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# Finite Element Analysis of Pump Head - Plunger Assemblies: Impact of Plunger Geometry on Stress Distribution and Mechanical Integrity

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**Abstract:** ***Pump systems play a crucial role in various industries, and the performance and durability of their components, particularly the pump head - plunger assembly, are paramount. These assemblies are subjected to significant mechanical stresses, which can lead to premature failures if not thoroughly understood and mitigated. This study aims to investigate the failure mechanisms of pump head - plunger assemblies through finite element analysis (FEA). The primary objective of this research is to assess the impact of varying plunger designs on the stress distribution within the pump head. Two plunger designs, differentiated by their nose areas, were analyzed. The study involved simulating an impact velocity of 2.6 m/s to evaluate stress responses. The FEA model, developed using advanced computational techniques, allowed for a detailed analysis of stress patterns, highlighting critical zones where failure is most likely to occur.***

**Keywords:** Finite Element Analysis, Pump Head - Plunger Assembly, Stress Distribution, Design Optimization

## 1. Introduction

The performance and durability of pump systems, particularly the pump head - plunger assembly, are paramount across various industrial sectors. These components are subjected to a wide range of mechanical stresses, which can lead to premature failure if not properly understood and managed [1]. The failure of pump head - plunger assemblies during operation is a critical issue in various industries, affecting the efficiency and safety of mechanical systems. Understanding the causes and mechanisms behind these failures is essential for designing more reliable and durable pump systems. The interaction between the plunger and pump head is a particularly vital aspect of this problem, as it directly influences the assembly's stress distribution and mechanical integrity.

The performance and durability of pump systems, particularly the pump head - plunger assembly, are paramount across various industrial sectors. These components are subjected to a wide range of mechanical stresses, which can lead to premature failure if not properly understood and managed [1]. The failure of pump head - plunger assemblies during operation is a critical issue in various industries, affecting the efficiency and safety of mechanical systems. Understanding the causes and mechanisms behind these failures is essential for designing more reliable and durable pump systems. The interaction between the plunger and pump head is a particularly vital aspect of this problem, as it directly influences the assembly's stress distribution and mechanical integrity.

In this study, the failure mechanisms of pump head - plunger assemblies were investigated using finite element analysis (FEA). Previous studies on pump head - plunger assemblies have often focused on empirical observations and simplified analytical models, which may not fully capture the complexities of interaction between components [2]. These studies have provided valuable insights but are limited in accounting for variations in material properties, geometrical intricacies, and dynamic loading conditions. The existing literature often lacks comprehensive analyses of the failure mechanisms, particularly in the context of different plunger geometries and their impact on stress distribution.

The study aimed to address these gaps by conducting a detailed FEA study of two different plunger designs, distinguished by their nose area. The study involves subjecting the plunger to an impact velocity of 2.6 m/s, resulting in a load of 2 kN on the pump head hole. The primary objective is to compute the von Mises stresses and first principal stress distribution in the pump head and understand how different plunger geometries influence these stresses. The Goodman diagram was also plotted, and the pump head was checked for failure under repeated loading. This analysis will help identify the conditions under which the pump head is most likely to fail and provide recommendations for design improvements.

## 2. Literature Review

Stepanov et al. [3] investigated wear patterns on plungers in response to cyclic loading. Baart et al. (2009) [4] demonstrated that inadequate lubrication can cause wear and decrease pump system performance. Finite element analysis (FEA) has been proven to be an efficient technique providing detailed insights into stress distributions and failure mechanisms of pump assembly. Houzeaux and Codina (2007) [5] utilized FEA to model the stress distribution in pump components, providing a more precise understanding of the mechanical interactions within the assembly. This approach allowed for the simulation of complex geometries and material behaviors, surpassing the limitations of earlier empirical studies. Boglietti et al. (2009) [6] integrated thermal analysis into FEA studies. They demonstrated that temperature variations significantly affect the stress distribution within pump head - plunger assemblies, which can lead to thermal fatigue and subsequent failure. This finding was crucial in understanding the multi - physics interactions in pump systems, which include thermal and mechanical stresses. Langbauer and Antretter (2017) [7] explored the impact of geometric modifications on the performance of pump assemblies, specifically focusing on the plunger's nose area. Their work revealed that altering the geometry could significantly affect the stress concentration in the pump head, thereby influencing the likelihood of failure.

