# DESIGN OF HYBRID SETUP FOR DETERMINATION OF MECHANICAL PROPERTIES OF SERVICE EXPOSED MATERIALS USING SMALL PUNCH TEST AND FEM.

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
**COMPUTER AIDED ANALYSIS AND DESIGN**

Submitted by:

**SHIVAM SHEKHAR**

**(2023/CAD/04)**

Under the supervision of

**Dr. SANJAY KUMAR**

**DEPARTMENT OF MECHANICAL ENGINEERING**
**DELHI TECHNOLOGICAL UNIVERSITY**
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

**MAY, 2025**

# CANDIDATE DECLARATION

I, SHIVAM SHEKHAR, Roll No. 2023/CAD/04 student of M.Tech-Computer Aided Analysis and Design, hereby declare that the project Dissertation titled "Design of hybrid setup for determination of mechanical properties of service exposed materials using small punch test and FEM " which is submitted by me to the Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma, Associateship, Fellowship or other similar title or recognition.

Place: Delhi

Date: **SHIVAM SHEKHAR**

**DEPARTMENT OF MECHANICAL ENGINEERING**

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

# CERTIFICATE

I hereby certify that the Project Dissertation titled "Design of hybrid setup for determination of mechanical properties of service exposed materials using small punch test and FEM" which is submitted by **Shivam Shekhar**, Roll No. **2023/CAD/04**, Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi

Date:

**Dr. SANJAY KUMAR**
**ASSOCIATE PROFESSOR**
**SUPERVISOR**

# ABSTRACT

The accurate determination of mechanical properties for materials exposed to harsh service conditions is critical for ensuring the safety, reliability, and extended operational life of components in industries such as nuclear power, aerospace, and oil and gas. Traditional mechanical testing methods often demand large material volumes, which is impractical for in-service components or hazardous materials like irradiated specimens. The Small Punch Test (SPT) offers a miniaturised, semi-nondestructive alternative, yet its standalone application is limited by reliance on empirical correlations and the complex biaxial stress state, hindering direct property extraction. This research addresses these limitations by proposing a novel hybrid experimental-numerical setup that integrates SPT with the Finite Element Method (FEM).

Our methodology involves a meticulously designed hybrid setup that combines a miniaturised SPT fixture with high-precision extensometers for accurate punch displacement measurement. The iterative optimisation process, managed through ABAQUS routines, enables the extraction of fundamental material properties.

Through rigorous validation and case studies, the hybrid SPT-FEM approach demonstrated significant improvements in material property characterisation. Finite Element Analysis (FEA) results, including load-displacement curves and deformed specimen shapes, showed strong agreement with experimental data.

Notably, FEM analysis helped refine empirical correlations, leading to improved estimations for ultimate tensile strength. The setup's efficacy was validated across diverse service-exposed materials, including AL6082 alloy & Cr-Mo Steel. This research transforms the Small Punch Test from a qualitative screening tool into a robust, quantitative method for material characterisation, particularly for scenarios with limited or hazardous sample availability. The hybrid SPT-FEM setup provides critical insights into material degradation, enabling more accurate fitness-for-service assessments and reliable life extension predictions for ageing industrial infrastructure.

# ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my guide, **Dr. SANJAY KUMAR**, Associate Professor in the Department of Mechanical Engineering, for his invaluable guidance, support, and expertise throughout the course of this research project. His constant encouragement, insightful feedback, and dedication have been instrumental in shaping the direction and progress of this work. His deep knowledge and passion for the subject have inspired me to strive for excellence and explore new avenues in the field of jet impingement electronic chip cooling.

I would also like to extend my heartfelt appreciation to **Prof. B.B ARORA**, Head of the Department of Mechanical Engineering, for his support and encouragement. His vision and leadership have provided a conducive environment for academic and research pursuits. I am grateful for his valuable insights and guidance that have contributed to the overall success of this project.

Lastly, I would like to acknowledge my family and friends for their unwavering support, encouragement, and understanding throughout this research endeavour. Their love, belief in my abilities, and motivation have been the driving force behind my perseverance and determination.



