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Design and Fabrication of High Temperature Creep Testing Machine

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Abstract The study involves the design and fabrication of a machine in order to perform creep test of various materials being used in high temperature applications. Maximum applied load on the specimen can be 10kN and tests could be carried out at maxi-mum temperature of 700°C. Machine uses lever loading mechanism for load application and measures extension up to 55% of gauge length of the specimen. All components were designed and stress analysis was performed. Components were fabricated separately and then assembled. The machine was able to successfully perform tensile creep tests for different materials at various temperatures according to ASTM standard E-139-06.

Keywords: *creep, machine, design, fabrication, high temperature*

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1. Introduction

Creep is a time dependent slow deformation of materials under constant stress. This phenomenon usually occurs at higher stress (less than yield strength) and temperature values and rate of deformation of material is dependent on stress value, material properties, time and the temperature. [1].

Engineering components in power plants, oil refineries and chemical industries normally operate at temperature around 500°C. The operating temperatures of nuclear power plants and space rockets are even higher (around 1000°C), which necessitates materials with high creep resistance. Creep in system components may have catastrophic consequences, therefore, by using testing methods, we are capable of determining the condition and development of creep at any early and non-critical stage.

In literature [2-4] it is revealed that the compressive creep test is relatively simple and has been frequently used to characterize the creep behavior of materials at high temperatures. The tensile creep test, on the other hand, has been used to a more limited extent [5-8]. In these studies, where the creep tests have been conducted, the costs of test fixtures and specimen preparation were one of the limiting factors. This paper will describe design, stress analysis, material selection and fabrication of creep testing machine which is able to perform tensile creep tests at various loads and temperatures upto 700°C.

2. Design of Machine Components

Components of creep testing machine were designed and assembled in Pro Engineer Wildfire 4.0 which is a parametric, integrated three dimensional computer-aided design, computer-aided manufacturing and computer-aided engineering (3D CAD/CAM/CAE) solution created by Para-metric Technology Corporation (PTC). The components of creep testing machine are shown in Figure 1 and their description is given below.

(a) Lever

Lever mechanism is used for applying load at specimen subjected to creep testing. Lever is used with dead weights to produce load up to 10kN. Lever has arm length ratio of 1:13, total length of 1400mm and three holes in it as shown in Figure 1(a). At one end, dead weights will be hanged and center hole is designed for fulcrum which will provide free movement to lever about the fulcrum. Hole on the left side will be connected with upper cold pull rod to apply a constant load on the sample.

(b) Cold Pull Rods

There are two cold pull rods in creep testing machine and each has length of 350mm. One is connected at the top with lever and other one is connected with the base plate. Design of cold pull rod is shown in ure 1(b). Both cold pull rods are further connected to hot pull rods. They have given the name of cold pull rods because they are outside the furnace i.e. at ambient temperature. Top cold pull rod will be connected by pin connector with the lever whereas lower cold pull rod will be connected with the help of a bolt with the base plate.

