticity [9] and on plastic deformation due to magneto-plasticity [10]. However, existing literature provides conflicting evidence. Clatterbuck et al. [6] 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 [7] a saturating magnetic field was shown to reduce the fatigue cycle life of pure iron at room temperature. Bose et al. [7] suggested that the possible reasons for this behaviour 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 of the materials. However, no further microscopy examinations have been performed to support these assumptions. Sidhom et al. [8] 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 [8] 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 would be required to draw firm conclusions. Most recently, Xie et al. [11] indicated that the magnetic field decreased the critical fracture force of the China low activation martensitic steel manifestly. However, no physical explanation has been given [11].

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 [12] 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 with the composition Fe-8.95Cr-0.11C-0.03Si-0.55Mn-0.013Ni-1.06W-0.202 V (in wt.%) was employed for this study [13]. 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 cylinder Halbach Array (contains eight NdFeB magnetics) with an in-bored diameter of 30 mm, out-bored diameter of 90 mm and height of 30 mm (Fig. 1b) was adapted for this study. A hall probe confirmed that the Halbach Array can provide a uniform magnetic field of ~1.5 T in the centre of the in-bored, perpendicular to sample loading direction. For each test, the sample was assembled into the load frame and locked in place (Fig. 1b), preceding this the magnet was moved and aligned to ensure the gauge length of the samples was within the centre of the magnet bore (Fig. 1c). The samples were then soaked in a 1.5 T magnetic field for 2 h 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 ~200 MPa. 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 the correction (blue line) are shown in Fig. 2a. The engineering stress-strain curve of each test with and without applied magnetic field is plotted in Fig. 2b and c. Notably, all of the engineering stress-strain curves were identical to each other, this proving the tests are repeatable. It should also be noted that only the slope of the elastic region for each test can be obtained, which reflects the corresponding Young's modulus.

Fig. 3 compares the slopes, proportionality limit, ultimate tensile strengths and elongations of the tests with and without the applied 1.5 T magnetic field. The corresponding mean values of 15 tests are reported and the errors are given as one standard deviation. This result shows that the differences in average ultimate tensile strength and elongation with and without applied magnetic field were less than 1%. This difference is likely due to experimental errors arising from the measurement error of the sample dimension (~ ± 10 μm) and the changing of the load cell off-set value (~ ± 2 MPa). The average ultimate tensile strength and elongation obtained from the current tests without magnetic field agreed well with the results present in [14]. Notably, Fig. 3b shows that the saturated magnetic field increases the value of proportionality limit by ~2.6% (from 514 ± 4.5 MPa to 528 ± 10 MPa). This is in disagreement with the results presented in [15], which shows a longitudinal magnetic field reduced the upper and lower yield points. It could be due to the current work applied the magnetic field transversely rather than longitudinally.

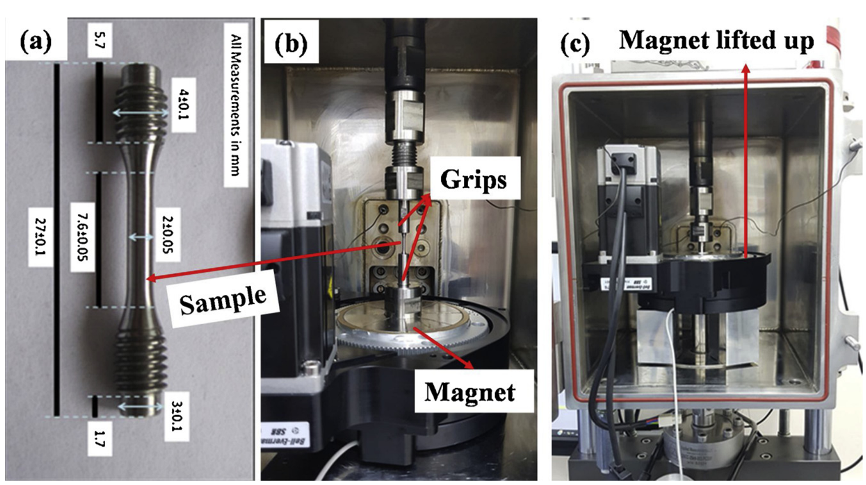


Fig. 1. (a) Geometry the tensile specimens, (b) the sample, grips and overall set-up of the tensile test with applied magnetic field and (c) the permanent magnet was lifted up to a pre-designed height which allows placing the samples in the centre of the magnet.