**SHIVAM SHEKHAR**
2023/CAD/04
M.Tech (CAAD)
Delhi Technological University

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

## Abbreviations

| | |
|---|---|
| SPT | Small Punch Test |
| NDT | Non-destructive Testing |
| FEM | Finite Element Method |
| FEA | Finite Element Analysis |
| SSTT | Small Specimen Test Techniques |
| DBTT | Ductile Brittle Transition Temperature |
| MS | Mild Steel |
| STS | Structural Steels |
| MPa | Mega Pascal |
| KN | Kilo Newton |
| mm | millimeter |
| Res | Research |
| Mat | Materials |
| Ind | Industries |
| JAERI | Japenese Atomic Energy Research Institute |
| Std | standardarization |
| Iso | International |
| Stds | Standards |
| Num | Numerical |
| Comp | Comprehensive |
| Prop | Properties |
| Mech | Mechanical |
| Asso | Associated |
| YS | yield strength |
| Ult | Ultimate |
| US | Ultimate strength |
| PD | Plastic Deformation |
| Temp | Temperature |
| QC | Quality Control |
| Str. | Strength |
| Ten | Tensile |
| MSA | Medium strength alloy |
| Hard. | Hardening |

# CHAPTER 1

# INTRODUCTION

## 1.2 Context: Importance of Characterising Mechanical Properties for Materials Exposed to Services

The accurate characterization of mechanical properties for materials exposed to operational conditions is of paramount importance in various critical industries. Components in nuclear reactors, steam power plants, aerospace structures, and oil and gas infrastructure are subjected to prolonged periods of high temperature, mechanical loading, irradiation, and environmental aging [1]. These service conditions induce significant changes in the material's mechanical behavior, which directly impact its fitness for service, remaining useful life, and overall structural integrity. [2] Consequently, reliable assessment of these altered properties is essential for ensuring operational safety, guiding maintenance decisions, and facilitating life extension studies for industrial assets.

Conventional mechanical testing techniques, including uniaxial tensile testing, usually need for large amounts of material. The structural integrity of the system being assessed is frequently compromised while extracting large samples, which presents a substantial issue for in-service components.[2]Furthermore, in specialized fields like nuclear energy, the high activity levels of irradiated specimens severely limit the amount of material that can be safely extracted and handled.[4] This constraint is not merely a matter of convenience; it underscores a profound safety and logistical imperative for miniaturized testing techniques. The Small Punch Test (SPT), by inherently minimizing both material extraction and subsequent radioactive waste, becomes an indispensable methodology for nuclear applications. This necessity in the nuclear field provides a compelling validation for the broader adoption of SPT in other industries where material scarcity, hazardous environments, or the need for in-situ assessment are critical factors, including advanced manufacturing, biomedical implants, and high-performance aerospace components.

## 1.2 Overview of SPT and FEM in Material Science

The SPT is a semi-nondestructive, miniature experimental method used to assess a material's mechanical properties. Although even smaller Transmission Electron Microscope (TEM)-sized discs (3 mm diameter, 0.26 mm thickness) have been successfully used, it usually uses tiny disk-shaped specimens, which are 8 mm in diameter and 0.5 mm thick.[1] A distinctive force-displacement curve is produced in an SPT by centrally loading a tiny disc specimen that is securely clamped between an upper and lower die [1].

A powerful computer method that complements experimental methodologies for simulating complex physical events is the

Finite Element Method (FEM). FEM is commonly used in material science to anticipate strain fields inside a component under various loading situations, predict complex material behaviour, and analyse stress distributions.[4] SPT and FEM, when applied separately, aim to characterise a range of mechanical attributes, including tensile properties (including yield strength and UTS), fracture toughness, DBTT, and creep properties. [1].

The inherent complexity of the SPT lies in its biaxial loading mode, which generates a non-uniform stress state within the specimen, making it challenging to directly translate the experimental load-displacement curve into conventional uniaxial material properties[1]. This is where FEM offers a crucial advantage. FEM possesses the unique capability to simulate and visualize these complex, non-uniform stress and strain states within the SPT specimen.[9] This means that FEM does not merely validate SPT results; it actively deconstructs the intricate mechanics occurring within the SPT specimen. By doing so, it enables the extraction of fundamental uniaxial properties that the SPT alone cannot directly provide. This establishes a profound complementarity between the two methods, transforming their relationship from simple support to mutual enablement. This inherent synergy suggests that a hybrid approach is not solely about improving efficiency but fundamentally about enabling the extraction of critical material information that would otherwise be inaccessible or highly unreliable if either method were used in isolation.

