Response Model for Kodak Biomax-MS Film to X Rays

Introduction

X-ray–sensitive film is used for a variety of imaging and spectroscopic diagnostics for high-temperature plasmas. New film becomes available as older films are phased out of production. Biomax-MS is a "T-grain" class of film that is proposed as a replacement for Kodak direct-exposure film (DEF). A model of its response to x rays is presented. Data from dimensional measurements of the film, x-ray transmission measurements, scanning electron microscope (SEM) micrograph images, and x-ray calibration are used to develop this sensitivity model of Biomax-MS film as a function of x-ray energy and angle of incidence. Relative response data provide a check of the applicability of this model to determine the x-ray flux from spectrum data. This detailed film characterization starts with simple mathematical models and extends them to T-grain–type film.

Kodak Biomax-MS film is manufactured as a double-emulsion film made with a T-grain silver halide. A schematic showing the physical layout of this film is shown in Fig. 107.15. An emulsion is coated onto both the top and bottom of a thick polyester base; the layers are assumed to be symmetric, i.e., the top emulsion layer is identical to the bottom emulsion layer. T-grain–type silver-halide grains have a large surface area but are very thin. They are best described as plates, not spheres. These plates are modeled as layers of grains suspended in a gelatin matrix. There is a protective coating of gelatin over the silver-halide gelatin structure. The bulk film parameters are the thickness of the polyester base, t_b; thickness of the emulsion layer, T; thickness of the overcoat, t_0; and volume fraction of silver-halide grains within the gelatin grain emulsion layer, V_f. Figure 107.16 shows an SEM picture of the structure of the Biomax-MS film. This is an image of a cleaved edge of the film showing the layers of thin silver-halide grains surrounded by gelatin.

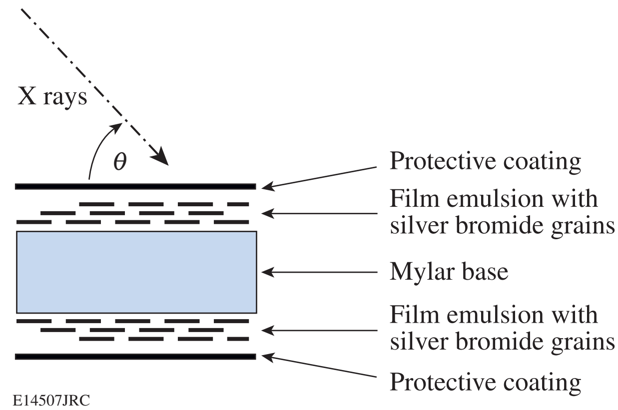

Figure 107.15
Schematic of the Biomax-MS film structure. An emulsion of grains of silver halide suspended in a gelatin is coated onto the top and bottom of a polyester base of thickness t_b.

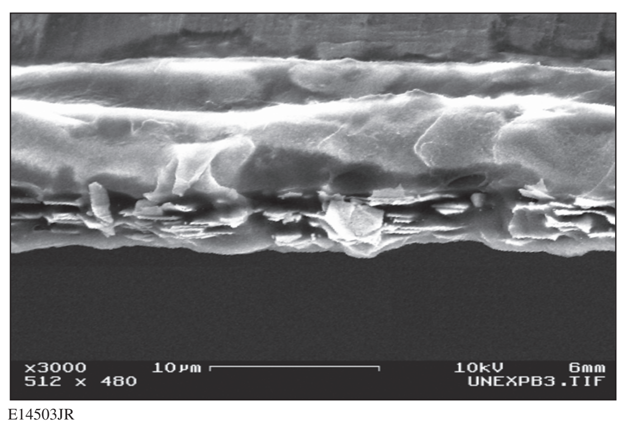

Figure 107.16
An SEM image of the edge of a cleaved edge of Biomax-MS film. The thin, layered structure of the emulsion is clearly visible within the gelatin medium.

