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AN X-RAY FLUORESCENCE SPECTROMETER AND ITS APPLICATIONS IN MATERIALS STUDIES

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An X-ray fluorescence spectrometer based on a Co$^{57}$ γ-ray source has been developed for verification of the atomic percentages of iron atoms implanted in titanium fatigue targets. The iron ions were implanted in a 100 mm$^2$ area centered at the middle of the titanium targets to provide a 126 nm deep uniform profile containing 1, 5, and 8 a/o iron atoms. The implantation regions of the targets were bombarded with collimated Co$^{57}$ γ-rays and the elemental characteristic X-rays detected with a 30 mm$^2$, 3 mm deep Si(Li) detector. The total system resolution (detector + electronics) was < 250 eV. Measured relative intensities of Fe($k_a + k_b$) and Ti($k_a + k_b$) X-rays from Fe-Ti targets have been compared with the values computed using fluorescent yield data reported in the literature. The computed and the measured values of $R = \frac{Fe(k_a + k_b)}{Ti(k_a + k_b)}$ at the three iron concentrations are in agreement, within experimental errors, as seen below: $R(1\ a/o) = 2.78 \times 10^{-4}$ ($3 \times 10^{-4}$), $R(5\ a/o) = 1.38 \times 10^{-3}$ ($1.5 \times 10^{-3}$), $R(8\ a/o) = 2.22 \times 10^{-3}$ ($2.6 \times 10^{-3}$). The experimental values, given in parentheses, have an estimated error of $\pm 25\%$. 

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INTRODUCTION

Current interest in hypersonic vehicles has aroused a great deal of interest in the fatigue damage characteristics of titanium metal and its alloys. Recently, a study of fatigue damage mechanisms in titanium metal using Fe$^{57}$ Mossbauer spectrometry$^{1,2}$ has been initiated. High purity (99.9%) iron ions were implanted in the high stress zone of the titanium fatigue targets. It was anticipated that the fatigue induced atomic changes in the region of iron implantation would affect Mossbauer parameters of iron atoms.$^{1,2}$

A measurement of such changes could then be used to infer the changes in the iron atomic environments. Before the Mossbauer measurements of the iron implanted titanium targets could be started, it was felt desirable to confirm the iron atom concentration in the titanium substrate. An X-ray fluorescence technique$^{3}$ was considered to be the most appropriate nondestructive technique for this purpose. Since a 25 millicuries Co$^{57}$ Mossbauer source was already available, it was decided to develop an X-ray fluorescence system (XRF system) based on the Co$^{57}$ γ-rays as the exciter radiation. The XRF system, its performance and the results on ion-implanted titanium targets are described in the following pages.

X-RAY FLUORESCENCE SYSTEM

The XRF system consists of three major components: An exciter radioactive source, target holder, and X-radiation detection system. Figure 1 shows a schematic diagram of the system. A well-collimated beam of the Co$^{57}$ γ-rays is

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*This conclusion was dictated by the fact that the FeTi targets should not be modified in any way, either by heating under charged particle bombardment or by impurity contamination if the targets are placed in a vacuum.
allowed to fall on the (Fe-Ti) target. The target is positioned so that the exciter beam covers the entire implantation zone. The target atoms get excited under γ-bombardment and then de-excite by emitting their characteristic radiations. These characteristic X-rays are detected with a 30 mm$^2$, 3-mm-thick Si(Li) detector with an 8.5-μm-thick Be window. The Si(Li) detector output, after amplification, is analyzed using a 400-channel pulse height analyzer. Figures 2 and 3 show typical X-ray spectrum from Ti and Fe targets. The total system resolution (FWHM) is calculated to be 250 eV. The Si(Li) detector resolution has been quoted at 185 eV (5.9 keV/1000 cps) by the manufacturer.

FE-TI TARGET PREPARATION

The Ti targets were fabricated in the form shown in figure 4. This target geometry was selected because of the availability of extensive fatigue damage data in targets of this configuration. The Fe$^+$ ions were implanted in a 100 mm$^2$ circle centered at the elox cut in the middle of the titanium target. The ion implantation accelerator available could operate reliably only in the range 10-300 keV. It was therefore decided to implant Fe atoms in Ti uniformly up to a thickness of 126 nm, which is the projected range of 275 keV Fe$^+$ ions in Ti. Table I lists the various Fe$^+$ ion energies and the corresponding implantation doses (ions/cm$^2$) to provide flat 1, 5, and 8 atomic percent of Fe atoms profiles in 126 nm deep layer in titanium.