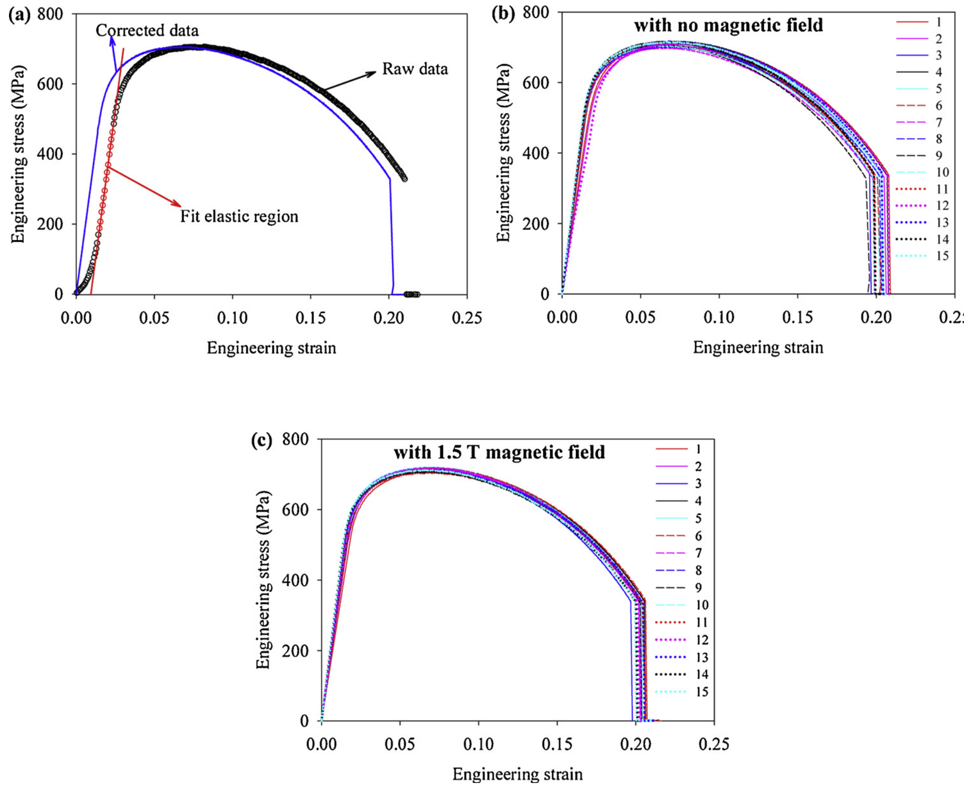


Fig. 2. (a) Data correction method of a typical loading-up curve. Corrected engineering stress versus engineering strain curves (b) without and (c) with 1.5 T magnetic field. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