Several researchers have noted the limitations of existing studies. Rundo (2017) [8] pointed out that many FEA studies oversimplify material models, failing to account for real - world material behaviors such as plasticity and strain - rate dependence under dynamic loading conditions. Valentin et al. (2009) [9] echoed these concerns, emphasizing the necessity for empirical validation of FEA models to ensure their accuracy and reliability in predicting real - world performance. Recent studies have employed advanced materials and coatings to enhance pump components' wear resistance and durability. Zhang et al. (2011) [10] investigated the application of hard coatings on plungers, finding that these coatings can significantly reduce wear and extend the service life of pump assemblies. The integration of modern computational methods with experimental approaches has also been highlighted in the literature. Nagavally (2016) [11] employed a hybrid approach combining FEA with experimental testing to study the impact resistance of pump components. Their work demonstrated that such integrated methods could provide a more comprehensive understanding of the failure mechanisms, offering a pathway for developing more resilient designs.

## 3. Methodology

A 3 - dimensional CAD model of a pump head and two plunder designs (Design #1 and #2) were developed using PTC Pro/ENGINEER software (Fig.1). Design #1 and #2 have the same geometry, except the nose area of Design #2 was smaller than Design #1. Due to geometric and loading symmetry, one - quarter of the pump head and half of the plunger were modeled (Fig.2). This was done to save computational time for CAD modeling and FEA. The CAD model was exported to Altair Hypermesh as a STEP file for meshing.

(a) (b) (c)

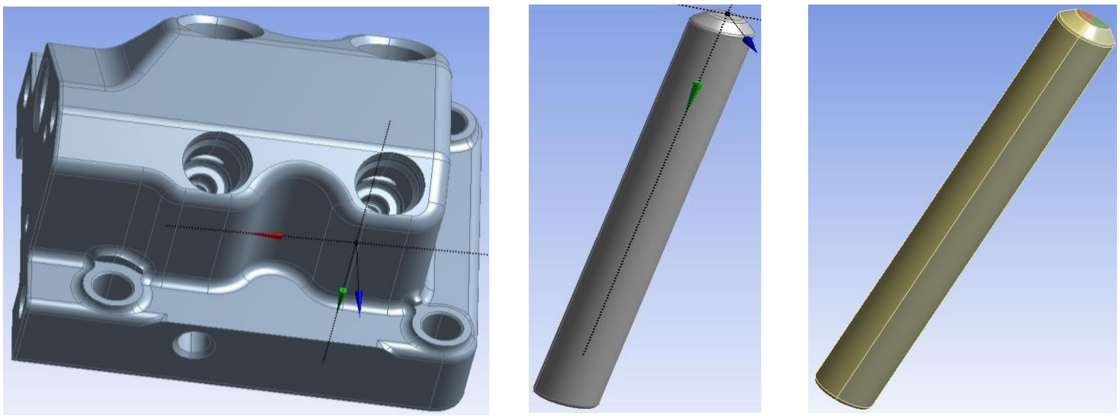

**Figure 1:** CAD model of (a) pump head and plunger Design (b) #1 and (c) #2

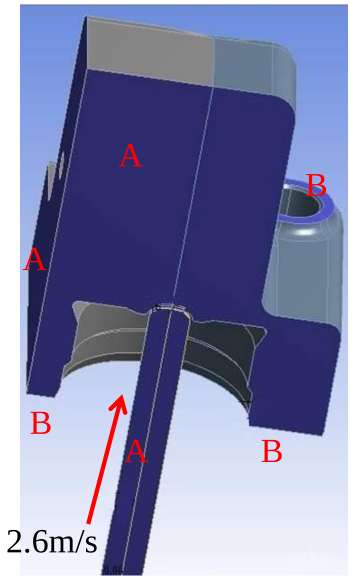


**Figure 2:** Loading and boundary conditions on pump head - plunger assembly. Symbol A denotes symmetric boundary conditions along the planes. Symbol B denotes SPC boundary conditions, where all nodes were fixed to move along six degrees of freedom (x, y, and z translational and rotational).

