STUDY OF WINDOW FOIL THICKNESS FOR ACCELERATOR SCANNER

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Abstract

An industrial electron accelerator requires the electron beam to be scanned and transported from accelerator on to the product using a thin metal foil. The electron transmission efficiency, mechanical strength to sustain the atmospheric pressure and formability to make defect free thin foil are the main concerns in the selection of the foil. The paper discusses suitability of thin foil of various materials that qualify the criteria of electron transmission efficiency against the membrane stress produced in its curved shape. Based on this study, the required thickness has been calculated with reference to the material property.

INTRODUCTION

A thin metal foil acts as a barrier between the vacuum envelop and the atmosphere of the scanner of an industrial accelerator. It aims to maximise transmission of electron beam without attenuation on to the product. The foil thickness is to be optimized to satisfy the contradictory requirements of mechanical strength to sustain the differential pressure and those of maximising the electron transmission through the foil.

A theoretical analysis is done to estimate the foil thickness and the average transmission power loss. The effect of initial curvature is also studied.

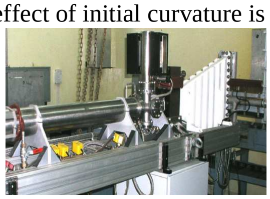

Fig-1.Typical accelerator

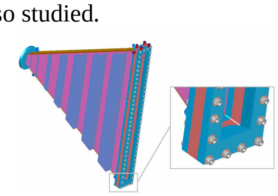

Fig-2. Typical scanner

THEORY

A thin metal foil is considered as a membrane clamped all along its edges (Fig-1).

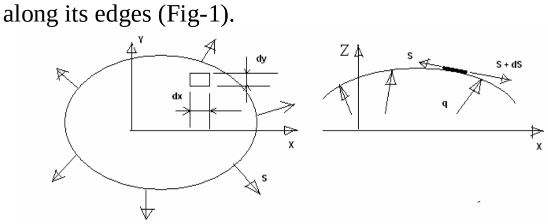

Fig-1.Typical stretched membrane

The foil is subjected to uniform tension S (N/m) all along the edges and uniform pressure in transverse direction q (N/m^2).

The governing equation of the stretched foil is defined following Prandtle's formulation as;

$$\nabla^2 w = -\frac{q}{s}\nabla \quad \text{--------------------(1a)}$$

The ratio of larger to smaller side for a typical scanner foil is greater than 10. So, the foil can be represented as;

$$\frac{d^2 w}{d^2 x} = -\frac{q}{s} \quad \text{--------------------------------(1b)}$$

Solving equation(1b) using clamped boundary condition and the transverse pressure loading; expressions for deflection (w) and the maximum deflection (w_m) are:

$$w = -\frac{q}{s}\frac{x^2}{2} + \frac{qb^2}{8S} \quad \text{and} \quad w_m = \frac{qb^2}{8S} \quad \text{-----(2)}$$

The loaded membrane undergoes large deflection and is assumed to take cylindrical shape. Therefore, state of the loading is expressed with constitutive equation considering the geometrical non linearity (GNL) and stress stiffening as follow;

$$S - S_0 = EAE_G \quad \text{-------------------------(3)}$$

Where, E = Modulus of elasticity
A =foil cross section
S_0= Initial stretching /length
S = Final stretching/length
E_G= $(L^2-L_0^2)/2L_0^2$

If the load increases to the value of limit load (σ_{ys}), then a slight increase in load above the limit load may cause dynamic movement of the foil followed by restoration of static equilibrium attaining a large deflection in transverse direction (z-direction).

ESTIMATION FOR THE OPTIMAL THICKNESS OF THE FOIL

A foil member of length b/2 and unit width in y-direction is taken for the analysis (Fig-3and 4). One bar pressure differential is applied in transverse direction that deflects the foil member to w_m from its initial height *h* (Fig-4).

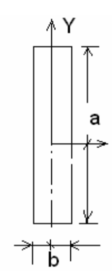

Fig-3.The foil

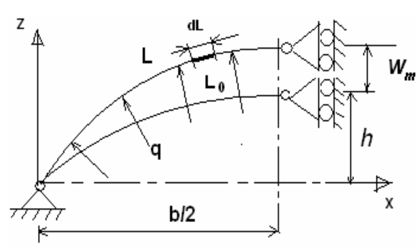

Fig-4.The thin foil element

Considering a small element dL making a small angle α at the centre;

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$$2\int_0^{\alpha} S d\alpha = \int_0^{L} \frac{q}{L_0} dL$$

So, the final stretching load can be expressed as ;

$$S = \frac{1}{2} * \frac{qL^2}{h + w_m} * \frac{1}{L_0} \text{ ---------(4)}$$

The expression for S shows that the behaviour is in large deformation domain.

