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Finite element simulation of creep behavior in enhanced refractory material for glass furnace

Praveen Kumar Kuntamalla
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FINITE ELEMENT SIMULATION OF CREEP BEHAVIOR IN
ENHANCED REFRACTORY MATERIAL FOR
GLASS FURNACE

By

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A Thesis Submitted to
College of Engineering and Mineral Resources
West Virginia University
in Partial Fulfillment of the Requirements
for the Degree of
Master of Science in Mechanical Engineering

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2004

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ABSTRACT

Finite Element Simulation of Creep Behavior in Enhanced Refractory Material for Glass Furnace

Praveen Kumar Kuntamalla

An important focus in the glass melting industry, which is an energy intensive industry, is towards greater output and increased energy efficiency in the glass melting process. Conversion to the oxy-fuel-fired furnace from the traditional air-fuel-fired furnace is one means to achieve greater output and energy efficiency, since the capital cost per ton of glass pulled is approximately 58% less for the oxy-fuel-fired furnace compared to the air-fuel-fired furnace.

The main disadvantages of the oxy-fuel-fired furnace are its higher operating temperature, possibly to more than 2200 °F, and its alkali partial pressure that hasten the corrosion of refractory materials, particularly in silica refractories. Thus, the refractories used in the oxy-fuel-fired furnace are subjected to high temperatures and stresses during its service life. Considerable creep could occur in the furnace, if the refractory material is not creep resistant.

In order to improve the performance of refractory materials, Oak Ridge National Laboratory (ORNL) is utilizing High Density Infrared (HDI) technology. This technology, which is relatively new to materials processing, is increasingly being researched in the development of coatings and surface modifications for refractory materials.

This thesis studies the creep resistance effectiveness of the HDI surface treatment for refractory materials. In particular, the dependencies of creep strain on operating temperature and applied stress are studied to determine whether the HDI treated refractory materials can be utilized for glass furnace with oxy-fuel environment.

The ABAQUS finite element program has been used to perform numerical simulation of creep analysis for both untreated and HDI treated refractory materials. Creep user subroutines have been developed in conjunction with a mathematical creep model for both untreated and HDI treated refractory materials.

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LIST OF SYMBOLS

ε_c	-	Creep of a Refractory Material
t	-	Time
σ	-	Applied Stress by Molten Glass
T	-	Temperature Experienced by the Refractory Material
t_c	-	Thickness of HDI Coated Refractory Material
Q	-	Activation Energy
R	-	Universal Gas Constant
ε_0	-	Initial Strain
$\dot{\varepsilon}_c$	-	Creep Strain Rate
ε_T	-	Transient Creep Strain
m	-	Rate of Exhaustion of Transient Creep
E	-	Young's Modulus
μ	-	Poisson's Ratio
σ_w	-	Normal Stress at Wall of the Plunger
τ_w	-	Shear Stress at Wall of the Plunger
ρ	-	Mass Density of Glass
g	-	Acceleration Due to Gravity
h	-	Length of the Plunger in the Molten Glass Below the Melt Line
U_0	-	Initial Velocity of the Plunger at the Melt Line
ω	-	Frequency of Oscillation of the Plunger
n	-	Number of Oscillations of the Plunger Per Second

- μ - Coefficient of Viscosity of the Molten Glass
- a_1, b_1, c_1 - Material Constants of a Substrate Material
- a_2, b_2, c_2 - Material Constants of a Coating Material

CHAPTER 1. INTRODUCTION

1.1 Background

A large amount of natural gas is expended while melting glass in the glass industry¹. Unfortunately, degradation of furnace refractories decreases the performance of the furnace due to penetration of molten glass, which is caused by porosity of the refractory material and corrosion by the molten glass⁴. Materials used for furnace refractory vary from common firebricks to highly specialized materials for specific environments.

Refractory materials play a crucial role in glass melting industries. There is an ongoing research at Oak Ridge National Laboratory (ORNL) to develop new high performance refractory materials as well as surface treatment technologies for refractory materials to extend the life of furnaces for glass melting⁵. Improved refractory materials will also reduce heat losses from furnaces, thereby reducing the energy required for industrial heating processes.

Furnace designers recognize that increased optimization of furnace design through advanced refractories is needed as glass production furnaces are driven toward greater output and increased energy efficiency⁵. The conversion to oxy-fuel from traditional air-fuel firing is one means to meet the above mentioned objectives. Refractories for both oxy-fuel and air-fuel fired furnaces are subjected to high temperatures and stresses during service and may appreciably creep if the refractory material is not creep resistant⁵. Economically viable breakthroughs in refractory research are needed in corrosion/erosion resistance, improved strength, improved stiffness, reduced surface porosity and last but not the least increased creep resistance⁴.

As a method to improve the performance of refractory materials, ORNL is utilizing High Density Infrared (HDI) technology, which is relatively new to the materials processing, and is gradually being used in coatings and surface modifications of refractory materials¹⁰. To date, HDI treatment has mainly been applied to the treatment

of metals. However, recently it has been applied to the surface treatment of ceramic materials^{9, 10}. With this in mind and carefully reviewing Journal publications^{2, 3, 4, 5, 9, 10}, this thesis is focused on the study of creep resistance effectiveness of HDI treatment of refractory material.

The essential requirement for furnace designers and manufacturers is to have appropriate engineering creep models for predicting the structural integrity of the Furnace. According to the information available from Journals^{2, 5}, published engineering creep data are essentially non-existent for almost all commercially available refractories used for glass furnaces. Thus, there is a need to build a creep model for the enhanced refractory material studied. Current research funded by the West Virginia Development Office (WVDO) Glass Industry Assistance Project in association with an ORNL ongoing applied refractory project is focused to study creep resistance reliability of HDI treatment of refractory material to promote HDI treated refractory material as an enhanced furnace material.

1.2 Enhanced Refractories for Glass Melting Furnace

Ceramic refractories are widely found in high-temperature, chemically demanding applications. These materials are critical construction materials for glass melting industry, which is one of the energy intensive industries⁴. Ceramic refractories have exceptional properties such as high hardness enabling them to wear less and last longer, ability to operate at very high temperatures because of their high melting temperatures and capacity to withstand very harsh and corrosive environments such as acids, alkalis and organic solvents¹⁴. These refractory materials have remained largely unchanged for many years. The degradation of these materials due to penetration, corrosion and creep failure by molten glass demands the pursuit of new refractory materials. In the process of exploring new techniques for enhancing the existing materials, ORNL developed a unique method called HDI treatment for surface modification of ceramic refractory materials. However, this method was mainly applied to the surface treatment of metals

before exploring its application to ceramics to reduce surface porosity and reduce molten glass penetration^{9, 10}.

The term enhanced refractory material refers to the fact that HDI treatment is employed to enhance the material properties of existing commercial refractories. The enhanced refractory material is being proved by ORNL to have better corrosion resistance and reduced surface porosity. Hence it could be a candidate refractory material in use for Oxyfuel technology in the glass industry.

In the glass industry, alumina-zirconia-silica (AZS) refractories have been used for many years for glass contact applications. Previous work at the ORNL in association with University of Missouri Rolla (UMR) has shown that corrosion resistance is better with increasing zirconia content and also has demonstrated that zirconia-rich coatings can be formed on the surfaces of AZS refractories using HDI thermal treatment¹⁰. Typical uses of AZS refractory materials for sidewall and bottom blocks are shown in the Figure 1.1. Other uses include expendable feeder parts such as plungers, feeder tubes, spouts and orifice rings.

Figure 1.1 Refractories Commonly Used in a Soda-Lime Glass Melt Furnace

1.3 Research Objectives

Comparative creep curves of both untreated and HDI treated refractory materials have to be developed with appropriate mathematical creep models. With the information available from creep curves, creep resistance effectiveness of HDI treatment has to be determined. Temperature and stress dependence of creep strain are also explored to account for the shift of conventional natural gas firing to oxy-fuel firing. An attempt is made to predict better material constants for the mathematical creep model being employed to study the creep response of untreated refractory material. The material constants of the untreated refractory material are obtained through regression of the experimental data collected from masters' thesis at Alfred University²³. Material constants of the coating material for the HDI treated refractory material are assumed so that the coating material would have better properties compared to the substrate material. A finite element program using ABAQUS has been implemented to study the creep behavior of untreated and HDI treated refractory materials. The five main objectives of this research are as listed below.

1. Identifying critical range for key parameters that control creep strain of HDI treated refractory material such as time, temperature, stress and percentage of HDI treatment.
2. Developing creep curves for both untreated and HDI treated refractory materials.
3. Studying the creep resistance effectiveness of HDI treatment of refractory materials.
4. Determining temperature dependence of creep strain to effectively utilize the HDI treated refractory material for glass furnace with oxy-fuel environment.
5. Determining stress dependence of creep strain to see the possibility of improving furnace efficiency.

CHAPTER 2. LITERATURE REVIEW

2.1 Assessment of Degradation Mechanisms of Refractories in Glass Industry

The Handbook of Industrial Refractories Technology¹⁶ published by William Andrew provides a good insight into refractory zones in the glass-melting furnace and constitutive laws of elasticity and plasticity of Ceramic materials. This information was critical in knowing the temperatures, aggressive environment and severity of damage at different refractory zones within the furnace. The reasons for degradation of refractories are due to penetration and corrosion by molten glass and creep^{4, 16}. Furnace designers recognize that increased optimization of furnace design through advanced refractories are needed as glass production furnaces are driven toward greater output and increased energy efficiency. The conversion to oxy-fuel from traditional air-fuel firing is one means to meet the above mentioned objectives. Refractories for both oxy-fuel and air-fuel fired furnaces are subjected to high temperatures and stresses during service and may appreciably creep if the refractory material is not creep resistant⁵. Economically viable breakthroughs in refractory research are needed in corrosion/erosion resistance, improved strength, improved stiffness, reduced surface porosity and last but not the least increased creep resistance⁴. The Handbook of Industrial Refractories Technology and other literature^{20, 21, 22} describe the temperature and stress dependence of creep behavior of ceramic materials.