*The Fe$^+$ ions were implanted by KSW Electronics Corporation, Burlington, MA, under contract to NASA Langley Research Center.
Table I.- Fe⁺ ion energies and implantation doses for a flat 126 nm deep profile

<table>
<thead>
<tr>
<th>No.</th>
<th>Fe⁺ Energy (keV)</th>
<th>Implantation Dose (ions/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 a/o</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
<td>3.48 x 10¹⁴</td>
</tr>
<tr>
<td>2</td>
<td>33</td>
<td>5.46 x 10¹⁴</td>
</tr>
<tr>
<td>3</td>
<td>63</td>
<td>9.10 x 10¹⁴</td>
</tr>
<tr>
<td>4</td>
<td>111</td>
<td>1.47 x 10¹⁵</td>
</tr>
<tr>
<td>5</td>
<td>180</td>
<td>1.72 x 10¹⁵</td>
</tr>
<tr>
<td>6</td>
<td>275</td>
<td>4.89 x 10¹⁵</td>
</tr>
</tbody>
</table>

CALCULATIONS OF RELATIVE CONCENTRATION OF FE AND TI ATOMS ON THE BASIS OF MEASURED FE AND TI CHARACTERISTIC X-RAY INTENSITIES

For the purpose of calculations, the 126 nm deep ion-implanted region will be divided into six parallel strips. Both the Ti and Fe k-X-rays will have to pass through all the overlying strips before escaping from the target. Since the Ti X-rays cannot escape the target if they have to penetrate through more than 126 μm of Ti, * the effective thickness of the Ti substrate

*This is easily seen from the following equation:

\[ I(126 \ \mu m) = I_o \ e^{-\mu(4.5 \ \text{keV}) \times 0.0126} \]

\[ = I_o (0.0017) \]
would be considered to be 126 μm, even though the nominal substrate thickness is 1500 μm. The effective Ti thickness would be subdivided into 30 parallel strips for the purpose of calculating attenuation suffered by Ti X-rays starting from various sublayers. Figure 5 shows the proposed calculational model detailed in Appendix 1.

For illustrative purposes, calculations will be made for the target having 8 percent Fe implanted in Ti. The relevant information about the X-rays of interest are listed below:

<table>
<thead>
<tr>
<th>X-Ray Energy</th>
<th>Absorption Coefficient (cm²/gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ti</td>
</tr>
<tr>
<td>4.51 keV (Ti-(k_\alpha))</td>
<td>111.4</td>
</tr>
<tr>
<td>4.93 keV (Ti-(k_\beta))</td>
<td>86.8</td>
</tr>
<tr>
<td>6.40 keV (Fe-(k_\alpha))</td>
<td>370.1</td>
</tr>
<tr>
<td>7.06 keV (Fe-(k_\beta))</td>
<td>285.7</td>
</tr>
</tbody>
</table>

For calculating attenuation through the implantation zone, it will be assumed that:

\[
\mu_p^{(\text{mixture})} = \frac{\mu_1}{\rho_1} w_1 + \frac{\mu_2}{\rho_2} w_2
\]  

(1)

where \(\mu_1,2\) and \(\rho_1,2\) are the attenuation coefficients (cm⁻¹) and the densities (gms/cc), respectively, and \(w_1\) and \(w_2\) are weight fractions of the constituents in the implantation zone. The following values of the attenuation coefficients are thus calculated for the implantation zone:
4.51 keV → 544.9 cm⁻¹; 4.93 keV → 424.6 cm⁻¹
6.40 keV → 1575.3 cm⁻¹; 7.06 keV → 1215.6 cm⁻¹

Using these values, it is calculated that 99.0 percent of the Fe(\(k_a\)) and 99.7 percent of the Ti(\(k_a\)) X-rays will pass through the implantation zone. Similar calculations show that 15.5 percent of all the Ti k-X-rays produced in the 126 μm "effective" Ti substrate will pass through it.

