Piezonuclear evidences from laboratory tests on steel

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Abstract. Piezonuclear reactions concern neutron emissions triggered by high pressure waves in inert non-radioactive materials. This phenomenon has recently been documented in liquid solutions and brittle solids. In the present paper the investigation is extended to a more ductile material, like steel, subjected to different loading conditions. Although piezonuclear phenomena are more likely to take place during the failure of brittle materials, the phenomenon is revealed also with the more ductile failure of metallic materials.

Introduction

In recent years, neutron emission measurements were successfully performed on brittle solid test specimens during crushing failure. From those experiments, it can be clearly seen that piezonuclear reactions giving rise to neutron emissions were possible in inert non-radioactive brittle solids like Luserna granite or concrete [1-5].

The term "piezonuclear" reaction refers to low energy nuclear reactions, which are triggered by the fundamental action of pressure. The phenomenon, firstly recognized in stable iron nuclides contained in aqueous solutions of iron chloride or nitrate subjected to cavitation induced by ultrasounds [6], has recently been detected also in solids during mechanical tests on laboratory specimens.

Quantitative scanning electron microscope (SEM) analyses of the fracture surfaces of broken rock specimens showed that different kinds of element transmutation could be the results of the low energy fission responsible for the neutron emission [7-8].

In the present paper, the investigation is extended to a more ductile material, like steel, subjected to different laboratory tests for the mechanical characterization of materials.

Steel bars subjected to uniform tensile loading, as well as notched specimen subjected to the Charpy test, and uniform compression tests are described. Some positive evidences of neutron emission are reported, which depend on the loading condition, the size and, therefore, the brittleness of the mechanical response.

Neutron emission measurements were made by means of a He^3 detector placed at a close distance from the test specimen and enclosed in a polystyrene case so as to prevent the results from being altered by vibrations or impacts. This detector was also calibrated for the measurement of thermal

neutrons. Careful assessment of the neutron background was performed prior to each acquisition test.
In addition, a set of passive neutron detectors insensitive to electro-magnetic noise and with zero gamma sensitivity was used. The dosimeters, based on superheated bubble detectors (BTI), were calibrated at the factory against an AmBe source.
When possible, the neutron emission was monitored together with electromagnetic and acoustic emissions. Quantitative results from SEM analyses of the fracture surfaces of the broken specimens are also described.
Although piezonuclear phenomena are more likely to take place during the failure of brittle materials, the phenomenon can be revealed also with the more ductile failure of metallic materials.

Steel specimens under tension and compressions loading

Experimental set-up. Specific tests have been conducted on 9 steel specimens subjected to tension loading and one specimen subjected to compression loading condition respectively [9]. In Table 1, the applied loads, as well as the geometrical and mechanical characteristics of the specimens are summarized. In this work the experimental data of one steel bar (S1) subjected to tension loading and the data of the specimen (S2) under compression are reported. The first specimen (S1), tested in tension, has diameter D = 24 mm and length L = 1000 mm, the second specimen (S2), tested in compression, has diameter D = 40 mm and length L = 50 mm. The specimen S1 was subjected to tension up to failure according to EN ISO 6892 recommendation [10]. At the end of the test, a bar elongation of about 58% of the initial length was obtained. The specimen S2, instead, was subjected to compression loading up to obtain a final shortening of about 50% of the initial length.
In Fig. 1a the test configuration for specimen S1 is reported. To carry out these experiments, an hydraulic press, Walter Bai type, with electronic control was used. The test was conducted in three subsequent stages. In the first stage it was controlled by stress increments of 15 MPa/s up to the value of about 500 MPa, which corresponds to the yield stress of the material. Subsequently, the test was controlled by an imposed strain of 0.16 mm/s up to an elongation equal to 10% of the initial length. In the last stage, which ended with the specimen failure (Fig. 1b), the imposed strain was applied by displacement increments of 0.33 mm/s.
The compression test on specimen S2 was performed under loading control using an hydraulic press, Galdabini type, with a maximum load of 5000 kN (Fig 2a). A loading ramp of 58 kN/min was applied and the test stopped after 34 minutes, at a load of 2000 kN, corresponding to a specimen shortening approximately of 50% (see Fig 2b). Considering a symmetric behaviour of steel in tension and compression, the yield strength (638.56 kN) limit and the ultimate strength (850.31 kN) of specimen S2 were identified considering the yielding stress and the ultimate strength obtained during the tensions test (see Tab. 4).