### 1.3 Rationale for a Hybrid SPT-FEM Approach

The standalone application of the Small Punch Test, despite its advantages, faces significant limitations. SPT alone frequently relies on empirical correlations to infer conventional mechanical properties. These correlations are often highly material-dependent, primarily developed and validated for specific classes of steels, and tend to yield weaker and less reliable correlations for other metallic materials, such as certain additively manufactured alloys.[1] One significant disadvantage is the significant scattering in findings that occurs when correlations are applied to a variety of materials. This is mainly because current correlation methods depend on many mechanical properties [2]. Furthermore, accurately estimating strain and complex stress states directly from raw SPT force-displacement data is inherently challenging due to the specimen's complex biaxial deformation involving both bending and membrane stretching.[2]

To overcome these intrinsic constraints, the Finite Element Method (FEM) is in a unique position. FEM offers in-depth understanding of the intricate stress and strain distributions found in the SPT specimen, which makes it possible to validate current empirical correlations and—more significantly—to create new, stronger connections that are grounded in physics.[4] The prediction accuracy of material property characterisation is greatly improved by the integration of multi-fidelity data, which combines the plentiful, but lower-fidelity, data from FEM simulations with the high-fidelity experimental observations from SPT.[12]

To overcome these intrinsic constraints, the Finite Element Method (FEM) is in a unique position. FEM offers in-depth understanding of the intricate stress and strain distributions found in the SPT specimen, which makes it possible to validate current empirical correlations and—more significantly—to create new, stronger connections that are grounded in physics.[4]The prediction accuracy of material property characterisation is greatly improved by the integration of multi-fidelity data, which combines the plentiful, but lower-fidelity, data from FEM simulations with the high-fidelity experimental observations from SPT.[12]

### 1.4 Thesis Objectives and Structure

Developing a thorough grasp of the design and use of a hybrid experimental-numerical setup for assessing the mechanical properties of materials exposed to service is the goal of this thesis. The main goals are as follows:

- To elucidate the fundamental principles, advantages, and limitations of the SPT for characterizing in-service materials.
- To detail the theoretical basis and practical application of the FEM in simulating SPT and extracting material properties.

# CHAPTER 2

# LITRAURE REVIEW

-

## 2.1. Introduction

To foresee the elements' [7] remaining useful life, ensure their structural integrity, and make well-informed judgements on maintenance plans and possible life extension projects, it is critical to accurately and promptly assess these deteriorated attributes.[8]. However, to prepare standard-sized specimens, traditional mechanical testing procedures frequently need the extraction of huge amounts of material. For in-service components, where material removal must be completely non-destructive or maintained to a minimal in order to maintain the component's structural integrity, this criterion makes them impracticable or even impossible.[10]. This basic limitation emphasises how urgently alternative characterisation methods that can yield trustworthy mechanical property information from minuscule samples are needed.

## 2.2 Small Punch Test(SPT):

### 2.2.1 Fundamental Principles and Experimental Setup

In the mid-1980s, a novel approach to material characterisation was created: the Small Punch Test (SPT), also referred to as the disc bend test.[1]. The basic concept is to subject a thin, small disc specimen to a central load. Typically round, these specimens have an 8 mm diameter and 0.5 mm thickness, while research has examined considerably smaller dimensions, such as 3 mm in diameter and 0.26 mm in thickness, with promising results.[8] The specimen is secured between an upper and a lower die, and then a spherical or hemispherical punch is forced through the specimen's centre. In contrast to earlier techniques such as the shear punch test, this process results in a bulging distortion of the disc rather than a clean shear cut.[1].

A modular device intended to be positioned between the loading platens of a traditional tensile testing apparatus is frequently used as the experimental setup for SPT. [1] Critical data points, such as the applied force, the actuator displacement, and the exact punch displacement, are constantly recorded throughout the test, usually at a sampling frequency of 1 Hz.[1]. A calibration process is carried out to guarantee the precision of punch displacement measurements and take into consideration the testing system's intrinsic compliance. Without a specimen present, actuator and extensometer displacements are recorded. These compliance values are then deducted from the displacements recorded during the real tests.[1]

### 2.2.2 Specimen Geometries and Test Procedure

Because of the technique's adaptability, smaller variations, including 3 mm in diameter and 0.26 mm in thickness, have shown positive results even though the conventional specimen specifications for SPT are 8 mm in diameter and 0.5 mm in thickness.[5]. Another geometry that has been documented in the literature is square specimens, which are often 10 mm by 10 mm.[1].

