Study of mass attenuation properties for cobalt-free maraging steels at photon energies from 200 to 3000keV

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Abstract

Over the past 40 years a generic class of ultra- high strength maraging steels have been developed mainly for aircraft, aerospace and tooling applications the ultra–high strength of the most expensive maraging steels is due to the precipitation of intermetallic compounds (high nickel and molybdenum) during ageing process such as Ni_3Mo, FeMo and Fe_7Mo_6.

Production of such steels faces many great problems first, a great quantity of strategic elements Co, Ni, Mo, second, retention of austenite, third, production methods which need double vacuum process.

Due to the sharp increase in the cobalt price the development of a cobalt free maraging steel family is promoted. Titanium and chromium are used as the primary strengthening elements replacing cobalt in steels. Furthermore, to overcome the problem of retained austenite, it is supposed that nickel content can be reduced to 12%. Maraging steels are usually produced using a double vacuum melting technique. Due to the high cost of the double vacuum technique, electro-slag remelting technique (ESR) can be successfully used to remelt the maraging steel and in turn improve its mechanical strength and ductility by selecting the suitable fluxes.

Some physical properties were measured for the new alloys such as the total mass attenuation coefficients (μ/ρ), Half-value layers (HVL) and mean free paths (MFP). Furthermore; some mechanical properties such as density and hardness of the new alloys were measured. Also, a high nitrogen low nickel stainless steel was introduced for the sake of comparison.

Keywords:

Cobalt-free. Gamma ray shielding. Mass attenuation coefficients.

1. Introduction

There are some methods that control the intensity of radiation received from a radioactive source. One of the most significant of these methods is the radiation shielding, which is the science of protecting people and the environment from the harmful effects of radiation. The principle of the radiation shielding is to decrease the intensity of external radiation to the desired level. A good photon shielding material should have high value of photon attenuation coefficients and irradiation effects on its mechanical properties should be small. Steel alloys are excellent shielding material most widely used for radiation shielding of nuclear plants, in the walls of radiology and oncology departments in hospitals (Kaplan, 1989).

Maraging steels were originally low-carbon iron–nickel martensites which are hardened by the precipitation of molybdenum and titanium containing intermetallic compounds. Maraging steels possess certain distinctive characteristics, such as lack of distortion during hardening, good weldability and good combination of strength and toughness that have made them attractive for many applications, e.g., dies. In these cases, the main benefit of the maraging steels was that they can be machined to complex shapes in soft non-aged conditions and then be maraged with minimum distortion during hardening (e.g. aluminum die casting)[1-4].

The standard maraging steel contains 18% Ni, 8% Co, 5% Mo and 0.4% Ti. But Ni, Co and Mo are very expensive strategic alloying elements as cobalt reaches to levels as high as 8 to 13%. This keeps the steels rather expensive, preventing wider selection and application, but with maximum strength levels reaching 2400 MPa, accompanied by good toughness and ductility. Therefore, developing cobalt-free maraging steel with reduced quantities of expensive alloying elements to lower the production cost has been an important direction of maraging steels research. Over the past two decades, enormous advances have been achieved in the development of cobalt-free maraging steels to high strength levels with Ni and Ti as the major precipitation hardening phase in cobalt-free maraging steels [5-7].

To overcome this problem, titanium was used as one of the primary strengthening elements replacing Co in steels, and to overcome the problem of retained austenitic, nickel content is reduced to 10~12%, to enhance toughness and to improve corrosion resistance [8-11]. The cobalt in maraging steels lowers the solid solubility of molybdenum in martensite matrix which in turn raises the opportunity to form Ni3Mo inter-metallic precipitate, hence more molybdenum is free to take part in the aging reaction giving an effective increase of hardness compared with that of the base alloy containing no cobalt. However, Vanderwalker [12] found that Ni3Ti precipitates rapidly, strongly and completely during the aging. Ni3Ti is much more heavily redistributed than Ni3Mo precipitate in the very early stage of aging, when both Ti and Mo are present in the material.

Another point to remove cobalt that it has radioactive isotopes resulted from irradiation with high energy neutron flux so this is too dangerous to be used as a shielding material. The most common radioactive isotope is cobalt-60 that is produced when structural materials, such as steel, are exposed to neutron radiation. ^{60}Co nucleus emits two gamma rays with energies of 1.17 and 1.33 MeV.

