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Comparative Evaluation of Shielding Performance according to the Characteristics of Eco-friendly Shielding Material Tungsten

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친환경 차폐재료 텅스텐 특성에 따른 차폐성능 평가

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Abstract Radiation shields used in medical institutions mainly use lead to manufacture products and fitments. Although lead has excellent processability and economic efficiency, its use is being reduced due to environmental issues when it is disposed of. In addition, when used for a long time, there is a limit to using it as a shielding film, shielding wall, medical device parts, etc. due to cracking and sagging due to gravity. To solve this problem, copper, tin, etc. are used, but tungsten is mostly used because there is a difficulty in the manufacturing process to control the shielding performance. However, it is difficult to compare with other shielding materials because the characteristics according to the type of tungsten are not well presented. Therefore, in this study, a medical radiation shielding sheet was manufactured in the same process using pure tungsten, tungsten carbide, and tungsten oxide, and the particle composition and shielding performance of the sheet cross-section were compared.As a result of comparison, it was found that the shielding performance was excellent in the order of pure tungsten, tungsten carbide, and tungsten oxide.

Key Words : Tungsten, Tungsten carbide, Tungsten oxide, Shielding sheet, Medical radiation

요 약 본 의료기관에서 사용되는 방사선 차폐체는 주로 납을 활용하여 제품과 부속품을 제작한다. 납은 가공성과 경제성이 우수하지만 폐기 시 환경 문제로 인해 사용량을 줄이고 있으며, 오랫동안 사용했을 시 크랙 현상과 중력에 의한 처짐 현상으로 인해 차폐막, 차폐벽, 의료기기 부품 등으로 장기간 사용하기에는 한계가 있다. 이러한 문제점을 해결하기 위해 구리, 주석 등을 사용하지만, 아직 차폐성능을 제어하기에는 제작 공정에 어려움이 있어 대부분 텅스텐을 많이 사용하고 있다. 그러나 아직 텅스텐의 종류에 따른 특성이 잘 제시되지 못해 다른 차폐재와의 비교가 어렵다. 따라서 본 연구에서는 순수 텅스텐, 탄화텅스텐, 산화 텅스텐을 이용하여 동일한 공정으로 의료 방사선 차폐시트를 제작하여 시트 단면의 입자 구성과 차폐성능을 비교하였다. 비교 결과 순수 텅스텐, 탄화텅스텐, 산화 텅스텐 순으로 차폐성능이 우수한 것으로 나타났다.

주제어 : 텅스텐, 탄화텅스텐, 산화텅스텐, 차폐 시트, 의료방사선

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1. Introduction

The larger the proportion of radiographic imaging in modern medicine, the more effective it is for diagnosis and treatment, but at the same time, the risk of medical radiation exposure to patients and medical personnel has increased[1]. The number of X-ray examinations worldwide increased from 1.6 billion in 1985 to 1990 to 1.9 billion in 1990 to 1995. Recently, in developed countries, it is reported that the number of radiological examinations used for diagnosis reaches once per person per year[2]. Lead is mainly used as the main material for shields used in medical institutions. Lead is a heavy metal and is regulated by most countries due to problems in use, risk of workers in the manufacturing process, and environmental problems when discarding, and it is recommended to use lead-free shields for medical institutions[3,4]. In addition, lead-based shields have physical limitations for long-term use as they can cause holes such as crack phenomena depending on storage conditions[5,6]. As such, due to the regulation of lead in medical institutions, a lot of eco-friendly materials have been produced and distributed recently, and representative materials are tungsten and bismuth. The selection criteria for shielding materials consider economical efficiency, processability, eco-friendly materials and light weight first, and when it is difficult to solve these problems, various fusion materials using composites are used[7,8].

Shielding suits are the most common shields used in medical institutions, and most prefer eco-friendly and lightweight materials[9]. Tungsten is the most effective material that meets these conditions. Tungsten's atomic number is 74, which is similar to lead's atomic number (82), and its density is 19.25 g/cm^3, which corresponds to a high density and is known to have a shielding effect similar to lead. However, the melting point is 3422 ℃, which is the highest among elements, so it is difficult to process into a desired shape[10,11]. Accordingly, it is mixed with a polymer material and coated in a film form, or manufactured in a sheet form and widely used as a lining for shielding clothing[12,13]. Therefore, the final product, the medical radiation shielding sheet, depends on the process technology used in mixing with the polymer material for its flexibility and shielding effect[14].