Tests are often conducted under actuator displacement control at slow, controlled speeds, typically between 0.001 and 0.003 mm/s.[1]. High-temperature testing is rather prevalent, especially for materials that are exposed to hot extremes when in use, even though the majority of testing is done at ambient temperature (around 21 °C ± 2 °C).[1]. The test continuously collects force and displacement data, resulting in the characteristic load-displacement curve that forms the basis for subsequent mat. property computations.

### 2.2.3 Advantages and Limitations of Standalone SPT

The Small Punch Test has a number of strong benefits, especially when traditional material characterisation is difficult.

**Advantages:**

- **Minimal Sample Requirements**: Operating with very small material volumes is one of SPT's main advantages. It is therefore the perfect method for evaluating the mechanical characteristics of components exposed to service in situations where material extraction must be restricted, is unaffordable, or is just hard to come by.[5] This feature is particularly important for characterising samples that are extremely active or in development, as those used in the nuclear industry.[7]

- **Quasi-Non-Destructive Nature**: The original component's structural integrity is frequently unaffected by the tiny amount of material that is normally removed for an SPT specimen. This offers a major advantage over conventional, more destructive testing procedures since it frequently eliminates the need for considerable repairs following sampling.[7]

- **Localized Property Assessment**: SPT enables the precise characterization of material properties that may vary with location within a component. This includes assessing specific areas of weld joints, heat-affected zones, or very thin layers such as coatings or decarburized surfaces.[7]

- **Efficiency and Cost-Effectiveness**: The method can expedite material property studies and optimization processes. Furthermore, the development of automated SPT systems allows for high-throughput testing, further enhancing efficiency and reducing overall costs compared to manual, standard testing procedures.[8]

**Limitations:**

- **Complex Stress State**: A significant challenge of SPT lies in the complex, non-uniform, and continuously evolving multiaxial stress state experienced by the specimen during the test. The deformation involves a sequence of elastic bending, plastic bending, and membrane stretching.[5] This intricate stress distribution makes the direct interpretation of results and their correlation to conventional uniaxial properties inherently difficult.[11]

- **Standardization Gaps**: Despite considerable development, the SPT method still lacks universal standardization across all applications.4 While standards like ASTM E3205-20 exist [5], empirical correlations used to derive mechanical properties are often not universally accurate and are highly dependent on specific material properties and test geometry.[6] For example, the correlation factor for yield stress is influenced by geometrical parameters and material properties, leading to notable uncertainty in estimations.[13]
- **Anisotropy Challenges**: The biaxial loading mode characteristic of SPT can be problematic for materials exhibiting high anisotropy, such as certain additively manufactured (AM) metals. This can limit the applicability and accuracy of the technique for such materials.[1] Additionally, prior plastic deformation (pre-straining) can alter the material's isotropy, further affecting the reliability of SPT results.[12]
- **Weakness in Specific Property Characterization**: Standalone SPT methods traditionally show limitations in accurately characterizing certain properties, particularly in the areas of fracture and fatigue.[4]

The inherent complexity of the SPT's multiaxial stress state [16] stands in stark contrast to the simplicity of its experimental setup and small sample size.[4] This fundamental tension, where the ease of obtaining data from a small sample is met with the difficulty of accurately interpreting that data, is a critical underlying factor driving the development of hybrid SPT-FEM approaches. The analytical power of FEM is essential to deconvolve these complex stress states and extract meaningful uniaxial properties, thereby bridging the gap between experimental practicality and accurate material characterization.

## 2.3. Finite Element Method (FEM)

### 2.3.1 Fundamentals of FEM and Simulation Capabilities

A key component of contemporary engineering analysis, the Finite Element Method (FEM) is a potent numerical method for resolving challenging physical issues. A continuous domain, such a component or a whole assembly, is discretised into a finite number of smaller, geometrically simpler sub-regions called "elements" in order to achieve its basic idea.[22] FEM can precisely determine the mechanical behaviour of the complete system under a variety of factors, such as applied loads, temperatures, and pressures, by applying differential equations that control the physical behaviour to each of these components and then putting the findings together.[17]