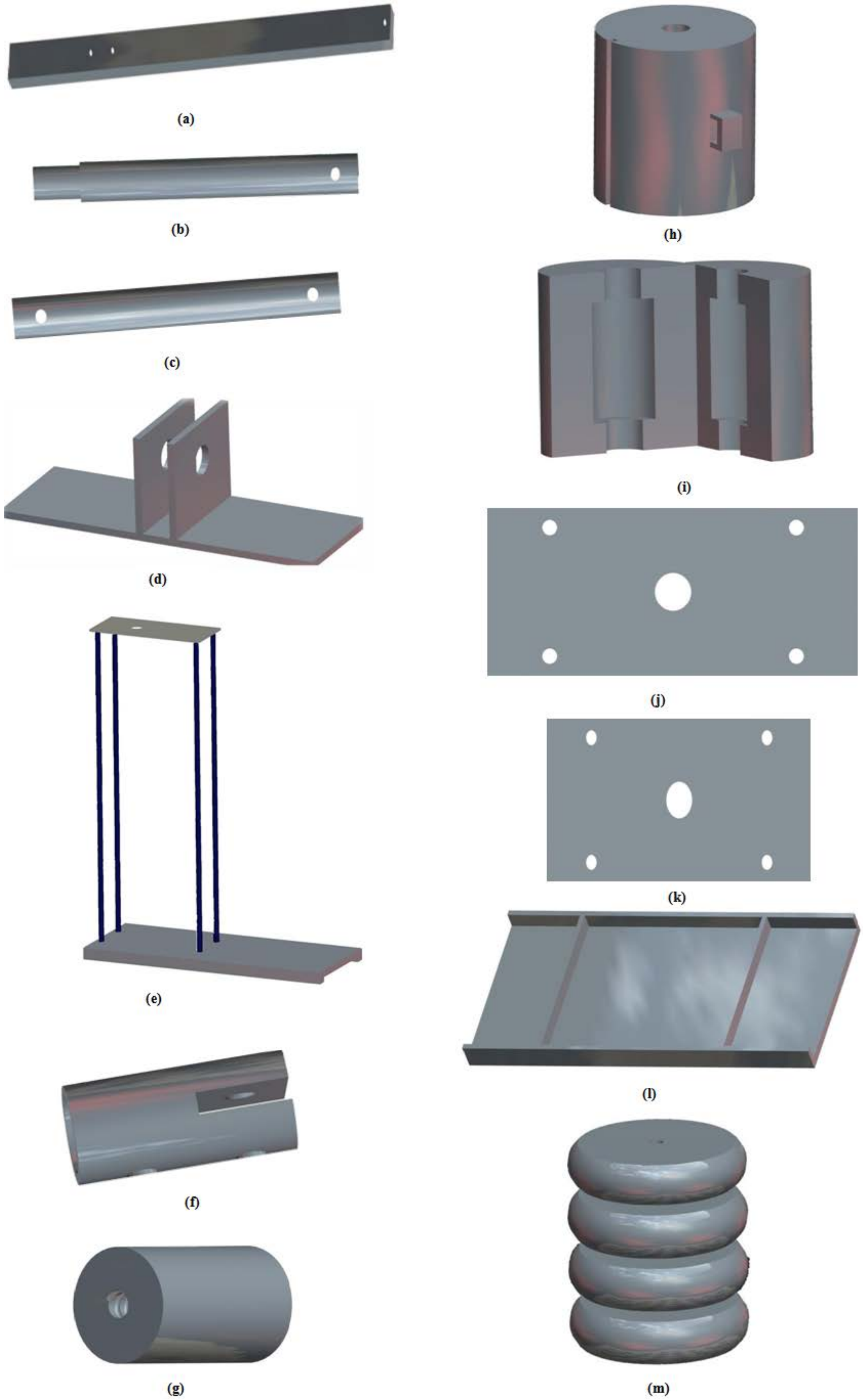


Figure 1. Components of creep testing machine (a) Lever (b) Cold pull rods (c) Hot pull rods (d) Fulcrum (e) Columns (f) Grip for rectangular specimen (g) Grip for circular specimen (h) Furnace (closed view) (i) Furnace (open view) (j) Top plate (k) Base plate (front view) (l) Double I beam structure of base plate (m) Dead weights

(c) Hot Pull rods

The two hot pull rods (upper and lower) of 300mm length are used in the creep testing machine. These are called hot pull rods because some of the part of these pull rods is inside the furnace or above room temperature along with the sample to be tested. Upper hot pull rod is connected upper cold pull rod and lower hot pull rod is connected with lower cold pull rod with the help of pin connectors. Other end of hot pull rod is connected with the grips, either threaded or with the help of pin connector. The design of hot pull rod is shown in Figure 1(c).

(d) Fulcrum

Fulcrum is a very important part of the creep testing ma-chine which is required to provide motion to lever and to create a moment. Fulcrum is connected with the center hole of the lever by a pin connection which permits lever to rotate about this pin. This fulcrum is connected with the top plate by four nut and bolt joints. Figure 1(d) is the design of fulcrum.

(e) Columns

Four column design was used in creep testing machine as shown in Figure 1(e). In this design four rods are connected with top and bottom plates of a machine. Total length of each column is 1400mm. The design is the most stable one under high load applications because its structure provides high resistance to buckling, high durability and less material requirement for fabrication.

(f) Grips

Figure 1(f) and Figure 1(g) show grip designs for holding rectangular and round specimen, respectively. For round samples, internal threads are created on both sides of grip. One end will be connected with the hot pull rod and other to the sample. For rectangular sample, one grip end is internally threaded and the other end has a pin type connection with sample. These grips are in the furnace along with the sample to be tested.

