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Mechanical characterization of EUROFER97 in tension at high strain rate

Ezio Cadoni[1], Matteo Dotta[1], Daniele Forni[1], Philippe Spätig[2]

[1] *University of Applied Sciences of Southern Switzerland, P.O. Box 105, CH-6952 Canobbio, Switzerland*
[2] *Fusion Technology-Materials, CRPP-EPFL, Association EURATOM-Confédération Suisse, 5232 Villigen PSI, Switzerland*

Introduction

Reduced activation tempered martensitic steels are leading candidate materials for fusion reactor structural components due to their resistance to void swelling and good balance of physical and mechanical properties. The development of those steels was realized on an international collaboration basis under the auspices of the International Energy Agency (IEA) Implement Agreement on Fusion Materials.
In a real fusion reactor, plasma disruptions are expected to occur that will yield disruption stress peaking in about 1 ms: that represents the typical loading rate of dynamical tests. Thus, up to now, not enough attention has been paid to characterize both the dynamic constitutive behaviour and dynamic fracture toughness behaviour of the tempered martensitic steels. As a first step to fill that gap, this study has been undertaken to investigate the tensile properties, yield stress and strain-hardening, from static to highly dynamic regime at room temperature of Eurofer97 steel. Those data are necessary to calculate the stress/strain field around the crack tip by finite element simulations to model the toughness-temperature behaviour in the transition region.
An experimental investigation on the strain rate sensitivity of reduced activation steel Eurofer97 under uniaxial tensile loads in the strain rate range from 0,001 s^{-1} to 600 s^{-1} is here presented. Round undamaged specimens of this material having gauge length 5 mm, diameter 3 mm, were tested in an universal machine to obtain its stress-strain relation under quasi-static condition (0,001s^{-1}), and in a modified Hopkinson bar to study its mechanical behaviour at high strain rates (300 s^{-1}, 1000 s^{-1}) respectively. This tempered-martensitic stainless steel shows a quite high strain rate sensitivity.

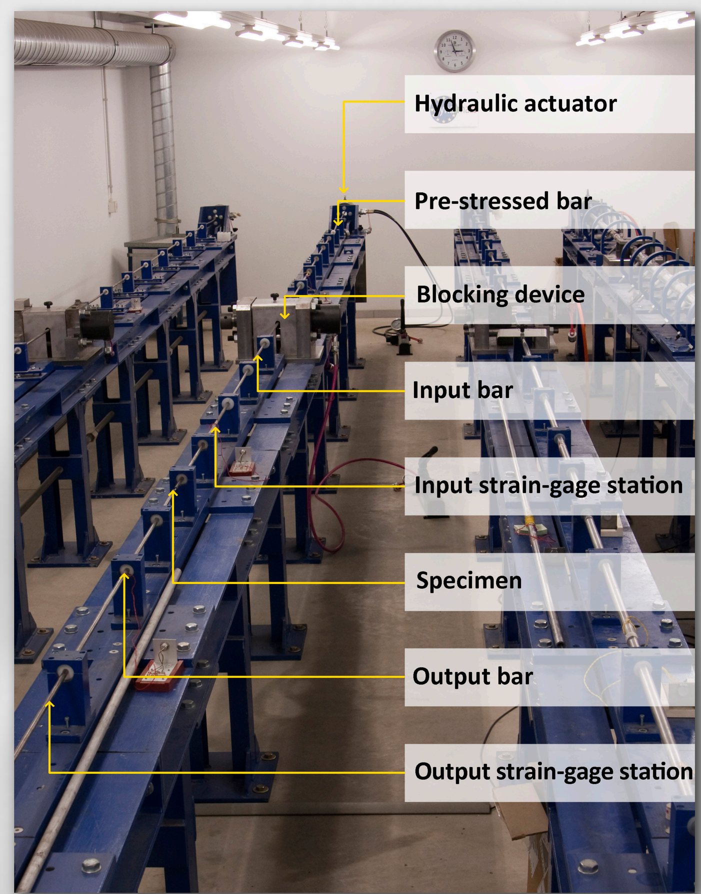
Set-ups

Tensile testing at several strain-rates has been performed using different experimental set-ups. For medium and high strain-rate regimes a hydro-pneumatic apparatus and a JRC-split Hopkinson tensile bar (JRC-SHTB) have been used respectively. See Figure 1 and Figure 2. The target strain-rates were set at the following five levels: 5, 30, 300, and 600 s^{-1}, and the specimens used were cylindrical samples having 3 mm in diameter and 5 mm of gauge length.