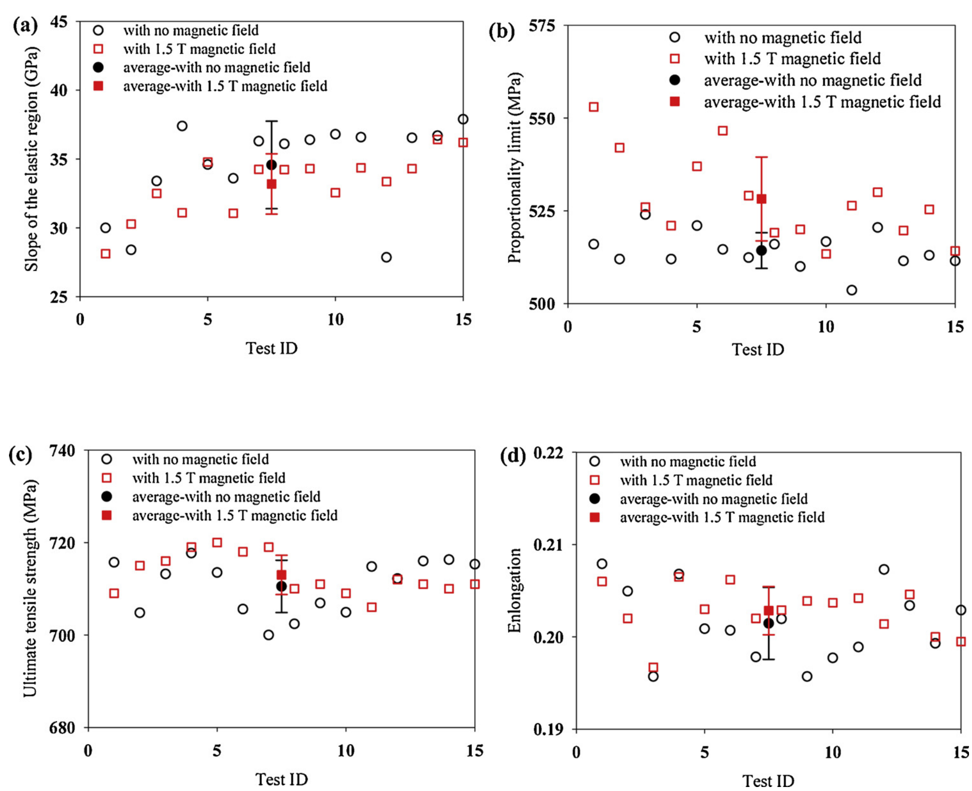


Fig. 3. Comparison of (a) slope of the elastic region, (b) proportionality limit, (c) ultimate tensile strength and (d) elongation of Eurofer-97 with and without applied 1.5 T magnetic fields. The corresponding mean values of 15 measurements are reported and the errors are given as one standard deviation.

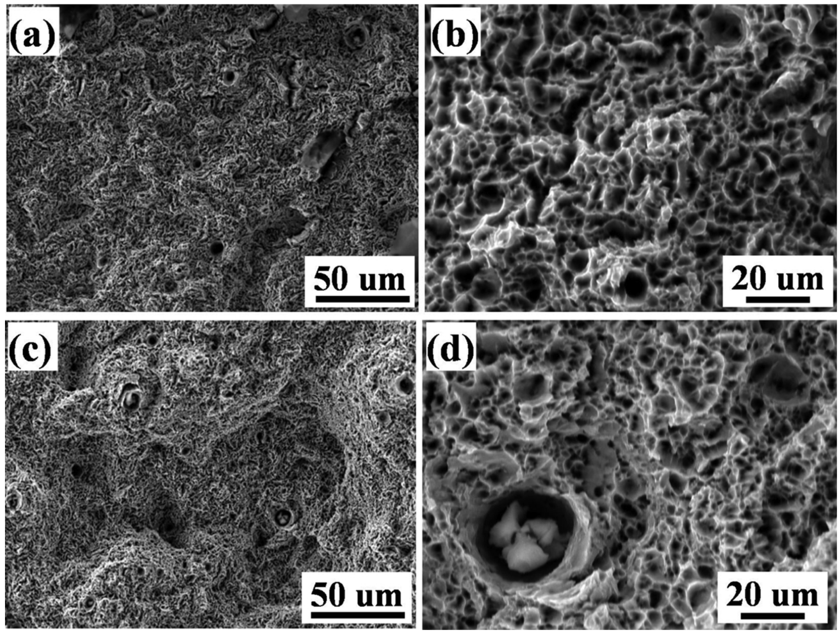


Fig. 4. Comparison between fracture surfaces of Eurofer-97 samples tested at room temperature (a-b) without and (c-d) with applied a 1.5 T magnetic field. (a) and (c) are low magnification images while (b) and (d) are relative high magnification images.

The fracture surfaces of the tested samples (ID 13 with and ID13 without applied magnetic field) 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 field often affects the mechanical properties of materials through affecting (i) the phase transformation [5], (ii) precipitation kinetics [16–17], and (iii) the interaction behaviour between microstructure/dislocations and magnetic domain wall [7,15,18–20]. There are very few direct theoretical, experimental or microscopy studies to further elucidate the behind mechanisms for case (iii). Fig. 5 shows the schematic drawing of the current tensile deformation behaviour of ferritic/martensitic Eurofer_97 steel samples without and with the saturated magnetic field. The dislocations can pin magnetic domain walls, creating obstacles to the domain wall movement [18,19]. Domain walls could also affect the mobility of dislocations as well as grain boundaries. 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. [21,22] indicated that the microstructure (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 field might have a significant effect on the fatigue properties of Eurofer-97.