Description of Model

X rays are incident on the film from the top at an angle of θ relative to the film surface, transmitted through the gelatin and base, and absorbed in the silver-halide grains in the top and bottom emulsion layers. The absorption of one x-ray photon is assumed to be sufficient to render that grain, and only that grain, developable. Once developed, the silver-halide grain becomes a silver structure that is opaque to light, allowing a measurement of the film's optical density. It is assumed here that the individual grain layers are independent and the total film transmission is equal to the product of each individual layer's transmission—the Nutting[1] model for optical density measurement. It has been shown to work to values of optical density near the film saturation. The silver-halide grains are modeled as being all silver bromide (AgBr) and the gelatin is modeled as $C_8H_{16}N_2O_5$. These are the same assumptions used to model the response of DEF film.[2]

The reader is referred to Henke *et al.*[2–4] and Brown *et al.*[5] for a detailed description of how film x-ray response is modeled. Only a brief discussion of the model and the differences required to model a T-grain film is presented in this article. Film response is defined as the relation of the recorded optical density (OD) to the incident x-ray flux (I). Reference 2 modeled the film response as $\alpha(E)\mathrm{OD} = f[\beta(E)I]$ with the dependence of the response to the x-ray energy contained in the $\alpha(E)$ and $\beta(E)$ terms. The x-ray response model of a Biomax-MS double emulsion film is

$$\alpha \mathrm{OD} = a \cdot \ln\left[\frac{1 + b\sin(\theta)\beta I}{1 + b\tau_e\sin(\theta)\beta I}\,\frac{1 + b\tau_b\tau_e\sin(\theta)\beta I}{1 + b\tau_e\tau_b\tau_e\sin(\theta)\beta I}\right] \tag{1}$$

with

$$\alpha = \left[\mu'/\sin(\theta)\right], \tag{2a}$$

$$\beta = e^{-\left[\mu_0 t_0/\sin(\theta)\right]}\left\{1 - e^{-\left[\mu_1 d/\sin(\theta)\right]}\right\}, \tag{2b}$$

$$\tau_e = e^{-\left[\mu' T/\sin(\theta)\right]}, \tag{2c}$$

$$\tau_b = e^{-\left[\mu_b t_b/\sin(\theta)\right]}, \tag{2d}$$

and

$$\mu' = \mu_0 - \frac{1}{d}\ln\left\{1 - V_f\left[1 - e^{-(\mu_1 - \mu_0)d}\right]\right\}. \tag{2e}$$

Variables in Eqs. (1) and (2) with their units are defined in Table 107.II.

Table 107.II: List of variables used in modeling x-ray response of Biomax-MS film.

	Parameter	Units
θ	Angle of incidence	
μ_1	X-ray mass absorption of grain (AgBr)	μm^{-1}
μ_b	X-ray mass absorption of base (Mylar)	μm^{-1}
μ_0	X-ray mass absorption of gelatin matrix	μm^{-1}
d	Silver-halide grain thickness	μm
t_b	Base thickness	μm
T	Emulsion thickness	μm
V_f	Volume of fraction of grains	
t_0	Protective layer thickness	μm
a	Optical density constant	μm^{-1}
b	Flux constant	μm^2

Equations (1) and (2a)–(2e) form a heuristic model for the physical response of Biomax-MS film to x rays. Transmission of x rays through the emulsion layer (τ_e) and film base (τ_b) is given by Eqs. (2c) and (2d). Equation (2e) is the linear x-ray absorption coefficient (μ') for the emulsion layer. The emulsion layer is modeled as a heterogeneous mixture of AgBr and gelatin. The transmission of x rays through the protective top coat and subsequent absorption in a ArBr grain (β) are given by Eq. (2b). Reference 3 describes a methodology to determine the OD from the number of exposed grains (M) that uses the reciprocal of the exposed grain scale length, $(1/M) \times (dM/dx)$. This reciprocal scale length is given by Eq. (2a). The film response in OD calculated by using Eq. (1) has two terms in the argument of the logarithm. These terms come from the "thin-emulsion model"[2,3] applied to the top and bottom emulsion layers, respectively.

The primary difference in this model compared to the Henke model for DEF film is the added $\sin(\theta)$ term in Eq. (2b) for the absorption of a photon in a silver-halide grain and $\sin(\theta)$ terms multiplying the x-ray flux in both the numerator and denominator of Eq. (1). These terms reflect the fact that the grains are thin plates rather than spherical: a is related to the maximum optical depth OD_s of the film and has the same dimensions as $\alpha(\mathrm{cm}^{-1})$, and b is related to the developed silver structure area with dimensions of μm^2. Tabulated x-ray, mass absorptions,[6] and bulk mass densities are used to compute the linear x-ray absorption coefficients [$\mu_{\mathrm{linear}}\ (\mathrm{cm}^{-1}) = \mu_{\mathrm{tabulated}}\ (\mathrm{cm}^2/\mathrm{g}) \times \rho_{\mathrm{bulk}}\ (\mathrm{g/cm}^3)$]. In this model, $\rho_{\mathrm{polyester}} = 1.4\ \mathrm{g/cm}^3$, $\rho_{\mathrm{gelatin}} = 1.4\ \mathrm{g/cm}^3$, and $\rho_{\mathrm{AgBr}} = 6.47\ \mathrm{g/cm}^3$.