Neutron emission detections.

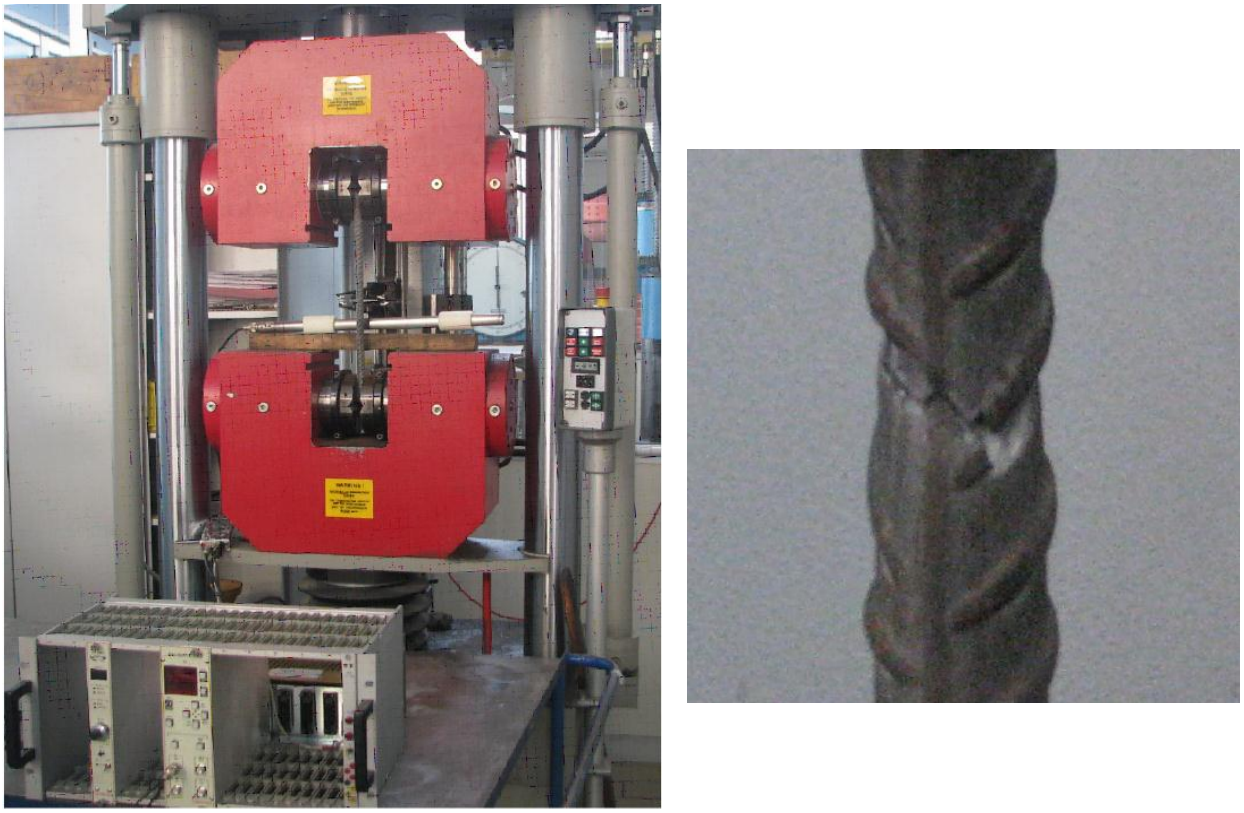
Both the tension and compression tests performed on specimens S1 and S2 have been monitored by the He^3 neutron detector. In Fig. 1a and 2a the positions of the He^3 proportional counter are described together with the experimental set-up of the two tests. In Fig. 3a, the load vs. time diagram for specimen S1 is reported with the neutron emission measurements. The average neutron background level measured before the test was equal to $(7.22\pm1.42)\times10^{-2}$ cps. It can be noted that during the test, and in particular in correspondence to the achievement of the yield strength limit equal to 230 kN (see Fig. 3a), neutron emissions increased up to $(11.67\pm2.29)\times10^{-2}$ cps. The increment was about 1.5 times higher with respect to the background level. In addition, in correspondence to the ultimate strength (306 kN) a maximum neutron emission of about $(16.67\pm2.29)\times10^{-2}$ cps was measured. This last emission level corresponds to an increment more than twice with respect to the background level measured before the experiment. Finally, after the steel bar failure, the neutron emissions decreased almost instantaneously down to the background level measured before the experiment.

