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Investigation of Potential Material Inhomogeneity in the Magnetically Detected Neutron-Irradiation-Generated Structural Degradation of Nuclear Reactor Pressure Vessel Steel

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Abstract: A novel nondestructive method called magnetic adaptive testing has been previously applied to detect the neutron-irradiation-generated structural changes in reactor pressure vessel steel material. This method has been found to be a useful tool for this purpose, and good correlation—as a tendency—has been found between the estimated ductile-to-brittle transition temperature and magnetic parameters. However, a significant scattering of measured points was also observed for the investigated set of Charpy specimens. The main result of the work was that by magnetic selection of samples, the scatter can be notably reduced. As a conclusion, the magnetically measured parameters seemed to be precise and reliable for the detection of embrittlement of the reactor pressure vessel steel, with lower scattering of points than in the conventionally used destructive mechanical characteristics (ductile-to-brittle transition temperature). This result is surprising and needs further verification. The purpose of the present work is to repeat the measurement on irradiated reactor steel blocks. In this work, instead of the DBTT transition temperature, individually measured Vickers hardness (VH) data were used to help characterize the mechanical properties of the material. The so-called "property transformation" is a known and applied technique in the nuclear industry. The mechanical property characterized by the transition temperature cannot be determined individually for each specimen; instead, it can be obtained only on a set of samples by statistical fitting. Therefore, the individually measured Vickers hardness values can be utilized in order to predict the individual transition temperature values by the help of the property transformation technique. In this paper, however, not these derived transition temperature values, but their origins, the Vickers hardness values, are studied in a direct manner. The same behavior of blocks was observed as in the case of Charpy specimens, which is considered to validate the previously published results. As a possible reason for the scattering of points, large magnetic inhomogeneity of samples cut even from the same block was also proved. The magnetic parameters and Vickers hardness correlate well with each other. This result justifies the potential future application of magnetic techniques in practice aimed at the regular inspection of nuclear reactors.

Keywords: neutron irradiation; reactor pressure vessel steel; magnetic nondestructive evaluation; magnetic adaptive testing

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1. Introduction

Nuclear power plants play a very important role in energy production in many industrially developed countries of the world, and their importance has been recently enhanced due to the energy crisis and climate problems. Several new nuclear power plants are being planned or being built. The safety aspects of these power plants are crucial. It means that any time, safe operation should be guaranteed. A great majority of nuclear power plants belong to the family of the so-called light water reactors, where pressurized and boiling water is used as a cooling material. In the case of light water reactors, the most important, irreplaceable component of reactors is the reactor pressure vessel (RPV). The material of the RPV is under permanent, long-term, and high-energy neutron irradiation within the whole nuclear power plant's lifetime.

The mechanical properties of the RPV are modified by this neutron irradiation. Hardness, tensile strength, and yield stress are increased, and toughness is decreased, which is generated by the influence of fast neutrons on material structure interaction processes [1]. The neutron-irradiation-caused material embrittlement is the most important ageing phenomenon.

Because of the above arguments, it cannot be overemphasized that the regular inspection of nuclear reactors is an extremely important task. During the operation of the nuclear reactor, the permanent neutron irradiation on the pressure vessel material structure generates modification of the mechanical properties (decrease in toughness; increase in yield stress, hardness, and tensile strength) [1]. The radiation-induced embrittlement is measured by examining the shift in the energy–temperature relation by impact testing of Charpy V-notch specimens, which increases the brittle-to-ductile transition temperature (DBTT) and is followed by hardening.

Evidently, all methods that are suitable for the monitoring of neutron-irradiation-generated degradation of nuclear pressure vessel steel are a very important recent duty. Surveillance specimens are used in the second generation of nuclear power plants. They are placed inside the RPV, and after certain periods, they are withdrawn and destructively tested. Mechanical testing methods, i.e., Charpy impact, tensile, fracture toughness, and hardness testing, are used as a traditional way of evaluating the embrittlement [2].

In nuclear industry, the DBTT measured by destructive Charpy tests is the standardized parameter that characterizes the embrittlement. One of the drawbacks of this technique is that many samples are necessary for this inspection, and the measurement error is high. Because of this, several nondestructive techniques have also been recommended for monitoring material degradation. For instance, the Seebeck coefficient measurement [3] or the well-known ultrasonic technique [4] can be applied.

Nondestructive tests, in contrast to destructive tests, do not measure directly the mechanical properties of the measured material. Evidently, before practical application of any nondestructive test, the results must be rigorously compared to the standardized destructive ones.

Taking into account that the majority of the presently used nuclear reactors are pressurized water reactors (PWRs) with a pressure vessel made of ferromagnetic steel, magnetic methods can be successfully applied for this purpose. It is known experimentally and theoretically that some magnetic properties are sensitive to the material microstructure [5]. These magnetic methods can be Barkhausen noise measurement, hysteresis measurement, or magnetoacoustics emission measurement. A summary of the possible applications of magnetic techniques in nondestructive testing can be found in Ref. [6].