Modified Hopkinson Bar

The high strain-rate tests have been performed using a JRC-split Hopkinson tensile bar installed in the DynaMat Laboratory of the University of Applied Sciences of Southern Switzerland. The JRC-SHTB is shown schematically in Figure 1.
It consists of two half-bars, the input and output bar respectively, with the specimen screwed in between. The input and output bars are in high strength steel, with 10 mm in diameter and respectively 9 m and 6 m in length. Part of the input bar is used as pretension bar (6 m) in which the elastic energy is stored. By releasing this energy (rupturing the blocking brittle intermediate piece),a rectangular tension wave with small rise-time (30 μs) is generated and transmitted along the input bar loading the specimen to fracture. This is a uniaxial elastic plane stress wave because the pulse wave length is long compared to the bar diameter, and the pulse amplitude does not exceed the yield strength of the bar.

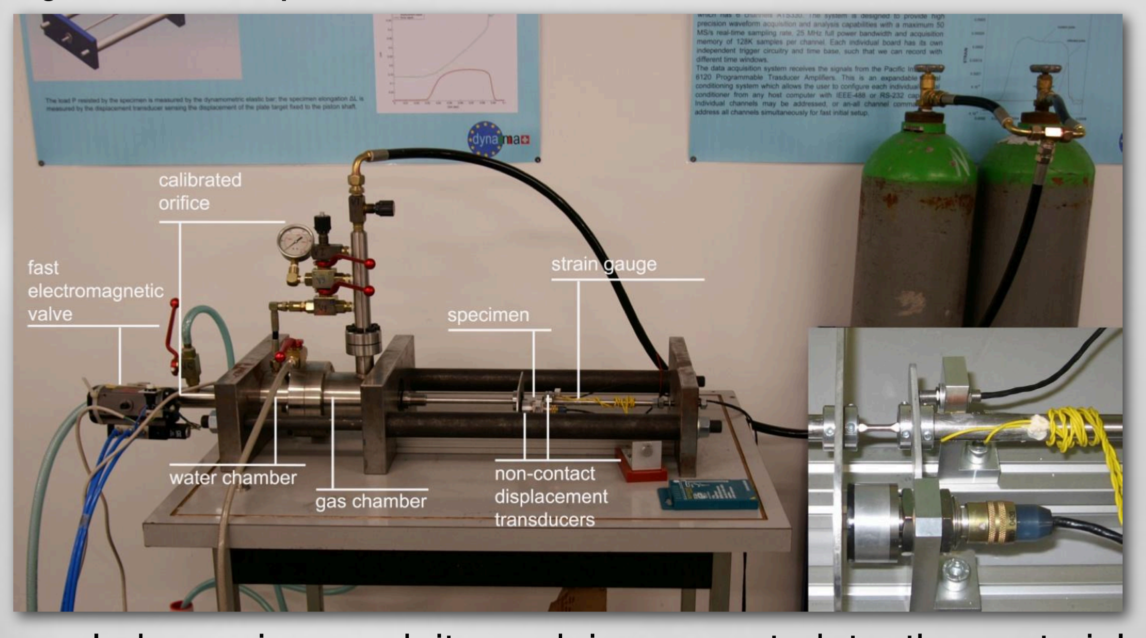
Figure 1 - MHB set-up



Hydro-Pneumatic Machine

Medium strain-rate behaviour in tension of the Eurofer97 steel has been investigated by means of a hydro-pneumatic machine (HPM). The HPM shown in Figure 2 consists of: (i) a cylindrical tank divided in two chambers by a sealed piston (one chamber to be filled with gas at high pressure – e.g. 150 bars – , the other chamber to be filled with water); (ii) the piston shaft which extends out of the gas chamber through a sealed opening, and its end is connected to the material specimen; (iii) the elastic bar, one end of which is connected to the material specimen and the other end is rigidly fixed to the machine supporting structure; the elastic bar is instrumented with a strain-gauge and is used to measure the load on the specimen during the test.
The water chamber can discharge the water through a calibrated orifice when the fast electro-valve is opened in order to start the test.

Figure 2 - HPM set-up



Results

The average standard tensile data at room temperature are summarized in Table 1.
Figure 3 presents the results, in terms of average engineering stress versus strain curves, of the quasi-static and dynamic mechanical tests at the five strain-rates selected. It is clear that the strain-rate has a significant effect, not only on the strength of the specimen, but also on the fracture strain.
It can be noted that the material keeps its strain hardening capacity with increasing strain-rate.