2.2 Creep Modeling of Ceramic Refractory Materials

Creep of refractories is an important mechanical property to be considered at elevated temperatures in order to understand the structural behavior of refractory material. Creep response of refractory materials has been expressed using different mathematical models. In the literature, one popular form of the creep mathematical model, defining the total percent of creep strain of ceramic materials is the Power Law^{20, 21, 22, 23}. The mathematical model employed in this thesis accounts for stress and temperature dependence in addition to time dependence. There are also other forms of Power Law

mathematical models, but these models are simpler without implementing the temperature dependence of creep strain. This thesis concentrates on static analysis of a cylindrical plunger that is used to control molten glass flow in bottle and jar manufacturing. The plunger experiences multiaxial loading as well as variable thermal loading during its service life and the mathematical creep model employed is supposed to be the best available model to implement actual environment experienced by the plunger.

2.3 Strengthening of Ceramic Materials

The industry goal to increase the energy efficiency of glass melting by applying new technologies has led to the following surface treatment technologies for strengthening refractory materials.

2.3.1 Shot Peening Technology

Shot peening technology application to strengthen ceramic materials is a new advancement in materials processing investigated by researchers at Fraunhofer Institute for Werkstoffmechanik, Germany¹². The researchers proved dramatic increase in the near surface strength of the refractory.

2.3.2 High Density Infrared (HDI) Technology

Surface treatment of materials by HDI heating is also relatively new to the materials processing area. HDI treatment has mainly been applied to the treatment of metals. However, recently it has been applied to the surface treatment of ceramic materials^{9, 10}. This treatment has proved to improve corrosion resistance and reduced porosity preventing penetration by molten glass. In this thesis, the focus is to study the effectiveness of HDI treatment in controlling creep of ceramic refractory material for use in glass furnace. The emphasis is on HDI treatment because there is an extensive research going on at ORNL and extension of this treatment to all the commercial refractory materials including those used for glass melting furnace.

CHAPTER 3. HIGH DENSITY INFRARED TREATMENT

3.1 Introduction

Surface treatment of materials by High Density Infrared (HDI) technology is relatively new to materials processing. The HDI technique has been applied to the surface treatment of both metals and ceramic materials^{9, 10}. The HDI material processing facility at Oak Ridge National Laboratory (ORNL) utilizes a plasma arc lamp to produce extremely high-power densities of up to 3.5 KW/cm^2 . See Figure 3.1. A controlled and contained plasma generated between two tungsten electrodes within a water-cooled quartz tube is utilized for HDI treatment of materials. The plasma arc generated beam can be scanned across a surface of the refractory material, which can generate extremely high heating and cooling rates.

Figure 3.1 Principle of HDI Technology

Prior studies on surface treatment of refractories have examined the surface modification of refractories using short wavelength radiation about $10.6 \mu\text{m}^{10}$. For the most part, these studies have relied on laser melting of the surface. With the laser technology, the area being treated is quite small in the order of with usual spot sizes less than 6 mm in diameter. To surface treat a large area, the laser must be scanned across the

part at speeds of 0.05 to 0.5 cm/sec with typically a 20 to 50% overlay from the previous scan. To do a large area requires several minutes up to hours. In addition, the overlapping of the scans also affects the resulting microstructure and causes significant micro cracking of the surface. Thus, laser melting technique is of limited interest.

On the other hand, HDI is capable of much larger area coverage, up to 35 cm across at a reasonable scan speed of 1 cm/sec. The radiant energy spectrum is between 0.2 and 1.4 μm . This advancement in surface treatment technology makes HDI treatment a viable industrial technique that is capable of continuously processing a larger number of parts. See Figure 3.2, which shows the HDI surface treatment facility at ORNL. Earlier research at ORNL has shown that HDI processing can be applied to refractory materials to reduce surface porosity by 90 % and the X-ray Diffraction of the specimen showed very little to no penetration of molten glass into the refractory^{9, 10}.

Figure 3.2 HDI Treatment Processing Facility at ORNL

The five main advantages of the HDI technology over laser technology are:

1. It can cover larger areas at scan speed of 1 cm/sec compared to Laser technology, which has a scan speed in the range of 0.05 to 0.5 cm/sec.
2. It consists of short wavelength radiation (0.2 – 1.2 μm) compared to 10.6 μm .

3. It has ability to produce fast heating and cooling rates.
4. It is capable of attaining very high power densities of up to 3.5 kW/cm^2 .
5. It has potential for continuous processing.

3.2 Importance of HDI Technology to Glass Industry

The successful extension of HDI technology to the surface treatment of ceramic materials has provided a means for enhancing material properties, such as increased corrosion resistance and reduced surface porosity of existing commercial refractory materials. The enhanced material properties of HDI treated ceramic materials make them candidate materials for use in oxy-fuel-fired furnaces. The use of oxy-fuel-fired furnaces for glass production has following four benefits⁵.

1. The elimination of regenerative structures shown in the Figure 3.3.
2. The NO_x emission is less for oxy-fuel-fired furnaces compared to air-fuel-fired furnaces.
3. The particulate level is much less compared to that of air-fuel-fired furnaces.
4. The capital cost per ton of glass pulled is approximately 58% less for oxy-fuel-fired furnaces compared to air-fuel-fired furnaces⁵.

Figure 3.3 Flat Glass Production Furnace

The main disadvantage of an oxy-fuel-fired furnace is its higher operating temperature and alkali partial pressure that hasten the corrosion of refractory materials, particularly in

silica refractories⁵. This disadvantage necessitates that both increased creep- and corrosion-resistant refractories be used.

In the glass industry, Alumina-Zirconia-Silica (AZS) refractories are commonly used in glass contact applications¹⁰, such as sidewall and bottom blocks of the furnace and in expendables - plungers, feeder tubes, spouts and orifice rings. HDI surface treatment of AZS refractories with Zirconia-rich coatings would extend their useful life in oxy-fuel-fired furnaces.

3.3 Experimental Procedure at ORNL

The plasma arc lamp used in the HDI surface modification of ceramics at ORNL consists of 3.175 cm-diameter quartz tube that is 11.5 cm long. The quartz tube is cooled by a film of water on the inner diameter and a flow of argon through the tube. The plasma arc is generated between two tungsten electrodes inside the tube. Figure 3.1 shows the principle of plasma arc generation. The lamp is typically configured with a reflector to produce different areas of uniform irradiance and also the distance between the lamp and the sample can be changed to vary the intensity of radiation impinging on the surface of the refractory material. However, at ORNL the lamp is operated in a stationary mode with the plasma arc beam defocused to produce a uniform irradiance over the surface of the refractory material^{9, 10}. Only the power of the lamp and the position of the refractory product are varied to control the irradiation intensity at the surface of the refractory material.

3.4 Successful Applications

The four glass industry refractories that have been surface treated using HDI at ORNL are as follows:

1. High Alumina Castable, with a composition of 88% Al_2O_3 , 4% SiO_2 , 4% calcium aluminate cement, 4% MgO .

2. Aluminosilicate, with a composition of 88% Al_2O_3 , 12% SiO_2 .
3. Fused cast AZS, with 33% ZrO_2 (referred to as F. C. AZS-33).
4. Cast and sintered AZS, with 20% ZrO_2 (referred to as C. S. AZS-20).

The coatings for refractories 3 and 4 above are made with slurries of ZrO_2 (3% Y_2O_3) powder and ethanol. The weight of powder applied to the surface of the refractory material is estimated to produce a well bonded dense coating of Zirconia, approximately 200 μm thick.

CHAPTER 4. CREEP MECHANISM AND CREEP MODEL VALIDATION

4.1 Introduction

Thermal stresses and creep would result in the failure of refractory materials. If the thermal stresses and creep are calculated for different controlling parameters such as temperature, time, applied stress and percent of HDI treatment, it may be possible to optimize these parameters to enhance the life expectancy of the refractories, and therefore, the furnace.

The operating life of a furnace will last until the refractories need replacement due to mechanical failure and corrosion. The lifetime of the glass-melting furnace largely depends on the thermo-mechanical behavior of the refractory that forms the furnace. Corrosion resistance, mechanical strength, maximum service temperature, increased creep resistance and resistance to thermal shock are some of the factors that are important in the selection of the refractories for different parts of the furnace²³.

Refractories are subject to heat-up stresses, long term deformations under steady state temperature, and applied stresses. Stresses develop due to temperature gradients and restraint of a structural steel framework.

4.2 Creep Mechanism

Creep of refractories is a mechanical phenomenon that plays an important role in understanding the structural behavior of the refractory lining system²². Refractories are often in operation under stress at elevated temperatures for considerable time periods. Refractory creep rate increases at high temperatures. It is important to understand high temperature creep behavior in order to estimate the service reliability of refractory materials. The creep threshold temperature, the temperature at which refractory creep should be considered, varies among different types of refractory materials.

The classic definition of creep is a thermally activated deformation process that occurs when materials are exposed to high temperatures (> 0.5 melting point) under a constant stress, resulting in permanent deformation of the material. The creep response of materials is usually expressed in three parts: primary, secondary and tertiary creep. Tertiary creep is generally not modeled since it leads quickly to failure. The primary creep and secondary creep strains are typically expressed by separate and distinct equations. The initial non-linear portion of the strain versus time curve represents primary creep. The secondary creep strain typically continues to increase linearly as a function of time.