Several attempts have been made to solve this problem, and it has been shown that a good correlation exists between nondestructively measured magnetic parameters and the ductile-to-brittle transition temperature (DBTT) of pressure vessel steel. In Ref. [7], the embrittlement of nuclear pressure vessel steels (A508 Cl.2 and 15Kh2NMFA) was investigated on Charpy specimens by applying two different magnetic nondestructive testing methods: 3MA-X8 (micromagnetic multiparameter microstructure and stress analysis [8]) and MAT (magnetic adaptive testing) [9]. Well detectable modification of the material properties due to neutron irradiation was found on the same specimens. A reasonable correlation between magnetic properties and neutron-irradiation-generated damage was found, regardless of the type of material or the measurement method used. As a conclusion, the results of the individual micromagnetic measurements demonstrated their suitability for characterizing RPV steel degradation under simulated operating conditions. A calibration procedure was also applied on the merged outcome of both methods, giving excellent results in predicting the transition temperature, yield strength, and mechanical hardness in both materials.

In spite of the generally good correlation between the embrittlement and magnetic characteristics, large scattering of the points was also observed [7]. To perform a kind of interpretation of the scattering of the points, the results of MAT measurements performed on irradiated 15Kh2NMFA Charpy specimens were analyzed. Magnetic parameters were considered as functions of the DBBT. The scattering of points could originate either in errors of the magnetic measurement itself, or in some inhomogeneity of the investigated samples. Possible error in the MAT measurements was carefully analyzed in [10], and it was demonstrated that the point scatter cannot be explained by measurement error. As a conclusion, it was stated that the neutron-irradiation-induced embrittlement depends very much on local material conditions/inhomogeneities. Surprisingly, samples cut from the same block of reactor steel were different from a magnetic point of view, implicating different trajectories of neutron-irradiation-generated degradation, with identifiable differences in the results of the nondestructive magnetic evaluation. Magnetic parameters seem to result in more reliable and precise determination of the local embrittlement in pressure vessel steel than the traditionally used mechanical characteristics.

This conclusion is rather striking, and not all nuclear reactor experts can accept it. Because of the importance of these measurement results for the potential application of magnetic measurements in the future, our previous result needs further verification.

The purpose of the present work was to repeat the measurement on irradiated reactor steel blocks, and not only on Charpy specimens, as conducted in previous studies. Furthermore, in this work, instead of the transition temperature (which is an estimated value with large error, as mentioned above), individually measured Vickers hardness data were used to characterize the mechanical properties of the material. The same magnetic preselection was applied as described in [10], and the results obtained on block and Charpy specimens were compared with each other.

The main goal of the present work is to prove on both irradiated Charpy and block specimens that by suitable magnetic separation of the investigated samples, the scattering of points can be significantly reduced, verifying the efficiency of magnetic measurements. As outlined in Ref. [10], the scatter was mainly attributed to the original inhomogeneity of the samples. To prove this assumption, another (not irradiated) set of samples cut from the *same* reactor steel block was also investigated to study the homogeneity of individual samples. In this experiment, we systematically measured the individual samples—both mechanically and magnetically—to reach a conclusion about the scattering of mechanical and magnetic parameters and to obtain a correlation between mechanical hardness and magnetic parameters.

2. Materials

2.1. Charpy Samples

Cr–Ni–MoV reactor pressure vessel steel was used in our experiments. The IZHORA company (St. Petersburg, Russia) manufactured the 15Kh2NMFA forging steel. The original heat number was 181,358, produced according to the Russian TU 108.765-78 specification. Table 1 shows the chemical composition. The as-received samples had a mixed tempered ferrite–bainite microstructure.

Table 1. The amount of polluting elements of material 15Kh2NMFA other than the chemical components indicated by the standard (wt.%).

C	Mn	Si	S	P	Cr	Ni	Mo	V	Cu
0.16	0.42	0.29	0.008	0.0012	1.97	1.29	0.52	0.12	0.12

The geometry and dimensions of standard Charpy specimens are shown in Figure 1. Each sample has a V-notch on one face. Magnetic measurements were performed in all cases on the opposite face.

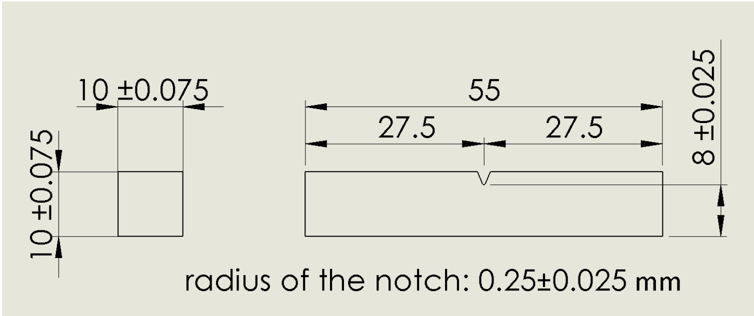

Figure 1. Shape and nominal dimensions of the measured samples. Values are given in mm.

