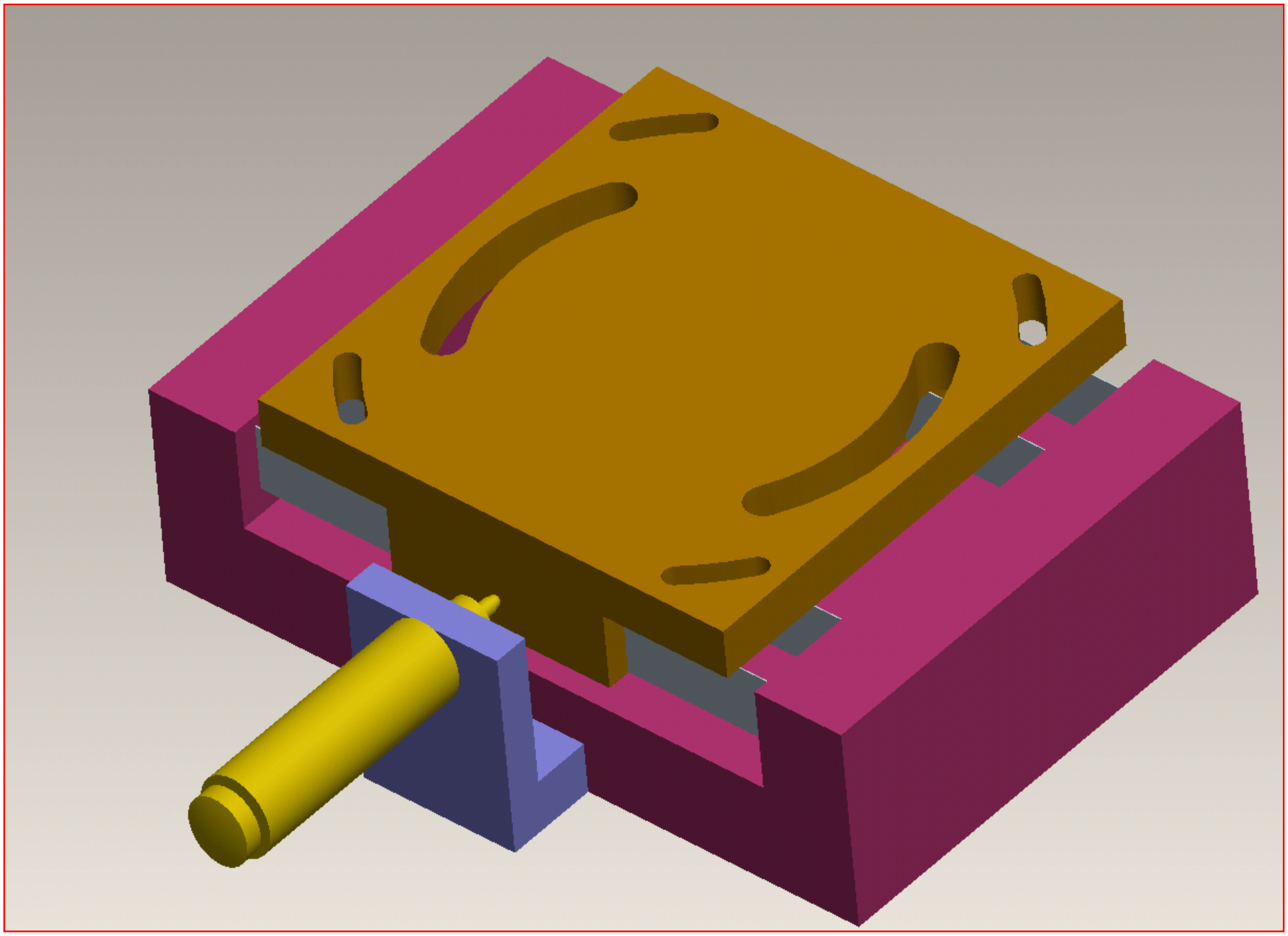
Profiler Translation Stage



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Fall 2004

Acknowledgements

Knowledge itself is a continuous process. At this moment of our substantial enhancement we would like to thank following people for their kind support and encouragement.

We would like to thank Dr. B. J. Furman for providing us with an opportunity to implement the concepts presented in the class in a practical way. Moreover, his guidance throughout the project preparation phase was very resourceful and valuable to us.

We would also like to thank Mr. Oscar Amster for his supportive presentation which helped us to understand the scope of the project. We thank him for discussing different aspects of our project design during the poster fair.

We express our sincere gratitude towards Mr. Patrick J. O'Hara (CEO and President-Ambios Technology, Inc.) to provide us the opportunity to work on a real world problem.

Last but not the least we would like to thank Ni Zhou, Christian Gomez, Orlando Hui, Shrikant Racherla, Deepika Popuri, Kiranmai Sathulur, our (ME 250) classmates for discussing different aspects of the project from time to time and thereby creating pleasant and enthusiastic environment to work on the same project.

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Problem Statement

The term project was focused on designing a translation stage for a profiler. The translation stage is the device that moves a semiconductor wafer underneath the stylus of the profiler, so that the vertical profile of the wafer surface can be measured along a straight-line path on the surface of the wafer. Apart from profiling wafer surface, profilers are often used to profile surface of different machine components.

1.1 Design Requirements and Constraints

We are given two types design requirements. One is functional requirements (FR's) and other is desirable requirements (DR's).

Functional Requirements are as follows:

1. The translation stage must be capable of forward and reverse linear (X-direction) translation
   - 1.1. X-Displacement range to be 10mm minimum
   - 1.2. X-displacement velocity to be 2mm/sec minimum
   - 1.3. Out of plane Z-motion to be less than 150 • over 1mm translation (in one direction only)
   - 1.4. Resolution of the travel to be less than one micron

Desirable requirements are as follows:

Translation stage to be capable of moving in Y-direction.

In addition to these requirements we are also given some important constraints

1. Translation stage must fit within existing design space
   - 1.1 Height in Z to be less than 0.75 inches *
   - 1.2 The footprint of the stage to be within existing platen that accommodates 8" diameter wafer
2. Stage actuation must be controlled by a microcontroller or PC Interface
3. Cost of manufacturing to be less than approximately $1500.