Figure 4.1 Three Parts of a Typical Creep vs Time Curve

Creep data are commonly obtained by holding a specimen at a constant stress and temperature and measuring strain vs. time. For the present finite element analysis, experimental primary creep data on fused cast alumina was obtained from a masters' thesis at Alfred University²³.

4.3 Critical Parameters of an Enhanced Refractory Material in Glass Furnace

Table 4.1 lists the critical parameters that affect the creep behavior of an enhanced refractory material.

Table 4.1 Critical Parameters of an Enhanced Refractory Material in Glass Furnace

Critical Parameters	Symbol (Units)
Creep of a Refractory Material	ϵ_c (in./in.)
Time	t (hours)
Applied Stress by Molten Glass	σ (psi)
Temperature Experienced by the Plunger	T (°F)
Thickness of HDI Coated Material	t_c (μm)

4.4 Creep Models

The creep response of refractory materials has been expressed by many different equations. In a recent study²², various creep equation forms were developed in the analysis of a given set of creep data to provide a comparison of the relative effectiveness of these expressions in representing transient strain-time behavior. One popular form of the primary creep equation, defining the total percent of creep strain (ϵ_c), is:

$$\epsilon_c = e^a t^b \sigma^c \exp (-Q/RT) \quad (4.1)$$

where a, b and c are constants unique to the refractory material under consideration, e is the constant 2.71828, t is the time of interest, σ is the applied stress, Q is the activation energy, R is the universal gas constant and T is the absolute temperature.

A number of different types of creep curves have been recorded for ceramic materials²¹. With most ceramics of engineering significance, after the initial strain on loading (ϵ_0), the primary stage is found in which the creep rate decreases continuously with time until a steady state or secondary stage is reached when the creep rate, $\dot{\epsilon}_c$, is essentially constant. Because of the difficulties of obtaining reliable strain readings as a function of time, most creep studies of ceramics have reported only the steady-state

behavior. Nevertheless, it appears that the change in creep strain, ϵ , with time, t , through primary and secondary creep can be accurately described as

$$\epsilon = \epsilon_0 + \epsilon_T (1 - e^{-mt}) + \dot{\epsilon}_c t \quad (4.2)$$

where ϵ_T is the primary creep and m relates to the rate of exhaustion of transient creep. With engineering ceramics, the primary creep is usually small and, at low strain rates, a secondary creep can be attained immediately after loading.

4.5 Creep Dependence on Stress and Temperature

The dependence of $\dot{\epsilon}_c$ on the applied stress, σ , and the operating temperature, T , during long-term creep tests can be described as²¹

$$\dot{\epsilon}_c = K \sigma^n \exp (-Q/RT) \quad (4.3)$$

where K and n are constants. The wide variation in the values of n and Q reported for ceramic materials can be rationalized according to the type of ceramic and test conditions.

Figures 4.2 and 4.3 show the predicted creep behavior of a ceramic refractory material as a function of stress and temperature with temperature and time as parameters. These creep behavior curves can be used to optimize the parameters, stress and temperature.

Figure 4.2 Creep Strain Rate Dependence on Stress

Figure 4.3 Creep Strain Dependence on Temperature

4.5.1 Interpretation of Figure 4.2 and Figure 4.3

- T_3 , the higher operating temperature, might indicate oxy-fuel firing and T_2 or T_1 , the lower operating temperatures, would indicate natural-gas firing.
- The glass melting furnace can be operated at higher temperatures by incorporating oxy-fuel environment. Figure 4.2 indicates the need for more creep resistant refractory materials that can withstand higher operating temperatures and more applied stress.

4.6 High Density Infrared Treated Refractory Material Versus Untreated Refractory Material

Figure 4.4. Comparative Creep Curve of HDI Treated Material and Untreated Material

Figures 4.4, 4.5 and 4.6 show the creep behavior of refractory material as a function of time, stress and temperature respectively, with surface coating, glass temperature and operating time as parameters respectively.

Figure 4.5 Comparative Stress Dependence Curves of HDI and Untreated Materials

Figure 4.6 Comparative Temperature Dependence Curves of HDI and Untreated Materials

4.6.1 Interpretation of Figure 4.4, Figure 4.5 and Figure 4.6

- Figure 4.4 indicates the expected increased effectiveness of HDI surface treatment of refractory material (solid line). It illustrates the extended life of refractory material through HDI surface treatment.
- Figure 4.5 shows that more glass can be melted for the same creep strain rate of the refractory material. The HDI treated refractory material (dashed lines) can withstand more applied stress compared to that of untreated refractory material (solid lines) to reach the same creep strain rate.
- Figure 4.6 illustrates the possible effective usefulness of HDI treated refractory materials for oxy-fuel-fired furnace. The HDI treated refractory material (dashed lines) can withstand higher operating temperature for the same creep strain than untreated refractory material (solid lines).

4.7 Validation of Creep Equation

The mathematical creep model has material constants a , b and c as shown in Equation 4.1. These material constants for fused cast alumina are obtained by curve fitting procedure of the published experimental data. For the present analysis, the data has been collected from masters' thesis at Alfred University²³.

4.7.1 Experimental Creep Data

Table 4.2 Experimental Creep Data of Fused Cast Alumina

Temperature (°F)	Stress (psi)	Time (hrs)	Experimental Creep Strain (ϵ_c)
2600	50	5.0	1.00e-03
		12.0	2.50e-03
		24.0	3.50e-03
		48.0	4.50e-03
2600	100	5.0	5.00e-03
		12.0	8.00e-03
		24.0	1.10e-02
		48.0	1.30e-02
2650	50	7.5	2.00e-03
		37.5	6.00e-03
		63.0	7.00e-03
2650	150	4.0	5.00e-03
		10.0	9.00e-03
		24.0	1.30e-02
		70.0	1.80e-02

4.7.2 Curve Fit of Experimental Data

The material constants obtained by curve fitting of experimental data are substituted into the mathematical model expressed by Equation 4.1 to predict the creep strain values. These values are plotted against time and compared against the experimental data creep curves for 2600 °F. The two plots for each pressure are in good agreement as shown in Figure 4.7.

Figure 4.7 Comparative Experimental and Mathematical Creep Curves

CHAPTER 5. FINITE ELEMENT APPROACH FOR CREEP ANALYSIS

5.1 Introduction

Finite element method (FEM) for creep analysis in this thesis involves primarily the implementation of creep mathematical model to study the creep resistance effectiveness of HDI treated refractory material. The present analysis involves a cylindrical plunger model that is used in the control of molten glass in the manufacture of jars and bottles. The finite element model of a plunger is an axisymmetric model with symmetric boundary conditions and loading. Two FEM models are studied. One model is an axisymmetric model of a substrate material, fused cast alumina, and the other model is an axisymmetric model of the fused cast alumina that has been HDI surface treated with Zirconia.

5.2 Principles and Analysis Considerations

In an axisymmetric model, the geometry and boundary conditions are assumed to be revolved 360° about the vertical axis of the plunger. Plunger models are planar models in which the solver understands that the modeled half of the cross section is revolved 360°. By using a planar model instead of a full 3D solid model especially for nonlinear creep analysis solution, there is a significant gain in run time and cost saving.

The analysis of the plunger assumes that the plunger remains in the molten glass without oscillating. This assumption is based on the fact that the plunger does operate (oscillate) so fast that the thermal strains would remain almost the same should the plunger be considered oscillating or static at its operating position in the molten glass. The operating position in the analysis is when 3/4th of the plunger is in the molten glass, which is assumed to be at 2100 °F, and the remaining portion of the plunger is at 170 °F, positioned above the molten glass level.

5.3 Procedure for Creep Analysis

The FEA package considered in this thesis is ABAQUS. The ABAQUS program is implemented on a brick model by using the mathematical creep model with curve fitted values of material constants to reflect the experimental values. This procedure is considered as a means of validating the program and then, it is extended to study the HDI surface treatment of the Plunger model. The finite element analysis in this thesis involves primarily two steps, static analysis and visco analysis. The importance of these two steps is discussed as below.

5.3.1 Static Analysis

Since creep is a nonlinear problem, the sizes of element mesh in the model and time increment setting have a strong bearing on the convergence and accuracy of the solution²⁴. Initially, the loads are assumed to be applied so quickly that it involves purely elastic response, which is obtained by using the static analysis. Thus, using the known static solution and the creep data as a guide, the mesh refinement is designed.

5.3.2 Visco Analysis

The second step in the analysis involves creep response, which is obtained by using the visco analysis. This step is exclusively considered for creep response after allowing the structure to deform elastically so that the structure can be analyzed for elastic deformation followed by creep deformation. This procedure gives a broader understanding of the physical behavior of the structure both graphically and numerically because of the versatile finite element package. The convergence of this nonlinear mathematical creep problem can be assured by keeping the time interval, Δt_i , sufficiently small such that the variations of the stress tensor, $\Delta \sigma_{ij}$, do not exceed two percent of σ_{ij} ²⁶.

5.4 Reliability of Creep Analysis

This section is about the validation of the ABAQUS program. The following information is about the finite element analysis of the brick model and the validation of creep analysis results.

5.4.1 Finite Element Modeling of a Refractory Brick

The specimen under consideration for validating the ABAQUS program is a fused cast alumina brick for which experimental data is collected. The specimen is 4.5 in. x 1.5 in. x 1.5 in. with a square cross section. These dimensions are equivalent to 0.114 m x 0.038 m x 0.038 m in SI units.

Figure 5.1 Finite Element Model of Standard Brick

Material Properties: Young's Modulus (E) = 28.0e06 psi

Poisson's Ratio (μ) = 0.47

Type of Element: Plane Stress Element, CPS4

Constants in FEA creep equation that is referred in Equation 4.1: $a = 6.74$, $b = 0.54$, $c = 1.80$, $Q = 71,500$ cal/mol, $R = 1.98$ cal/mol-K.