Vickers hardness HV10 tests were performed using an automatic Falcon 505 type hardness tester according to ASTM E92-17 (Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials) for each Charpy sample [11].

2.1.1. Charpy Samples for Irradiation

Thirteen Charpy samples according to ASTM E23-18 were cut at $\frac{3}{4}$ depth from a vessel block. T-L orientation of the samples was selected according to ASTM E23-16b (Standard Test Methods for Notched Bar Impact Testing of Metallic Materials). Samples were irradiated in the BR2 reactor of the Belgian Nuclear Research Centre (SCK CEN) by neutrons at different fluences. The irradiation temperature was between 100 and 120 °C. The difference in damage caused by irradiation temperature between 100 and 120 °C is negligible compared to the damage caused by neutron fluence. However, it is necessary to limit the heat generated by γ radiation when irradiating large blocks. Neutron irradiation was performed in a rig called NOMAD_3 [12]. In this case, the generated damage was large enough to be influenced by nondestructive techniques. Fluence of 1.55 and 7.90×10^{19} neutron/cm^2 (E > 1 MeV) was applied.

2.1.2. Charpy Samples for Homogeneity Control

Another set of 24 Charpy samples was produced by cutting a reactor pressure vessel steel block. Figure 2 shows how the individual samples were cut from the blocks.

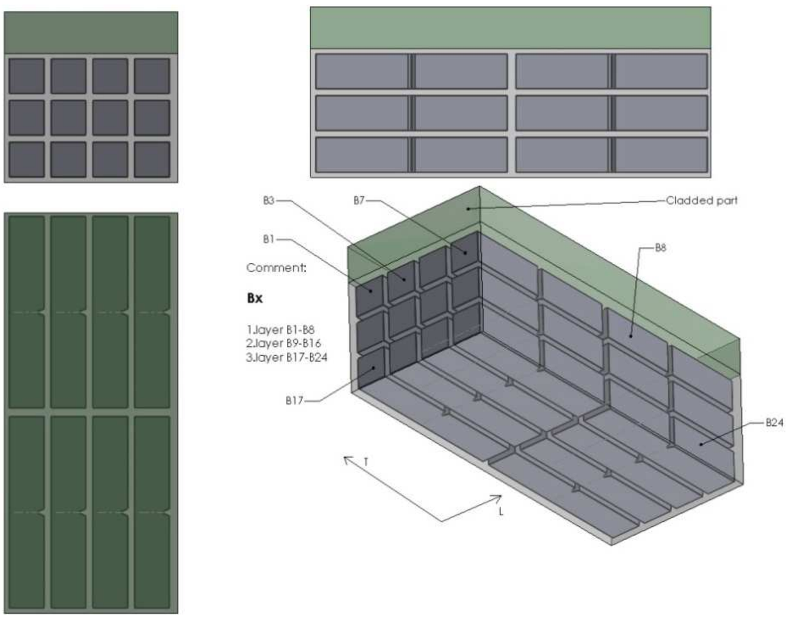

Figure 2. Scheme of cutting a reactor pressure vessel steel block into 24 individual Charpy specimens. Values are given in mm.

2.1.3. Reactor Pressure Vessel Steel Blocks

Block samples made of a Western RPV material, A508 Cl.2, were manufactured to study the damage caused by neutron irradiation. Specimens had a mixed tempered ferrite–bainite microstructure. The chemical composition of the material is given in Table 2. The size of blocks was 115 mm × 47 mm × 42.5 mm.

Table 2. The amount of polluting elements of base metal A508 Cl.2 other than the chemical components indicated by the standard (wt.%).

C	Mn	Si	S	P	Cr	Ni	Mo	Cu
0.201	0.578	0.27	0.0085	0.0091	0.372	0.668	0.599	0.0472

Similar to the Charpy samples, these blocks were also irradiated in SCK CEN to different neutron fluence levels by keeping the irradiation temperature below 100 °C. Again, this low neutron irradiation temperature was applied to induce as much irradiation damage as possible but also to decrease the thermal gradient caused by γ-heating. The range of the fast neutron fluence of the blocks was between 1.48 and 21.40 × 10^{19} n/cm (E > 1MeV). Vickers hardness HV10 tests were also performed on the blocks.

3. Magnetic Adaptive Testing

A special method of magnetic measurement, the so-called magnetic adaptive testing (MAT), was recently developed. MAT belongs to the family of magnetic hysteresis measurement techniques, but in contrast to the conventional hysteresis technique, minor magnetic hysteresis loops are measured instead of the major hysteresis loop. By applying this technique, a large data pool is generated, and those elements of this data pool that are the best characteristics of the investigated material degradation are taken into account. A detailed description of this technique is given in Ref. [13]. It is shown in this work that the MAT method results in more sensitive and more reliable parameters than traditional magnetic hysteresis measurement does. Furthermore, magnetic saturation of the measured samples is not necessary, which is a very important advantage in practical applications. In this measurement, the series of minor magnetic hysteresis loops is measured. Demagnetization of samples is conducted before each measurement by decreasing the amplitude of the alternating magnetizing field. The amplitude of the magnetizing current with a triangular waveform is then increased step by step. This linearly increasing magnetizing field generates a voltage signal in the pick-up coil, which is proportional to the differential permeability of the measured sample. These measured permeability loops are the input for the further data evaluation. All points of the loops give information about the magnetic behavior of the sample. Using the measured data, an evaluation process is applied: Matrices are calculated from the permeability data. All matrix elements are compared with the same element of the reference sample. In this way, a large data pool that magnetically characterizes the investigated sample is calculated. These magnetic descriptors are taken as functions of any independent parameter that describes the material degradation due to any external influence. Within MAT evaluation, those descriptors are chosen to best characterize the actual material degradation.