Determination of Model Parameters

A digital micrometer was used to measure the total thickness of the polyester base, undeveloped film, and the developed film. The micrometer faces were flat and not spherical to minimize the compression of a soft layer by the force of measurement. The polyester base was measured to be 179±1 μm, the thickness of the undeveloped film was 188±1 μm, and the thickness of the developed fully exposed film was 187±1 μm. There is little difference between the thickness of the undeveloped film and the exposed developed film, indicating that there is only a small change in grain volume when silver halide is changed to silver. The thicknesses of the two emulsion layers and their overcoats are 9±2 μm. The emulsion layer thickness T is calculated from the total emulsion thickness once the overcoat thickness t_0 is determined.

The SEM image shown in Fig. 107.16 was used to determine the silver-halide grain thickness. This image was rotated so that the grains were horizontal, and lineouts of the spatial profile across the grain images were used. Silver-halide grain thickness is defined to be the full width at half maximum of the spatial profile for each grain.

X-ray transmission data for Mn Kα, Mn Kβ, Cu Kα, and Cu Kβ were acquired to determine the volume fraction of silver-halide grains in the emulsion layer. First, the digital micrometer data were checked by calculating the polyester base thickness needed to match the measured x-ray transmission. The base thickness calculated from these data is 180±5 μm. This is in good agreement with the micrometer measurement. X-ray transmission through the emulsion layer can be shown to be proportional to the product of the volume fraction times the emulsion thickness $V_f \times T$, 1.3±0.4 μm. V_f is then calculated once T is known.

The remaining parameters a, b, and t_0 are determined by fitting the model for optical density to the x-ray exposure data and minimizing χ^2. The absorption of higher-energy x rays (Ti Kα, Fe Kα, and Cu Kα) is low in the overcoat and, thus, insensitive to t_0. The model formula was used to determine the constants a and b from the measured sensitivity by doing a nonlinear minimization of the calculated χ^2 of the high-energy x-ray data. A nonlinear minimum χ^2 fit for the low energy (Al Kα and Ag Lα) was then used to determine t_0 since the low-energy x rays are more affected by the overcoat. The developing process used and the densitometer measurement of the film are described in a companion paper by Marshall *et al.*[7] Biomax-MS film parameters determined by the above methodology are listed in Table 107.III along with the corresponding values for DEF from Ref. 2.

This model was used to calculate the x-ray flux in photons/μm^2 to give an exposure in optical density of 0.5, 1.0, and 2.0 for Biomax-MS film as a function of x-ray energy from 1.0 to 10.0 keV. The Henke model was used to calculate the same information for DEF film. In general, the Biomax-MS film is less sensitive, i.e., requires more photons/μm^2 for the same optical density than DEF film. Biomax-MS sensitivity is

Table 107.III: List of values, errors, and method of determination for Biomax-MS film parameters. DEF values for comparison are taken from Ref. 2.

	Biomax-MS	DEF
Micrometer data		
Base thickness (t_b)	179±1 μm	185 μm
Emulsion thickness (T)	4±1 μm	13 μm
SEM data		
Grain thickness (d)	0.12±0.03 μm	1.6 μm
X-ray transmission data		
Volume fraction of grains (V_f)	0.34±0.08	0.4
Calibration data		
Protective layer thickness (t_0)	0.4±0.1 μm	1 μm
Optical density constant (a)	0.58±0.01 μm^{-1}	0.68 μm^{-1}
Flux constant (b)	12.4±0.3 μm^2	1.69 μm^2

equal to or somewhat greater than that of DEF only for x-ray energies <2 keV and for optical densities <2.0. This confirms measurements previously reported by Chandler *et al.*[8] on the comparison of Biomax-MS to DEF sensitivity.

Marshall *et al.*[7] reported in a companion paper on the comparison of the response of Biomax-MS to that of DEF for spectrally dispersed data recorded with a transmission grating in a KB microscope. These data were converted to x-ray intensity versus energy with the model described in this article and the Henke model for DEF. The results are plotted in Fig. 107.17, where the maximum optical density recorded on DEF was ~1.8 and the maximum for Biomax-MS ~1.0. The calculated x-ray flux from the DEF exposure agrees very well with the x-ray flux calculated from the Biomax-MS exposure. The incident angle of the x rays onto the film for these data was ~90°.