The state of the loading of the foil member can be expressed by equation (3) following the constitutive equation for GNL. As per membrane theory maximum deflection (w_m) and stretching load (S) for the pressurised foil can be expressed by equation (2).

The initial stretching load (S_0) due to curvature is calculated by considering that the flat foil member is subjected to a in-plane load that deflects it in transverse direction. Therefore, as per the Rankine formulation we can express the initial stretching load as;

Where,

$$S_0 = \frac{-\sigma_c}{1 + a\frac{l_e^2}{\kappa^2}} \text{ --(5)} \qquad a = \frac{\sigma_c}{\pi^2 E} \quad \& \quad \kappa = \sqrt{I/A}$$

le = Equivalent length I = Second moment of inertia

A = Cross section E = Modulus of elasticity

σ_c = Compressive stress

If the foil stretched up to the limit load (σ_{ys}), then,

$$\sigma_{ys} = \frac{E}{2}\left(\frac{L^2 - L_0^2}{L_0^2}\right) \text{ or } L = \sqrt{\left(\frac{2\sigma_c}{E} + 1\right)} \text{ ---(6)}$$

The initial length (L_0) and the final length (L) of the half segment of unit foil member can be calculated as;

$$L_0 = \frac{(\frac{b}{2})^2 + h^2}{2h} \sin^{-1}\left(\frac{2(\frac{b}{2})h}{(\frac{b}{2})^2 + h^2}\right) \text{ ------------(7)}$$

$$L = \frac{(\frac{b}{2})^2 + (h + w_m)^2}{2(h + w_m)} \sin^{-1}\left(\frac{2(\frac{b}{2})(h + w_m)}{(\frac{b}{2})^2 + (h + w_m)^2}\right) \text{ -------(8)}$$

The foil is assembled with initial curvature and therefore the value of the initial maximum height *h* is known.

Therefore, equating the equations (6) and (8) the value of maximum foil deflection (w_m) is obtained.

The final stretching (S) can be obtained as equation (2).

Since the foil member is expected to be stretched just below the yield point, therefore, the limiting stress condition can be applied;

$$\frac{S}{t} - \frac{S_0}{t} = \sigma_c \text{ --------------------(9a)}$$

$$\frac{qb^2}{8w_m} - \frac{-\sigma_c}{1 + \frac{\sigma_c}{\pi^2 E} * \frac{(2b)^2}{1} * \frac{12}{t^2}} = \sigma_c \text{ ----(9b)}$$

The optimum thickness (t) of the rectangular foil is finally obtained from equation (9b).

The calculated stresses are conservative and can be used for the case where all four edges of the foil are clamped.

TRANSMISSION POWER LOSS

If high energy electron beam impinges on the thin metal foil target, electrons loose energy mainly by collision and radiation. The energy absorbed per unit thickness of the foil can be calculated from electron mass stopping power [3]. The expression for loss of average peak power for the estimated thickness (t) is as follow;

$$P_{avg} = \frac{dE}{dx} * 10^6 * i_p * T * PRR \text{ ------(10)}$$

Where, $\frac{dE}{dx}\left(\frac{MeV}{cm}\right)$ value is taken from Berger and Seltzer [3]

i_p = peak beam current, T = pulse length and

P = density of foil, PRR = Pulse repetition rate

The percentage loss of average power (P_{avg}) due to stopping by target foil material and thickness is estimated for the candidate material for the 10 MeV,10 kW electron beam having parameters of pulse length 10 µs, pulse current 330 mA and PRR of 300 Hz.

RESULTS

The optimal thickness for foil for the scanner window is estimated for several potential materials (Table-1). Maximum height (*h*) due to initial curvature of the foil member is taken as 0.5 mm. The table also lists the transmission power loss for the 10 MeV beam that impinges on the foil.

Table-1: Estimated thickness and average power loss

Material	Annealed/ cold worked	E (Gpa)	σ_{ys} (MPa)	t (mm)	P_{avg}
Titanium	A	120	250	0.036	0.32%
HAVAR	A	204	483	0.041	0.69%
SS316L	A	190	172	0.022	0.34%
SS316L	CW	190	690	0.015	0.23%

The behaviour of thin metal foil is established analytically and the optimal thicknesses for different candidate materials are estimated. The initial curvature is found to have an effect on final configuration of the thin metal foil subjected to transverse differential pressure.

The percentage average power loss (P_{avg}) for these materials with their estimated thicknesses are estimated.

REFERENCES

[1] Mohamad Ameen,' Computational elasticity', pp 179-186.

[2] Johnney Hassen et. al, 'A technique for temperature and ultimate load calculation of thin target'.

[3] Berger & Sletzer, 'Table of energy losses and ranges of electrons'pp 45-125