These parameters can be taken either from the permeability matrix (μ matrix) obtained directly from measured permeability data, or from the hysteresis matrix, which is the integrated permeability along the field h_a, or from the derivative of the permeability (μ' matrix) with respect to the magnetic field (second derivative of the magnetic induction with respect to the field). Each MAT descriptor is characterized by the actual (h_a, h_b) pairs, where h_b is the minor loop amplitude. Special care has always been taken by determining both the optimal MAT descriptor of maximal sensitivity with respect to the independent parameter (degradation parameter) and the maximal reproducibility of the descriptor. This optimization depends on the actual material. Once the best parameter is chosen, the same parameter is used for each sample and in future measurements for all other similar samples.

In the following sections, we use the term "optimally chosen MAT descriptor" without going into details about the exact matrix element. This is the descriptor, chosen from the calculated data pool, that results in the best correlation between the magnetic and independent parameters (Vickers hardness).

The measured specimens were magnetized by a yoke placed on top of the sample. A half transformer core, made of laminated Fe–Si sheets, was used as the magnetizing yoke. A pick-up coil and an exciting coil were used, wound on the legs of the yoke. The size of the yoke was chosen according to the dimensions of the samples to be measured. Sample holders were designed for usage in a hot cell. They enabled the replacement of the samples by a manipulator. The two sample holders that were used for the measurement of Charpy and block samples are shown in Figure 3.

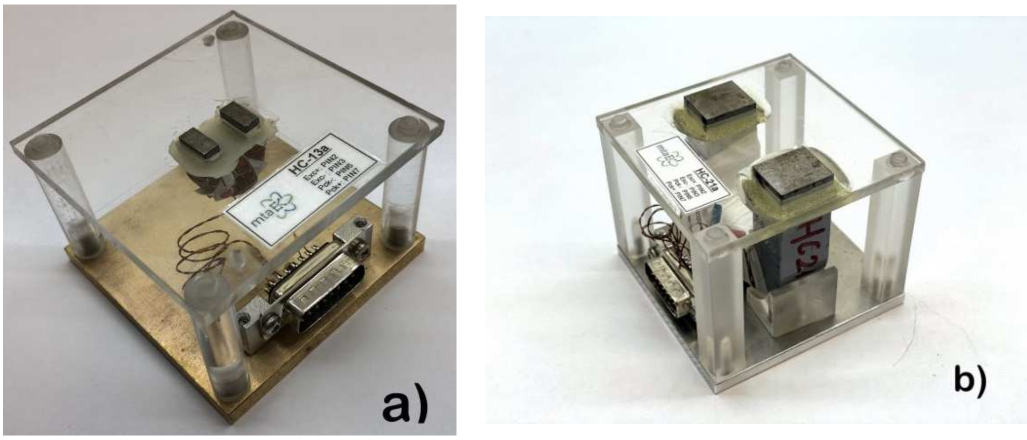

Figure 3. Sample holders designed for the measurement of Charpy samples (**a**) and block samples (**b**). Samples were put directly on the top (on the legs) of the magnetizing yokes.

As mentioned above, possible errors in those MAT descriptors that characterize the material degradation were carefully analyzed in [10]. It was found that the uncertainty of MAT descriptors was less than 1%. According to this analysis, it is clear that the MAT measurement error is not responsible for the large point scatter. As can be seen in Figures 4a and 5a, this scatter in certain cases exceeds 25%.