5.4.2 Finite Element Analysis and Validation

The ABAQUS program was implemented for the finite element brick model. The load applied is 50 psi at one end by holding the specimen at the other end. Refer to Appendix A. The creep analysis was carried out for a time period of 50 hours and the results obtained are compared to the results of curve fit of experimental data. Good agreement has been achieved between FEA model and curve fit data.

Figure 5.2 shows the creep strain distribution after a time period of 50 hours. The maximum strain value is about 4.92×10^{-3} in magnitude as indicated by the blue color.

Figure 5.2 Creep Strain Distribution after 50 Hours

The analysis results over the time period of 50 hours are tabulated in Table 5.1 and plotted against the curve fitted plot of experimental data in Figure 5.3.

Table 5.1 FEA Creep Strain Data

Maximum Strain (in./in.)	Time (hrs)
1.85e-04	0.125
3.77e-04	0.463
5.72e-04	0.999
7.64e-04	1.7
9.22e-04	2.4
1.1e-03	3.33
1.33e-03	4.73
1.53e-03	6.13
1.72e-03	7.54
1.88e-03	8.94
2.04e-03	10.3
2.18e-03	11.7
2.32e-03	13.1
2.58e-03	15.9
2.82e-03	18.8
3.25e-03	24.4
3.45e-03	27.2
3.64e-03	30
3.82e-03	32.8
4.0e-03	35.6
4.16e-03	38.4
4.32e-03	41.2
4.48e-03	44
4.63e-03	46.8
4.78e-03	49.6
4.92e-03	50

Figure 5.3 shows validation of the ABAQUS program since the two curves show good agreement with each other.

Figure 5.3 Finite Element Analysis Validation

CHAPTER 6. Refractory Material Without HDI Treatment

6.1 Introduction

The refractory material considered for creep analysis is a fused cast alumina. This refractory material has dense crystal structure and little potential for glass contamination. Hence fused cast alumina is suitable for glass contact applications such as refiner, fore hearth, etc. Another material that is equally important for manufacture of expendables such as plungers, feeder tubes, spouts and orifice rings is Alumina-Zirconia-Silica (AZS). The reason for analyzing fused cast alumina is that the creep experimental data of fused cast alumina is collected from a masters' thesis at Alfred University²³.

6.2 Design Considerations for Untreated Refractory Material

The finite element analysis of the untreated plunger is based on certain assumptions. The assumptions and as well as the steps involved to study the behavior of the plunger are as described below.

6.2.1 Finite Element Model of Untreated Refractory Material

The steps involved in implementing the finite element model of the untreated plunger model are explained as below.

6.2.1.1 Geometry and Material Model

The untreated plunger is a cylindrical model with assumed dimensions of 26 in. long and 3.74 in. diameter. These dimensions are taken from an online refractories catalog of Emhart Glass. See Table 6.1 for an online refractories catalog of Emhart Glass. The axisymmetric finite element model is shown in the Figure 6.1.

Table 6.1 Online Catalog Showing Standard Plunger Dimensions

EMHARTGLASS Online Refractories Catalog

Orifice Rings
Plungers
 Tubes

Spouts
 Spout Assemblies
 Metering Spout System

Stirrers & Rotor Segments
 Spout Insulation & Cements
 Forehearth Maintenance

Plungers

Plungers - Ball Point

	Part #	X		Y		Z	
		IN	MM	IN	MM	IN	MM
144-11794	3	76	25 1/2	648	2 3/4	70
	144-11795	3 1/4	83	25 1/2	648	3 1/8	79
	144-11796	3 1/2	89	25 1/2	648	3 1/8	79
	144-11797	3 3/4	95	25 1/2	648	3 1/8	79
	144-780	3 1/4	83	26	660	3 1/8	79
	144-781	3 1/2	89	26	660	3 1/8	79
	144-3985	3 3/4	95	26	660	3 1/8	79
	81-4566	3 1/4	83	27	686	2 3/4	70

Figure 6.1 Finite Element Model of Untreated Plunger

The creep behavior is predicted by using the creep mathematical model referred in Equation 4.1. This model is implemented in the finite element program by making use of the creep subroutine program. See Appendix B. The following are the material properties of fused cast alumina. These material constants are used in the user creep subroutine program²⁶.

Material Properties of Alumina: Young's Modulus (E) = 28.0e6

Poisson's Ratio (μ) = 0.47

Type of Element: Axisymmetric Element, CAX4

Constants in FEA creep equation that is referred in Equation 4.1: $a = 6.74$, $b = 0.54$, $c = 1.80$, $Q = 71500$ cal/mol, $R = 1.98$ cal/mol-K.

6.2.1.2 Boundary Conditions

In order to save the computational time only half of the model is considered. Axisymmetric boundary conditions are applied to represent the other half of the model. The plunger model is also assumed to have a constraint in the Y-direction while it reaches nearer to the orifice plate in the process of pushing the molten glass.

Plunger is subjected to a temperature of 2100 °F over 3/4th of its length and the remaining portion is subjected to an assumed temperature of 170 °F as per the assumption described in Section 5.2. Axial load on the plunger is assumed to be about 30 lb. The pressures exerted by the molten glass are calculated based on an assumption of steady oscillation of a plane below a viscous fluid²⁵. The normal and shear stresses exerted on the plunger are calculated as follows.

1. **Normal Stress at Wall:** Normal stress on the plunger is calculated based on the assumption that the plunger is immersed in the molten glass through 3/4th of its length. The profile of the normal pressure load is as shown in Figure 6.2.

The formula²⁵ for normal stress is,

$$\sigma_w = \rho gh \quad (6.1)$$

where ρ is mass density of glass.

g is acceleration due to gravity.

h is height of the molten glass measured from the melt line.

Figure 6.2 Loading Profile in a Plunger

2. **Shear Stress at wall:** Shear stress on the plunger is due to the traction force exerted by the molten glass.

The formula²⁵ used to calculate the shear stress is

$$\tau_w = U_0 \sqrt{\rho \omega \mu} \sin\left(\omega t - \frac{\pi}{4}\right) \quad (6.2)$$

where U_0 is Initial Velocity

$$\omega \text{ is plate frequency, } \omega = 2\pi n \quad (6.3)$$

n is number of oscillations of the plunger per second (Assume $n = 5$).

μ is coefficient of viscosity, μ of glass at about 2100° F is 10^3 Poise. See Figures 6.3 and 6.4 for viscosity variation with temperature.

The approximate calculation of the shear stress at the wall of the plunger is about 6.36 psi.

Table 6.2 Critical Range of Key Parameters of a Coated Refractory Plunger

Critical Parameters	Symbol (Units)	Range Assumed
Creep of a Refractory Material	ϵ_c (in./in.)	-----
Time	t (hours)	0-500
Applied Stress by Molten Glass	Normal Stress (psi)	1.76 - 3.5
	Shear Stress (psi)	6.36 - 10
Temperature experienced by the Plunger	T (F)	2010 – 2200
Thickness of HDI coated material	t_c (μm)	200 - 400

Figure 6.3 Viscosity Variation with Temperature

Figure 6.4 Viscosity Variation with Temperature of Soda-Lime Glass

6.2.2 Creep Curve Behavior

Creep behavior of untreated fused cast alumina plunger is analyzed for a period of 500 hours. Figure 6.5 shows the creep strain contour of the untreated plunger after a period of 500 hours.

Figure 6.5 Creep Strain Contour after 500 Hours

The strain contour indicates that the maximum strain occurs at the bottom right corner of the plunger under assumed boundary conditions as specified in the Section 6.2.1.2.

Table 6.3 illustrates the creep strain values obtained over a period of 500 hours, which is the life time the refractory material is in use in the glass melting furnace. The average glass temperature is assumed to be 2060 °F.

Table 6.3 FEA Creep Strain Data

Time (hrs)	Maximum Strain (At Bottom Right Corner)
0.01	1.58e-08
0.03	3.68e-08
0.09	7.49e-08
0.17	1.09e-07
0.33	1.60e-07
0.65	2.33e-07

1.93	4.28e-07
2.01	4.39e-07
2.25	4.70e-07
2.49	5.00e-07
2.73	5.28e-07
2.89	5.47e-07
3.37	5.99e-07
3.85	6.48e-07
5.53	8.00e-07
6.81	9.03e-07
7.93	9.85e-07
9.21	1.07e-06
10.3	1.15e-06
11.6	1.23e-06
12.7	1.29e-06
14.0	1.36e-06
15.1	1.42e-06
16.4	1.49e-06
17.3	1.54e-06
18.5	1.59e-06
20.9	1.71e-06
25.7	1.92e-06
30.5	2.11e-06
35.3	2.29e-06
40.1	2.46e-06
44.9	2.62e-06
50.0	2.78e-06
55.8	2.95e-06
61.5	3.12e-06
68.9	3.32e-06
74.6	3.47e-06
80.4	3.62e-06
86.2	3.76e-06
93.2	3.93e-06
107.6	4.25e-06

126.8	4.65e-06
146.6	5.04e-06
167.1	5.42e-06
185.0	5.73e-06
204.2	6.05e-06
223.4	6.36e-06
242.6	6.65e-06
263.1	6.95e-06
282.3	7.23e-06
301.5	7.49e-06
320.7	7.75e-06
339.9	8.00e-06
359.1	8.25e-06
378.3	8.49e-06
398.2	8.73e-06
417.4	8.95e-06
436.6	9.18e-06
491.6	9.80e-06
500.0	9.89e-06

Figure 6.6 Creep Curve of Untreated Plunger

6.2.3 Creep Strain Dependence on Stress

Stress dependence of creep strain in the untreated plunger model is studied by the variation of applied normal stress and shear stress due to the molten glass at a constant temperature. The varied normal stress and the shear stress at the wall by the molten glass are taken as 1.76 psi, 2 psi, 2.75 psi, 3.5 psi and 6.5 psi, 7 psi, 8.5 psi, 10 psi respectively. Figures 6.7, 6.8, 6.9 and 6.10 show the creep strain contours with varied stresses after 500 hours. The average glass temperature is assumed to be 2060 °F

Figure 6.7 Creep Strain Contour for Applied Stresses of $\sigma_w = 6.5$ psi and $\tau_w = 1.76$ psi at 2060 °F

Figure 6.8 Creep Strain Contour for Applied Stresses of $\sigma_w = 7$ psi and $\tau_w = 2$ psi at 2060 °F

Figure 6.9 Creep Strain Contour for Applied Stresses of $\sigma_w = 8.5$ psi and $\tau_w = 2.75$ psi at 2060 °F

Figure 6.10 Creep Strain Contour for Applied Stresses of $\sigma_w = 10$ psi and $\tau_w = 3.5$ psi at 2060 °F

6.2.3.1 Creep Strain Dependence on Normal Stress

Table 6.4 illustrates the creep strain values obtained for varied normal stress at a glass temperature of 2060 °F over a time period of 500 hours.

