A COMPARISON OF RADIATION SHIELDING OF STAINLESS STEEL WITH DIFFERENT MAGNETIC PROPERTIES

by

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The radiation shielding properties of three different stainless steels have been investigated. For this purpose, linear attenuation coefficients at photon energy levels of 662 keV and 1250 keV have been measured. The obtained results showed that ferritic stainless steel was more capable in stopping the high energy photons than its non-magnetic counterpart.

Key words: stainless steel, magnetization, radiation shielding

INTRODUCTION

The radiation shielding of personnel and the public at the workplace means placing a suitable material between the radioactive source and the personnel. It is well known that some materials are more effective than others in shielding particular types of radiation. On the other hand, the type and amount of shielding material needed for the shielding vary with the type and quantity of radioactive material being shielded [1]. The shielding of gamma-rays and neutrons by 12 concrete specimens prepared with and without mineral additives was studied by Yilmaz *et al*. [2]. The recorded values showed a change in energy of the incident beam and concrete composition. In addition to this, Akkurt *et al*. [3] measured the linear attenuation coefficients for concrete containing zeolite as an aggregate in different concentrations (0%, 10%, 30%, and 50%). The linear attenuation coefficient measured on four concrete blocks decreased by increasing the quantity of zeolite. It was concluded that the addition of zeolite as an aggregate in the concrete is not an alternative option to be used for the purposes of radiation shielding. In the meantime, Rezaei-Ochbelagh and Azimkhani [4] studied the gamma-ray shielding properties of concrete containing varying percentages of lead powder and silica fume. The authors reported a slight decrease in the gamma-ray attenuation with the addition of silica fume. They suggested the usefulness of 15% silica fume cement concrete containing lead as a gamma shield.

Carbon steel or stainless steel, as lead, has been commonly used as materials for thermal and radiation shields [5, 6]. Corresponding to this, it has been found that the measured effective linear attenuation coefficient of carbon steel gives an average value of 0.340 cm^{-1}. On the other hand, it has been shown that the total mass attenuation coefficients (μ/ρ) values of steel decrease by increasing the photon energy [7]. This result shows that the mass attenuation coefficients vary with the variation of the atomic and electronic number for different steel compositions. Thus, understanding the basic principles involved in the physical interactions of gamma radiation with matter can help in the choice of shielding for a given application. In addition, the magnetization is an important parameter for the steel and under the magnetic field the behavior of those materials can be different for different characteristics. It is therefore necessary to further examine the radiation shielding of steel with different magnetic properties. In this study, the magnetic behavior on the radiation shielding of three different stainless steels is investigated.

EXPERIMENTAL METHOD

The substrates used for this study were AISI 304, AISI 316 L, and AISI 430 stainless steel, received in the annealed condition. Chemical compositions of the test materials are listed in tab. 1.

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Table 1. Chemical composition of steel used [wt.%]

	C	Cr	Ni	Si	P	S	Mn
316 L	0.03	18	10	1.0	0.04	0.03	1.5
304	0.08	18	10	1.0	0.04	0.03	1.5
430	0.12	18	–	1.0	0.05	0.03	1.0

The samples were cut into dimensions of 2 mm × 2 mm 15 mm and the magnetization of the steel specimens was measured using a Cryogenic Q-3398 vibrating sample magnetometer (VSM). The measurements of magnetic hysteresis loops were performed at 295 K with the applied magnetic fields of up to 7 T.

Finally, to investigate the radiation shielding properties of the AISI 304, AISI 316 L, and AISI 430 stainless steel, the linear attenuation coefficients (μ) were measured at the photon energy of 662 keV and 1250 keV obtained from the ^{137}Cs and ^{60}Co γ-ray sources, respectively. For this purpose, γ-rays transmitted through the steel were detected using a gamma spectrometer that consists of a 3 × 3-inch NaI(Tl) detector connected to a multichannel analyzer (MCA). The detector system communicates with a PC using the Genie 200 software. If N and N_0 are the measured count rates in the detector with and without the absorber of thickness x [cm], respectively, then the radiation absorption coefficient μ can be extracted by the standard equation

$$N \quad N_0 e^{\mu x}$$

The slope of the ln(N/N_0) *vs*. x plot gives μ. Further experimental details are described in [8].

EXPERIMENTAL RESULTS AND DISCUSSION

Stainless steel is an iron-based alloy primarily known for its excellent corrosion resistance, which is largely due to the steel's chromium concentration. There are several different types of stainless steel. The two main types are austenitic and ferritic, each of which exhibits a different atomic arrangement. Due to this difference, ferritic stainless steel is generally magnetic while the austenitic stainless steel usually is not [9].

The typical hysteresis loops obtained from the steel are shown in fig. 1. From this figure, the magnetic behaviour of the AISI 430 ferritic stainless steel is shown clearly. The high magnetic saturation of the AISI 430 is due to its Fe and C concentration. In literature, it has been pointed out that the saturation magnetization is known to be insensitive to the structure in the sense that it does not depend on the details of the fine structure, such as the strain, lattice imperfection and/or small amounts of impurities [10, 11]. Crangle [12] showed that iron with carbon exists as Fe_3C through high temperature, *i. e*.