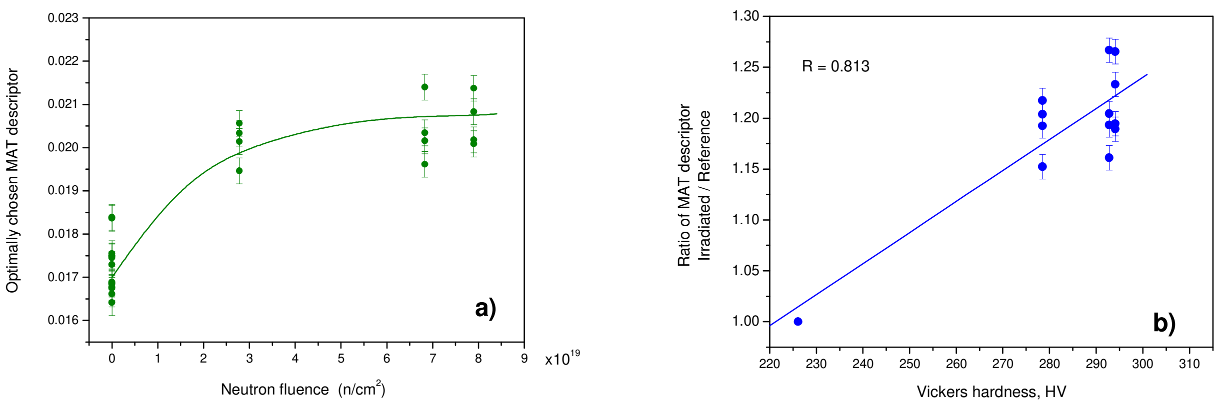

Figure 4. Optimally chosen MAT descriptor as a function of neutron fluence in Charpy samples (**a**), and the ratio of MAT descriptors of individual irradiated and reference samples as a function of Vickers hardness (**b**).

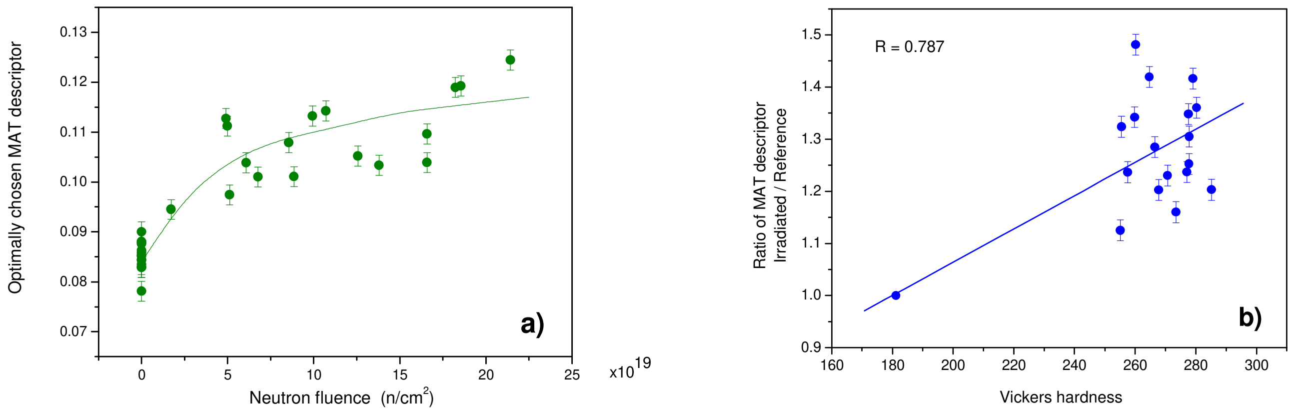

Figure 5. Optimally chosen MAT descriptor as a function of neutron fluence in block samples (**a**), and the ratio of MAT descriptors of individual irradiated and reference samples as a function of Vickers hardness (**b**).

4. Results

MAT measurements were performed on reference and irradiated Charpy samples, and also on reference and irradiated block samples. Every sample from the block cut into many pieces was measured as well (not irradiated). The optimally chosen MAT descriptors were considered in all cases as functions of the Vickers hardness. In the case of irradiated samples, the MAT descriptors were also illustrated as a function of the neutron fluence. The results are presented below.

4.1. Irradiated Charpy Specimens

The influence of neutron irradiation on the magnetic parameters (optimally chosen MAT descriptor) is shown in Figure 4a. In these measurements μ (h_a = 30 mA, h_b = 1080 mA) was used as optimal.

To better show the correlation between mechanical hardening and magnetic parameters, another style of plot is presented in Figure 4b. Here, magnetic parameters are shown as functions of the Vickers hardness. In this case, each point corresponds to one sample, and the MAT parameter is normalized to the same parameter measured on the same sample before irradiation. This interpretation better reflects the sample hardening of individual samples due to neutron irradiation. This is the reason why only one point indicates the magnetic property of the reference case. A close to linear correlation was found. The point scatter is demonstrated by the R = 0.813 regression factor of the linear fit.

4.2. Irradiated Blocks

The correlation between MAT descriptors and neutron fluence is shown in Figure 5a in the case of block samples, while Figure 5b shows the correlation between MAT descriptors and Vickers hardness when using normalized parameters, similar to the case of Charpy samples. In these measurements μ' (h_a = −600 mA, h_b = 1200 mA) was used as optimal.

These two graphs (Figure 5a,b) and similar graphs in case of Charpy samples (Figure 4a,b) show very well the large scatter of measured points. Explanation of this phenomenon is the main purpose of the present work. One can even question the presence of any correlation at all. However, in our opinion the tendency of the increase in magnetic parameters is clearly seen, especially if we compare the modification of parameters generated by neutron irradiation with the values of unirradiated reference samples. On the average, about 20% increase in magnetic descriptors can be detected. In other words, some correlation definitely exists, but it is questionable if this correlation is linear or not, which is also reflected by the low values of the regression coefficients.