FEM offers extensive simulation capabilities, allowing for calculations across a wide spectrum of engineering problems. These include linear and non-linear static analyses, thermomechanics, dynamic responses, forming simulations, assessments of operational stability, and vibration analyses.[17] It is widely employed for structural analyses to determine material and component loads, deformations, and contact interactions. Furthermore, FEM facilitates stiffness analyses to quantify component deformation under pressure or tension, strength calculations to ensure compliance with relevant standards, and life cycle analyses, which are crucial for developing durable products and avoiding costly recalls.[17] Commercial finite element software packages, such as ABAQUS and ANSYS, provide a comprehensive array of pre-defined material models, enabling engineers to simulate a vast range of loading situations and material responses.[11]

### 2.3.2 Application of FEM in Material Behavior Prediction

FEM simulation plays a pivotal role in predicting how a component or material will react to various external and internal influences. It provides engineers with invaluable insights into the behavior of complex systems and structures, enabling more informed design decisions and optimizing the product development cycle.[17] This predictive capability contributes significantly to the manufacture of durable and highly resilient products, ultimately ensuring optimal operational safety.[17]

The utility of FEM is particularly pronounced for prototypes or products that are inherently expensive or time-consuming to manufacture and test physically. By creating virtual models of real-world assets, FEM simulations allow for safe, rapid, and economical validation and testing of designs, thereby reducing the need for costly physical prototyping.[17] FEM's versatility extends to modeling virtually any shape geometry, from nanoscale structures to large passenger aircraft, and simulating diverse physical phenomena, including heat transfer, fluid dynamics, and structural mechanics.[17]In the context of material characterization, FEM is employed to simulate the elastoplastic response of materials, integrating the influence of structural parameters on mechanical properties.[5] It is also instrumental in understanding complex damage mechanisms, particularly in composite materials, by analyzing the behavior of individual phases and their interactions.[18]

### 2.3.3 Advantages and Limitations of Standalone FEM

The Finite Element Method offers numerous benefits in material characterization, but it also comes with certain limitations.

**Advantages:**

- **Cost and Time Efficiency:** The potential of FEM to lessen the requirement for intensive physical prototyping is a major benefit. Before any actual building begins, engineers may electronically assess designs for performance, safety, and dependability, which results in significant time and resource savings.[17]
- **Versatility and Scope:** FEM is highly versatile, capable of modeling intricate geometries, various material properties (including isotropic, orthotropic, and

anisotropic behaviors), and a wide range of physical phenomena, such as mechanical, thermal, and dynamic responses.[18]

- **Detailed Behavioral Insights:** The method provides granular insights into both the localized and global behavior of materials. This includes detailed information on stress distribution, comprehensive failure analysis, and precise deformation patterns, which are often difficult or impossible to obtain solely through experimental means.[18]

- **Non-Destructive Design Iteration:** FEM allows for the non-destructive manipulation of geometrical configurations and material parameters. This enables engineers to predict how designs will behave under various applied stresses and conditions without physically altering or damaging a prototype.[24]

**Limitations:**

- **Input Data Quality:** The quality and correctness of the input data have a significant impact on the precision and dependability of FEM simulations. The "garbage in, garbage out" principle can be embodied in findings that are incorrect or misleading because to errors or inconsistencies in mesh settings, material properties, boundary conditions, or applied loads.[17]

- **Material Data Requirements:** Exact constitutive laws and elastic constants (Young's modulus, shear modulus, and Poisson's ratio) must be obtained experimentally in order for FEM simulations to be accurate. This kind of information might not always be easily accessible, particularly for new materials, intricate composites, or materials that have seen severe deterioration while in use.[19].

- **Computational Intensity:** While FEM saves time compared to physical testing, complex simulations, particularly those involving very fine meshes, non-linear material behavior, or transient analyses, can be computationally intensive, requiring significant processing power and time.[17]

- **Reliance on Assumptions:** The accuracy of FEM is also contingent upon the assumptions and simplifications made during the modeling process. For highly complex materials like composites, micro-mechanical approaches in FEM, while detailed, still rely heavily on assumptions about material data and interaction behaviors.[18]

The capability of FEM to simulate "any physical behavior described using differential equations"[23] positions it as a foundational tool for materials science, extending beyond its role as a mere computational aid. This implies that as material science advances its understanding of fundamental physical processes—such as degradation mechanisms at a microstructural level or the intricate time-dependent behavior of materials—and develops more sophisticated constitutive models, FEM will become increasingly indispensable for predictive modeling. This progression moves FEM beyond simple design validation to a platform for deeper scientific discovery and application, underscoring a symbiotic relationship where advancements in understanding material physics directly enhance the power and utility of FEM.