In Figure 3b, similarly to Fig. 3a, the load versus time curve has been reported together with the neutron emission measurements for specimen S2. Also in this case the neutron emissions show an appreciable increase immediately after the achievement of the ultimate strength (850 kN). At this point, the maximum neutron emission level $(19.99\pm2.96)\times10^{-2}$ cps corresponds to an increment of about three times the background level. As can be seen from the diagram of Figs. 2b and 3b, the final section area of specimen S2 is sensibly larger than the initial nominal area, so that the theoretical ultimate strength was widely overcome.

As regards the tensile loading tests on the other steel bars reported in Table 1, a similar behaviour in neutron emission measurements has been evidenced for specimens characterized by diameters equal or greater than 24 mm.

Table 1: Tensile and compressive loading test on steel specimens.

Tensile loading test comprised Specimen S_1							
Bar Type	Section S_0 (mm^2)	Yield Strength Limit P_y (kN)	Ultimate Strength P_u (kN)	Yielding Stress σ_y (MPa)	Stress Peak Load σ_u (MPa)	Elongation at P_u, ε_u (%)	Elongation at Failure ε_f (%)
D14	153.94	84.68	96.81	550.11	628.88	25.56	37.71
D20	314.16	160.36	194.17	510.45	618.06	34.39	53.72
D20	314.16	166.61	193.24	530.33	615.10	39.28	54.81
D22	380.13	148.52	182.35	390.71	479.70	27.71	46.07
D22	380.13	155.39	188.08	408.78	494.78	33.72	52.26
D24 (S1)	452.39	230.00	306.41	508.66	677.65	38.18	58.99
D24	452.39	290.05	337.10	641.15	745.15	31.36	50.74
D28	615.44	351.42	437.58	571.02	711.00	37.96	61.27
D28	615.44	362.30	441.62	588.69	717.57	36.69	55.77
Compressive Loading test: Specimen S_2							
Section S_0				1256 (mm^2)			
Yield Strength Limit, P_y				638.56 (kN)			
Ultimate Strength, P_u				850.31 (kN)			



(a) (b)

Figure 1: (a) Experimental set-up for the tensile test performed on specimen S1 using the Walter Bai hydraulic press. The He3 neutron detector has been placed at a distance of about 10 cm from the monitored specimen. (b) Specimen S1 at the end of the test [9].

(a) (b)

Figure 2: (a) Experimental set-up for the compressive test performed on specimen S2 using the Galdabini hydraulic press. The He3 neutron detector has been placed at a distance of about 10 cm from the monitored specimen. (b) Specimen S2 at the end of the test [9].