1.2 Assumptions: As per customer, the profiler will be operating at normal room temperature in most of the cases and it was assumed that there are not much significant thermal layers throughout the atmosphere.

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* This requirement was later removed form important constraint

2. Problem Solution

The intent of the term project is to design a translation stage for a profiler that satisfies given requirements and constraints. Design was started by sketching rough drawings and putting our initial thoughts on paper.

While deciding our prime design concept, we came up with thought of using flexure for our translation stage instead of using regular ball bearing or roller bearing. As one of the functional requirements was to maintain the out of plane Z-motion within 150 •, decision was made to use flexure bearing. Roller bearings can have accuracy in microns, but to achieve 150 • limit, flexure is the best choice. Moreover, text book was referred and following advantages of flexures over regular bearings were noted:

- Wear free since there are no sliding pairs
- Can be manufactured from a single piece of material to provide a monolithic mechanism which eliminates interface wear
- Displacements are smooth and continuous at all levels
- Displacements can be accurately predicted from the application of known forces and, conversely, predictable forces can be generated by controlled displacements
- They will be closely linear in their force / displacements characteristics, “If designed correctly”
- Elastic flexures are especially attractive for systems that must have extremely high repeatability

In our design we mainly focused on the following important concepts:

- To come up with solution which satisfies the given requirements and constraints as close as possible
- To perform finite element analysis to estimate X-displacement, out of plane Z motion, maximum von-mises stress and finally factor of safety

- Selection of materials which makes the design sound from performance and manufacturing point of view

- Selection of actuator which satisfies the force and displacement requirement with less than one micron resolution

- Cost analysis

3. Prime Design Concept:

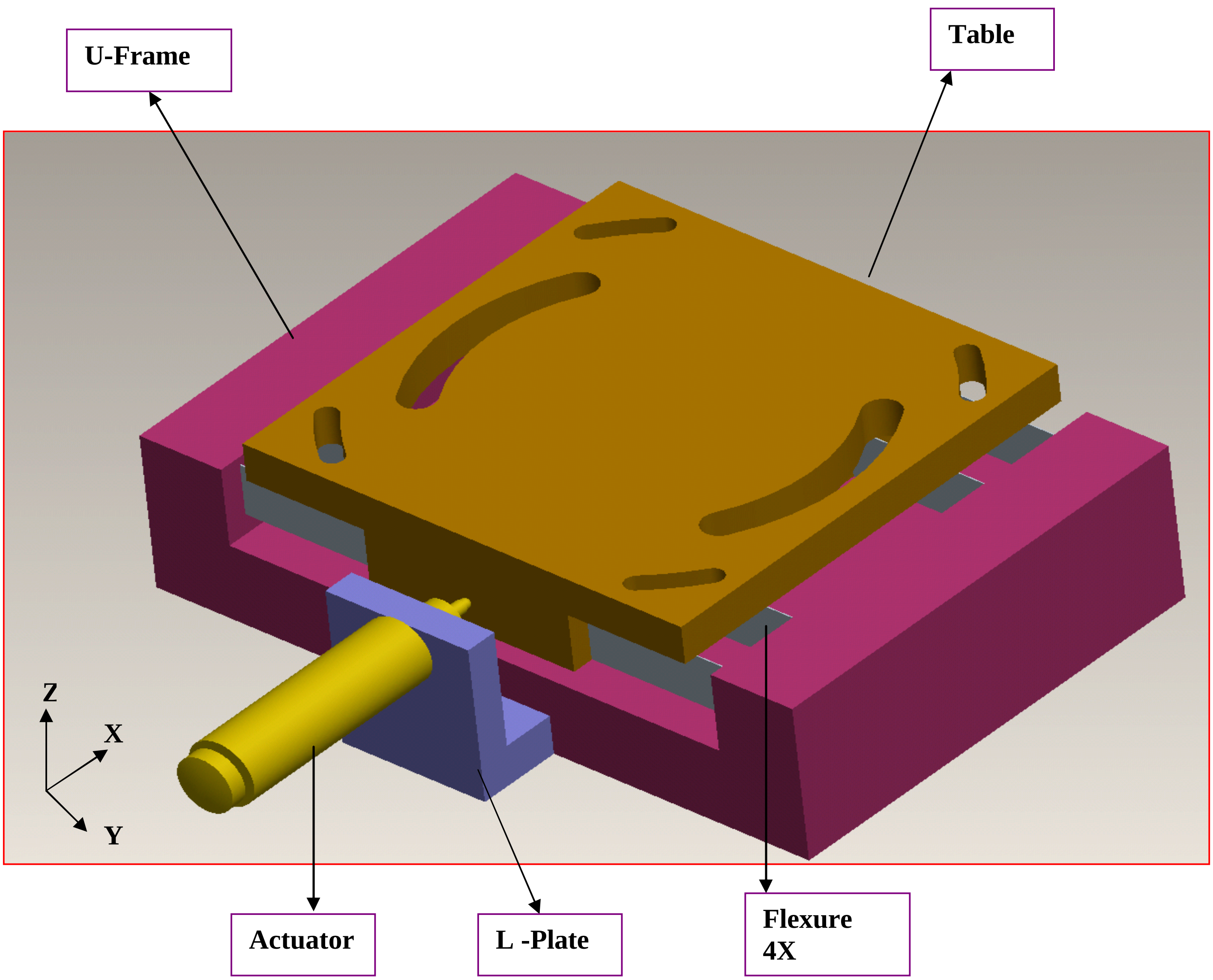


Figure 3.1: Prime design for the translation stage

Prime design concept consists of mainly five different components:

1. U-Frame
2. Table
3. Flexure (4X)
4. L-Plate
5. Actuator

All above mentioned components in our design are discussed below:

U-Frame:

U-Frame provides the support to the whole assembly. Four flexures and table are mounted on it. L-plate is also mounted on it which supports the actuator. As U-frame is the main support of the whole assembly, material for U-frame should have high stiffness. Steel 440C was used as the material for U-frame which is having high stiffness of 199.9 GPa. Overall dimension of the U-frame is 320 X 215 mm.