## 2.4 Overview of SPT and FEM Modelling

To overcome the drawbacks of traditional approaches, the SPT was created as a miniature, testing that is almost non-destructive procedure. It uses small disk-like objects, typically 0.5 mm thick and 8 mm in diameter.; But even tiny ones, such those that are 3 mm in diameter and 0.26 mm in thickness, have been successfully employed.. Two upper and lower die securely clamp a disc specimen in an SPT, and a spherical or hemispherical punch subsequently loads the disc specimen in the centre. An ongoing record of force versus displacement is produced when the punch is delivered through the specimen, causing it to bulge instead of shear.[15] When there is a limited amount of material available for characterisation, this technique is especially beneficial.

When combined with experimental techniques, the FEM is a powerful numerical simulation technique. Complex geometries, like a component or a complete assembly, are discretised into a limited number of smaller, more straightforward "elements" or sub-areas in order for FEM to function. This segmentation makes it possible to calculate the mechanical behaviour of each sub-area separately, and then the component as a whole, under a variety of conditions, such as applied loads, pressures, and temperatures.[17] FEM is widely used in many engineering specialities for tasks including life cycle assessments, stiffness and strength calculations, and structural analyses. It helps with design optimisation and offers vital insights into system performance.[17]

### 2.4.1 Rationale for the Hybrid SPT-FEM Approach

In addition to experimental techniques, the Finite Element Method (FEM) is a potent numerical simulation method. FEM works by breaking down large geometries—like an assembly or a component—into a limited number of more manageable "elements" or sub-areas. The mechanical behaviour of each sub-area and, eventually, the component as a whole, under a variety of conditions, such as applied loads, temperatures, and pressures, can be calculated thanks to this subdivision.[17]. For tasks like life cycle assessments, stiffness and strength calculations, and structural studies, FEM is widely used in many engineering fields. It helps with design optimisation and offers vital insights into system performance.[20]

Hybrid SPT-FEM techniques are primarily driven by the inherent tension between the analytical difficulties of interpreting the complicated stress state of SPT and its practical utility for tiny samples. To accurately simulate and analyse the changing stress and strain fields inside the SPT specimen during the test, the Finite Element Method offers the required computational framework.Four Inverse analyses can be carried out by researchers using FEM, which efficiently deconvolutes the intricate experimental data to identify the fundamental basic material qualities that control the behaviour of the specimen. The experimental viability of SPT for scarce materials and the potent analytical powers of FEM are combined in this synergistic approach, which overcomes the drawbacks of each separate technique and makes it possible to reliably determine mechanical properties thatempirical correlations alone cannot provide.

### 2.4.2 . Integration of Experimental SPT Data and Numerical FEM Models:

The careful fusion of reliable numerical models with experimental data is essential to the hybrid SPT-FEM approach's effective use. To obtain the raw force-displacement (L-D) curve of the material being studied, SPT experiments are usually conducted first.[15]

A thorough Finite Element Method (FEM) model of the SPT setup is built after the experimentation phase. The actual elements, such as the dies, punch, and specimen geometry, are faithfully portrayed in this model. A powerful numerical simulation technique that can be combined with experimental techniques is the FEM.to maximise computing efficiency because they are non-deformable and don't require meshing or material characteristics.[10]. On the other hand, the actual specimen is modelled as a deformable solid, which makes it possible to apply material properties and create an appropriate mesh.10. The mesh density is important; finer meshes are frequently used for damage analysis in areas of significant strain, such the specimen's centre.[10].

Following the experiment, a comprehensive model of the SPT setup is produced using the FEM.This model faithfully captures the physical elements, such as the dies, punch, and specimen geometry. Because they are non-deformable and don't require meshing or material properties, analytical rigid shells are frequently used to simulate stiff components like punches and dies in order to maximise computational efficiency.[15] By modelling the specimen as a deformable solid, on the other hand, material properties can be applied and an appropriate mesh can be created.[10] In areas of significant strain, like the centre of the specimen, finer meshes are frequently used, especially for damage analysis, making mesh density an important consideration.[10]

A load-displacement curve is then generated by the FEM simulation using the parameters and material model that were chosen. We next compare this calculated curve with the experimental curve obtained by the SPT. By using the previously mentioned inverse analysis techniques (such as machine learning or optimisation algorithms), the "error" or disparity between these two curves is reduced. The material parameters are adjusted iteratively until the simulated and experimental results fit each other well.[10]. Lastly, it is critical to validate the optimised material parameters. This is frequently accomplished by predicting standard mechanical qualities (such as Ultimate Tensile Strength using the Considére criterion) using the derived parameters, then comparing the predictions to the outcomes of full-scale, standard tensile testing.[10].