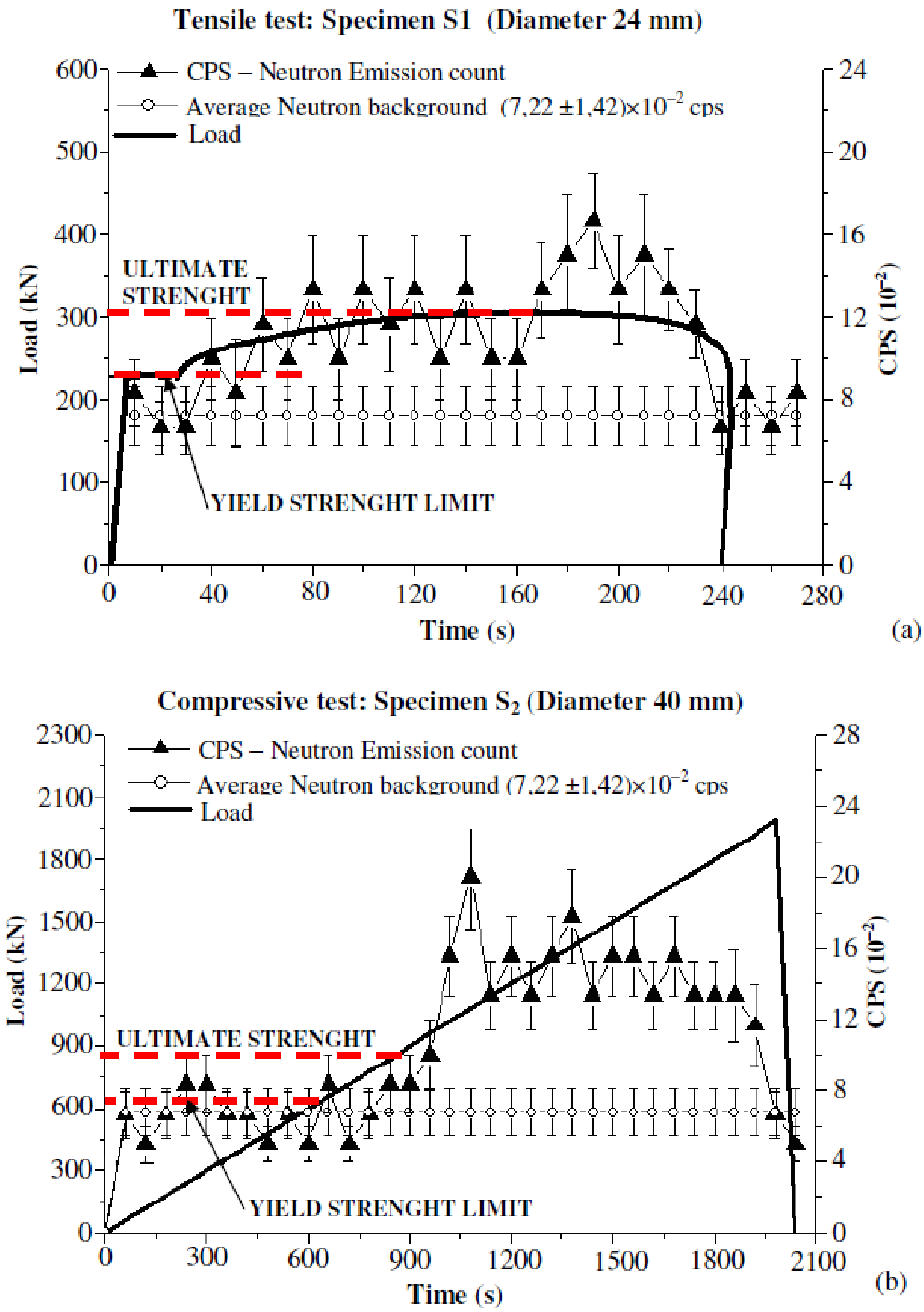
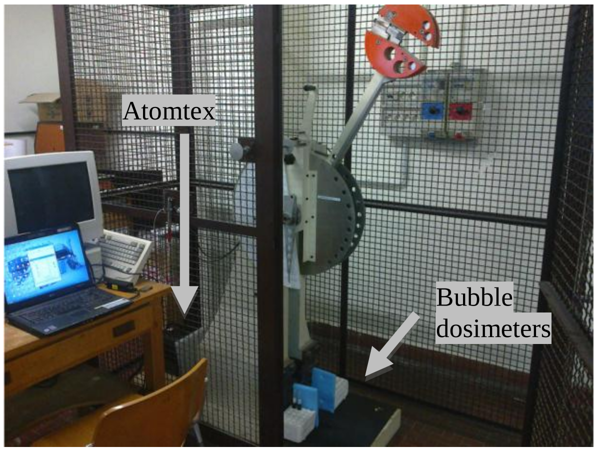