The purpose of the present work is to investigate the interactions of the new alloys with the gamma radiation by measuring mass attenuation coefficients for different gamma energies ranged from 200 to 3000keV by using different point radioactive sources ^{133}Ba (302.9keV, 356keV), ^{137}Cs (661keV), ^{60}Co (1173keV, 1133keV) and ^{232}Th (238keV, 583keV, 911keV, 2614keV), also comparing the experimental results with the theoretical calculation.

2. Theory

2.1 Total mass attenuation coefficients of gamma ray (μ/ρ)

A parallel collimated beam of mono-energetic gamma ray photons is attenuated in the matter according to the relation [13]:

$$I(x) = I_0 e^{-\mu x} \quad (1)$$

Where I_0 is the initial photon density, I(x) is the photons that penetrates the alloy at distance x and μ is the linear attenuation coefficient. We can write it

$$\frac{\mu}{\rho} = \frac{\ln\left(\frac{I_0}{I}\right)}{\rho x} \quad (2)$$

To reduce the intensity to half of its original value, a thickness called half value layer (HVL) can be calculated by:

$$\mathrm{HVL} = \frac{0.693}{\mu} \quad (3)$$

Another parameter that characterizes the gamma ray photon energy is their mean free path (MFP) that represented by λ, which is defined as the average distance travelled in the absorber before an interaction takes place. It can be calculated from:

$$\lambda = \frac{\int_0^\infty x e^{-\mu x} dx}{\int_0^\infty e^{-\mu x} dx} = \frac{1}{\mu} \quad (4)$$

Also the mass attenuation coefficient μ/ρ for any mixtures of elements in an alloy can be calculated by [14-17].

$$\frac{\mu}{\rho} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \quad (5)$$

Where ρ_i and $(\mu/\rho)_i$ are the partial density and the mass attenuation of the i_{th} constituent, respectively and w_i is the weight fraction of i_{th} constituent[18-22].

2.2 The Density of the alloys

The densities of the samples were measured using indirect method based on Archimedes principle using glycerin as immersion liquid according to the relation:

$$\rho = \frac{W_{air}}{W_{air} - W_{liquid}} \times \rho_{liquid} \quad (6)$$

Where ρ is the density of the sample, W_{air} and W_{liquid} are the weights of the sample in air and in the immerging liquid respectively. ρ_{liquid} is the density of the immerging liquid.

2.3 The Hardness of the alloy

The hardness is defined as the ratio of the applied test load to the projected area of the resultant indentation impression [10]. Micro-hardness can be calculated according to

$$H_V = 1854 \times P/d^2 \quad (\mathrm{Kg/mm^2}) \quad (7)$$

Where P is the applied force to the diamond in kilograms and d is the average length of the diagonal left by the indenter in millimeters.

3. Preparation of shielding material

The cobalt-free steel samples were prepared in the steel technology department, Central Metallurgical Research and Development Institute (CMRDI), using Electro-Slag Remelting technique (ESR). Titanium was used instead of Cobalt, and Nickel content was reduced to 10~12% (in order to overcome the problem of retained austenitic). Table 1 gives the variation of constituent of the cobalt-free maraging steel (S_{17}, S_{24}). Furthermore a high nitrogen stainless steel (N_s) is also presented for the sake of comparison.

Chemical compositions	S_{17}	S_{24}	S_N
Ni	0.1062	0.1045	0.0007
Cr	0.1025	0.1737	0.1908
Mo	0.0581	0.0477	0.0241
Ti	0.0106	0.0039	0.0001
Al	0.0082	0.0083	0.0034
V	0.0009	0.0012	0.0005
Mn	0.0041	0.0043	0.0153
Si	0.0092	0.0089	0.0153

Table 1 Variation of chemical composition of the steel alloys with iron as the remainder.

4. Experimental procedures

4.1 Calculating the mass attenuation coefficient

The mass attenuation coefficient of gamma radiation was measured with a narrow beam array using gamma spectroscopy technique in the physics department, Faculty of Science, Ain shams university. The arrangement of the device consists of hyper pure germanium (HPGe) detector with relative efficiency ~10% relative to a 7.62cm x 7.62cm NaI(TI) detector connected to multichannel pulse height analyzer. The necessary power to the detector as well as the acquisition of gamma spectra was achieved by an integrated spectroscopic system at 2900 volts. This system is controlled by a personal computer.