The careful fusion of reliable numerical models with experimental data is essential to the hybrid SPT-FEM approach's effective use. To obtain the raw force-displacement (L-D) curve of the material being studied, SPT experiments are usually conducted first.[15].

Following the experimentation phase, a comprehensive FEM model of the SPT system is constructed. The actual elements, such as the dies, punch, and specimen geometry, are faithfully portrayed in this model. Rigid parts like the punch and dies are frequently modelled as analytical rigid shells to maximise computing efficiency because they are non-deformable and don't require meshing or material characteristics.10. On the other hand, the actual specimen is modelled as a deformable solid, which makes it possible to apply material properties and create an appropriate mesh.10. The mesh density is important; finer meshes are frequently used for damage analysis in areas of significant strain, such the specimen's centre.[10].

A thorough model of the SPT setup is created using the Finite Element Method (FEM) after the experimentation phase. This model faithfully captures the physical elements, such as the dies, punch, and specimen geometry. Because they are non-deformable and don't require meshing or material properties, analytical rigid shells are frequently used to simulate stiff components like punches and dies in order to maximise computational efficiency.Ten By modelling the specimen as a deformable solid, on the other hand, material properties can be applied and an appropriate mesh can be created.Ten In areas of significant strain, like the centre of the specimen, finer meshes are frequently used, especially for damage analysis, making mesh density an important consideration.[15]

After that, the FEM simulation uses the parameters and material model that were chosen to create a load-displacement curve. The experimental curve derived from the SPT is then contrasted with this simulated curve. By using the previously mentioned inverse analysis techniques (such as machine learning or optimisation algorithms), the "error" or disparity between these two curves is reduced. The material parameters are adjusted iteratively until the simulated and experimental results fit each other well.[10] Lastly, it is critical to validate the optimised material parameters. This is frequently accomplished by predicting standard mechanical qualities (such as Ultimate Tensile Strength using the Considére criterion) using the derived parameters, then comparing the predictions to the outcomes of full-scale, standard tensile testing.[10]

### 2.4.3 Role of Constitutive Models

Constitutive models are mathematical frameworks that describe how a material deforms and flows under various stress and temperature conditions. Their accurate selection and precise parameterization are paramount for achieving reliable FEM simulations within the hybrid SPT-FEM framework.

**Mao et al** [20], calculated the mechanical characteristics of nuclear pressure vessel steel that has been exposed to radiation using a tiny punch specimen. For a multipurpose experimental high temperature gas cooled reactor, 2 1/4 Cr.1Mo steel has been chosen as the material for the reactor pressure vessel (RPV). Non-irradiated and irradiated specimens were punched in a specifically made holder to conduct small punch tests, and the load-deflection curve was produced.[20]

**Hafeez et al** [20], highlighted a review of the literature on a number of miniature specimen test methods for assessing the mechanical and fracture characteristics of materials under extreme stress, including fracture toughness (KIC and JIC), yield strength, ultimate strength, ductility (fracture strain), and fracture appearance transition temperature (FATT). Several empirical equations were presented and analysed that were put forth by different researchers to predict these mechanical and fracture parameters. There was also discussion of the numerical simulation of such small punch test specimens by different researchers utilising the finite element method.

**Ruan et al** [20], used punch tests to evaluate the mechanical characteristics of the martensitic steel EUROFER97. The traditional tensile and impact characteristics of the tempered martensitic steel EUROFER97 were assessed using the ball punch test method. Tensile tests were conducted across the same temperature range for comparison. The yield stress and the ultimate tensile stress of the tension tests were found to correlate with the load at the beginning of plastic bending and the highest load of the punch tests.[20]

**Manahan et al** [20], conducted a miniature disc bend test that can be used to collect information about post-irradiation mechanical behaviour from disk-shaped specimens that are no bigger than those utilised for transmission electron microscopy. To transform the experimentally recorded load-deflection data into practical engineering knowledge, finite element analysis was done. The main objective of this work is to use the MDBT to generate biaxial stress/strain response and biaxial ductility information..