(g) Furnace

Figure 1(h) and Figure (i) show the closed and split views of split type tube furnace for high temperature creep testing, respectively. Furnace is hanged in the center of machine with the help of two rods which are connected with furnace from one end and with column from the other end. Furnace has a hole at the top and bottom for the passage of hot pull rods. Furnace is designed in such a way that heating element, refractory material and insulation can be placed easily and specimen can be gripped and un-gripped easily.

(h) Top Plate

Top plate is placed on top of four cylindrical columns and fulcrum is added onto the top plate. Top plate is 600mm in length, 260mm in width and 30mm in thickness. These columns are connected with the help of nuts and bolts with top plate. Other end of these columns is connected to base plate. Top plate has a hole exactly in center for the passage of cold pull rod. The design of top plate is illustrated in Figure 1(j).

(i) Base Plate

Base plate is connected with four columns with the help of nuts and bolts. Base plate is 30mm thick and 600mm in both length and width. At center of the plate, cold pull rod is connected with the help of nut and bolt. Whole load of the machine is acting upon the base plate, therefore double I-beam structure is designed for the base plate to avoid bending. Front view and double I-beam structure of base plate are shown in Figure 1(k) and Figure 1(l), respectively.

(j) Dead Weights

Dead weights are used to apply a constant load on the sample and one end of lever is connected with the dead weights. These dead weights are placed in a weight holder which is connected with the one end of lever. Dead weights are cylindrical in shape and different sizes and weights of 1,2,3,5 and 10kg. The design of dead weights is shown in Figure 1(m).

2.1. Complete Assembled Model

Bottom up approach for the assembly of machine components in Pro-E was used. First of all, subassemblies were made and then these were assembled to form complete model of creep testing machine which is shown in Figure 2.

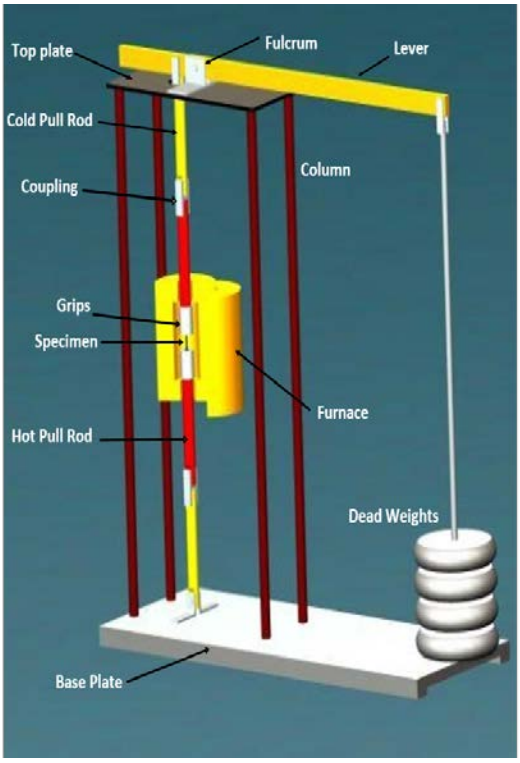


Figure 2. Complete assembled model of creep testing machine

2.2. Material Selection

Material selection is an important step in the process of designing any physical system. In the context of product design, the main goal of material selection is to minimize cost while meeting product performance goals. Systematic selection of the best material for a given application begins with properties and costs of candidate materials. The materials for components are selected depending upon the type of force/stress acting on the component.

2.2.1. Components under Tension

Upper and Lower Cold Pull Rods:

Upper and lower cold pull rod will always be under tension during creep test. A main criterion for selection of material of upper and lower cold pull rod is yield strength and corrosion resistance. Calculations were made by considering the maximum load capacity of the machine (10kN).

Stresses acting on the rod when maximum load is applied:

$$\sigma = F / A = 10,000N / \pi r^2$$

where r is the radius of rod=30mm, F is applied load, A is cross sectional area of rod and σ is the tensile stress acting on rod which outcomes to be 14.14MPa.

Based on above calculations and availability, AISI SS 201 was selected for the cold pull rods. It is cheap, easily available in Pakistan and has good corrosion resistance. Mechanical properties of this material are given in Table 1.