In previous studies, the shielding effect according to the particle size of tungsten or the shielding effect according to the characteristics of the polymer material, which is a mixed base material, has been studied a lot[15]. In this study, the shielding effect according to the intrinsic properties of tungsten was examined. In general, three types of tungsten trioxide (WO_3), tungsten carbide (WC), and pure tungsten (W), which are commonly used as X-ray shielding sheet materials, were compared. Tungsten oxide or tungsten trioxide is an intermediate stage material for tungsten extraction, and tungsten carbide is a material obtained by reacting carbon powder and tungsten powder at a high temperature of 1,500 ℃[16,17]. Looking at the cost of the extraction process, the purchase price of tungsten oxide can be said to be the cheapest, and tungsten carbide and pure tungsten are produced and sold at a similar price. Therefore, considering the same shielding effect, it is reasonable to select the most economical material.

In this study, the shielding performance of three types of tungsten presented was comparatively analyzed by manufacturing a shielding sheet using the same polymer material and the same manufacturing technology. In addition, the cross section was analyzed with an optical microscope to compare and observe factors affecting the shielding performance, such as particle arrangement and density. In the case of manufacturing lightweight shielding clothing in the future, we tried to compare the shielding performance of three types of tungsten shielding sheets to provide a basis for suggesting the validity of the shielding material composition.

2. Materials and Methods

To protect against radiation has the same meaning as to attenuate energy. Therefore, the concept of the mean free path (MFP) can be applied as energy is attenuated while interacting with the shielding material particles of the shield[18]. Assuming that the initial intensity of radiation is I_0 and the absorption coefficient of the shield is μ, when the radiation passes through the shield, the transmission intensity t is expressed as Eq 1 when the length t of the shield is transmitted [19].

$$I = I_0 e^{-\mu t} \qquad \text{Eq. 1}$$

Here, the length t of the shield means the thickness of the shield, and at the same time, it can be described as a space where radiation collides with particles and attenuation of energy intensity occurs. Therefore, if the density of the shield is N and the collision area with the particles is A, the mean free path (λ) can be expressed as in Eq 2.

$$\lambda = \frac{1}{N \cdot A} \qquad \text{Eq. 2}$$

Therefore, it is possible to apply a method to increase the shielding performance by increasing the collision probability with the distance that is the thickness of the shield and the density that can represent the particle composition inside the shield[20]. In this experiment, three types of shielding material particles were manufactured in the form of a sheet through the same method and the shielding performance was compared, and the size of the tungsten particles were all less than 10 ㎛. The polymer used as the base material used in this experiment was Polydimethyl Siloxane (PDMS, Mw 100,000~150,000). As a solvent, N-dimethylformamide (DMF, 99.5%) was used.

The shielding sheet manufacturing process using three types of tungsten single material is to first make a casting solution, and it was left to stand for at least 12 hours in a state where PDMS and DMF were completely dissolved through a stirrer at a certain ratio to remove internal air bubbles. Tungsten oxide powder was added to the casting solution thus completed and stirred at 3000 rpm for 10 to 15 minutes to disperse tungsten particles. Additional additives used in the manufacturing process are colorants, stabilizers, plasticizers, lubricants, antioxidants, heat stabilizers, and the like. Finally, the plasticizer used to remove the pinholes, which are micropores and the flexibility of the sheet, was Diisononyl phthalate (DINP). Casting application was carried out with a defoaming process after completely removing foreign substances through filtering, and the size of the sheet for compression molding was performed in a size of 300 ㎜ × 300 ㎜ × 0.3 ㎜.

Therefore, the finally manufactured shielding sheet is of three types: pure tungsten, tungsten carbide (WC), and tungsten oxide (WO_3). In addition, an optical microscope (OM, Axiotech 100 HD, Zeizz) and SEM (JSM-5410, Jeol) were used to check the internal cross-sectional structure of the manufactured shielding sheet.