Four - nodded tetrahedral elements were generated to develop the finite element (FE) model. In all, 86, 246 elements and 92, 822 nodes were developed. The FE model was exported to the Ansys Mechanical 14.0 software package for assigning material properties, loading and boundary conditions, and FEA. Loading and boundary conditions are shown in Fig.2. Symbol A denotes symmetric boundary conditions along the plane. B denotes an SPC boundary condition, where all surface nodes are fixed and constrained to not move in any direction. The material property of each component was defined until the fracture limit. Yield stress was 957 MPa, and fracture stress was assigned to be 607 MPa. The von Mises and first principal stress distributions were computed by impacting the plunger (Design #1 or #2) at the head of the pump head at a constant velocity of 2.6m/s. The Goodman diagram was also plotted for both loading scenarios (i. e., using plunger #1 or #2).

Automatic single - surface frictionless contact was assigned between the pump head and the plunger.

## 4. Results and Discussions

Von Mises stress distribution at pump head after impact with plunger #1 is shown in Figure 3 (a). Maximum von Mises stress was 1328 MPa (Figure 3 (a) and (b)). Maximum principal stress was 690 MPa (Figure 3 (c)). The Goodman diagram in Figure 3 (d) illustrates the relationship between alternating stress and mean stress to assess the fatigue life of materials under cyclic loading. The red line represents the Mean Goodman Line, indicating a 50% probability of failure at 10 million cycles, showing the trade - off between mean stress and alternating stress to avoid failure. The blue dashed line, or the - 3 Sigma Goodman Line, offers a more conservative estimate by considering a 5% variation coefficient on fatigue and ultimate tensile strength. This provides a lower boundary for failure risk under material property variability. The green dashed line accounts for surface finish effects, specifically a 3.2 Ra derate factor, showing how surface roughness can reduce fatigue by serving as a stress concentrator. The solid green line represents the - 3 Sigma Tensile Yield Line, marking the threshold beyond which the material would yield rather than fail due to fatigue. The triangle marker (HCF1) indicates the operational stress conditions for a specific location, suggesting the component is safe under given conditions.