Figure 3 - Average engineering data at five strain-rates

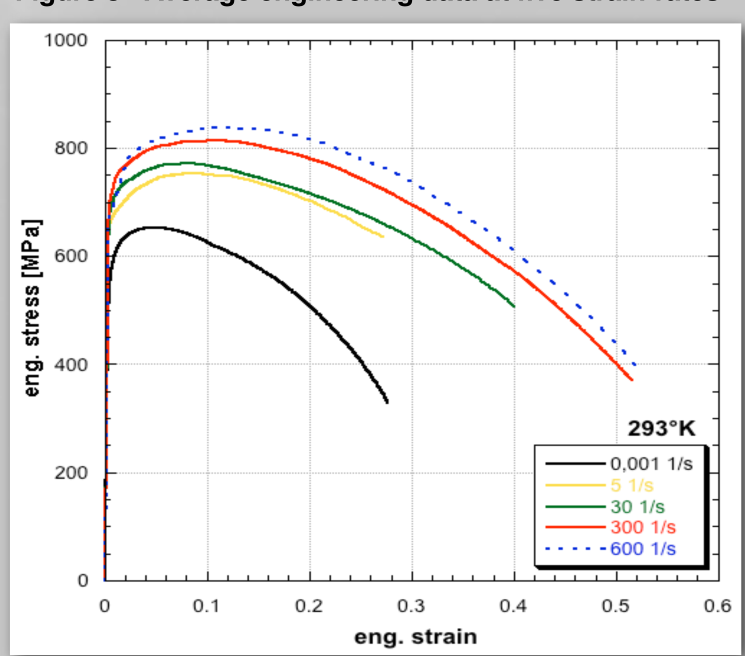


Table 1 - Average standard tensile data at room temperature

Strain Rate [s^{-1}]	$R_{0,2}$ [MPa]	R_m [MPa]	True ultimate tensile stress [MPa]	Uniform strain [%]	Fracture strain [%]	Modulus of toughness [kJ/mm³]	Reduction of area, Z [%]
10^{-3}	560	652	683	4,8	27,7	152,94	80,7
5	665	753	819	8,6	33,3	230,41	77,2
30	690	770	833	8,2	39,9	273,50	78,1
300	716	814	895	10,0	51,9	351,80	77,7
600	720	837	936	11,5	53,1	372,45	77,3

Tests at high and low temperatures

Figure 4 - Set-ups and specimens for MHB high and low temperature tests:

- **Cooling system and oven for high temperature test at 723°K (A).**
- **Oven's particulars before an high temperature test at 723°K (B) and (C).**
- **Specimens after an high temperature test (723°K) at 1000 s^{-1} (D) and 600 s^{-1} (E).**
- **Fridge cell for low temperature test at 77°K (F).**
- **Refrigerating system with liquid nitrogen for low temperature test at 77°K (G).**
- **Specimen after a low temperature test at 77°K (H).**
- **Specimens after a low temperature test (77°K) at 1000 s^{-1} (I) and 300 s^{-1} (L).**