The shielding performance evaluation

experiment of the fabricated shielding sheet was configured as shown in Fig. 1[21], and the shielding rate measurement of the fabricated shielding sheet was calculated as in Eq 3. T is the irradiation dose measured when there is a shielding sheet between the X-rays and the detector, and T_0 is the irradiation dose measured when there is no shielding sheet between the X-rays and the detector[22]. As for the measured dose conditions, the tube current was 200 mA and the irradiation time was 0.1 seconds, and the average value was applied after measuring 10 times. The irradiation dose was measured using an X-ray generator (DK-525, Toshiba E7239X) and a calibrated Ion Chamber (Model PM-30, PR-18).

$$S = (1 - \frac{T}{T_0}) \times 100 \qquad \text{Eq. 3}$$

S = Shielding rate(%)

T_0 = Irradiation dose(mR)

T = Transmitted dose(mR)

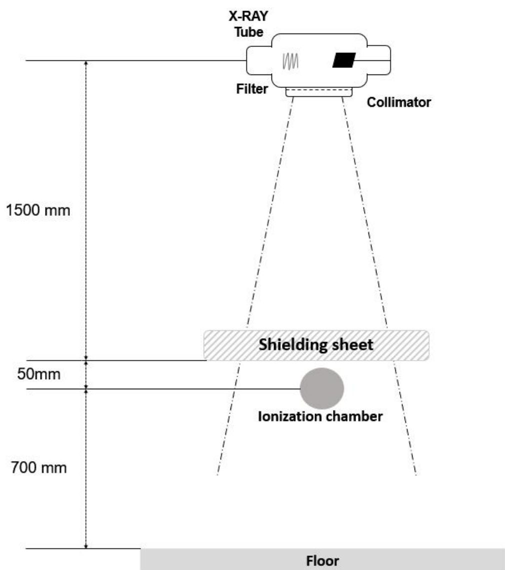


Fig. 1. Shielding experiment schematic

3. Results

The manufactured shielding sheet is shown in Fig. 2. Although it is difficult to distinguish clearly with the naked eye, the color of pure tungsten was the darkest black, and tungsten oxide showed a color close to gray.

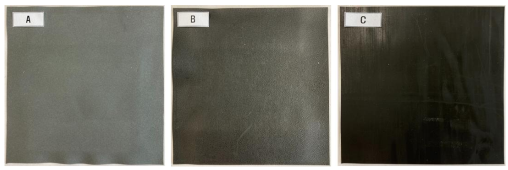
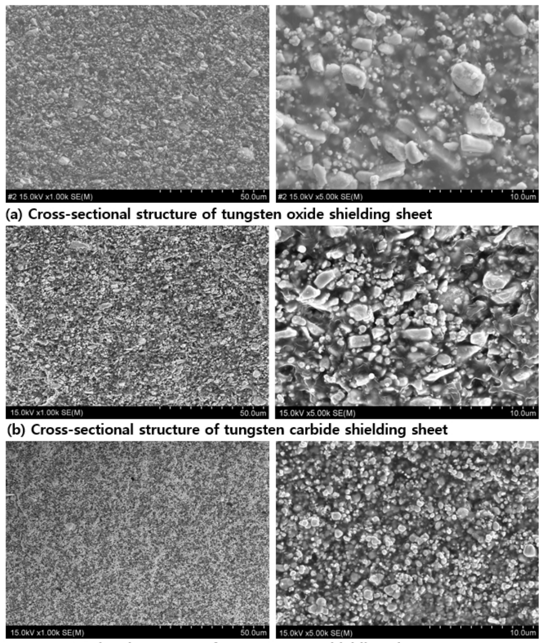


Fig. 2. Manufactured tungsten shielding sheet appearance. (a) tungsten oxide shielding sheet, (b) tungsten carbide shielding sheet, (c) pure tungsten shielding sheet



(a) Cross-sectional structure of tungsten oxide shielding sheet

(b) Cross-sectional structure of tungsten carbide shielding sheet

(c) Cross-sectional structure of pure tungsten shielding sheet

Fig. 3. Comparison of cross-sectional images of fabricated tungsten shielding sheets

The particle composition inside the shielding sheet realized through the same manufacturing process is shown in Fig. 3. The particle sizes were all similar, and pure tungsten showed relatively low voids, indicating excellent affinity with the polymer. In the particle distribution, tungsten carbide and pure tungsten appeared almost evenly, but tungsten oxide showed a slightly inferior shape. It can be explained that the particle itself is low in density and thus does not have the polymer material to be mixed properly.

