Thermo-mechanical Analysis of the Hibachi Foil for the Electra Laser System

A. Aoyama[1], J. Blanchard[2], J. Sethian[3], N. Ghoniem[1], and S. Sharafat[1]

[1]University of California Los Angeles, Los Angeles, CA

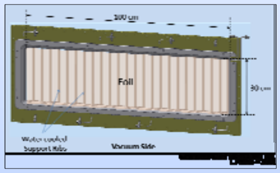
[2]University of Wisconsin, Madison, WI [3]Naval Research Laboratory, Washington D.C.

Introduction

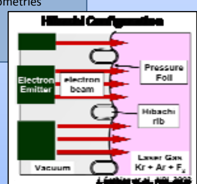
In support of the High Average Power Laser (HAPL) project the Electra Laser, a KrF Gas Laser system is being developed at NRL.

- Laser uses high voltage (500-800 keV), high current (100-500 kA), short pulse (100-600 ns) electron beam
- Electron beam pumps 0.14 MPa pressurized KrF gas cell
- Gas cell is separated from the vacuum region by a 25 µm-thick stainless steel (SUS304) foil, the Hibachi Foil
- Foil operates between 180 °C and 450 °C
- Typical foil dimensions are about 0.3 m x 1.0 m
- Laser pulses at up to 5 Hz, subjecting foil to repetitive thermal and mechanical stresses
- Foil experimentally lasts 1,000-20,000 shots before failure
- Various design modifications are being considered to improve foil performance
- In this study we report on the comparative thermo-mechanical analysis between different foil geometries
- It is demonstrated that the scalloped design reduces stresses to within yield limits of the SUS304 material

Hibachi Foil Geometry



Foil Characteristics:
- Stainless steel 304
- Temper: ANN
- Finish: 4F
- Thickness: 0.001 in (25 µm)
- Foil is pinhole free, and appears to have uniform thickness within 2%

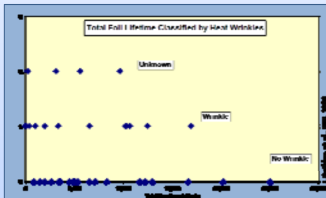


Temperatures:
- T_{foil} ≈ 180˚C - 450˚C
- Δt_{foil} ≈ 30˚C (swing/shot)

Laser Gas Pressure:
- P ≈ 20 psi (0.138 Mpa)

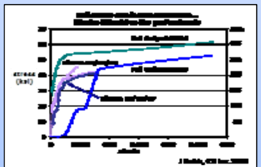
Times:
- f = 5 Hz
- Δ ≈ 140 ns (heating)
- Δ ≈ 10 µs (mechanical)

Global Performance Statistics

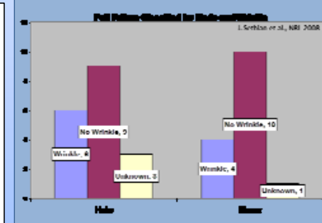


For runs: 5/13/2004 to 1/16/2008

- 447,963 shots
- 63 different foils
- 33 foil failures
- 18 failures due to holes
- 15 failures due to "blows"
- Max: ~25,000 shots (no wrinkles)

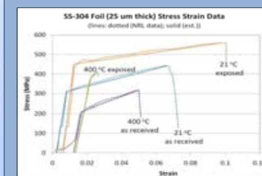


In-situ stress-strain measurements show more consistency than professional data



Mechanical Properties

- Young's Modulus (E) and Tangent Modulus (E_{tan}) estimated based on NRL data.
- Shell elements used for elastic and plastic analysis.



Test Temp. & Condition	E (GPa)	E_{tan} (GPa)	Yield (MPa) NRL Data
21 °C as received	39.16	2.26	310
21 °C exposed	36.82	1.27	434
400 °C as received	12.59	3.29	209
400 °C exposed	17.22	8.41	365

Thermo-Structural Analysis

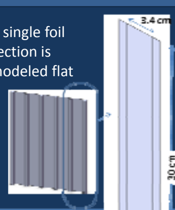
FEM analysis is performed on a variety of geometrical models and analysis types using ANSYS Multiphysics and COSMOSWorks.

Four Models:
- (1) Flat Foil
- (2) Curved Foil
- (3) Flat Foil & Curved Support
- (4) Scalloped Foil

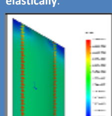
Analysis
- Shell Elements
- Pressure
- Thermal
- Pressure +Thermal
- Linear/Non-linear

Model 1: Flat Foil

A single foil section is modeled flat

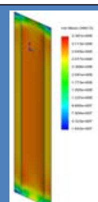


Pressure Only:
With all four outer edges held fixed, and pressure applied, model deforms **elastically**.



Strain

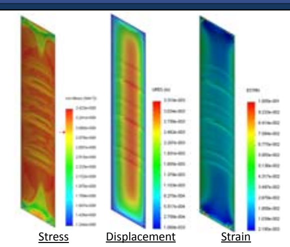
5 Cycles at 400 °C:
Stress ~ 340 MPa
Strain ~ 3.9 %
(max along rib edges)



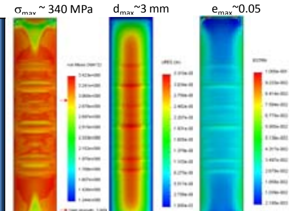
Stress

Pressure and Temperature Loading Applied:

Addition of thermal loading creates ripple effects running parallel to width of foil.