Table:

Table is mounted on four flexures and it have overall dimension of 215 X 215 X 19.50 mm. We chose material for the table as Aluminum. Initial design was not provided with slots on the top of the table, but later on as design modification, slots were included on the table to reduce the weight and thereby putting less load on flexures. Furthermore, prime design has slots on the bottom side to place flexures in them. This makes the design sturdier because the table has more area in contact with the flexures and thereby it eliminates any yawing effect of the table.

Flexure:

Flexure is one of the unique components in our design. There are four flexures both ends of which are fixed to the U-Frame. Advantages of using flexures are discussed earlier. Material selection for the flexure is one of the most crucial criteria. In the initial design material for the flexure was Steel 400C which has higher stiffness. Thus, the force required to move the table for the given displacement was very high. Extensive search was done for the actuator which could provide us that much force with the given requirements like resolution of less then one micron and velocity of minimum 2mm/sec. Efforts were also made to optimize the design by elongating flexures and keeping the thickness low than 0.50 mm. Even then the force requirement was as high as 350N for 10 mm displacement. After much such iteration we kept the material of the flexure as Aluminum.

One of the distinctive features of the flexures is that it of longer length. Length of the flexures is 250mm. This longer length provides significant X-displacement while keeping less stress at the extreme ends.

L-Plate:

L-plate is attached to the U-frame and its main function is to support the actuator. L-plate is such located that the point of actuation is exactly on the center of the flexure.

Actuator:

Actuator for the design is Thorlabs EAH503 steeper motor. Further details about the actuator are given in the actuator selection topic.

Note: Detailed sketches of each component are attached hereby as an appendix.

4. Material Selection

4.1 General Material Selection

For the material selection in general, the consideration was given to five different materials and they are:

- Aluminum (Al.2024-T3)
- Steel (440C)
- Beryllium-Copper (BeCu)
- Silicon Nitride (SiN)
- Invar

The initial selection was not that difficult since all of the materials mentioned above are already known for their useful properties. Aluminum and steel are the first choice many times due to their availability and cost effectiveness. They are also known for their good machinability. Beryllium-Copper and Silicon Nitride are not that commonly found due to their relative high cost in spite of having good machinability. Among the selected materials invar has the least value of coefficient of thermal expansion meaning that it is most stable for any dimensional changes when subjected to thermal loading; however, it stands last in the selection because of its relatively higher cost and poor machinability.

Apart from the general considerations for material selection mentioned above, the key factors involved in the final selection of materials are the material property ratios namely,

- (k / •)
- (D = k / • C) and
- (E / •)

The comparison of these ratios for all of the selected materials above is shown in fig. (4.1), fig. (4.2) and fig. (4.3) respectively.

The significance of these ratios can be explained as:

- High values of (k / •) are desired. The material should have high thermal conductivity to conduct large amount of heat and it should have low value of coefficient of thermal expansion for dimensional stability under the influence of thermal loading

- High values of the diffusivity (D = k / • C) are desired. The material should have high thermal conductivity to conduct large amount of heat, should have low density (light weight) and it should have low value of specific heat

- High values of (E / •) are desired. The material should have high value of modulus of elasticity and low value of density to obtain the highest resonant behavior

4.2 Final selection of materials

Based on the comparison of materials for different property ratios following materials were assigned to different components in the assembly:

Flexure and Wafer Table	**Aluminum (Al.2024-T3)**

The essential requirements for the material for flexure are:-

- Should be flexible to produce required amount of deflection
- Should be light weight
- Should have long term dimensional stability (microcreep)
- Should have good corrosion resistance
- Should have good machinability

From the comparison of material property ratios, it was found that Aluminum (Al.2024-T3) is the best fit for the flexure material requirements.

U-Frame	**Steel (440C)**

The essential requirements for the material for U-Frame are:-

- Should be stiff and sturdy to act as the basic support for the assembly
- Should have good damping ability and highest resonance behavior
- Should have good dimensional stability

- Should have good machinability

From the comparison of material property ratios, it was found that Steel (440C) is the best fit for the U-Frame material requirements.

Silicon Nitride (SiN) was a close call in the final material selection, but was eliminated finally on account of its very low value of diffusivity, relatively higher cost and relatively poor machinability.