4.3. Selection of Samples

As can be clearly seen in the above figures, the point scatter is very large. The samples were magnetically different, even before irradiation. The directly measured permeability loops seem to be the best for studying the magnetic behavior. These loops of all nonirradiated Charpy (reference) samples are shown in Figure 6a. Here, the series of all loops is shown (including all minor loops as well). A magnified part of the graph can be seen in Figure 6b. For better visibility, only the envelope of the loops (minor loops with the largest amplitude) can be seen in this latter case.

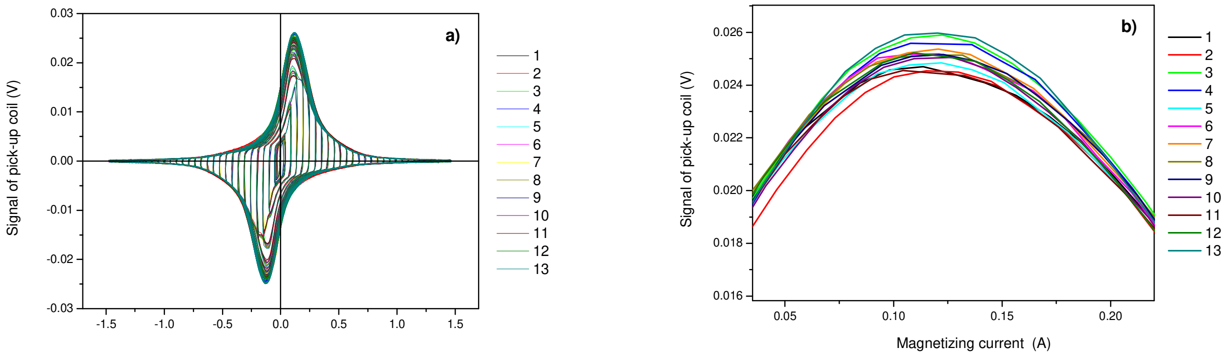

Figure 6. The measured permeability loops of the nonirradiated reference Charpy samples: (**a**) full loops; (**b**) magnified parts of the loops [10].

Four samples were magnetically similar. Their maximal permeability values were very close to each other. The same MAT evaluation process was repeated while taking into account only the selected samples (samples No. 6, 7, 10, and 12). The result is shown in Figure 7.

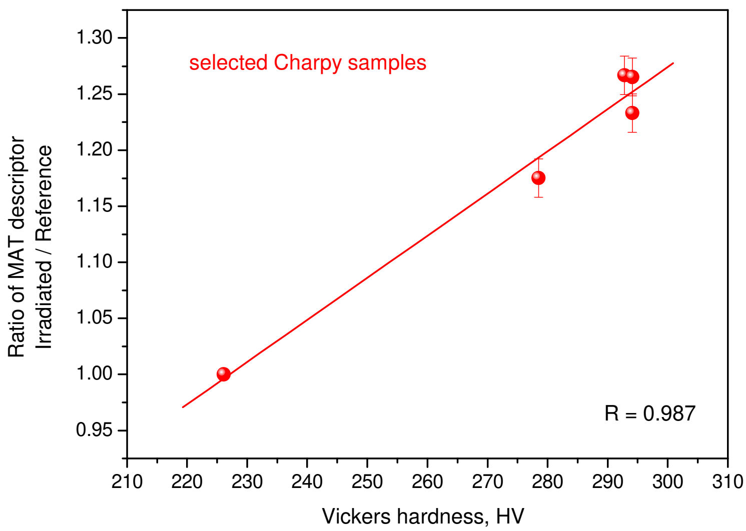

Figure 7. The ratio of MAT descriptors of selected, individual irradiated and reference Charpy samples (optimally chosen MAT descriptor) as a function of Vickers hardness.

Exactly the same selection was also made for block samples. In this case, five samples were found to be magnetically close to each other. Due to space limitations, the permeability loops of the blocks are not shown here, but the graph was very close to that in Figure 6. The result is shown in Figure 8.

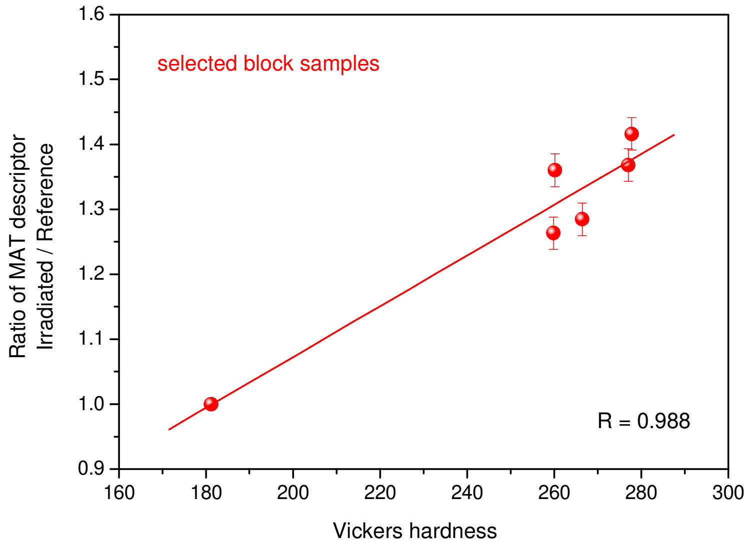

Figure 8. The ratio of MAT descriptors of selected, individual irradiated and reference block samples (optimally chosen MAT descriptor) as a function of Vickers hardness.