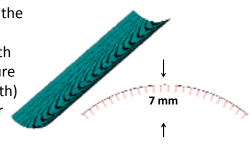
Stress σ_{max} ~ 340 MPa | Displacement d_{max}~3 mm | Strain e_{max}~0.05



Model 2: Curved Foil

Geometry:

To further examine the high strains along edges, a surface with pre-loading curvature (only along the width) was modeled under the same loading conditions.



Analysis Modes Performed:
- A. Pressure Loading Only
- B. Pressure And Temperature
- C. Static Buckling
- D. Non-Linear Buckling

A. Pressure Loading Only

With all four edges fixed, and pressure applied, the model deforms **elastically**.

B. Pressure and Temperature Loading

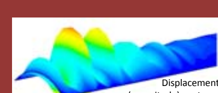
In this case, the "wrinkle" caused by thermal expansion is **very** localized.

Is the foil buckling?

C. Static Buckling Analysis

An conservative eigenvalue buckling analysis was performed to determine an approximate first buckling mode.

From this preliminary analysis, it appears that under temperature loading, when the foil buckles, the largest deflections are near the ends.



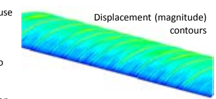
D. Non-Linear Buckling Analysis

A more conservative approach is to use a nonlinear buckling analysis.

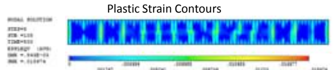
In this case, the temperature load is increased until the solution begins to diverge.

Then, an ANSYS nonlinear stabilization option adds an artificial damper to maintain a stable state.

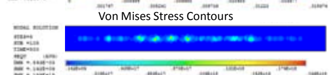
The damping coefficients are tracked and are used to make corrections to the results.



Plastic Strain Contours



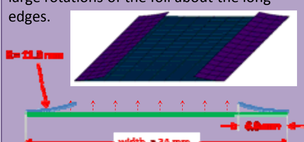
Von Mises Stress Contours

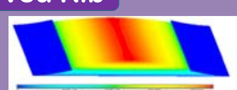


Model 3: Flat Foil + Curved Rib

Geometry:
This analysis examined the effects of curving the supports that hold the foil in place.

This is done to attempt to alleviate the very large rotations of the foil about the long edges.





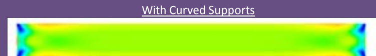
It is immediately apparent that the shape of these rigid supports *ease* the transition to the foil's equilibrium state.

Compared to the original flat model (Case 1) with a similar mesh density, we see a significant decrease in plastic strain.

Original Flat Foil

Max Plastic Strain: **0.039**

With Curved Supports



Max Plastic Strain: **0.016**

Model 4: Scalloped

Original Geometry:

This analysis examined the effects of **curving the supports** and **curving the foil.**

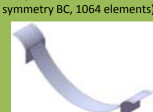
J Parish, CTI Inc. 2008

This is done to attempt to further alleviate the rotations of the foil about the long edges.

Details of the Scallops

J Parish, CTI Inc. 2008

FEM Model:
This non-linear analysis assumes the foil can slide on the curved rib (tough analysis small section is modeled with symmetry BC, 1064 elements).

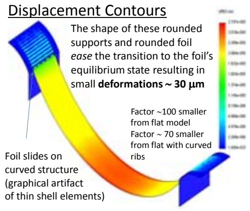


Effects of end foil end geometry is absent, which plays an important role in the stress state

At max. pressure: 26.6 psi

Displacement Contours

The shape of these rounded supports and rounded foil *ease* the transition to the foil's equilibrium state resulting in small **deformations ~ 30 µm**



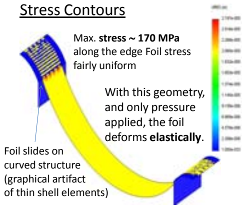
Factor ~100 smaller from flat model
Factor ~ 70 smaller from flat with curved ribs

Foil slides on curved structure (graphical artifact of thin shell elements)

Stress Contours

Max. **stress ~ 170 MPa** along the edge Foil stress fairly uniform

With this geometry, and only pressure applied, the foil deforms **elastically**.

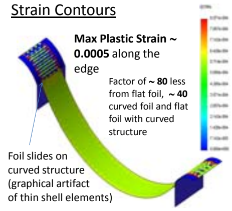


Foil slides on curved structure (graphical artifact of thin shell elements)

Strain Contours

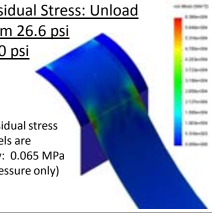
Max Plastic Strain ~ 0.0005 along the edge

Factor of **~ 80** less from flat foil, **~ 40** curved foil and flat foil with curved structure



Foil slides on curved structure (graphical artifact of thin shell elements)

Residual Stress: Unload from 26.6 psi to 0 psi



Residual stress levels are low: 0.065 MPa (pressure only)

Summary

Four Models were investigated:

- (1) Flat foil
- (2) Curved foil
- (3) Flat foil & curved support
- (4) Scalloped foil

I. Pressure + Thermal loads of **(1)** shows wrinkle formation
II. Pressure + Thermal load of **(2)** inconclusive (pressure alone shows ½ strain of flat; wrinkles using non-linear buckling)
III. Pressure (only) of **(3)** shows ½ strain of flat
IV. Pressure (only) of **(4)** shows:
  i. Max. Displacement factor of 100 less than **(1)**
  ii. Max. Stress factor of 2 less than **(1)**
  iii. Max. Plastic strain ~100 X less than **(1)** and 40 X less than **(2)** and **(3)**

- Effects of thermal load and "end-geometry" for scalloped foil remains to be analyzed