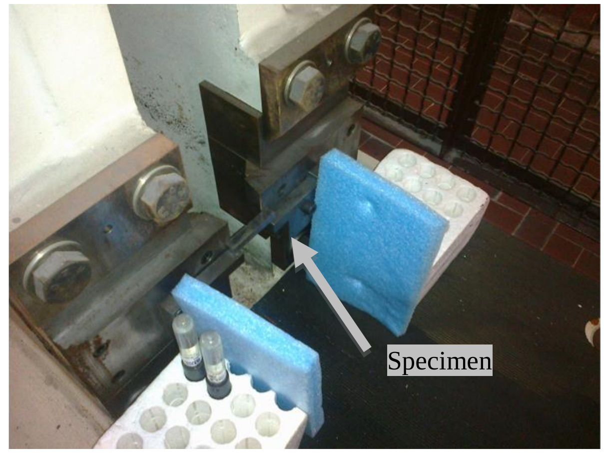
Figure 3: Load vs. Time curves and neutron emission measurements for specimen S1 (a) and S2 (b). For specimen S1 the maximum neutron emission level equal to (16.67±2.29)×10^{-2} cps, reached after the achievement of the ultimate strength, corresponds to an increment more than twice with respect to the background level. Similarly, for specimen S2 it is possible to observe that the maximum neutron emission level, reached after the ultimate strength and equal to (19.10±2.29)×10^{-2} cps corresponds to an increment of about three times with respect to the same background level [9].

Charpy tests

The test was carried out according the European code EN 10045/1-1990 [11]. The nominal energy of the adopted Charpy pendulum, shown in Fig. 4, was 300 J. Five standard steel specimens with V notch and 10x8 mm section were analyzed. The second specimen was preventively refrigerated in liquid nitrogen to increase the fragility. In this case, the dissipated energy during the test was about 6 J, and the specimen split in two separated halves.



(a)



(b)

Fig.4. View of the Charpy pendulum, with indication of the sensors position (a); detail of the BDT sensors positioning beside the specimen (b).

The other specimens, characterized by different carbon content and obtained from slightly different thermal treatment, dissipated energies ranging from 76 J to 175 J, and did not separate completely after the pendulum impact.

The Charpy tests were performed with approximately thirty minutes interval between each other, in order to allow for stable bubble nucleation in the bubble detector sensors. The analysis performed did not reveal any sensible bubble nucleation in any of the sensors, after each test. Contemporarily, the He^3 Atomtex acquisition was carried out.

Fig. 5 shows that in correspondence to the third and to the fifth test, the recorded neutron emission is well above the background mean level. Nevertheless, such difference is still comprised in the confidence bar.

In particular, it appears that the greater variations from the background level are recorded in correspondence of the first (150 J dissipated), the third (175 J dissipated), and the fifth test (135 J dissipated). This suggests that brittleness is not the only governing parameter. In fact, in order to be able to detect neutron emissions with the adopted instrumentations, a certain amount of energy dissipation has to take place. This is not the case of the very brittle refrigerated sample 2, which provided only 6 J, with no detectable neutron emissions.