Extensive theoretical and experimental data compilations have been published on the γ-ray attenuation coefficients in various elements. This data has been used to calculate the efficiency for characteristic X-ray production in Ti and Fe targets under Co⁵⁷ radiation * bombarding. The review paper of Bambuk et al.²(d) has been used as the source for fluorescent yield data to compute the k-X-ray production in Ti and Fe elements. Using these sets of data, the following relative intensities of the Ti and Fe k-X-rays are estimated:

\[
\text{Fe}(k_a + k_b) \approx \text{const} \times (4.75 \times 10^{-3}) \tag{2}
\]

\[
\text{Ti}(k_a + k_b) \approx \text{const} \times (2.14) \tag{3}
\]

i.e.,

\[
\frac{I[\text{Fe}(k_a + k_b)]}{I[\text{Ti}(k_a + k_b)]} = R \approx 2.22 \times 10^{-3} \tag{4}
\]

*The Co⁵⁷ source was covered with a 178 μm aluminum absorber to remove Fe⁵⁷ (\(k_a + k_b\)) X-rays from the incident radiation. The remaining radiations (γ-rays of energies 14.4 keV, 122 keV, and 137 keV) are effective in producing characteristic X-rays in both Ti and Fe targets.
The measured value of $R$ for 8 percent Fe-Ti target was $2.6 \times 10^{-3}$ (+25%).

Table II lists the measured and calculated values of $R$ for the three targets assayed.

Table II.- Comparison between the measured and calculated value of $R$ for the three (Fe-Ti) targets

<table>
<thead>
<tr>
<th>No.</th>
<th>Fe - percentage</th>
<th>$R$ (calculated)</th>
<th>$R$ (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 a/o</td>
<td>$2.78 \times 10^{-4}$</td>
<td>$3.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>2</td>
<td>5 a/o</td>
<td>$1.38 \times 10^{-3}$</td>
<td>$1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>3</td>
<td>8 a/o</td>
<td>$2.22 \times 10^{-3}$</td>
<td>$2.6 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

The calculated and the measured values are in agreement, within the experimental errors.

RESULTS AND DISCUSSION

The XRF system described has been used to experimentally verify the iron content in the three Fe-Ti targets described earlier. Each Fe-Ti target was subjected to the Co$^{57}$ exciter radiation for a period up to 48 hours and the resultant Fe and Ti X-ray spectra were accumulated. A typical spectrum is shown in figure 6. From such spectra, the intensities of Fe($k_{\alpha} + k_{\beta}$) and Ti($k_{\alpha} + k_{\beta}$) X-rays were determined. The ratio of these intensities are related to the Fe atomic percentage in Ti as described earlier. Measured relative intensities of Fe($k_{\alpha} + k_{\beta}$) and Ti($k_{\alpha} + k_{\beta}$) X-rays from Fe-Ti targets have been compared with the values computed using fluorescence yield data.
reported in the literature. The computed and measured values of
\[ R = \frac{\text{Fe}(k^\alpha + k^\beta)}{\text{Ti}(k^\alpha + k^\beta)} \]
at the three iron concentrations are in agreement, within
experimental errors, as seen below: \( R(1\,\text{a/o}) = 2.78 \times 10^{-4}\) \((3 \times 10^{-4})\),
\( R(5\,\text{a/o}) = 1.38 \times 10^{-3}\) \((1.5 \times 10^{-3})\), \( R(8\,\text{a/o}) = 2.22 \times 10^{-3}\) \((2.6 \times 10^{-3})\).
The experimental values, given in parentheses, have an estimated error of
\( \pm 25\% \).

CONCLUDING REMARKS

An X-ray fluorescence spectrometer, based on Co\(^{57}\) \(\gamma\)-ray source, has been
developed. The system has been used to measure the atomic percentages of
iron implanted in titanium targets. Measured relative intensities of
Fe\((k^\alpha + k^\beta)\) and Ti\((k^\alpha + k^\beta)\) X-rays from Fe-Ti targets are in agreement,
within experimental errors, with the calculated values based on appropriate
interaction cross sections of Co\(^{57}\) gamma rays with Ti and Fe atoms.
REFERENCES


4. Jag J. Singh and W. T. Davis:
   (a) Proceedings of 20th International Instrumentation Symp.,
   (b) NASA TN D-7695 (1974).

       Vid Selskab, 33, (No. 14) 1963.

6. (a) G. W. Grodstein: NBS Circular # 583, 1957.
   (b) R. T. McGillies: NBS Circular # 583 (Supplement), 1959.
   (c) W. E. McMaster et al: UCRL - 50174 (Section IV), 1969.
APPENDIX 1

METHOD OF CALCULATING RELATIVE INTENSITIES
OF IRON AND TITANIUM K-X-RAYS

For the purpose of calculating relative iron and titanium k-X-ray intensities, the Fe-Ti targets have been assumed to be titanium slabs of thickness 126 μm with a top implantation layer of thickness 126 nm. The incident Co$^{57}$ radiation, after passing through a 178 μm thick aluminum foil has the following spectrum:

<table>
<thead>
<tr>
<th>Gamma Ray Energy</th>
<th>No. of Gamma Rays/100 Disintegrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>137 keV</td>
<td>11</td>
</tr>
<tr>
<td>122 keV</td>
<td>88</td>
</tr>
<tr>
<td>14.4 keV</td>
<td>7</td>
</tr>
</tbody>
</table>

For calculating the intensity of Ti K-X-rays, the 126 μm thick titanium slab has been subdivided into 30 layers, each 4200 nm thick. The incident radiation at the nth layer has been calculated as follows:

$$I_{n,Y_1} = I_{0,i} e^{-μ_i[0.00042(n-1)]}$$

(1)

where $I_{0,i}$ represents the intensity of the respective gamma ray in the incident spectrum, $μ_i$ (in units of cm$^{-1}$) equals total attenuation coefficient for the ith gamma component (14.4 keV, 122 keV, or 137 keV radiation). The number of target atoms excited in the nth layer, $N_n$ (excited), has been calculated as follows:
\[ N_n^{\text{(excited)}} = \sum N_t \sigma_i I_{n,Y_i} \]  

where  
\[ N_t = \text{number of target atoms/cm}^2 \]  
\[ \sigma_i = \text{photoelectric cross section of the } i\text{th radiation} \]  
\[ I_{n,Y_i} = \text{number of } i\text{th radiation photons per cm}^2 \]  

Only the photoelectric cross sections of the radiations arriving at the \text{nth} layer have been considered in calculating the Ti \( k\)-X-ray intensity in that layer. A fluorescence yield, \( \gamma_k = 0.219 \) has been assumed for titanium.\(^3(d)\)

The \text{nth} layer Ti \( k\)-X-rays have to pass through overlying titanium layers of thickness \((n - 1/2)4200 \text{ nm}\) to reach the detector. The contributions from the 30 layers are added for the three-component radiations of the incident field to obtain total theoretical Ti \( k\)-X-ray intensity.

For calculating the intensity of iron \( k\)-X-rays, the implantation zone has been divided into six sublayers of thickness 21 nm each. The respective intensities of the three components of the incident radiation arriving at any layer are calculated as before. As before, only the photoelectric cross sections of the radiations arriving at any layer have been considered in calculating the Fe \( k\)-X-ray intensity. A fluorescence yield, \( \gamma_k = 0.342 \) has been assumed for iron.\(^3(d)\) The Fe \( k\)-X-rays produced in the \text{nth} layer of the implantation zone have to pass through the overlying Fe-Ti mixture of thickness \((n - 1/2)21 \text{ nm}\) to reach the detector. Contributions from the six layers are added to obtain total theoretical Fe \( k\)-X-ray intensity.

From the calculated intensities of Fe \( k\)-X-rays and Ti \( k\)-X-rays, \( R \) values have been determined for each level of Fe implantation dose. These
$R$ values have been compared with the ratio of the total number of counts in $Ti(k_{\alpha} + k_{\beta})$ and $Fe(k_{\alpha} + k_{\beta})$ peaks for each target. It has been assumed that the detection efficiency of the Si(Li) detector for the titanium and iron X-rays is the same.
Fig. 1. Block Diagram of the Experimental Set-up for XRF System.
FIGURE 2. X-RAY FLUORESCENCE SPECTRUM FROM Ti TARGET.
FIGURE 3. X-RAY FLUORESCENCE SPECTRUM FROM Fe TARGET.
Fig. 4. Fe-Ti Fatigue Target Configuration - Not to Scale
FIGURE 5.- CALCULATIONAL SCHEME FOR ATTENUATION SUFFERED BY Fe AND Ti k-X-RAYS IN PASSING THROUGH THE OVERLYING MATERIAL.
FIGURE 6 X-RAY FLOURESCENCE FROM Fe-Ti (80/o Fe) TARGET.
A radioisotope excitation X-ray fluorescence system has been developed and applied to determine the atomic fraction of iron implanted in titanium targets.

We have developed an X-Ray Fluorescence (XRF) system based on a Co$^{57}$ γ-ray source. The system has been used to calculate the atomic percentages of iron implanted in titanium targets. Measured relative intensities of Fe ($k_{\alpha} + k_{\beta}$) and Ti ($k_{\alpha} + k_{\beta}$) X-rays from the Fe-Ti targets are in good agreement with the calculated values based on photoelectric cross sections of Ti and Fe for the Co$^{57}$ gamma rays.

**Key Words (Suggested by Author(s))**
- Radioactive Isotopes, Photoelectric Effect, X-Ray Fluorescence, Ion Implantation, Quantitative Analysis

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