Table 6.4 Creep Strain Data with Variation of Normal Stress (σ_w) at 2060 °F

Normal Stress (psi)	Creep Strain
1.76	9.88e-06
2.00	1.19e-05
2.75	1.89e-05
3.50	2.72e-05

Table 6.5 illustrates the creep strain values obtained for varied normal stress at a glass temperature of 2010 °F over a time period of 500 hours.

Table 6.5 Creep Strain Data with Variation of Normal Stress (σ_w) at 2010 °F

Normal Stress (psi)	Creep Strain
1.76	5.60e-06
2.00	6.72e-06
2.75	1.07e-05
3.50	1.54e-05

Figure 6.11 shows the Creep Strain Dependence on Normal Stress at two glass temperatures 2060 °F and 2010 °F respectively after a time period of 500 hours.

Figure 6.11 Creep Strain Dependence on Normal Stress

6.2.3.2 Creep Strain Dependence on Shear Stress

Table 6.6 illustrates the creep strain values obtained for varied shear stress at a glass temperature of 2060 °F over a time period of 500 hours.

Table 6.6 Creep Strain Data with Variation of Shear Stress (τ_w) at 2060 °F

Shear Stress (psi)	Creep Strain
6.50	9.89e-06
7.00	1.19e-05
8.50	1.89e-05
10.00	2.72e-05

Table 6.7 illustrates the creep strain values obtained for varied shear stress at a glass temperature of 2010 °F over a time period of 500 hours.

Table 6.7 Creep Strain Data with Variation of Shear Stress (τ_w) at 2010 °F

Shear Stress (psi)	Creep Strain
6.50	5.60e-06
7.00	6.72e-06
8.50	1.07e-05
10.00	1.54e-05

Figure 6.12 shows the creep strain dependence on shear stress at two glass temperatures 2060 °F and 2010 °F respectively after a time period of 500 hours.

Figure 6.12 Creep Strain Dependence on Shear Stress

6.2.4 Creep Strain Dependence on Temperature

Creep Strain Dependence on Temperature in the untreated plunger model is studied by the variation of temperature at constant applied stresses over a specific period of time. For this analysis three different temperatures of 2010 °F, 2060 °F and 2200 °F are considered. Figures 6.13, 6.14 and 6.15 show the creep strain contours with varied temperatures.

Figure 6.13 Creep Strain Contour at 2010 °F after 500 Hours

Figure 6.14 Creep Strain Contour at 2060 °F after 500 Hours

Figure 6.15 Creep Strain Contour at 2200 °F after 500 Hours

Table 6.8 illustrates the creep strain values obtained for varied temperatures for the applied stresses of $\sigma_w = 6.5$ psi and $\tau_w = 1.76$ psi after a time period of 50 hours.

Table 6.8 Creep Strain Data after 50 Hours

Temperature (°F)	Creep Strain
2010	1.58e-06
2060	2.78e-06
2200	1.05e-05

Table 6.9 illustrates the creep strain values obtained for varied temperatures for the applied stresses of $\sigma_w = 6.5$ psi and $\tau_w = 1.76$ psi after a time period of 250 hours.

Table 6.9 Creep Strain Data after 250 Hours

Temperature (°F)	Creep Strain
2010	3.82e-06
2060	6.75e-06
2200	2.53e-05

Table 6.10 illustrates the creep strain values obtained for varied temperatures for the applied stresses of $\sigma_w = 6.5$ psi and $\tau_w = 1.76$ psi after a time period of 500 hours.

Table 6.10 Creep Strain Data after 500 Hours

Temperature (°F)	Creep Strain
2010	5.60e-06
2060	9.89e-06
2200	3.70e-05

Figure 6.16 shows the Creep Strain Dependence on Temperature after time periods of 50 hours, 250 hours and 500 hours for the applied stresses of $\sigma_w = 6.5$ psi and $\tau_w = 1.76$ psi.

Figure 6.16 Creep Strain Dependence on Temperature

CHAPTER 7. Refractory Material with HDI Treatment

7.1 Introduction

The HDI treated refractory material in this thesis is a composite material that consists of a substrate material (fused cast alumina) and a coating material (Zirconia). This refractory material is supposed to be a better creep resistant material than that of an untreated refractory material because the coating material will have higher strength at elevated temperatures compared to that of a substrate material. ABAQUS program has been implemented to study the creep behavior of HDI treated refractory material.

7.2 Design Considerations for Untreated Refractory Material

The finite element analysis of the HDI treated plunger is based on certain assumptions. The assumptions and the steps involved to study the behavior of the HDI treated plunger are described below.

7.2.1 Finite Element Model of HDI Treated Refractory Material

The steps involved in implementing the finite element model of the HDI treated plunger model are explained as below.

7.2.1.1 Geometry and Material Model

The HDI treated refractory material has a coating material of thickness about 200 μm . This coating thickness is relatively very low compared to that of the diameter of the substrate material. The diameter of the substrate material is 3.74 in. as indicated earlier in Section 6.2.1.1. The axisymmetric finite element model of the HDI treated refractory material is as shown in the Figure 7.1. Figure 7.2 shows the magnified view of the mesh.

Figure 7.1 Finite Element Model of HDI Treated Plunger

Figure 7.2 Magnified View of Finite Element Model

The creep behavior of the HDI treated refractory material is predicted by using two different sets of material constants a_1 , b_1 , c_1 and a_2 , b_2 , c_2 associated with the mathematical creep models.

$$\epsilon_{c1} = e^{a_1} t^{b_1} \sigma^{c_1} \exp(-Q/RT) \quad (7.1)$$

$$\epsilon_{c2} = e^{a_2} t^{b_2} \sigma^{c_2} \exp(-Q/RT) \quad (7.2)$$

Equation 7.1 is used to model the creep behavior of substrate material and Equation 7.2 is used to model the creep behavior of coating material, which are incorporated using the creep subroutine program. The material properties of fused cast alumina are same as indicated in the Section 6.2.1.1. The assumed material properties of coating material at a temperature, 2100 °F are as given below.

Material Properties of Coating Material: Young's Modulus (E) = 30e6 psi

Poisson's Ratio (μ) = 0.45

Type of Element: Axisymmetric Element, CAX4

Material Constants in Equation 7.1: $a_1 = 6.74$, $b_1 = 0.54$, $c_1 = 1.80$, $Q = 71500$ cal/mol, $R = 1.98$ cal/mol-K.

Material Constants in Equation 7.2: $a_2 = 6.6$, $b_2 = 0.45$, $c_1 = 1.7$, $Q = 71500$ cal/mol, $R = 1.98$ cal/mol-K.

7.2.1.2 Boundary Conditions

The boundary conditions for the HDI treated refractory material are same as mentioned in the Section 6.2.1.2. The interface between the fused cast alumina and the coating material, zirconia, is assumed to be perfectly bonded. This boundary condition has been taken care of by the nature of the 2D axisymmetric model that is implemented.

7.2.2 Creep Curve Behavior

Creep behavior of HDI treated fused cast alumina plunger with Zirconia coating is analyzed for a period of 500 hours. Refer to Appendix C. Figure 7.3 shows the creep strain contour of the HDI treated plunger after a period of 500 hours.

Figure 7.3 Creep Strain Contour after 500 Hours

Table 7.1 illustrates the creep strain values obtained over a period of 500 hours, which is the time the HDI treated refractory material is in use in the glass melting furnace.

Table 7.1 FEA Creep Strain Data

Time (hrs)	Maximum Strain
0.17	1.01e-07
2.37	3.89e-07
3.81	5.01e-07
5.25	5.92e-07
11.25	8.78e-07
17.73	1.11e-06
29.25	1.43e-06
40.77	1.69e-06
52.29	1.92e-06
63.81	2.12e-06
83.97	2.44e-06
107.00	2.76e-06
130.00	3.04e-06
153.00	3.30e-06
176.00	3.55e-06
199.20	3.77e-06
222.20	3.99e-06
245.20	4.19e-06
268.30	4.38e-06
314.40	4.75e-06
360.40	5.09e-06
406.50	5.40e-06
437.20	5.61e-06
469.90	5.81e-06
500.00	6.00e-06

Figure 7.4 Creep Curve of HDI Treated Plunger

7.2.3 Creep Strain Dependence on Stress

Stress dependence of creep strain in the HDI treated plunger model is also studied by the variation of applied normal stress and shear stress due to the molten glass at a constant temperature. The varied normal pressure and the shear stress at the wall by the molten glass are taken as 1.76 psi, 2 psi, 2.75 psi, 3.5 psi and 6.5 psi, 7 psi, 8.5 psi, 10 psi respectively. Figures 7.5, 7.6, 7.7 and 7.8 show the creep strain contours with varied stresses after 500 hours.