In order to obtain evidences of possible transmutation of Fe element, consequence of piezonuclear reactions, the specimens have been analyzed at the SEM (EDAX, see Fig. 6a), at the Department of Material Science of the Politecnico di Torino. The instrument can perform the Energy Dispersive X-Ray Spectroscopy. The volume of material involved in the measurement is schematized in Fig. 6b. In the present case, based on the energy of the laser beam and on the size of the acquisition spot (30x30 micron), the volume can be estimate equal to 1 cubic millimeter.

Different areas of each specimen have been analyzed, respectively in correspondence of the crack surface near the V notch (brittle propagation) or quite far from it (more stable propagation). In addition, the lateral surfaces of the specimens, and the area in correspondence of the impact have

been investigated. Most of the analyzed surfaces were rough, thus the acquisition was not in the ideal instrumental condition.
The quantitative element composition measured for the third specimen is reported in Table 2. An example of the element spectrum is shown in Fig. 7. No evidence of anomalous elements was recorded in correspondence of the fracture surface, of the lateral surface, or of the region of impact. On the other hand, Fig. 8a shows the spectrum when the acquisition is performed in vicinity of an inclusion, corresponding to the acquisition area shown in Fig. 8b. In this case the percentage composition of elements is different, but this could be due to the original composition of the inclusion.

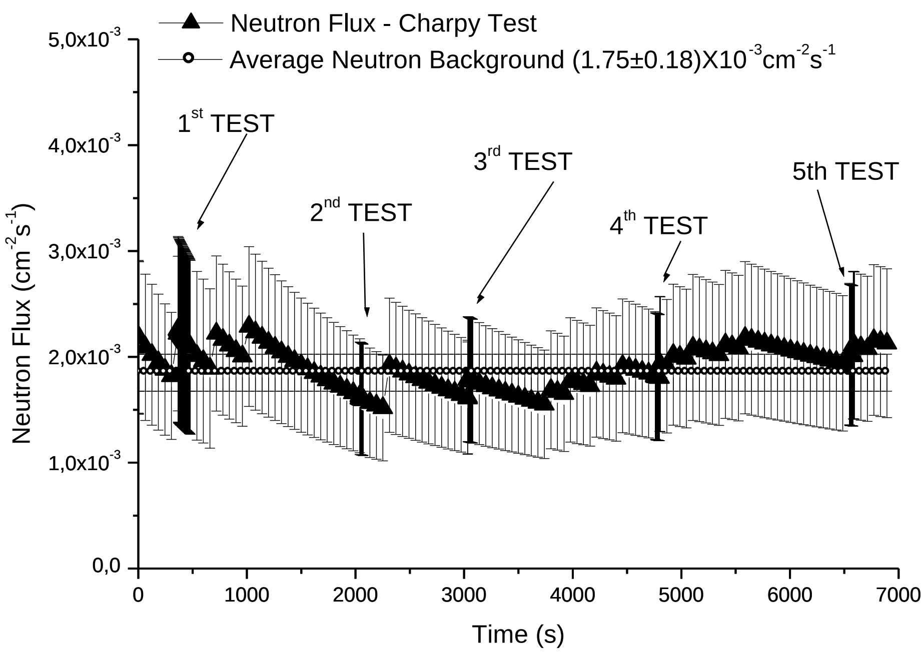
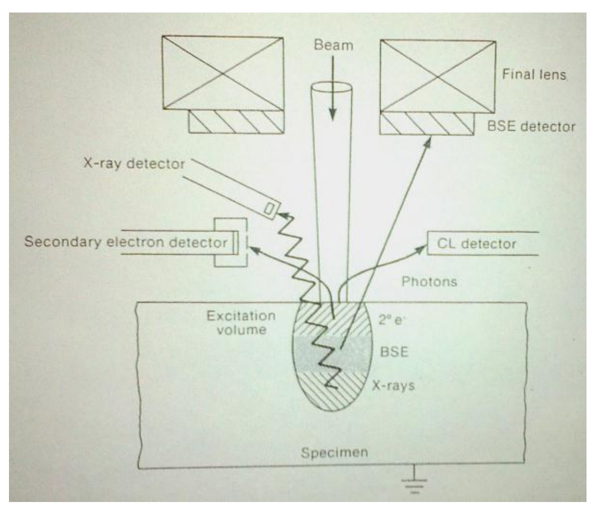


Fig.5. Diagram of the Atomtex neutron acquisition during the Charpy tests.