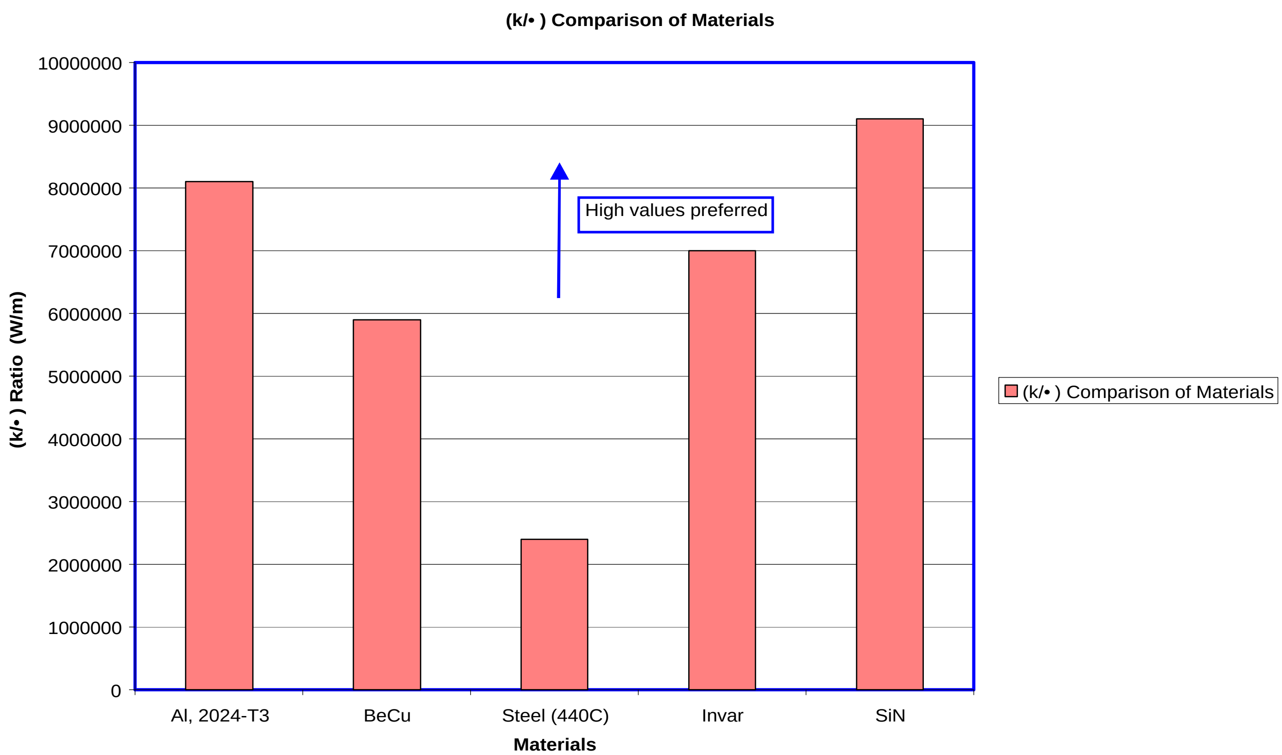


Figure (4.1)

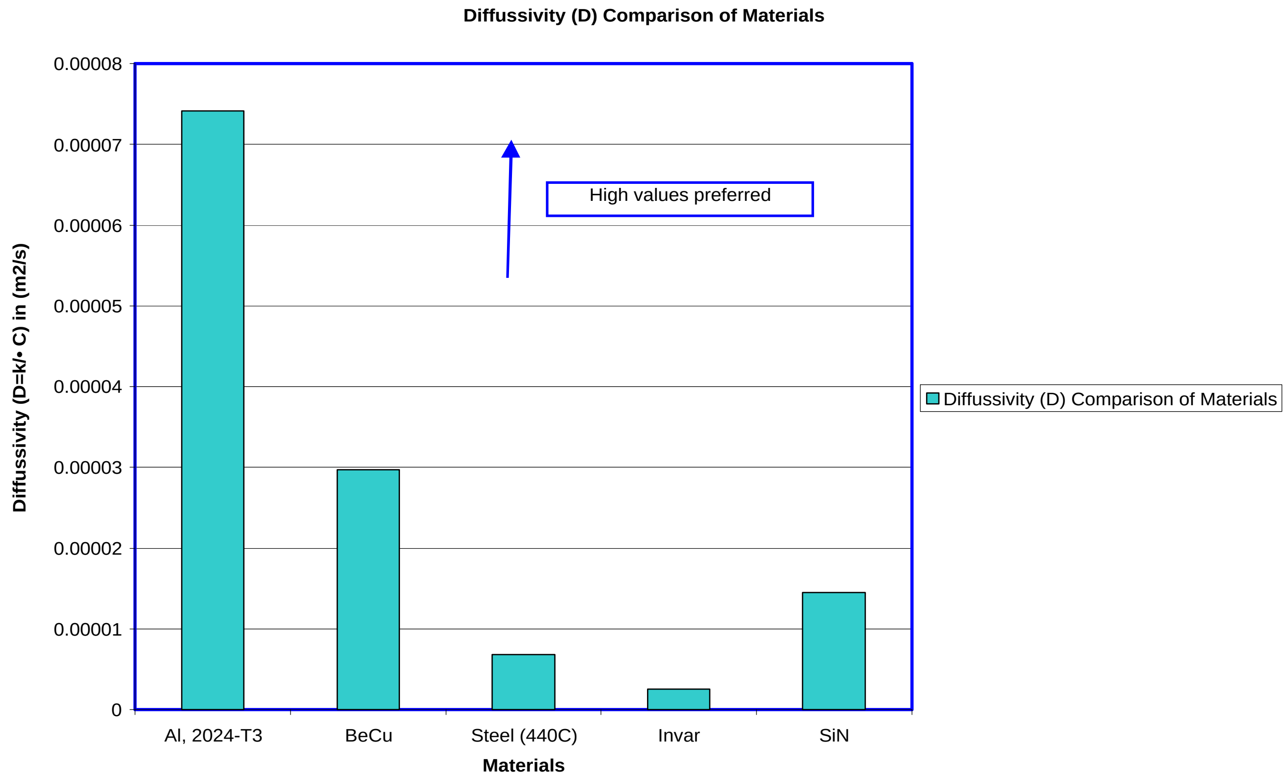


Figure: (4.2)