Figure 7.5 Creep Strain Contour for Applied Stresses of $\sigma_w = 6.5$ psi and $\tau_w = 1.76$ psi at 2060 °F

Figure 7.6 Creep Strain Contour for Applied Stresses of $\sigma_w = 7$ psi and $\tau_w = 2$ psi at 2060 °F

Figure 7.7 Creep Strain Contour for Applied Stresses of $\sigma_w = 8.5$ psi and $\tau_w = 2.75$ psi at 2060 °F

Figure 7.8 Creep Strain Contour for Applied Stresses of $\sigma_w = 10$ psi and $\tau_w = 3.5$ psi at 2060 °F

7.2.3.1 Creep Strain Dependence on Normal Stress

Table 7.2 illustrates the creep strain values obtained for varied normal stress at a temperature of 2060 °F over a time period of 500 hours.

Table 7.2 Creep Strain Data with Variation of Normal Stress (σ_w) at 2060 °F

Normal Stress (psi)	Creep Strain
1.76	6.00e-06
2.00	6.86e-06
2.75	1.10e-05
3.50	1.55e-05

Table 7.3 illustrates the creep strain values obtained for varied normal stress at a temperature of 2010 °F over a time period of 500 hours.

Table 7.3 Creep Strain Data with Variation of Normal Stress (σ_w) at 2010 °F

Normal Stress (psi)	Creep Strain
1.76	3.40e-06
2.00	4.03e-06
2.75	6.25e-06
3.50	8.80e-06

Figure 7.9 shows the creep strain dependence on normal stress at two temperatures 2060 °F and 2010 °F respectively after a time period of 500 hours.

Figure 7.9 Creep Strain Dependence on Normal Stress

7.2.3.2 Creep Strain Dependence on Shear Stress

Table 7.4 illustrates the creep strain values obtained for varied shear stress at a temperature of 2060 °F over a time period of 500 hours.

Table 7.4 Creep Strain Data with Variation of Shear Stress (τ_w) at 2060 °F

Shear Stress (psi)	Creep Strain
6.50	6.00e-06
7.00	6.86e-06
8.50	1.10e-05
10.00	1.55e-05

Table 7.5 illustrates the creep strain values obtained for varied shear stress at a temperature of 2010 °F over a time period of 500 hours.

Table 7.5 Creep Strain Data with Variation of Shear Stress (τ_w) at 2010 °F

Shear Stress (psi)	Creep Strain
6.50	3.40e-06
7.00	4.03e-06
8.50	6.25e-06
10.00	8.80e-06

Figure 7.10 shows the creep strain dependence on shear stress at two temperatures 2060 °F and 2010 °F respectively after a time period of 500 hours.

Figure 7.10 Creep Strain Dependence on Shear Stress

7.2.4 Creep Strain Dependence on Temperature

Temperature dependence of creep strain in the untreated plunger model is studied by the variation of temperature at a constant applied stress over a specific period of time. For the present analysis three different temperatures of 2010 °F, 2060 °F and 2200 °F are considered. Figures 7.11, 7.12 and 7.13 show the creep strain contours with varied temperatures.

Figure 7.11 Creep Strain Contour at 2010 °F after 500 Hours

Figure 7.12 Creep Strain Contour at 2060 °F after 500 Hours

Figure 7.13 Creep Strain Contour at 2200 °F after 500 Hours

Table 7.6 illustrates the creep strain values obtained for varied temperatures for the applied stresses of $\sigma_w = 6.5$ psi and $\tau_w = 1.76$ psi after a time period of 50 hours.

Table 7.6 Creep Strain Data after 50 Hours

Temperature (°F)	Creep Strain
2010	1.07e-06
2060	1.87e-06
2200	7.00e-06

Table 7.7 illustrates the creep strain values obtained for varied temperatures for the applied stresses of $\sigma_w = 6.5$ psi and $\tau_w = 1.76$ psi after a time period of 250 hours.

Table 7.7 Creep Strain Data after 250 Hours

Temperature (°F)	Creep Strain
2010	2.40e-06
2060	4.23e-06
2200	1.58e-05

Table 7.8 illustrates the creep strain values obtained for varied temperatures for the applied stresses of $\sigma_w = 6.5$ psi and $\tau_w = 1.76$ psi after a time period of 500 hours.

Table 7.8 Creep Strain Data after 500 Hours

Temperature (°F)	Creep Strain
2010	3.40e-06
2060	6.00e-06
2200	2.20e-05

Figure 7.14 shows the creep strain dependence on temperature after time periods of 50 hours, 250 hours and 500 hours respectively for an applied stress of $\sigma_w = 6.5$ psi and $\tau_w = 1.76$ psi.

Figure 7.14 Creep Strain Dependence on Temperature

CHAPTER 8. Results and Discussion

8.1 Results Comparison

The results obtained in Chapters 6 and 7 are compared as below to show the effectiveness of HDI surface treatment of ceramic refractory materials for glass furnace. All results are based on assumed values for the coating material. Refer Section 7.2.1.1.

8.1.1 Creep Curves Comparison

The creep strain vs time curves are plotted for both untreated and HDI treated refractory materials. The creep strains for both the refractory materials are obtained with finite element numerical simulation program using ABAQUS over a time period of 500 hours. The creep curve of HDI treated refractory material shows the effectiveness of HDI treatment to extend the useful life of refractory material.

8.1.1.1 Extension of Useful Life of Refractory Material

Figure 8.1 illustrates that the HDI treated refractory material creeps about $6.00\text{e-}06$ in./in. over a time period of 500 hours. On the other hand, the untreated refractory material creeps about the same over a time period of 200 hours. This result indicates that the useful life of the refractory material has been extended by 300 hours with HDI treatment.

Figure 8.1 Creep Curves Comparison of HDI and Untreated Refractory Materials

8.1.2 Stress Dependence Curves Comparison

A comparison of the stress dependence curves is made to study the possibility of increasing the amount of glass to be melted and also the possibility of increasing the productivity of glassware manufacturing.

8.1.2.1 Normal Stress Dependence Curves Comparison

Normal stress directly corresponds to the amount of glass present as the normal stress experienced by the plunger increases with the height of the molten glass level. The normal stress comparison curves of untreated and HDI treated refractory materials reveal the importance of HDI treatment in increasing the amount of glass that can be melted.

8.1.2.1.1 More Glass Output

If a creep strain of 1.5e-05 in./in. is taken as a reference in Figure 8.2, the HDI treated refractory material operating at 2060 ° F can withstand a normal stress of 3.5 psi. On the other hand, the untreated refractory material can only withstand a normal stress of about 2.3 psi. This illustration gives a good understanding that the HDI treatment can improve

the output efficiency of a glass melting furnace because the normal stress directly relates the height of the molten glass present in a molten glass feeder.

Figure 8.2 Creep Strain Dependence on Normal Stress of HDI and Untreated Refractory Materials

8.1.2.2 Shear Stress Dependence Curves Comparison

Shear stress dependence of creep strain suggests the possibility of increasing the operational speed of the plunger as the number of oscillations per second of the plunger is directly proportional to the shear stress on the wall of the plunger.

8.1.2.2.1 Increased Productivity

Figure 8.3 illustrates that the HDI treated refractory material can be used to withstand the higher shear stresses experienced by a plunger when it is operated at higher speeds because the shear stress is directly proportional to the number of oscillations per second of the plunger. This illustration indicates the increased productivity of glassware manufacturing.

Figure 8.3 Creep Strain Dependence on Shear Stress of HDI and Untreated Refractory Materials

8.1.3 Temperature Dependence Curves Comparison

Study of temperature dependence of creep strain suggests the effective utilization of HDI treated refractory material for a glass melting furnace that contains an oxy-fuel environment, which can operate at higher temperatures.

8.1.3.1 Enhanced Refractory Material for Oxy-Fuel Furnace

Figure 8.4 illustrates that the HDI treated refractory material operating at a temperature of 2200 °F creeps about 2.25 e-05 in./in. over a time period of 500 hours. On the other hand, the untreated refractory material operated over 500 hours creeps the same at a temperature of about 2120 °F. Also, the coincidence of normal stress dependence curves and as well as the shear stress dependence curves of HDI and Untreated refractory materials operating at 2060 °F and 2010 °F respectively gives a good reasoning for the effective utilization of HDI treated refractory materials at elevated temperatures, which would be an oxy-fuel environment.

Figure 8.4 Creep Strain Dependence on Temperature of HDI and Untreated Refractory Materials

CHAPTER 9. CONTRIBUTIONS AND FUTURE RESEARCH

9.1 Contributions

The goal of this thesis was to determine the effectiveness of HDI treatment to extend the useful life of refractory material. Numerical simulation studies were conducted to document the improved creep resistance of the treated refractory material. The main result of this thesis was to identify the importance of HDI surface treatment of refractory materials to the glass industry and, in particular, to project its effective use for enhancing an oxy-fuel furnace. The contributions are based on the assumed material constants for the surface coated material as given in Section 7.2.1.1.

The six key contributions of this thesis are:

1. Identified the critical range for the key parameters that control the creep strain in fused cast alumina material. See Table 6.2. These parameters include the time the refractory material is in use in the glass melting furnace, the operating temperature of the glass melting furnace, the state of stress in the refractory plunger material that includes the normal stress and the shear stress due to the molten glass, and the thickness of HDI coated material in the refractory material of interest.
2. Developed creep curves for both the untreated fused cast alumina material and the HDI treated alumina material using numerical results obtained using the finite element program, ABAQUS. These results, which are shown in Chapters 6 and 7, should aid furnace engineers better predict and maintain structural integrity of glass melting furnace.
3. Determined the effectiveness of HDI treatment on the fused cast alumina refractory material in terms of its improved creep resistance by calculating that

the relative effectiveness of HDI treated alumina material compared to untreated alumina material was 150%. See Figure 8.1.