4.4. Measurement of Charpy Samples Cut from the Same Block

Figure 9 shows the maximal permeability of individual samples depending on the sample number. The sample numbers and locations of the samples within the block are also indicated in Figure 2.

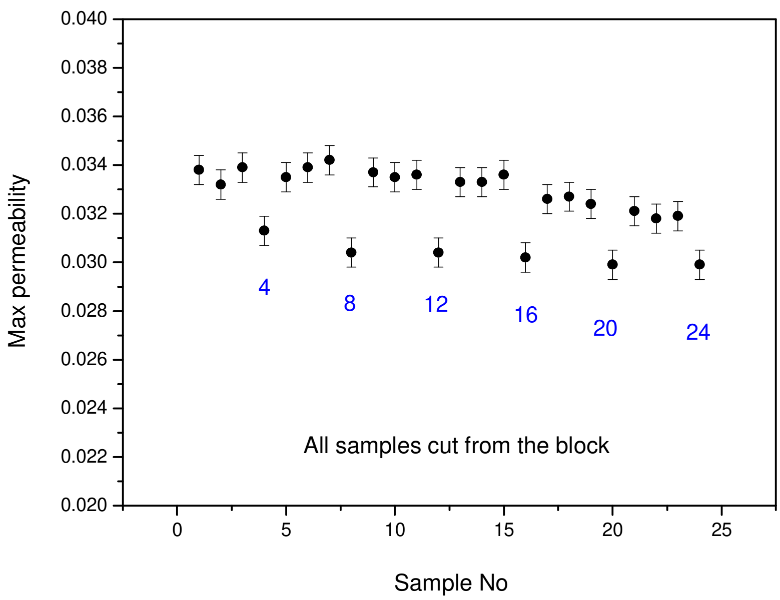

Figure 9. Correlation between maximal permeability and sample number.

The correlation between the optimal MAT descriptor and the Vickers hardness is shown in Figure 10.

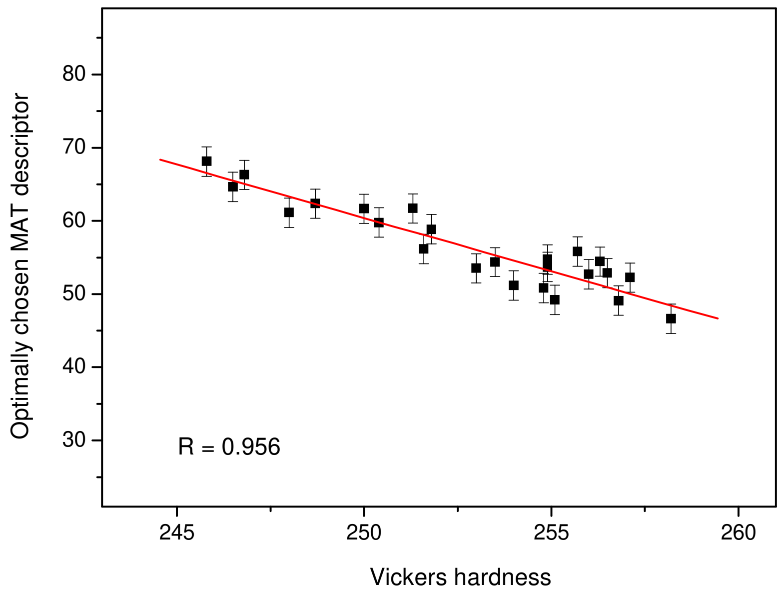

Figure 10. Correlation between MAT descriptor and Vickers hardness.

5. Discussion

Apart from the point scatter, a clear tendency is seen in both cases (Charpy samples and blocks) of irradiated specimens: a monotonic correlation exists between magnetic parameters and the dosage of neutron irradiation (Figures 4a and 5a), according to our expectation and previous results [14]. Neutron irradiation generated a 25–40% increase in magnetic parameters as compared with the virgin sample. These results can be considered to validate the usefulness of magnetic measurements for neutron-irradiation-generated embrittlement, regardless of the type or material of the investigated samples. Evidently, this manner of presentation did not reduce the scattering of points. Nevertheless, the tendency between MAT parameters and neutron fluence or Vickers hardness is clearly seen.

However, if a preselection of samples is made based on their magnetic behavior, this scatter is significantly decreased. As can be seen very well in Figure 7, if only the magnetically similar samples are taken into account, the point scatter is reduced. The regression of the linear fit increases from R = 0.813 to R = 0.987 in the case of Charpy specimens. The same can be observed in the case of irradiated blocks (Figure 8): the regression of the linear fit increased from R = 0.787 to R = 0.988. The correlation between mechanical hardening and magnetic descriptors is thus excellent.