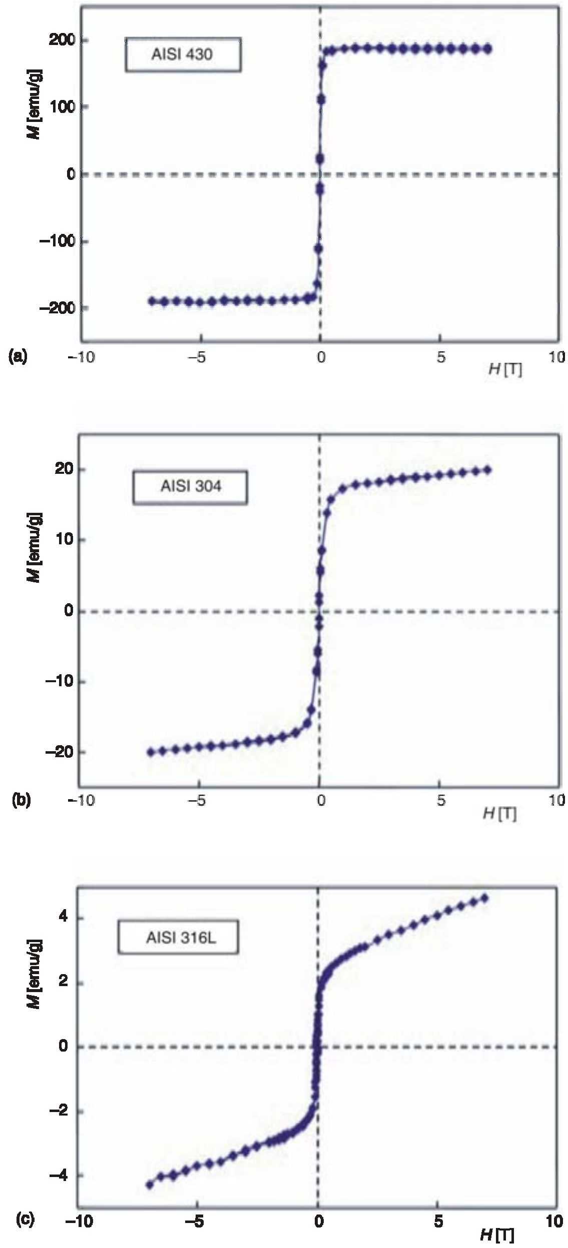

Figure 1. The typical hysteresis loops of steel used in this study

$$3Fe \quad C \quad Fe_3C$$

The Fe_3C is ferromagnetic. In addition, it has been shown that the stainless steel that contains nickel, generally referred to as a 300 series, is not magnetic at all. The reason is that the presence of the nickel alters the physical structure of the stainless steel and removes or inhibits any magnetic qualities. From fig. 1 and the microstructure (fig. 2) obtained from this study, we say that the AISI 304 and AISI 316 L steel are austenitic-stainless steel and do not show magnetic properties, whereas the AISI 430 ferritic stainless steel shows magnetic behaviour. This result is in a good agreement with the literature.

Now let us consider the relation between the radiation shielding and magnetic behaviour of steel. The