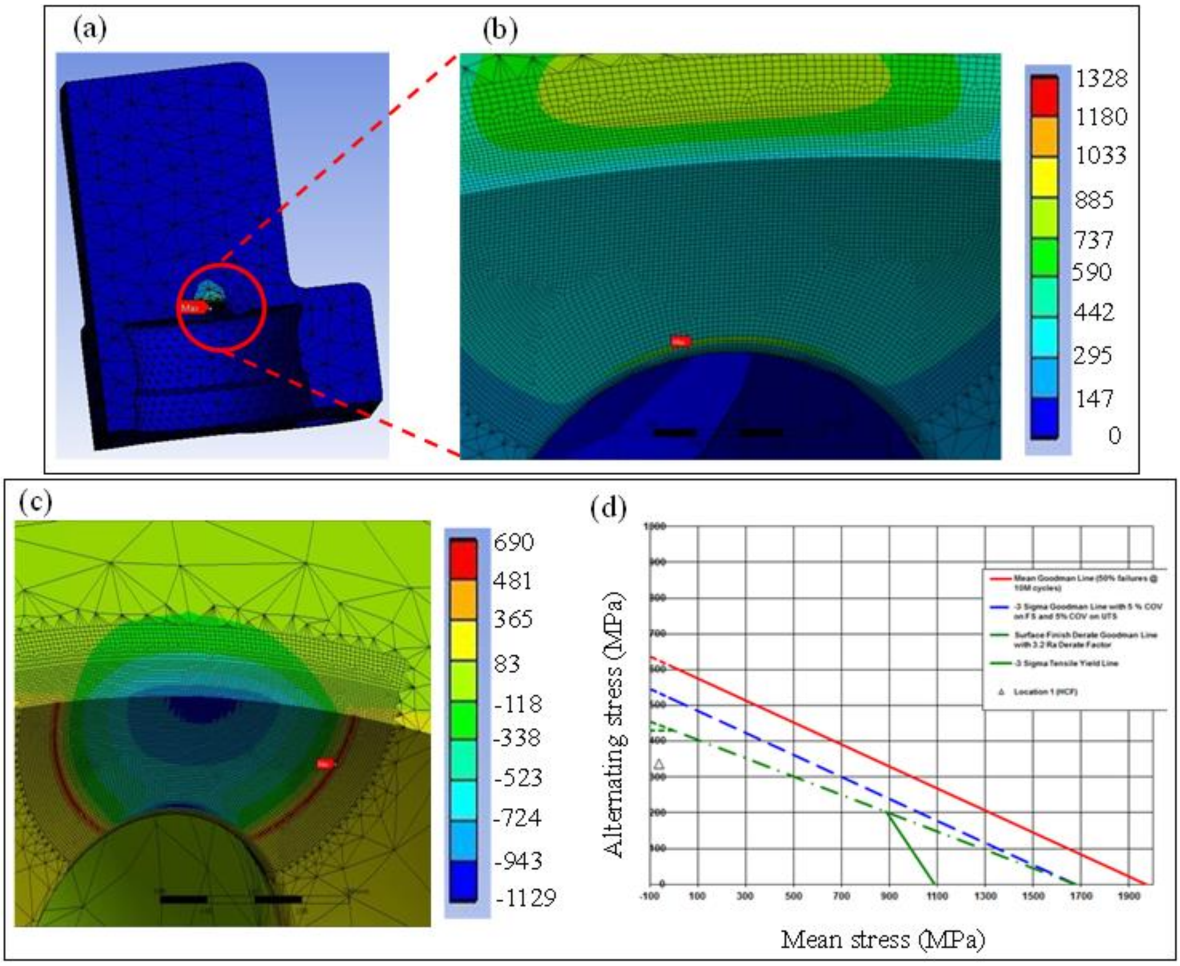


**Figure 3 (**a) Von Mises stress distribution at the (a) pump head and (b) impact site of the plunger (Design #1). (c) principal stress distribution at the impact site and (d) Goodman diagram of the pump head and stress plot (HCF1) of the pump head stresses.

Figure 4 illustrates the distribution of the von Mises and first principal stress distribution on the pump head following an impact with the Design #2 plunger, which featured a smaller nose diameter than the Design #1 plunger. Figure 4 (a) shows the von Mises stress distribution at the complete pump head. An enlarged view of the impact site in Figure 4 (a) is given in Figure 4 (b). Maximum von Mises stresses was 4049 MPa, surpassing the UTS value of 1678 MPa of the material at 550F. Similarly, maximum principal stress was significantly high (1313 MPa) (Figure 4 (c)). The Goodman diagram is given in Figure 4 (d). The triangle marker (HCF1) indicates the operational stress conditions for a specific location, suggesting the component's failure under given conditions.