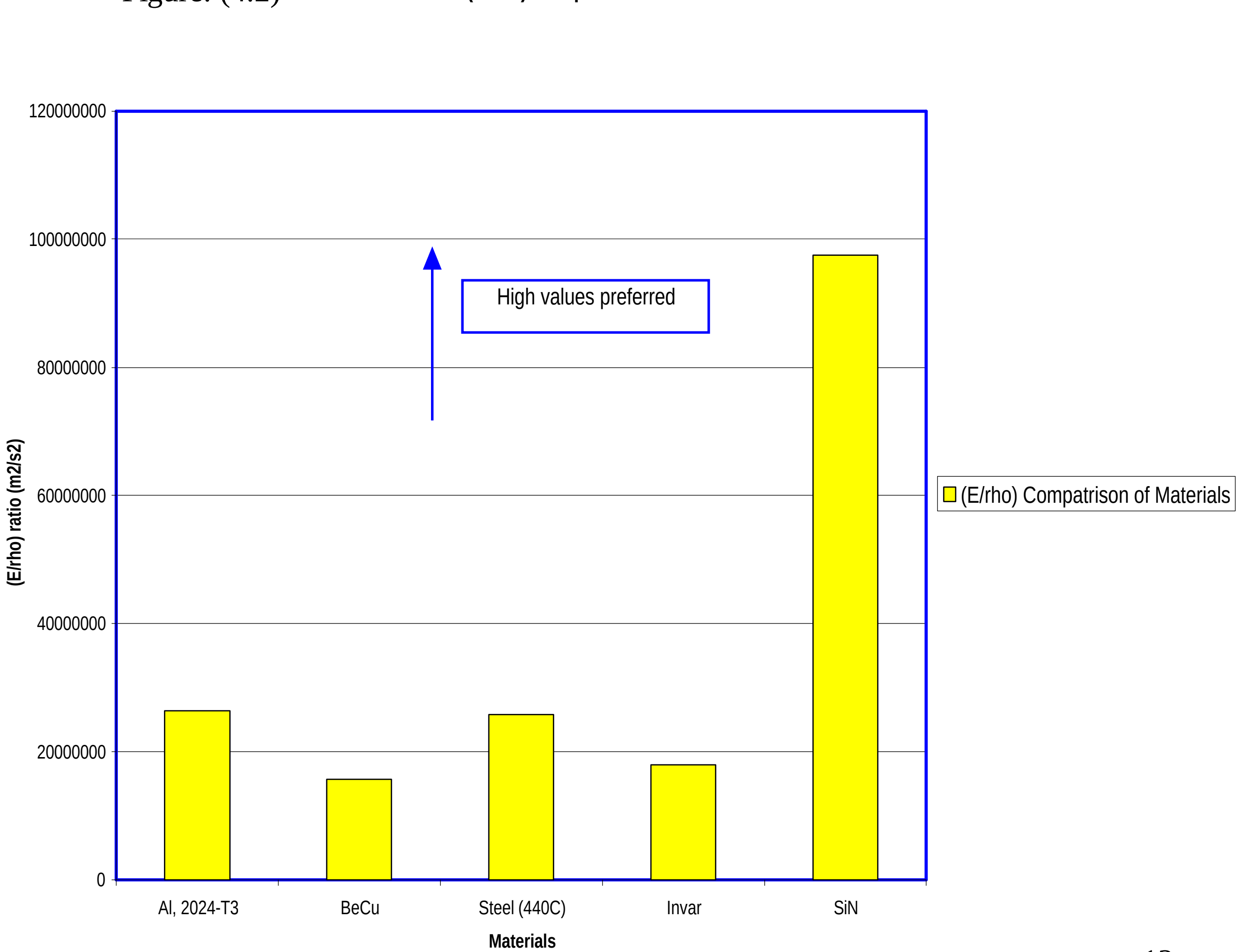


Figure: (4.3)

Table (4.1)

Properties of materials under consideration (at room temperature)					
	Coefficient of Thermal Expansion	Mass Density	Young's Modulus	Yield Stress	Ultimate Stress
Symbol	•	•	E	S_{yt}	S_{ut}
Material	$10^{-6}(1/^{o}C)$	(Kg/m^3)	Gpa	Mpa	Mpa
Al, 2024-T3	23.2	2768	73.1	344.7	482.6
BeCu	17.5	8359	131	1137.6	1310
Steel (440C)	10.1	7750	199.9	1896.1	1965
Invar	1.5	8055	144.8	482.6	620.5
SiN	3.6	3183	310.3	N/A	N/A

5. Actuator and controller Selection:-

Based on the design requirements for the actuator, a precision stepper motor actuator from Thorlabs was selected. Its picture as well as the key features is as follows:

Thorlabs Model: EAH 503

Price: - $1023.80

Ref: www.thorlabs.com

The key features of this actuator are:

- 13 mm travel range in X direction
- 4 mm/s velocity in X direction (max)
- 40 nm resolution of translation
- 12 kg driving load capacity
- 2 µm bidirectional repeatability

One of the important requirements in the selection of the actuator was that the selected actuator be compatible with a PC interface or a controller. The selected actuator is compatible with the feedback controller (optional) that comes with the actuator. Picture of the controller and its key features are mentioned below:

Thorlabs Model: BSC 001

Price: - $ 2187.50

Ref: www.thorlabs.com

Key features of the controller are:

- Single-channel control
- 25-W Maximum average power
- Dynamic step-resolution control
- Optically isolated input/output
- 25,600 microsteps maximum per revolution

6. Mathematical analysis of the flexure

The bending stresses induced in the flexure during the deflection were calculated based on the equations for the case of:

- A beam with fixed ends
- Point load applied at the centre

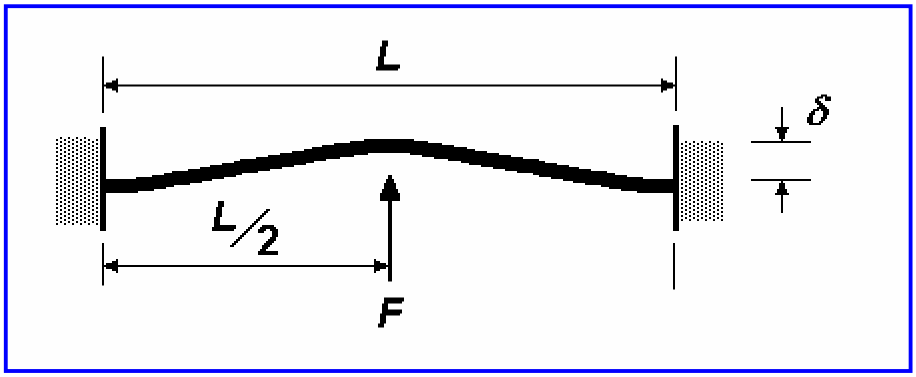


Figure (6.1)
(http://www.users.globalnet.co.uk/~phold/clag/beam.html)

For a beam with fixed ends and point load applied at the centre, the maximum deflection is at the centre which is given by the formula:

$$\delta = \frac{FL^3}{192\,EI} \qquad (6.1)$$

Where,

δ - Deflection at the centre (m)

F - Applied Load (N)

L - Length of the beam (flexure) (m)

E - Modulus of elasticity of the material (N/m^2)

I - Area moment of inertia of the flexure (m^4)

Also,

$$I = (b*h^3)/12, \qquad (6.2)$$

Where,

b – Width of the flexure (m)
h - Thickness of the flexure (m)