(a)


(b)

Fig.6. Scanning electron microscope SEM (a); Scheme of the volume for the EDX acquisition (b).

The Charpy test appears interesting because a condition of fracture by impact is reproduced, which in principle could trigger the occurrence of piezonuclear reactions. A small amount of neutron emission was recorded, which was not completely distinguishable from the background. The metallic crystalline structure does not appear to be particularly prone to the piezonuclear phenomena. In addition, the small volumes and dissipated energies, combined with some difficulties in the positioning of the sensors, negatively affect the chance of measuring neutron emissions.

Table 2. Quantitative spectrography for the third specimen.

Location	Weigth %				
	Fe	Si	Mn	Al	Ca
Fracture surface	98.50	0.39	1.11	--	--
	98.73	0.29	0.99	--	--
	98.57	0.24	1.19	--	--
	98.62	0.36	1.02	--	--
	98.42	0.41	1.17	--	--
	98.09	0.35	1.57	--	--
V notch surface	98.37	0.47	1.16	--	--
	98.23	0.47	1.30	--	--
Impact area	98.36	0.63	1.02	--	--
	97.53	0.96	1.52	--	--
	97.59	1.32	1.10	--	--
Inclusion	70.60	11.07	--	10.27	8.06

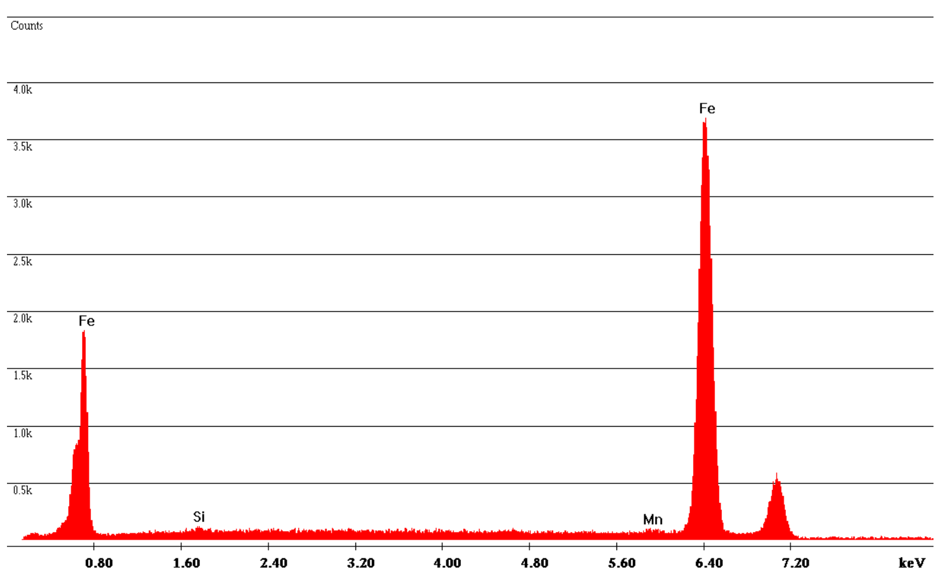


Fig.7. Typical isotopes spectrum, where no anomalous elements are detected.