Table 1. Material Properties of SS 201

UTS (MPa)	758
0.2% YS (MPa)	379
Elongation % in^2	52
Hardness Rockwell	B87
Impact Strength Izod V-Notch (J)	163
Elastic Modulus (GPa)	197

2.2.2. Components under Compression

Columns:

Lever is assembled with fulcrum by pin joint which is further assembled at the top plate by four nuts and bolts. Top plate is supported by four cylindrical columns and these columns are always under compressive force. When test is not being performed in the machine, weight of lever and fulcrum is continuously acting on columns. During creep test, dead weights will additionally act upon these columns. They main criterion for designing and selection of material of columns is to avoid buckling in them. AISI SS 201 (for properties refer to Table 1) was selected for columns by considering the critical stress acting upon columns, calculated by Euler's Formula for buckling, shape factor, high strength material and aspect ratio.

$$\text{Euler's Formula } [9] = F = \pi^2 EI / 4L^2$$

where F is maximum or critical force (vertical load on a column), E belongs to modulus of elasticity, I refers to area moment of inertia, L represents unsupported length of column. In this case, I is 0.0009 kgm^2 which implies critical load of 336 kN whereas only 4kN is being applied on one beam.

2.2.3. Components under Bending

Lever:

At one end of the lever, dead weights are connected and from the other end it is connected to cold pull rod which at end transfers the applied load to the sample. When test is being performed, bending forces act upon the lever as shown in Figure 3. Thus, lever should have such dimensions and material which should avoid any permanent bending in it and almost zero elastic bending. Maximum applied load is 10kN. Therefore, according to Lever rule:

$$R_1 x F_1 = R_2 x F_2$$

$$78.4mm x 10000N = 1000mm \text{ x } F_2$$

$$F_2 = 784N.$$

where R_1 is moment arm of force F_1 which is acting downwards on dead weights side, R_2 refers to moment arm of force F_2 acting upward to the opposite end. To produce 10kN of load, 80 kg of dead weight is required which is calculated by W=mg, W represents weight, g is gravity acceleration (9.8m/s^2). Maximum moment produced= M= 80x9.8 = 784N. However, bending stresses (σ) that will act on lever will be Mc/I, where c refers to distance from the neutral axis and I is moment of inertia.

$$\sigma = M / (c / I) = M / S(S = \text{shape factor} = c / I)$$

We have selected Mild Steel for fabrication of lever. By considering the yield strength of Mild Steel 230MPa, and keeping the safety factor of 3 dimensions of lever have been calculated as follows: I for rectangular beam is $bh^3/12$. Therefore, calculated dimensions are: b= breadth=20mm and h= height=52mm.

Top Plate:

Top Plate will be under compressive forces while the machine is in static or operating condition. Due to which it has to be designed and material has to be selected in such a way that it does not bend. There are two ways to avoid bending. First one is to use a material of high stiffness and second one is to increase the thickness of low stiffness material. In Pakistan, plates are generally available of Mild Steel with various thicknesses. Therefore, mild steel plate of 30mm thickness was considered appropriate for creep testing machine which is economical and easily available.

Base Plate:

Complete load of machine is acting upon the base plate and it is required to avoid bending. Therefore, material selected for base plate has to have high stiffness. As mentioned earlier that plates of the size being used in creep testing machine are generally available in the Mild Steel. To enhance its stiffness we have used double I beam design at base and thickness of plate is 30mm.

2.2.4. Components under Shear Stresses

Pin Joints:

There are several pin joints in creep testing machine but the critical one is between lever and fulcrum. Double shear is acting upon this joint as shown in Figure 3.

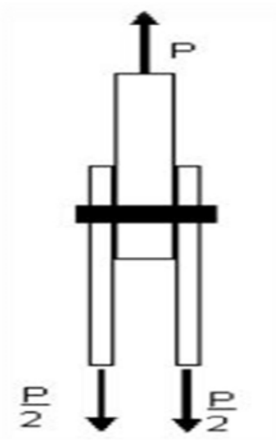


Figure 3. Schematic illustration of forces acting upon double shear joint

For pin joints, three kinds of stresses are calculated:

Shear stress in joint, F / 2A, where F is maximum load and A is cross sectional area of pin. Bearing stress in joint, F/dxl where d is fasteners diameter, l is its total length. Tear out shear stress in joint, F / m x t x h where h is distance from center, m is tear out shear plane and t is thickness of plate.

In current case, values of double shear stress, bearing stress, tear out shear stress in joint are 68.75, 27, 20.76 MPa, respectively. AISI SS 316 L was selected for the entire pin joints in creep testing machine on the basis of above mentioned stresses, material cost and availability. Material properties SS 316 and SS 316 L are given in Table 2.