The detector has a resolution of about 1.8keV at 1.33MeV γ -line, which is capable of distinguishing the gamma ray energies for the experimental purpose. The experiment operated at liquid nitrogen temperature (~77K).

The sample was placed between the standard gamma point source and the detector. The experiment was repeated with and without the sample for 15 min. The samples were irradiated by photons emitted from the radioactive point sources in the range from 200 to 3000keV.

4.2 Measuring the Hardness and Density

The samples have been cut using the wire-cut programming machine, in Laser lab in CMRDI, with 4mm thickness. The Rockwell hardness determines the hardness by measuring the depth of penetration of an indenter under a large load compared to the penetration made by a pre-load 980Kg, and then the readings were registered and converted to the Vickers hardness using the conversion tables.

All the readings were measured at room temperature using a micro-hardness tester type (Heckert, 0.01mm, made in German) in the laboratories test, El Nasr Steel for Pipes. The hardness and density of the samples are shown in table 2. The change in the density may be attributed to the variation of Mo, Ni and Fe which have the highest density. Where, the variation of hardness value may be attributed to the variation of nickel content, we can see that H_V decreases with increasing Ni content also variation of Cr, Mo and V affects the hardness.

Alloy	S_{17}	S_{24}	S_N
Density (g/cm^3)	7.86	7.77	7.65
Hardness (H_V)	238	257	279

Table 2 Density and Hardness of the steel samples.

5. Results and Discussions

The total mass attenuation coefficients (μ/ρ), half value layers and mean free paths MFP for different steel samples have been measured at different photon energies from 200 to 3000keV as shown in table 3. Form the table we reveal that steel S_{17} has the best attenuation properties followed by steel S_{24} and at last that of S_N.

Photon Energy (KeV)	S_{17}			S_N			S_{24}		
	μ/ρ(cm^2/g)	HVL(cm)	MFP(cm)	μ/ρ(cm^2/g)	HVL(cm)	MFP(cm)	μ/ρ(cm^2/g)	HVL(cm)	MFP(cm)
238	0.13100	0.67318	0.97119	0.12800	0.70787	1.02124	0.13000	0.68622	0.99000
356	0.10100	0.87314	1.25967	0.09980	0.90789	1.30981	0.10100	0.88325	1.27426
583	0.07840	1.12483	1.62279	0.07800	1.16163	1.67588	0.07830	1.13931	1.64368
662	0.07360	1.19819	1.72862	0.07330	1.23612	1.78334	0.07360	1.21207	1.74864
911	0.06290	1.40201	2.02268	0.06270	1.44510	2.08483	0.06290	1.41825	2.04611
1133	0.05530	1.59470	2.30066	0.05510	1.64442	2.37239	0.05530	1.61317	2.32731
1332	0.05190	1.69917	2.45138	0.05170	1.75256	2.52841	0.05180	1.72216	2.48456
2614	0.03820	2.30855	3.33054	0.03800	2.38441	3.43997	0.03801	2.34696	3.38595

Table 4 Mass attenuation coefficients, half value layers and mean free paths for different steel samples at different photon energies.

The values of mass attenuation coefficients (μ/ρ) for the new alloys at different energies with the width as a variable are shown in Fig 1.