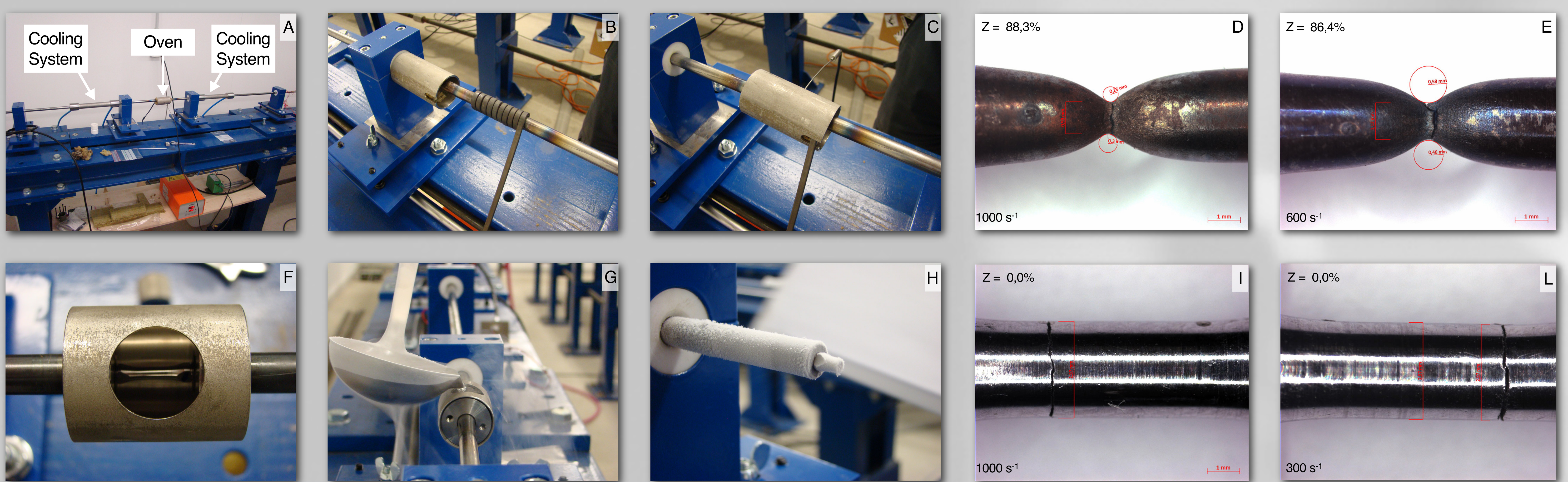
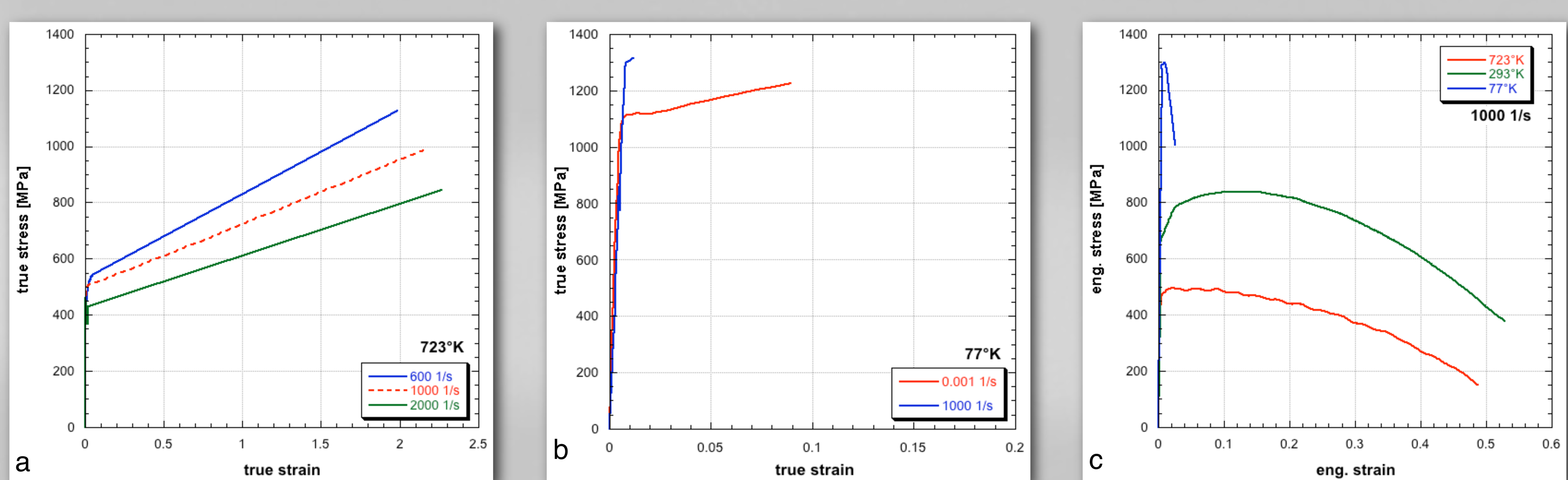


Figure 5:

- **True stress vs. strain at 723°K at different strain-rates (a).**
- **True stress vs. strain at 77°K at different strain-rates (b).**
- **Engineering stress vs. strain at 1000 s^{-1} at different temperatures (c).**



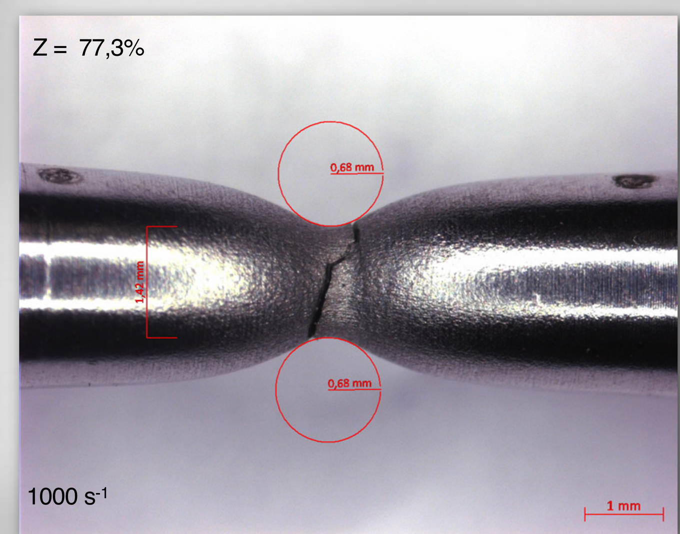


Figure 6 - Specimen after a room temperature test (293°K) at 1000 s^{-1} .

References

Ezio Cadoni, Matteo Dotta, Daniele Forni, Philippe Spätig, "*Strain-rate behaviour in tension of the tempered martensitic reduced activation steel Eurofer97*", accepted for publication on Journal of Nuclear Materials. (2011).