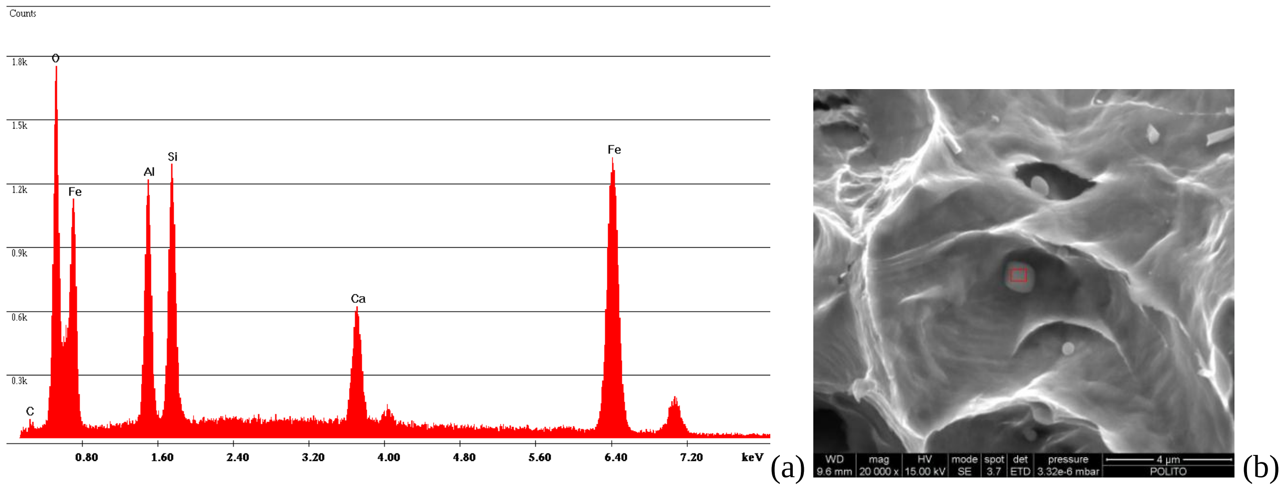


Fig.8. Acquisition in correspondence of an inclusion: elements spectrum (a), micrography (b).

Conclusions

In the present paper, an investigation about piezonuclear neutron emissions from ductile materials, like steel, subjected to different laboratory tests is presented. Steel bars subjected to uniform tensile loading, as well as notched specimen subjected to the Charpy test, and uniform compression tests are considered. Some positive evidences of neutron emission are reported, which depend on the loading condition, the size and the brittleness of the specimen, but also on the amount of the dissipated energy during damage.

Acknowledgements

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References

[1] A. Carpinteri, F. Cardone, and G. Lacidogna. Strain Vol. 45 (2009), pp. 332-339.
[2] F. Cardone, A. Carpinteri, and G. Lacidogna. Physics Letters A Vol. 373 (2009), pp. 4158-4163.
[3] A. Carpinteri, F. Cardone, and G. Lacidogna. Experimental Mechanics Vol. 50 (2010), pp. 1235-1243.
[4] A. Carpinteri, O. Borla, G. Lacidogna, and A. Manuello. Physical Mesomechanics Vol. 13 (2010), pp. 268-274.
[5] A. Carpinteri, G. Lacidogna, A. Manuello, and O. Borla. Strenght Fracture and Complexity (2011), doi: 10.3233/SFC-2011-0120.
[6] F. Cardone, G. Cherubini, A. Petrucci: Phys. Lett. A Vol. 373(8–9) (2009) p. 862
[7] A. Carpinteri, A. Chiodoni, A. Manuello and R. Sandrone: Strain Vol. 47(s2) (2011) p. 282
[8] A. Carpinteri and A. Manuello. Strain, Vol. 47 Suppl. 2(2010), pp. 267
[9] A. Carpinteri, , G. Lacidogna, A. Manuello, and O. Borla. Experimental Mechanics (2012), doi: 10.1007/s11340-012-9629-x
[10] EN ISO 6892 – 1:2009. (2009). Metallic materials -- Tensile testing -- Part 1: Method of test at room temperature.
[11] EN 10045/1 Metallic materials – Charpy impact test Test method. (1990) European Committee for Standardization. Rue de Stassart 36, Bruxelles, Belgium