4. Determined that 65 % more glass can be melted using HDI treated refractory material by studying the creep strain dependence on normal stress. See Figure 8.2.
5. Determined that the creep strain dependence on shear stress of the plunger enabled 70 % increased productivity of glassware manufacturing using HDI treated refractory material. See Figure 8.3.
6. Studied the creep strain dependence on glass melting temperature and determined a 40 % improved effective utilization when HDI treated refractory material is used for a glass melting furnace that contains an oxy-fuel environment. See Figure 8.4.

9.2 Future Research

1. Alumina-Zirconia-Silica (AZS) refractory materials are widely used in the glass industry and hence experimental creep data might become available for HDI treated AZS materials.
2. Finite element analysis can be performed to optimize the critical parameters, such as temperature, applied stress and coating material thickness, that control the useful life of the enhanced refractory material.
3. Secondary creep analysis of HDI treated refractory materials can be performed using FEA with the help of experimental data to predict the failure.
4. Refractory bricks in the critical failure regions of an oxy-fuel-fired furnace environment can be analyzed.

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Appendix A. Input File and Creep Subroutine of Brick Model

A.1 ABAQUS Input File of Brick Model

```
**
*****
****
**   Written by : FEMAP
**   Version    : 8.00
**   From Model :
**   Date       : Thu Jun 03 11:17:49 2004
**
*****
****
**
*HEADING
Creep of a Fused Cast Alumina Brick
*NODE, NSET=GLOBAL
    1,      0.,      0.,      0.
    2,      0.3,      0.,      0.
    3,      0.6,      0.,      0.
    4,      0.9,      0.,      0.
    5,      1.2,      0.,      0.
    .....
    .....
    91,      0.9,      0.6,      0.
    92,      0.9,      0.3,      0.
    93,      0.3,      0.9,      0.
    94,      0.3,      1.2,      0.
    95,      0.3,      0.6,      0.
    96,      0.3,      0.3,      0.
*ELEMENT, TYPE=CPS4, ELSET=P1
    1,      49,      50,      51,      52
    2,      45,      46,      49,      52
    3,      23,      24,      45,      52
    4,      22,      23,      52,      51
    5,      20,      21,      22,      51
    .....
    .....
    70,      87,      86,      93,      95
    71,      88,      87,      95,      96
    72,      2,      3,      88,      96
    73,      95,      93,      38,      39
    74,      96,      95,      39,      40
    75,      1,      2,      96,      40
*ELSET, ELSET=OUT_PLT, GENERATE
1,75,1
** FEMAP Property 1 : Plane Stress
*SOLID SECTION, ELSET=P1, MATERIAL=M1
    1.,
** FEMAP Material 1 : Alumina
*MATERIAL, NAME=M1
*ELASTIC, TYPE=ISOTROPIC
```

```

27992334.,      0.47,      0.
*CREEP,LAW=USER
*BOUNDARY, OP=NEW
  1,      1
  1,      2
 36,      1
 36,      2
 37,      1
 37,      2
 38,      1
 38,      2
 39,      1
 39,      2
 40,      1
 40,      2
** Load Step 1 -----
*STEP
*STATIC
*CLOAD, OP=NEW
 16,      1,      -7.5
 17,      1,      -15.
 18,      1,      -15.
 19,      1,      -15.
 20,      1,      -15.
 21,      1,      -7.5
*NODE PRINT
  CF
  RF
  U
*EL PRINT, ELSET=OUT_PLT,POSITION=NODES
  SF
  S
  SINV
*FILE FORMAT, ASCII
*NODE FILE
  CF
  RF
  U
*EL FILE, ELSET=OUT_PLT,POSITION=NODES
  SF
  S
  SINV
*END STEP
** Load Step 2 -----
*STEP, INC=65000
*VISCO,CETOL=0.000225
  0.0001,      50.,      1.e-9,      0.
*NODE PRINT,FREQUENCY=500
  U,
*EL PRINT, ELSET=OUT_PLT,FREQUENCY=500,POSITION=NODES
  E,
  PE,
  IE,
*NODE FILE,FREQUENCY=500
  U,
*EL FILE, ELSET=OUT_PLT,FREQUENCY=500,POSITION=NODES
  E,

```

```

    PE,
    IE,
*END STEP

```

A.2 User Creep Subroutine Program for Brick Model

```
c USER CREEP SUBROUTINE
```

```
c
```

```

    SUBROUTINE CREEP(DECRA,DESWA,STATEV,SERD,EC0,ESW0,P,QTILD,
    1 TEMP,DTEMP,PREDEF,DPRED,TIME,DTIME,CMNAME,LEXIMP,LEND,
    2 COORDS,NSTATV,NOEL,NPT,LAYER,KSPT,KSTEP,KINC)
    INCLUDE 'ABA_PARAM.INC'
    CHARACTER*80 CMNAME
    DIMENSION DECRA(1),DESWA(5),STATEV(*),PREDEF(*),DPRED(*)
    DIMENSION TIME(1),COORDS(2)

```

```
c
```

```

    a=848.5463
    b=0.5438
    c=1.795
    Q=71532
    R=1.978
    T1=EXP(-Q/(R*1700))

```

```
c    print *,T1
```

```
        DECRA(1) =a*b*(TIME(1)**(b-1.))*(QTILD**c)*(T1)*DTIME
```

```
c    print *,DECRA(1),P,TIME(1),DTIME
```

```
c    WRITE(6,*) QTILD
```

```
c    WRITE(6,*) 'aaa', LEXIMP
```

```
        IF(LEXIMP.EQ.1) THEN
```

```
            DECRA(4) = b*a*(TIME(1)**(b-1.))*c*(QTILD**(c-1.))*(T1)*DTIME
```

```
        END IF
```

```
c
```

```
    RETURN
```

```
    END
```

Appendix B. Input File and Creep Subroutine of Untreated Plunger Model

B.1 ABAQUS Input File of Untreated Plunger Model

```

**
*****
*****
**      Written by : FEMAP
**      Version   : 8.00
**      From Model : C:\Abaqus creep\Sample plunger\plungsmp1.MOD
**      Date      : Fri May 28 18:25:07 2004
**
*****
****
**
*HEADING
Creep of Refractory Plunger
*NODE, NSET=GLOBAL
    1,      1.87,      26.,      0.
    2,      1.2466667,      26.,      0.
    3,      0.6233333,      26.,      0.
    4,      0.,      26.,      0.
    5,      0.,      25.277778,      0.
    .....
    .....
    151,      1.2466667,      18.107143,      0.
    152,      0.6233333,      18.107143,      0.
    153,      1.2466667,      17.410714,      0.
    154,      0.6233333,      17.410714,      0.
    155,      1.2466667,      18.803571,      0.
    156,      0.6233333,      18.803571,      0.
*ELEMENT, TYPE=CAX4, ELSET=P1
    1,      42,      41,      17,      29
    2,      43,      42,      29,      30
    3,      12,      13,      43,      30
    4,      29,      17,      18,      27
    5,      30,      29,      27,      28
    .....
    .....
    106,      151,      101,      102,      155
    107,      152,      151,      155,      156
    108,      45,      46,      152,      156
    109,      43,      13,      45,      156
    110,      42,      43,      156,      155
    111,      41,      42,      155,      102
*ELSET, ELSET=OUT_PLT, GENERATE
1,111,1
*ELSET, ELSET=SIDE
28,31,34,37,40,43,46,49,52,55,58,61,64,67,70,73,76,79,82,85,88,91,94,97
,100,103,106,111
** FEMAP Property 1 : p1
*SOLID SECTION, ELSET=P1, MATERIAL=M1
```

```

      1.,
** FEMAP Material 1 : Alumina
*MATERIAL, NAME=M1
*ELASTIC, TYPE=ISOTROPIC
  27992334.,      0.47,      0.
*CREEP, LAW=USER
*BOUNDARY, OP=NEW
  4,      1
  5,      1
  6,      1
  7,      1
  8,      1
  9,      1
 10,      1
 11,      1
 12,      1
 13,      1
 45,      1
 46,      1
 47,      1
 48,      1
 49,      1
 50,      1
 51,      1
 52,      1
 53,      1
 54,      1
 55,      1
 56,      1
 57,      1
 58,      1
 59,      1
 60,      1
 61,      1
 62,      1
 63,      1
 64,      1
 65,      1
 66,      1
 67,      1
 68,      1
 69,      1
 70,      1
 71,      1
 72,      1
 72,      2
 73,      2
 74,      2
 75,      2
** Load Step 1 -----
*STEP
L1
*STATIC
*CLOAD, OP=NEW
  4,      2,      -30.
 75,      2,      2.26339
 76,      2,      4.52679