Since the required displacement of the wafer table was specified (10 mm), the value of applied load could be found out by equation (6.1). For final selection of the flexure material from the materials considered earlier, value of the load F, was calculated keeping the geometry of the flexure the same in each case. Results of the calculations could be found in table (6.1)

Table (6.1)

	Flexure Geometry					
	Thickness	Width	Length	Area Moment of Inertia	Deflection	Calculated force for the deflection
	h	b	L	$I = (b*h^3)/12$	δ	$F = (192EI\delta)/L^3$
Material	(m)	(m)	(m)	(m^4)	(m)	(N)
Al, 2024-T3	$4*10^{-4}$	$26*10^{-3}$	0.25	1.38667E-13	0.01	1.246
BeCu	$4*10^{-4}$	$26*10^{-3}$	0.25	1.38667E-13	0.01	2.232
Steel (440C)	$4*10^{-4}$	$26*10^{-3}$	0.25	1.38667E-13	0.01	3.406
Invar	$4*10^{-4}$	$26*10^{-3}$	0.25	1.38667E-13	0.01	2.467
SiN	$4*10^{-4}$	$26*10^{-3}$	0.25	1.38667E-13	0.01	5.287

With reference to the force results mentioned above, it could be concluded that Al, 2024-T3 produces the required deflection with least amount of applied force. Hence, the bending stresses that would be developed in the flexure would also be minimum for the same flexure geometry, among all the five stated materials. Here, it was confirmed that Al, 2024-T3 would be the material for flexures.

7.0 Finite Element Analysis:

The solid modeling of the prime design was done using Pro/E. Pro/Mechanica was used to perform finite element analysis. We performed maximum displacement analysis and maximum stress analysis. Results for the analysis are given below.

7.1 Displacement Analysis:

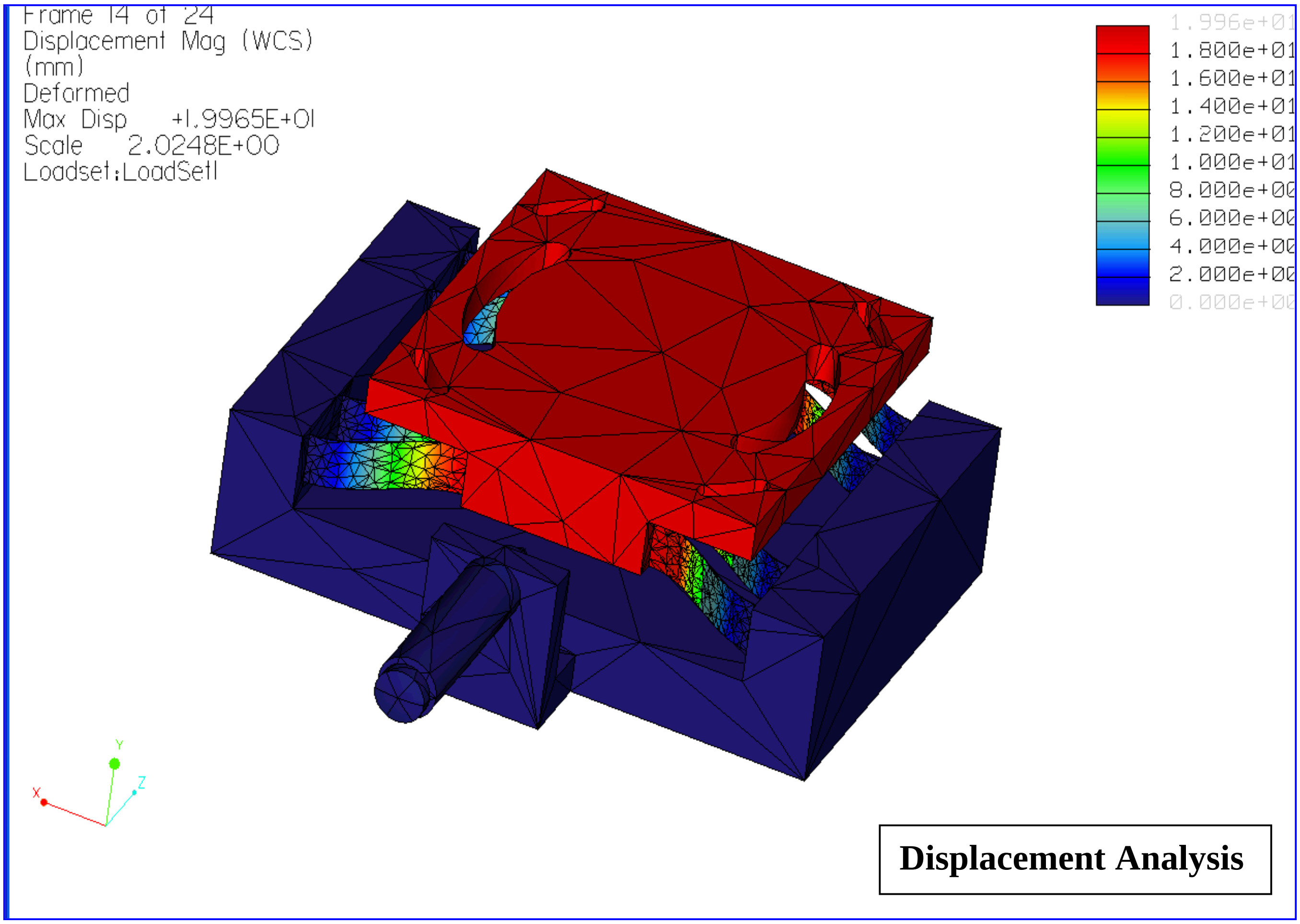


Figure (7.1): Finite element analysis for displacement

Principal System of Units: millimeter Newton Second (mm-N-s)
Length: mm
Force: N
Time: sec
Temperature: C
Force Applied: 5.000000e+01
Max_disp_mag: 1.996479e+01
Max_disp_x: -8.317224e-02
Max_disp_y: -8.813251e-05
Max_disp_z: 1.996479e+01

Outcome of the above given results are as below:

- Maximum displacement in X-direction comes as 1.9964 mm
- Out of plane Z-motion through the 1.9964 mm displacement comes as 8.813251E-05 mm