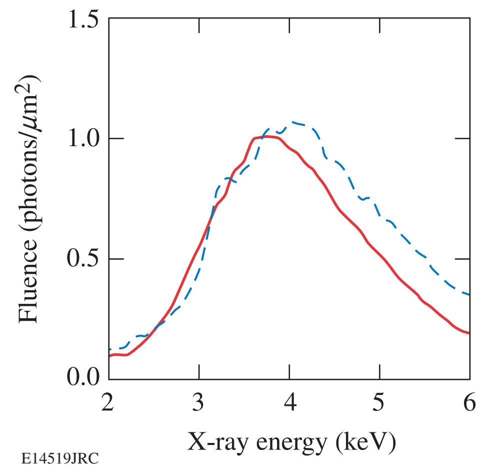

Figure 107.17
Comparison of the x-ray fluence calculated from KB microscope–dispersed spectra. The calculated DEF x-ray fluence is plotted as a solid line, and the calculated Biomax-MS x-ray fluence is plotted as a dashed line.

Relative sensitivity data were also recorded for x rays in a Rowland circle crystal spectrometer. A flat crystal was used to record the x-ray spectrum from an OMEGA shot from 2 to 6 keV. The x rays were recorded with an incident angle of ~50°. Again, the models for DEF and Biomax-MS were used to convert the film optical density to x-ray flux. The results shown in Fig. 107.18 indicate that calculated x-ray fluxes agree to 20% for the DEF and Biomax-MS data.

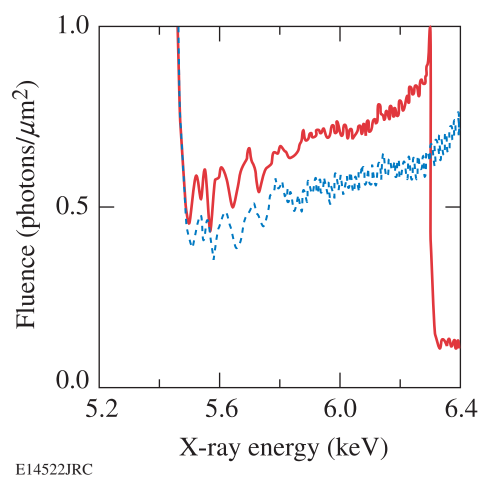

Figure 107.18
X-ray fluence calculated for a Rowland circle spectrometer for both DEF and Biomax-MS films. The solid curve is the x-ray fluence versus energy calculated from DEF film, and the dashed curve is calculated from the Biomax-MS film.

Conclusions

The x-ray flux calculated from DEF using the model of Henke *et al.*[2] and from Biomax-MS using this model are generally in agreement. The emulsion layer is thinner for Biomax-MS than it is for DEF; therefore, the absorption of higher-energy x rays is less in the Biomax-MS film than in the DEF film. This is reflected in the significantly reduced sensitivity for Biomax-MS when compared to DEF at x-ray energies >4 keV. The grain geometries are also very different: the DEF grains are typically spherical, while the Biomax-MS grains are flat plates with a large surface area and small thickness.

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REFERENCES

1. J. C. Dainty and R. Shaw, *Image Science: Principles, Analysis and Evaluation of Photographic-Type Imaging Processes* (Academic Press, London, 1974), p. 39.
2. B. L. Henke *et al.*, J. Opt. Soc. Am. B **3**, 1540 (1986).
3. B. L. Henke *et al.*, J. Opt. Soc. Am. B **1**, 818 (1984).
4. B. L. Henke *et al.*, J. Opt. Soc. Am. B **1**, 828 (1984).
5. D. B. Brown, J. W. Criss, and L. S. Birks, J. Appl. Phys. **47**, 3722 (1976).
6. B. L. Henke, E. M. Gullikson, and J. C. Davis, At. Data Nucl. Data Tables **54**, 181 (1993).
7. F. J. Marshall, J. P. Knauer, D. Anderson, and B. A. Schmitt, presented at the 16th Annual Conference on High-Temperature Plasma Diagnostics, Williamsburg, VA, 7–11 May 2006 (Paper WP40).
8. K. M. Chandler, S. A. Pikuz, T. A. Shelkovenko, M. D. Mitchell, D. A. Hammer, and J. P. Knauer, Rev. Sci. Instrum. **76**, 113111 (2005).