```

```

77,      2,      4.52679
78,      2,      4.52679
79,      2,      4.52679
80,      2,      4.52678
81,      2,      4.52679
82,      2,      4.52679
83,      2,      4.52679
84,      2,      4.52679
85,      2,      4.52679
86,      2,      4.52678
87,      2,      4.52679
88,      2,      4.52679
89,      2,      4.52678
90,      2,      4.52679
91,      2,      4.52679
92,      2,      4.52678
93,      2,      4.52678
94,      2,      4.52679
95,      2,      4.52679
96,      2,      4.52678
97,      2,      4.52678
98,      2,      4.52678
99,      2,      4.52679
100,     2,      4.52679
101,     2,      4.52678
102,     2,      4.52678
41,      2,      2.26339
*DLOAD
  SIDE,HP2,1.76074,19.5,0.
*NODE PRINT
  CF
  U
*EL PRINT, ELSET=OUT_PLT,POSITION=NODES
  S
  SINV
  E
  PE
  IE
*FILE FORMAT, ASCII
*NODE FILE
  CF
  U
*EL FILE, ELSET=OUT_PLT,POSITION=NODES
  S
  SINV
  E
  PE
  IE
*END STEP
** Load Step 2 -----
*STEP, INC=65000
*VISCO,CETOL=0.00000179
      0.01,      500.,      1.e-9,
*NODE PRINT,FREQUENCY=500
  U,
*EL PRINT, ELSET=OUT_PLT,FREQUENCY=500,POSITION=NODES
  E,

```

```

    PE,
    IE,
*NODE FILE,FREQUENCY=500
    U,
*EL FILE, ELSET=OUT_PLT,FREQUENCY=500,POSITION=NODES
    E,
    PE,
    IE,
*END STEP

```

B.2 User Creep Subroutine Program for Untreated Plunger Model

c USER CREEP SUBROUTINE

```

c
  SUBROUTINE CREEP(DECRA,DESWA,STATEV,SERD,EC0,ESW0,P,QTILD,
1 TEMP,DTEMP,PRED,DPRED,TIME,DTIME,CMNAME,LEXIMP,LEND,
2 COORDS,NSTATV,NOEL,NPT,LAYER,KSPT,KSTEP,KINC)
  INCLUDE 'ABA_PARAM.INC'
  CHARACTER*80 CMNAME
  DIMENSION DECRA(1),DESWA(5),STATEV(*),PRED(*),DPRED(*)
  DIMENSION TIME(1),COORDS(2)
c
  a=848.5463
  b=0.5438
  c=1.795
  Q=71532
  R=1.978
  if(COORDS(2).ge.19.5) then
    TEMP=350
  else
    TEMP=1400
  End if
  T1=EXP(-Q/(R*TEMP))
C   print *,T1
C   DECRA(1) = EXP(a)*50**b*T1*QTILD**c*TIME(1)**m*DTIME
  DECRA(1) =a*b*(TIME(1)**(b-1.))*(QTILD**c)*(T1)*DTIME
c   print *,DECRA(1),P,TIME(1),DTIME
c   WRITE(6,*) 'aaa', LEXIMP
  IF(LEXIMP.EQ.1) THEN
    DECRA(4) = b*a*(TIME(1)**(b-1.))*c*(QTILD**(c-1.))*(T1)*DTIME
  END IF
c
  RETURN
END

```


Appendix C. Input File and Creep Subroutine of HDI Treated Plunger Model

C.1 ABAQUS Input File of HDI Treated Plunger Model

```
*Heading
** Job name: Job-1 Model name: Model-1
** -----
**
** PART INSTANCE: Part-1-1
**
*Node
    1,      1.877874,      19.5
    2,      1.87,      19.5
    3,      1.87,      0.
    4,      1.877874,      0.
    5,      1.877874,      26.
    .....
    .....
    1733,    1.444075,    25.64016
    1734,    1.521691,    25.64016
    1735,    1.596526,    25.64016
    1736,    1.66868,    25.64016
    1737,    1.738249,    25.64016
    1738,    1.805326,    25.64016
*Element, type=CAX4
    1, 1, 2, 10, 113
    2, 113, 10, 11, 112
    3, 112, 11, 12, 111
    4, 111, 12, 13, 110
    5, 110, 13, 14, 109
    .....
    .....
    1634, 1734, 1735, 255, 256
    1635, 1735, 1736, 254, 255
    1636, 1736, 1737, 253, 254
    1637, 1737, 1738, 252, 253
    1638, 1738, 138, 6, 252
** Region: (Zirconia:Picked)
*Elset, elset=Part-1-1__I1, generate
    1, 78, 1
** Section: Zirconia
*Solid Section, elset=Part-1-1__I1, material=Zirconia
1.,
** Region: (Alumina:Picked)
*Elset, elset=Part-1-1__I2, generate
    79, 1638, 1
** Section: Alumina
*Solid Section, elset=Part-1-1__I2, material=Alumina
1.,
*System
*Nset, nset=_PickedSet4
    9,
*Nset, nset=_PickedSet6
    7, 8, 9, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191,
    192, 193
```

```

194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207,
208, 209
210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 222, 223,
224, 225
226, 227, 228, 229, 230, 231, 232, 271, 272, 273, 274, 275, 276, 277,
278, 279
280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293,
294
*Elset, elset=_PickedSet6
  98, 118, 138, 158, 178, 198, 218, 238, 258, 278, 298,
318, 338, 358, 378, 398
  418, 438, 458, 478, 498, 518, 538, 558, 578, 598, 618,
638, 658, 678, 698, 718
  738, 758, 778, 798, 818, 838, 858, 878, 898, 918, 938,
958, 978, 998, 1018, 1038
  1058, 1078, 1098, 1118, 1138, 1139, 1159, 1179, 1199, 1219, 1239,
1259, 1279, 1299, 1319, 1339
  1359, 1379, 1399, 1419, 1439, 1459, 1479, 1499, 1519, 1539, 1559,
1579, 1599, 1619
*Nset, nset=_PickedSet7
  3, 4, 8, 233, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243,
244, 245
  246, 247, 248, 249, 250, 251
*Elset, elset=_PickedSet7
  53, 1119, 1120, 1121, 1122, 1123, 1124, 1125, 1126, 1127, 1128,
1129, 1130, 1131, 1132, 1133
  1134, 1135, 1136, 1137, 1138
*Nset, nset=side
  62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75
  76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89,
90, 91
  92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105,
106, 107
  108, 109, 110, 111, 112, 113
*Elset, elset=side, generate
  1, 53, 1
*Elset, elset=__PickedSurf5_S4, generate
  1, 53, 1
*Surface, type=ELEMENT, name=_PickedSurf5
__PickedSurf5_S4, S4
**
** MATERIALS
**
*Material, name=Alumina
*Creep, law=USER
*Elastic
  2.79923e+07, 0.47
*Material, name=Zirconia
*Creep, law=USER
*Elastic
  3e+07, 0.45
** -----
**
** STEP: static
**
*Step, name=static
*Static

```

```

1., 1., 1e-05, 1.
**
*CLOAD
side,2,2.39
1,2,1.195
4,2,1.195
** BOUNDARY CONDITIONS
**
** Name: BC-1 Type: Displacement/Rotation
*Boundary
_PickedSet6, 1, 1
** Name: BC-2 Type: Displacement/Rotation
*Boundary
_PickedSet7, 2, 2
**
** LOADS
**
** Name: Actuating Load    Type: Concentrated force
*Cload
_PickedSet4, 2, -30.
** Name: Triangle Load    Type: Pressure
*Dload
_PickedSurf5, HP, 1.76074, 19.5, 0.
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=1
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, variable=PRESELECT
**
** FIELD OUTPUT: F-Output-2
**
*Output, field
*Element Output
S, PE, PEEQ, PEMAG, LE
**
** HISTORY OUTPUT: H-Output-1, H-Output-2
**
*Output, history, variable=PRESELECT
*El Print, freq=999999
*Node Print, freq=999999
*End Step
** -----
**
** STEP: Creep
**
*Step, name=Creep, inc=10000
*Visco, cetol=1.79e-06
0.01, 500., 1e-09, 500.
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=1
**
** FIELD OUTPUT: F-Output-1

```

```

**
*Output, field, variable=PRESELECT
**
** FIELD OUTPUT: F-Output-2
**
*Output, field
*Element Output
S, PE, PEEQ, PEMAG, LE
**
** FIELD OUTPUT: F-Output-3
**
*Output, field, frequency=500
*Element Output
S, PE, PEEQ, PEMAG, CE, CEEQ, CEMAG, LE
**
** HISTORY OUTPUT: H-Output-1, H-Output-2
**
*Output, history, variable=PRESELECT
**
** HISTORY OUTPUT: H-Output-3
**
*Output, history, variable=PRESELECT, frequency=500
*End Step

```

C.2 User Creep Subroutine Program for HDI Treated Plunger Model

c USER CREEP SUBROUTINE

c

```

SUBROUTINE CREEP(DECRA,DESWA,STATEV,SERD,EC0,ESW0,P,QTILD,
1 TEMP,DTEMP,PREDEF,DPRED,TIME,DTIME,CMNAME,LEXIMP,LEND,
2 COORDS,NSTATV,NOEL,NPT,LAYER,KSPT,KSTEP,KINC)
INCLUDE 'ABA_PARAM.INC'
CHARACTER*80 CMNAME
DIMENSION DECRA(1),DESWA(5),STATEV(*),PREDEF(*),DPRED(*)
DIMENSION TIME(1),COORDS(2)

```

c

```

if(CMNAME.EQ.'Alumina') then
a=848.5463
b=0.5438
c=1.795
Q=71532
R=1.978
else
a=812.4058
b=0.5
c=1.7
Q=71532
R=1.978
End if
if(COORDS(2).ge.19.5) then
TEMP=350
else
TEMP=1400
End if
T1=EXP(-Q/(R*TEMP))

```

```

c  print *,T1
    DECRA(1) =a*b*(TIME(1)**(b-1.))*(QTILD**c)*(T1)*DTIME
c  print *,DECRA(1),P,TIME(1),DTIME
c  WRITE(6,*) 'aaa', LEXIMP
    IF(LEXIMP.EQ.1) THEN
    DECRA(4) = b*a*(TIME(1)**(b-1.))*c*(QTILD**(c-1.))*(T1)*DTIME
    END IF
c
    RETURN
    END

```