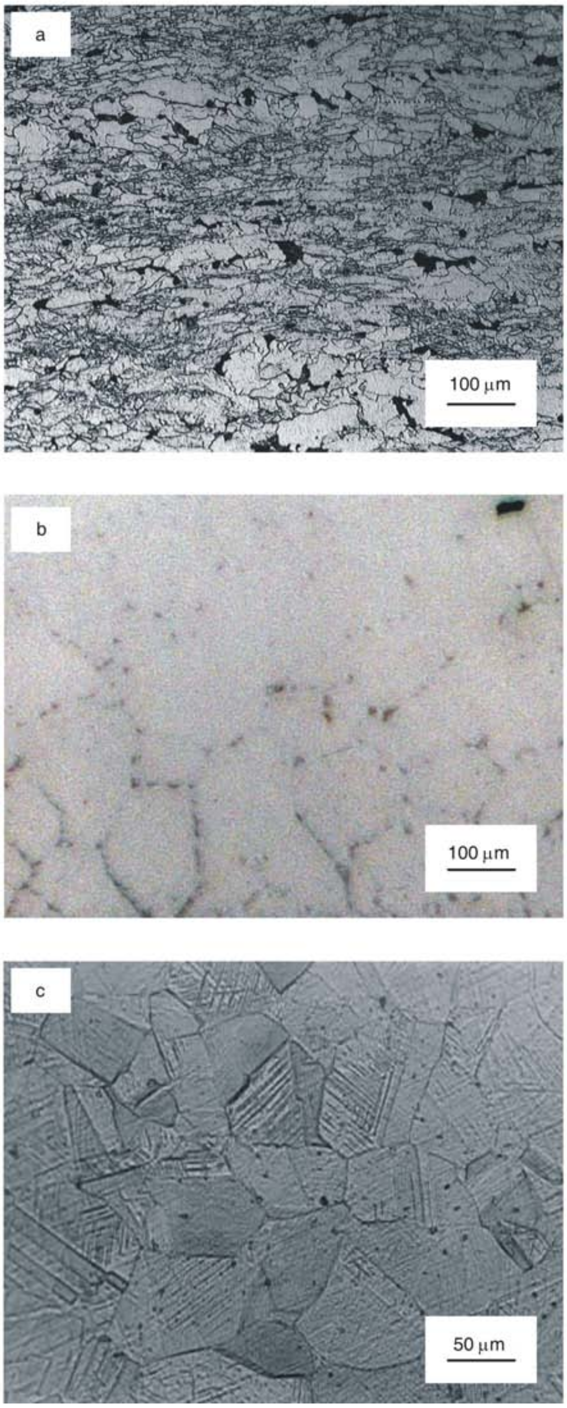

Figure 2. The microstructure of steel; (a) AISI 430, (b) AISI 304, and (c) AISI 316L

linear attenuation coefficients of steel were measured at the photon energy of 662 keV and 1250 keV obtained from ^{137}Cs and ^{60}Co γ-ray sources, respectively. This measurement has been performed for steel with different magnetic properties. This is displayed in fig. 3 where it can clearly be seen that the AISI 430 ferritic stainless steel has a high μ both at the photon energy of 662 keV and 1250 keV.

The radiation shielding is based on the principle of attenuation, which is the ability to reduce a wave's or

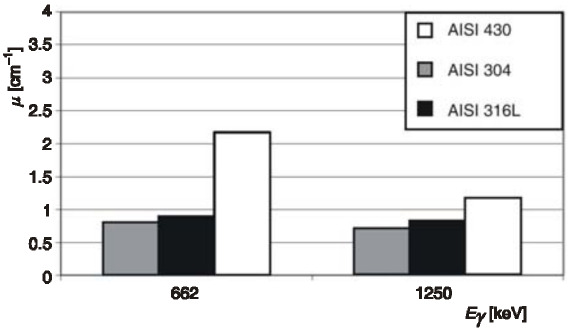

Figure 3. Linear attenuation coefficients for steel at the photon energy of 662 keV and 1250 keV

ray's effect by blocking or bouncing particles through a barrier material. Charged particles may be attenuated by losing the energy to the reactions with electrons in the barrier, while gamma radiation is attenuated through the scattering or pair production [13]. Thus, lead can effectively attenuate certain kinds of radiation because of its high density and high atomic number; principally, it is effective at stopping gamma rays, and X-rays. The high density of the lead is caused by the combination of its high atomic mass and the relatively small size of its bond lengths and atomic radius [14]. In addition to the lead, it has been shown that the steel-magnetite has higher linear and mass attenuation coefficients [15]. From our study, firstly, we say that μ depend on the incoming photon energies as the interaction mechanism of photons with the medium is different for different photon energies (fig. 3). By comparing μ of different steel, the linear attenuation coefficients of AISI 316 L and AISI 304 steel are very close together and these steel display the austenitic behaviour. On the other hand, it is clear that the highest μ was found for AISI 430 steel while the lowest value for AISI 304 steel. This could be the results of the different components of the steel. As can be seen from the tab. 1, the ferritic and austenitic steel have different Fe, C, and Ni concentrations. The same results has been obtained in the study by Han and Demir [16]. They showed that the linear attenuation coefficients depend on the concentration of elements within the alloy.

In conclusion, there is a relationship between the attenuation coefficient and the magnetic saturation, *i. e.*, the ferritic stainles steel which displays the ferromagnetic behaviour has a high linear attenuation coefficient due to the composition of the steel. Thus, the ferritic stainless steel was more capable in stopping the high energy photons than the non-magnetic steel. This could give a chance to the use of ferromagnetic steel in terms of radiation shielding purposes instead of the standard shielding material such as lead.

AUTHOR CONTRIBUTIONS

The boronizing treatments for the specimens were carried out by A. Calik. Metallography and microstructural analyses were conducted by N. Yilmaz. Radiation measurements were performed by S. Akbunar. All authors analysed and discussed the results presented in the manuscript. The manuscript was written by N. Ucar and I. Akkurt and the figures were prepared by M. S. Karakas. Research was co-ordinated by A. Calik.

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ПОРЕЂЕЊЕ РАДИЈАЦИОНИХ ЗАШТИТНИХ СВОЈСТАВА ЧЕЛИКА РАЗЛИЧИТИХ МАГНЕТНИХ ОСОБИНА

Приказани су резултати истраживања радијационих заштитних својстава три врсте челика. Мерени су линеарни коефицијенти слабљења при нивоима енергије фотона од 662 keV и 1250 keV. Добијени резултати показују да фотоне високих енергија боље зауставља феритни него немагнетни челик.

Кључне речи: челик, магнетизација, заштита од зрачења