Table 2. Material properties SS 316 and SS 316 L

Properties	SS316		SS316L	
	Typical	Minimum	Typical	Minimum
Tensile Strength (MPa)	580	515	570	485
Proof Stress (0.2 % offset) (MPa)	310	205	300	170

2.2.5. Components Subjected to Creep

Upper and Lower Hot Pull Rods:

Upper and lower hot pull rods will always be in tension during test and part of them will be inside the furnace to grip the sample. When material is subjected to constant load at high temperatures for a period of time, it under goes creep. Therefore, these rods should have high creep resistance. Maximum load capacity of machine is 10kN and maximum operating temperature is 700°C. When maximum load is applied, stress in hot pull rods is 14.14 MPa. By keeping the safety factor of 4, maximum stress acting on rods and maximum operating temperature in view, AISI SS 316 L was selected for hot pull rods. Its creep properties are shown in Table 3 by means of stress for a creep rate of 1% in 10,000h.

Table 3. Creep Properties of SS316

Temperature (°C)	550	600	650	700	750
Stress (MPa)	160	120	90	60	20

Summary of all selected materials for fabrication of creep testing machine components is given in Table 4.

Table 4. Selected materials for fabrication of components of creep testing machine

Lever	Mild Steel
Cold pull rods	AISI SS 201
Hot pull rods	AISI SS 316L
Fulcrum	Mild Steel
Column	AISI SS 201
Nuts and Bolts	Stainless steel
Pins	AISI SS 316L
Column top plate	Mild Steel
Column base plate	Mild Steel
Grips	AISI SS 316L
Dead weights	Mild Steel

2.2.6. Furnace Material Selection

Specifications of furnace and selected materials are given in a Table 5.

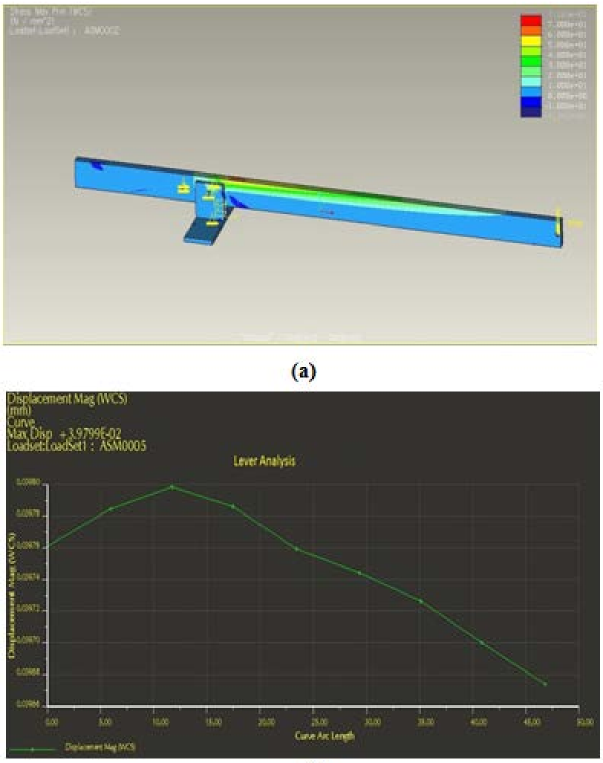
Table 5. Furnace specifications

Furnace type	Split tube
Heating element	Kanthal
Length of heating zone	100mm
Refractory	Silica
Insulation	Ceramic wool
Maximum working temperature	700°C
Power and control circuit	Solid state based
Temperature controller	Digital PID
Outer diameter	200mm
Total length	200mm

3. Stress Analysis

Structure analysis of few critical components of creep testing machine was performed in Pro-E Mechanica 4.0. Structural Analysis is a multi-discipline CAE tool that analyzes the physical behavior of a model in order to better understand and improve the mechanical performance of a design. Structural Analysis is available in the integrated mode of Pro/E and analysis can be performed within the Pro-E environment.

For this analysis, created model in Pro-E was opened in Pro-E Mechanica. After assigning material properties, load and displacement constraints were assigned. Mesh model was created and static analysis type was performed.



(a) (b)

Figure 4. (a) Stress analysis of lever (b) Displacement curve of lever

Lever:

For maximum load capacity of machine, we have to apply 80kg of dead weight at one end, which is approximately equal to 800 N. 800 N load is applied at one end of the lever and other end of the lever is constrained as zero displacement. Material properties of steel are assigned to the lever. Results of the stress analysis of lever are presented in Figure 4(a). As at maximum applied load at one end, maximum generated principal stress is 70.16 MPa which is very less as compared to the yield strength of Mild Steel (selected material for lever). Maximum stresses are generated at end near the pin joint whereas stresses decrease as we move away from the pin joint end.