Klypin [15] shows that longitudinally applied magnetic field has more notable effect on the tensile properties of commercial iron and creep rate of a wide range of materials (including paramagnetic titanium, aluminium alloys, diamagnetic copper and ferromagnetic cobalt nickel and carbon steel) than transversely applied magnetic field. Immediate changes of creep rates were observed when the longitudinal magnetic field was switched on and off during the primary or secondary creep stage. Klypin [15] suggested that this instant effect could be due to the electromagnetic nature of the force acting on dislocations, initiated the dislocation movements. Hence the effect of magnetic field on creep deformation is more significant with application of a magnetic field along the loading direction. It should be noted that temperature analysis was not included in [15], which the changing of the creep rate might be due to the electromagnetic radiation increased the creep temperature.

In conclusion, analysis of the statistical results show that a 1.5 T

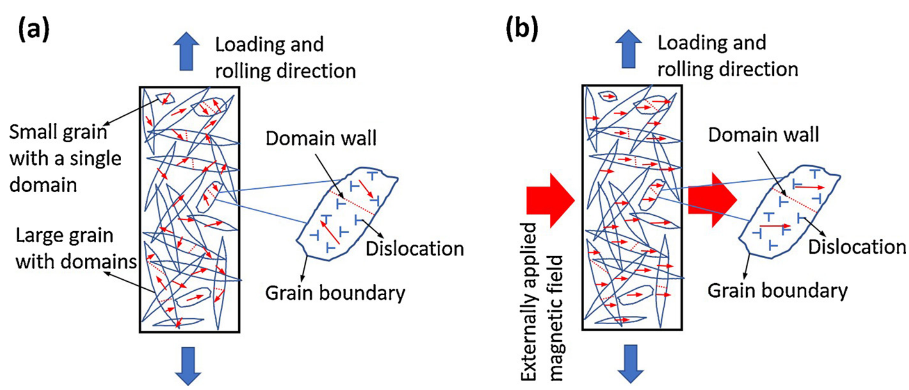


Fig. 5. Schematic of the tensile deformation behaviour of ferritic/martensitic Eurofer_97 steel samples (a) without and (b) with the saturated magnetic field. The saturated magnetic field might alter the interaction behaviour between the dislocations, domain walls and grain boundaries.

transversely applied magnetic field increases the average value of proportionality limit from 514 MPa to 528 MPa slightly, but has no discerbible effect (< 1%) on the ultimate tensile strengthen, elongation and fracture mechanisms of Eurofer-97 steel at room temperature. Further sophisticate experimental 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.

Acknowledgements

This work has been funded by the RCUK Energy Programme [grant number EP/P012450/1]. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ccfe.ac.uk. This research used UKAEA's Materials Research Facility, which has been funded by and is part of the UK's National Nuclear User Facility and Henry Royce Institute for Advanced Materials. The authors also wish to acknowledge the support of the Karlsruhe Institute of Technology through material supply (Eurofer-97rolled plate).