  =>One • = 10 $^{-10}$ Meter = 10 $^{-7}$ mm

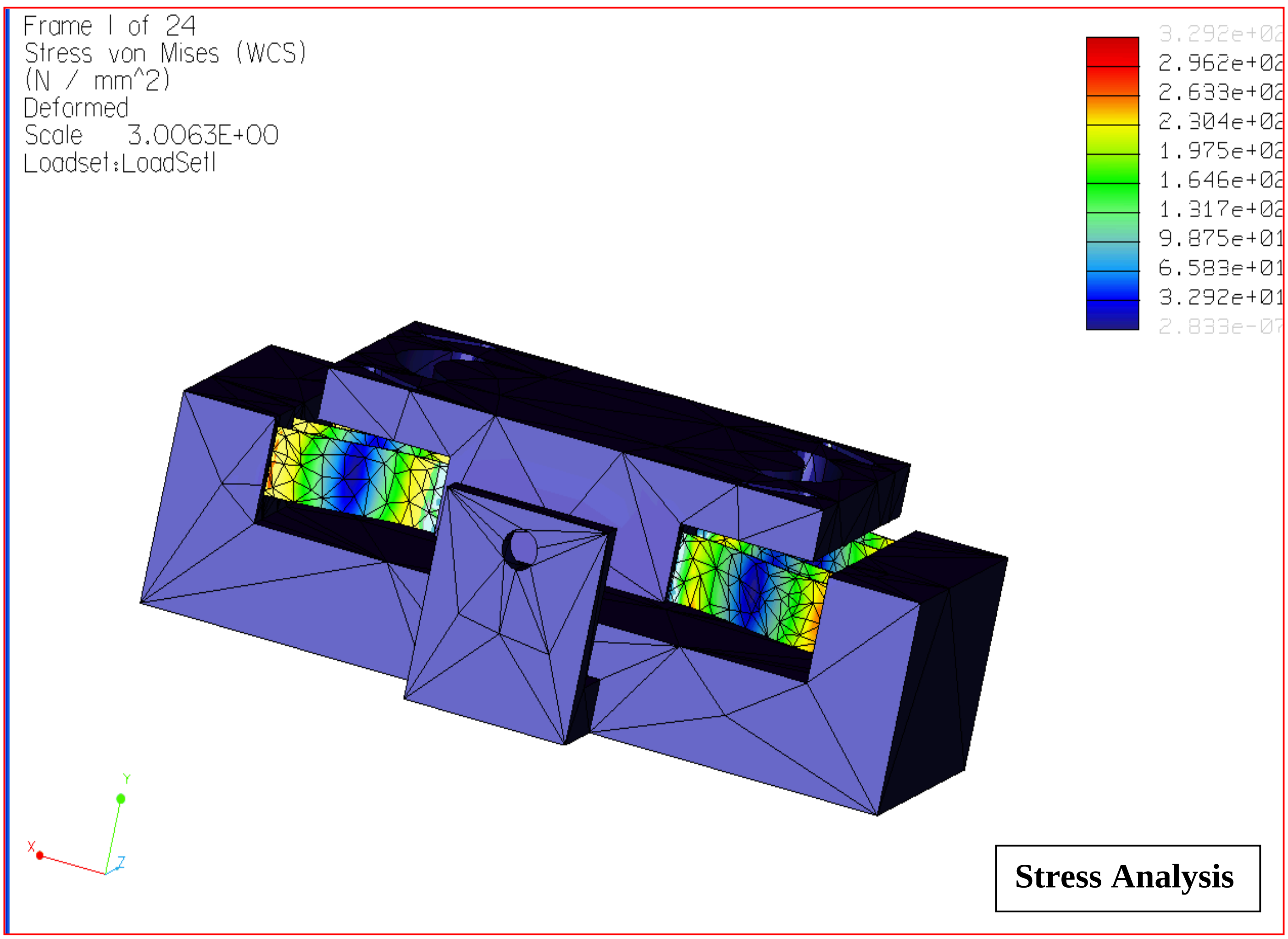
  ð One mm = 10^{7} •

  ð 8.813251E-05 mm = 881.325 •

  Therefore,

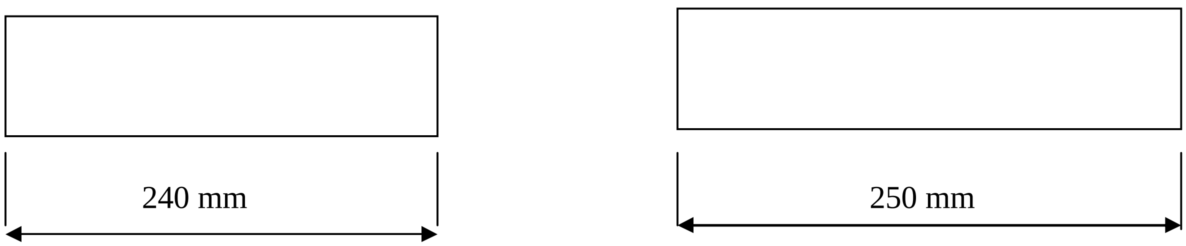
  Out of plane Z-motion through 1.9964 mm travel comes as 831.722 •. Here, it should be noted that the out of plane Z Motion is for the entire length not for 1mm travel
- Out of place Z motion for 1mm travel of the table in X-direction was not determined as Pro/Mechanica doesn't have that capability

7.2 Stress Analysis:



Figure(7.2): Finite element analysis for maximum stress

Finite element analysis was not straightforward as expected in the maximum stress analysis. In the first iteration, length of the flexure was 240mm and thickness was 0.55 mm. With this dimensions, factor of safety of 1.042 was determined, which was having very low margin between maximum von mises stress and yield strength. Subsequently, flexure design was modified to 250 mm length and thickness of 0.40mm. These dimensions gave us given below result.