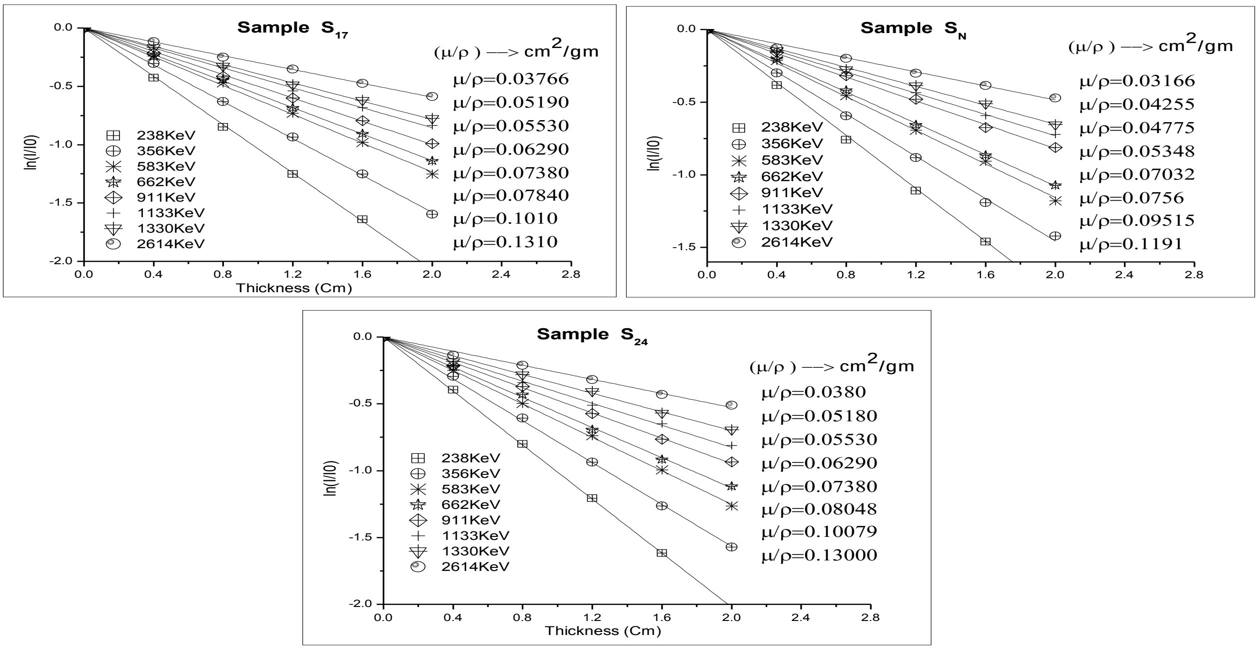

Fig. 1 Mass attenuation coefficients for the steel alloys at different energies.

A comparison between the theoretical and experimental values for the total mass attenuation coefficient of alloys S_{17} and S_N are presented in Fig 2, and the correlation theory is used to confirm the linearity of theoretical and experimental values. The correlation coefficients for S_{17} and S_N are 0.9973 and 0.9952 respectively. It can be noted that the calculated and measured values are in good agreement.

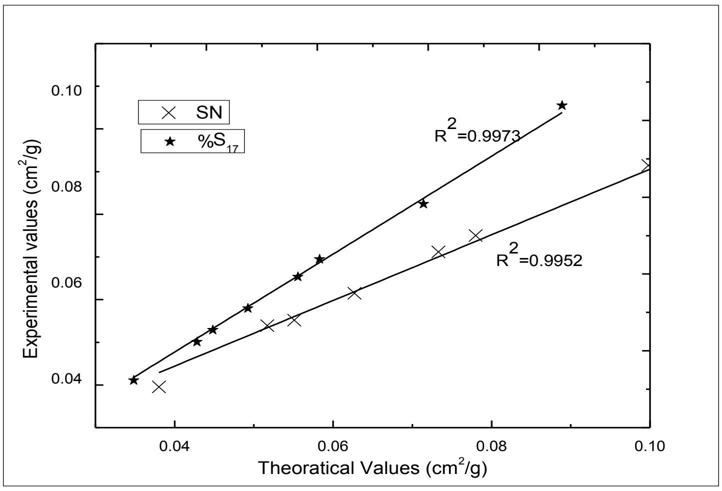

Fig. 2 Theoretical and experimental total mass attenuation coefficients for S_{17} and S_N alloys

6. Conclusions

New shielding cobalt-free maraging steel was developed by means of induction furnace-electro-slag remelting technique using titanium and chromium instead of cobalt and reducing nickel content to 10-13%.

Mass attenuation coefficients, half value layers and mean free paths have been evaluated. A comparison to the corresponding theoretical attenuation coefficients has been performed and a fair agreement is achieved. The achieved results reveal the superiority of S_{17} cobalt-free alloy (0.05%C-13.26%Ni-2.15%Cr-4.31%Mo-0.02%Ti-0.01%V) than the other remaining alloys to be used as a proper gamma ray shielding material in the nuclear field.

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