Comparing the performance of the manufactured shielding sheet, pure tungsten showed the highest in the medical radiation field, followed by tungsten carbide and tungsten oxide. As shown in Fig. 4 and Table 1, it can be seen that tungsten oxide has the lowest shielding performance when compared with pure tungsten and tungsten carbide. In addition, it can be seen that tungsten carbide and tungsten oxide exhibit similar shielding performance. When compared with standard lead, it was found that pure tungsten showed the most similar shielding rate to lead. Based on 100 kVp, which is a high energy region, tungsten oxide exhibited a shielding rate of 86%, tungsten carbide 88%, pure tungsten 90%, and lead 92%.

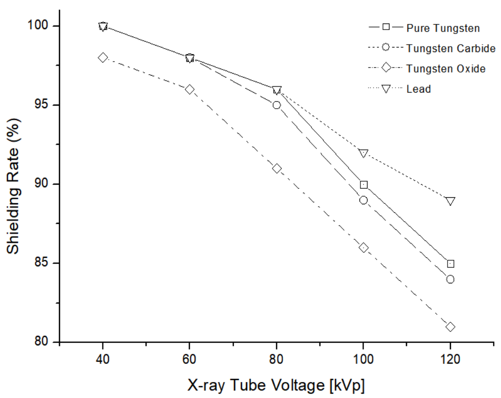


Fig. 4. Comparison of the shielding performance of the manufactured radiation shielding sheet

Table 1. Comparison of shielding rate between pure tungsten, tungsten carbide, tungsten oxide and lead according to kVp value

kVp	Shielding rate (%)			
	Pure Tungsten	Tungsten Carbide	Tungsten Oxide	Lead
40	100	100	98	100
60	98	98	96	98
80	96	94	91	96
100	90	88	86	92
120	88	83	81	89

4. Discussion

In medical institutions, tungsten oxide, bismuth oxide, and barium sulfate are mainly used as lead-free radiation shields. From a manufacturer's point of view, it is rare that pure tungsten is used in the medical radiation field in the actual manufacturing process in consideration of the conditions and economic feasibility of lightweight and eco-friendly materials. In the case of using a single material, since miscibility with the base material is the most important, in this experiment, the added additive was also prepared by administering the same amount. In this experiment, the same density should be realized in theory because the same amount was injected based on 0.3 mm, which is the same thickness as the suggested standard lead. Therefore, as observed in the cross-sectional analysis of the shielding sheet, the shielding performance had a close relationship with the particle composition. The fact that the more densely the particle composition is formed, the more linear attenuation occurs through interaction with the particles is used for the shielding performance. Therefore, density is an important factor in the performance of the shielding sheet[23]. As in this study, if the properties of the shielding material are well understood and the density is increased, it is thought that it will help to improve the shielding performance.

Most of the medical radiation shielding sheets manufactured using eco-friendly shielding materials use a mixture of tungsten with a polymer material instead of the conventional lead powder. In this study, the change of shielding performance according to the type of tungsten was presented. As a result, pure tungsten showed the best shielding rate. This is expected to be an important data that can be referenced in the future when tungsten is mixed with a polymer material.

Tungsten carbide has a density of 15.63 g/cm^3, almost no difference from pure tungsten, and as a result, the shielding performance is almost similar. In the case of tungsten oxide, the density was 10.8 g/cm^3, and the difference in density eventually resulted in the difference in shielding performance. Therefore, in the case of tungsten oxide, which is economical, it is considered that a process for increasing the affinity of polymer materials or minimizing air gaps is required.

In this experiment, there is a limit to research on continuity by manufacturing an experimental shielding sheet by compression molding, and the mass production process that can be used in medical institutions is a calendar process, so it is necessary to study the reproducibility of it. It is thought that temperature, time, and material mixing conditions will have the most important influence, and it will also contribute to improving the shielding performance of currently used tungsten oxide. Through this study, it is considered that it is necessary to study the manufacturing process that enables the economically most suitable tungsten oxide to exhibit the same shielding performance as pure tungsten or tungsten carbide.

5. Conclusions

By analyzing the characteristics of tungsten, which is most preferred as an eco-friendly shielding material, the same process was applied to three types of tungsten to produce a 0.3 mm medical radiation shielding sheet. Among the tungsten oxide, tungsten carbide, and pure tungsten shielding sheets, pure tungsten had the best shielding performance, and tungsten oxide showed the lowest. In the particle distribution of the polymer material in the shielding sheet, pure tungsten and tungsten carbide were well presented as dense structures.

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