Initial length

Modified after iterations

Unit: N/mm^2

Max_stress_prin:	4.632714e+02
Max_stress_vm:	3.291283e+02
Max_stress_xx:	4.622857e+02
Max_stress_xy:	-6.081241e+01
Max_stress_xz:	-1.279342e+02

$$\text{Factor of Safety} = \frac{\text{Yield Strength}}{\text{Maximum Von mises Stress}}$$

$$= (414)/\ (329.12)$$

$$= 1.259$$

• 1.26

7.3 Convergence Graph:

Graph below shows the strain energy vs P loop pass (Polynomial order). It is observed that the graph starts converging after pass four. Thus, graph indicates that we achieved the required results without any stress concentration which may result in localized stress and graph will start going up without any sign of converging.

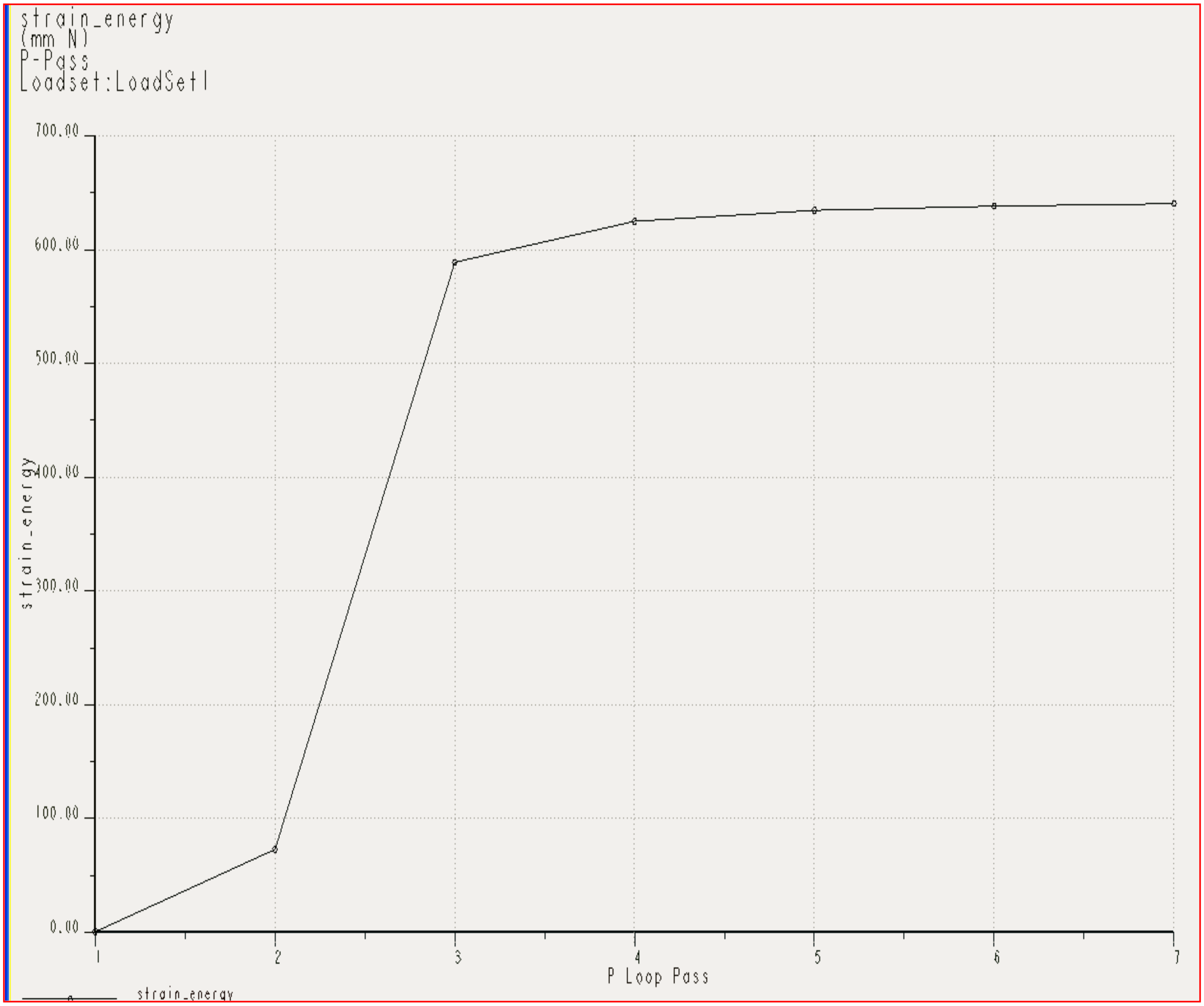


Figure (7.3): Strain energy convergence graph

8. Cost Analysis

No.	Part	Material	Material Cost	Manufacturing cost (Approx.)
1	U-Frame	Steel (440 C)	$ 45.00	$150.00
2	Wafer table	Aluminum Al, 2024-T3	$ 15.00	$325.00
3	Flexure (4X)	Aluminum Al, 2024-T3	$ 1.00	$50.00
4	L plate	Steel (440 C)	$ 2.00	$20.00
Addition			$ 63.00	$ 545.00

- Cost of Actuator: $ 1023.80

  Total cost without Controller Unit: (63+545+1023.80) = $ 1631.80

- Cost of the Controller Unit (Optional) : $ 2187.50

  Total Cost with Controller Unit: (1632.00+2187.50) = $ 3819.30/-

9. Conclusion

- § Selection of aluminum (Al, 2024-T3) as a flexure material proved to be effective as the desired x-displacement (functional requirement) of the translation stage was achieved (19.965 mm)

- § Out of plane Z-motion (over a travel of 19.965mm) was achieved to be 831.722 •, which is very close to the functional requirement of 150 • over 1mm travel.

- § Stress analysis of the flexures was carried out in Pro/M which furnished the factor of safety of 1.26. Hence the design is safe under the application of given force.

- § Total cost of the profiler translation stage assembly is obtained as $1631.80 (Without controller unit) which is in close proximity to to the given cost limit of $1500

- § Actuator selection proved to be efficient as the functional requirement of velocity and resolution is achieved.

10. Future Recommendations

- § Feedback control system could be implemented and the results could be verified with given functional requirements.

- § More research work could be carried out in the design to keep the out of plane Z-motion in control.

§ References

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