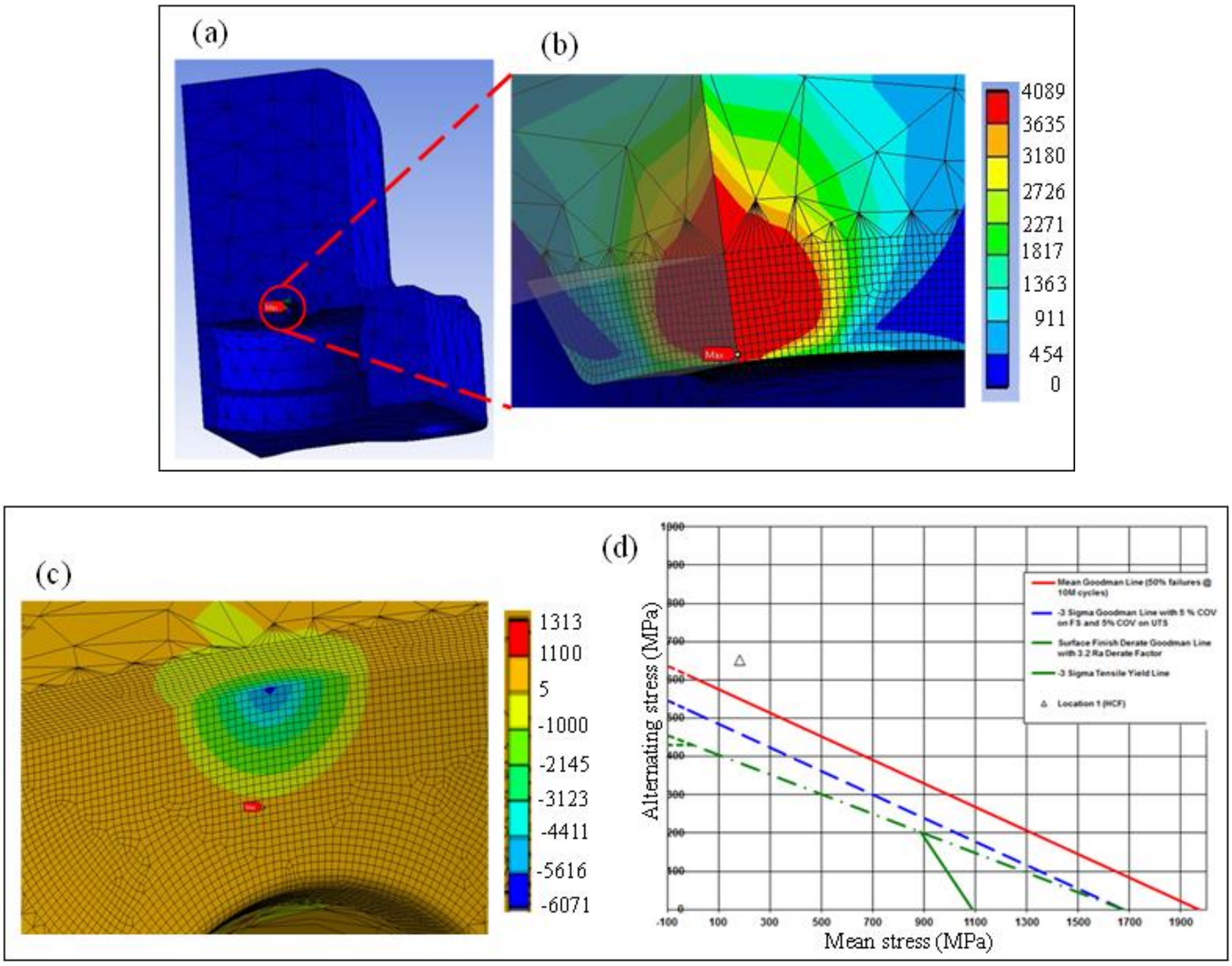


**Figure 4** (a) Von Mises stress distribution at the (a) pump head and (b) impact site of the plunger (Design #2). (c) principal stress distribution at the impact site and (d) Goodman diagram of the pump head and stress plot (HCF1) of the pump head stresses.

## 5. Conclusion

This study has provided a detailed analysis of the failure mechanisms in pump head - plunger assemblies, demonstrating that plunger geometry, particularly the nose area, plays a crucial role in stress distribution and mechanical integrity. The finite element analysis (FEA) revealed that a smaller nose diameter in the plunger design (Design #2) led to stress levels that exceeded the material's ultimate tensile strength, resulting in a higher likelihood of failure. In contrast, the larger nose diameter (Design #1) maintained stress within safe operational limits, indicating a more reliable design. These findings emphasize the importance of geometric optimization in enhancing the durability and reliability of pump systems.

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