We emphasize that it was not backward reasoning that was used to determine these points, which fit our hypothesis. To clarify this, the whole MAT process is briefly detailed: (1) Large scatter of the MAT descriptors measured on the reference and irradiated specimens was found. (2) Regardless of the result of this evaluation, the magnetic behavior of *reference* samples was considered. It was found that some samples behaved very similarly from a magnetic point of view. (3) The evaluation was performed once more, but considering only the selected samples. This selection did not provide any information about the mechanical hardening due to neutron irradiation, because samples were measured before irradiation. *Before* irradiation, we simply did not know how samples will behave *after* irradiation.

It is believed that the fact that the two, very different sample series (different chemical composition blocks and Charpy specimens) revealed the same behavior is a rather strong argument behind our hypothesis: neutron irradiation hardening depends very much on the actual local material parameters, and magnetic measurements properly indicate this behavior. The excellent correlation between destructively measured Vickers hardness values and nondestructively measured magnetic parameters shows that our magnetic method is suitable for the nondestructive characterization of neutron-irradiation-generated embrittlement.

The only reason for the large point scatter presented above, if all measured samples are considered, can be material inhomogeneity. We do not dare to provide any explanation or interpretation of this inhomogeneity, but we would like to call the attention of nuclear reactor experts to this fact. To show that this speculation could be true, we cut a single large block of real reactor steel material into 24 Charpy pieces and systematically investigated the different pieces. The result supports our assumption that samples even of the same block behave differently. It can be seen very well that there was a decrease (though not significant) in maximum permeability as a function of sample number, if the majority of samples are considered. However, every fourth sample revealed very different magnetic behavior. It is evident that samples cut from the *same* block can be magnetically rather different.

On the other side, the correlation between optimal MAT descriptors and Vickers hardness was rather good, regardless of the sample number, as can be seen in Figure 10. Both MAT parameters and Vickers hardness values properly characterize the individual samples. This observation is another indication of the previously observed and published advantage of magnetic adaptive testing.

In the specimen data presented above, we cannot exclude the possibility of a magnetic side effect theoretically, i.e., that irradiation affects the magnetic characteristics in a different manner than the mechanic ones. For instance, local variation in the mechanical stress can lead also to variation in the observed magnetic behavior. This could cause serious doubt about applicability if the magnetic evaluation was based only on a few measured magnetic properties. However, MAT is based on a large set of recorded magnetic minor loops that comprise several point pairs of excitation field-magnetization values. Therefore, the magnetic evaluation can be carried out on a large data pool that makes it possible to recognize and to distinguish the magnetic side effects and to even suppress them in this way. The presented MAT descriptors were selected by simultaneously finding the best correlation with the independent parameter and achieving the lowest scattering/highest reliability. This mitigates the possible sensitivity for such a side effect.

Perhaps our most important result is the demonstration of the sensitivity of the irradiation generated embrittlement to local material inhomogeneities. This result has a character of basic research and to our best knowledge, this behavior of reactor steel has not been investigated yet. Evidently, the research should be continued in order to reveal which material parameters are responsible for the neutron irradiation generated material degeneration. If our future research work will be successful, it would lead to important new result in materials science. Further investigation of this phenomenon is obviously outside of the scope of this paper, but we would like to continue our work in this direction. It is known that the material of reactor pressure vessel steel is not homogeneous (as shown directly in Section 4.4). It means that inspecting neutron irradiation generated embrittlement in nuclear industry by using samples that are magnetically similar from the beginning is not possible. We should find another way, for instance averaging of samples' behavior and trying to study the phenomenon in such a way. Nevertheless, the general tendency is obvious and there is no doubt that this nondestructive method will find its proper place among the testing techniques of nuclear industry.

6. Conclusions

The influence of neutron irradiation on reactor steel material hardening was investigated on two sample series of different types of reactor steel and of different shapes and sizes. The new results obtained on blocks verified our previous hypothesis that by magnetic selection of samples, the previously observed point scatter [3] can be notably reduced. As a conclusion, magnetically measured parameters seem to provide precise and reliable detection of the embrittlement of the reactor pressure vessel steel.

The assumption that the reason for the scatter is connected with inhomogeneity of the samples is supported by another measurement series of samples cut from the same block. Magnetic parameters of different pieces showed significant scattering, but the correlation between magnetic parameters and Vickers hardness was good. This result justifies the potential future application of magnetic techniques in practice aimed at the regular inspection of nuclear reactors.

The magnetic measurement described and discussed above is fully nondestructive and does not alter the sample in any way. Furthermore, this technique is completely reproducible. This offers the ability to reuse samples, because the measurement of interest would not consume the samples. The inspection can be repeated on the same sample after repeated irradiations, thus the effect of irradiation, or any other material degradation, over time can be tracked on the same specimen.

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