References

[1] M. Gorley, Critical assessment 12: prospects for reduced activation steel for fusion plant, Mater. Sci. Technol. 31 (8) (2015) 975–980.
[2] J. Ongena, R. Koch, R. Wolf, H. Zohm, Magnetic-confinement fusion, Nat. Phys. 12 (5) (2016) 398.
[3] I.A. Maione, M. Marracci, B. Tellini, Study on remanent magnetization of Fe-9Cr steel and its effect on in-vessel remote handling for future fusion reactors, Fusion Eng. Des. 88 (9–10) (2013) 2092–2095.
[4] R. Burrows, A. Baron-Wiechec, C. Harrington, S. Moore, D. Chaney, T. Martin, J. Likonen, R. Springell, E. Surrey, The possible effect of high magnetic fields on the aqueous corrosion behaviour of Eurofer, Fusion Eng. Des. (2018).
[5] S. Murase, S. Kobatake, M. Tanaka, I. Tashiro, O. Horigami, H. Ogiwara, K. Shibata, K. Nagai, K. Ishikawa, Effects of a high magnetic field on fracture toughness at 4.2 K for austenitic stainless steels, Fusion Eng. Des. 20 (1993) 451–454.
[6] D.M. Clatterbuck, J.W. Chan, J.W. Morris Jr., The influence of a magnetic field on the fracture toughness of ferromagnetic steel, Mater. Trans. JIM 41 (8) (2000) 888–892.
[7] M. Bose, Effect of saturated magnetic field on fatigue life of carbon steel, Phys. Status Solidi (a) 86 (2) (1984) 649–654.
[8] A.A. Sidhom, S.A. Sayed, S.A. Naga, The influence of magnetic field on the mechanical properties & microstructure of plain carbon steel, Mater. Sci. Eng. A 682 (2017) 636–639.
[9] B.D. Cullity, C.D. Graham, Introduction to Magnetic Materials, John Wiley & Sons, 2011.
[10] M.I. Molotskii, Theoretical basis for electro-and magnetoplasticity, Mater. Sci. Eng. A 287 (2) (2000) 248–258.
[11] Z. Xie, Q. Li, C. Pei, Z. Chen, A study on influence of magnetic field on fracture properties of China low activation martensitic steel, Fusion Eng. Des. (2018).
[12] K. Mergia, N. Boukos, Structural, thermal, electrical and magnetic properties of Eurofer 97 steel, J. Nucl. Mater. 373 (1–3) (2008) 1–8.
[13] A. Möslang, E. Diegele, M. Klimiankou, R. Lässer, R. Lindau, E. Lucon, E. Materna-Morris, C. Petersen, R. Pippan, J. Rensman, Towards reduced activation structural materials data for fusion DEMO reactors, Nucl. Fusion 45 (7) (2005) 649.
[14] Y. Yagodzinskyy, E. Malitckii, M. Ganchenkova, S. Binyukova, O. Emelyanova, T. Saukkonen, H. Hänninen, R. Lindau, P. Vladimirov, A. Moeslang, Hydrogen effects on tensile properties of EUROFER 97 and ODS-EUROFER steels, J. Nucl. Mater. 444 (1–3) (2014) 435–440.
[15] A. Klypin, Effect of magnetic and electric fields on creep, Met. Sci. Heat Treat. 15 (8) (1973) 639–642.
[16] Y. Zhang, N. Gey, C. He, X. Zhao, L. Zuo, C. Esling, High temperature tempering behaviors in a structural steel under high magnetic field, Acta Mater. 52 (12) (2004) 3467–3474.
[17] T.P. Hou, K.M. Wu, W.M. Liu, M.J. Peet, C.N. Hulme-Smith, L. Guo, L. Zhuang, Magnetism and high magnetic-field-induced stability of alloy carbides in Fe-based materials, Sci. Rep. 8 (1) (2018) 3049.
[18] H. Zhou, Y. Pei, D. Fang, Magnetic field tunable small-scale mechanical properties of nickel single crystals measured by nanoindentation technique, Sci. Rep. 4 (2014) 4583.
[19] C.-G. Stefanita, D. Atherton, L. Clapham, Plastic versus elastic deformation effects on magnetic Barkhausen noise in steel, Acta Mater. 48 (13) (2000) 3545–3551.
[20] T. Kovaleva, A. Shevchuk, Effect of a magnetic field on the elasticity characteristics for certain steels and alloys, Strength Mater. 15 (5) (1983) 701–703.
[21] M. Giordana, I. Alvarez-Armas, A. Armas, Microstructural characterization of EUROFER 97 during low-cycle fatigue, J. Nucl. Mater. 424 (1-3) (2012) 247–251.
[22] M. Giordana, P.-F. Giroux, I. Alvarez-Armas, M. Sauzay, A. Armas, T. Kruml, Microstructure evolution during cyclic tests on EUROFER 97 at room temperature. TEM observation and modelling, Mater. Sci. Eng. A 550 (2012) 103–111.