Figure 4(b) shows the displacement curve of lever as 800 N load is applied on one end. In these results maximum displacement that occurs in lever is 0.039 mm when machine is working at its full capacity. Displacement value increases from the pin joint end towards the end where load is applied.

Pin joint between cold and hot pull rod:

Hot and cold pull rods are connected with a pin joint connector and maximum applied load on these pull rods will be 10kN. Steel properties were assigned to cold pull rod and stainless steel properties to hot pull rod and pins.

Below end of the hot pull rod is constrained as zero and 10kN axial load is applied at top end of cold pull rod. Figure 5 show the stress analysis of pin joint which shows that when 10kN load is applied on cold pull rod, maximum stress of 28MPa is produced. Maximum stress is produced near pin joint and yield strength of selected material is way greater than the stress produced. Safety factor of at least 5 is kept, thus, there will be no plastic deformation.

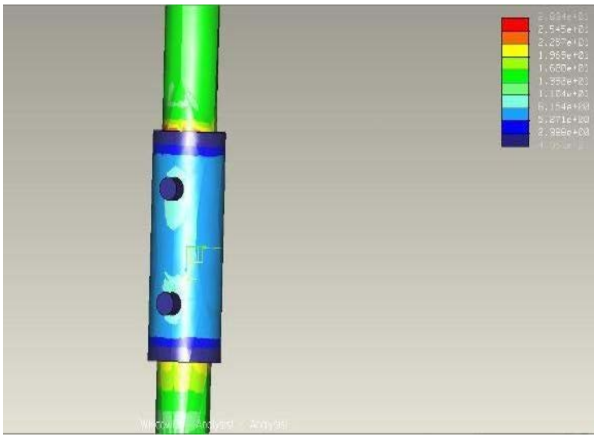


Figure 5. Stress analysis of pin joint

4. Creep Testing and Results

ASTM standard E-139-06 [10] was followed to perform creep test. Experiments were performed on Aluminium-6061 under three different loads of 875, 1250 and 1500N at 473K. Dimensions of the samples are 6.25mm in width, 2mm in thickness, and 25mm in gauge length. The creep test results as a function of applied load are shown in Figure 6 and summarized in Table 6. From the results it was found that with increased applied load minimum creep rate increased and highest of 3.12%/min was observed at 1500N.

Table 6. Summary of creep test results

Applied Load (N)	Creep (%)	Minimum creep rate (%/min)
850	18.25	0.075
1250	10.48	0.17
1500	13.2	3.12

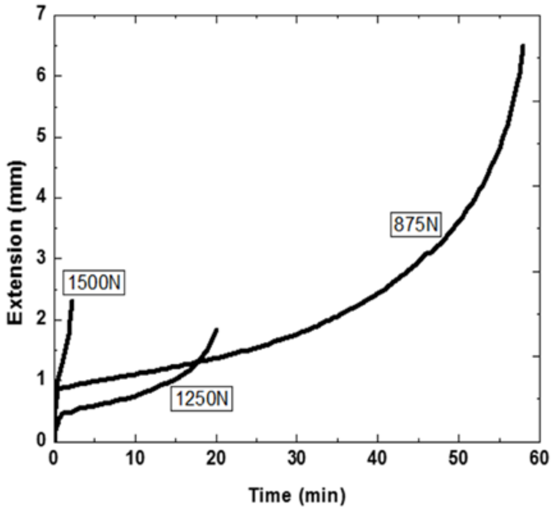


Figure 6. Creep test results of Aluminium-6061 as a function of applied load at 473K

5. Conclusions

The purpose of this work was design and fabrication of creep testing machine to evaluate tensile creep behaviors of engineering materials at high temperatures. Components of the creep testing machine were designed in Pro-E wildfire 4 and configuration design was made which includes location of each part with respect to other. Material selection based on practical conditions was done. Stress analysis of critical components was performed by using Pro-E Mechanica to evaluate material behavior under various conditions. Stress analysis showed that maximum principle stress is less than the yield strength of selected materials. After designing, creep testing machine was successfully fabricated and tensile creep tests were conducted on Aluminum-6061 under various applied load conditions.

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