## 2.5 Service-Exposed Materials

### 2.5.1. Assessment of Aged and Irradiated Materials (e.g., Nuclear Reactor Components)

When evaluating materials taken from nuclear reactors, the hybrid SPT-FEM approach is especially crucial. The main cause of this is the small amount of highly active material that can be collected for testing in a safe manner.[7]. The SPT can be used to assess neutron embrittlement and evaluate the irradiation-induced change of the DBTT in reactor pressure vessel steels, which is an important safety metric.[19]

Researchers may precisely match experimental force-deflection curves with computer projections to infer the mechanical constitutive behaviour of irradiated materials, such as Eurofer97' and Zircaloy, thanks to simulations using the Finite Element Method, which are a major component of this study. Moreover, sophisticated radiation damage modelling, which is frequently combined with FEM, models intricate degradation processes at the macroscopic and atomic levels, including swelling, embrittlement, and phase transitions. Important predictions about the durability and dependability of reactor components during extended radiation exposure are given by these simulations. To optimise the Johnson-Cook material and damage models, which describe material plasticity and failure, SPT-FEM inverse analysis techniques are frequently employed to accurately reflect the degrading features of irradiation steels like P91 and Eurofer97.[15]..

### 2.5.2. Remaining Life Assessment and Structural Integrity Applications

A crucial tool for assessing the structural integrity of several industries, including nuclear, oil and gas, and power production, is the hybrid SPT-FEM technique.and residual lifetime of important components.[5] This approach makes it easier to track material deterioration over time, enabling comparisons with earlier evaluations to precisely calculate the components' remaining useful lives.[7]

There are numerous essential components that are utilised in real-world applications, such as the assessment of turbine rotor steel behaviour, the integrity of nuclear power plant components, steam power plant structures, and pipelines in the oil and gas industry.[7] The technique is also being applied to additively manufactured (AM) metals, which aids in the development of rapid certification procedures for these novel materials.[15]

The adoption and ongoing development of the hybrid SPT-FEM approach are directly driven by the urgency of characterising service-exposed components [7] in-situ and with little material removal. Comparing the intricate hybrid approach to conventional bulk testing techniques, it would be less justifiable in the absence of this particular industrial and safety requirement. The use of SPT is required due to the necessity of evaluating materials in service while limited by minimal material removal. Nevertheless, the intrinsic intricacy of SPT in the stress state necessitates the analytical capability of FEM for precise property extraction. In order to characterise in-service components without compromising their structural integrity, the hybrid SPT-FEM was created in response to practical and safety-critical needs.

The capability for parametric sweep offered by the software will make it possible to systematically study the change in pull-in voltage as well as overall performance of the device as each geometric parameter (length, thickness, gap, etc.) and material properties are varied one at a time. This parametric study could lead to a rapid design optimization, as it has been performed in other studies, to fit a precise voltage threshold and a desired dynamic behaviour [12]. The ability to rapidly test different design implementations is a huge advantage over traditional fabrication-and-test cycles, tremendously reducing development time and costs.

## 2.6 Objectives of the Present Study

The purpose of this study is to develop a technique for determining the 10 characteristics of comp. that are now in use, which is essential for estimating how long they will last. The SPT, a type of miniature testing, will be the focus of this investigation. Ands validate the results using the FEA model

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

This chapter describes the full methodological foundation for utilising a hybrid approach that blends SPT and FEM to ascertain the mechanical properties of materials that are subjected to service. The objective is to provide a comprehensive and repeatable explanation of the study approach, data gathering techniques, analytical procedures, and validation strategies.

The project will proceed through a structured, step-by-step methodology:

- Finite Element Model Construction: Develop finite element models using ABAQUS/CAE to simulate the load-deflection behavior of miniature specimens, mirroring the experimental procedures outlined by Singh [2].
- Mat. Prop. Determination (Power Law Fitting): Utilize a power law curve fitting technique to analyze data from both conventional tensile tests and miniature punch tests. This step is critical for identifying key parameters such as the strength coefficient (H) and the strain hardening exponent (n).
- Analyse the effects of changing mat. parameters (such as ultimate strength, H, and n) on the resulting load-deflection curve by conducting a thorough sensitivity analysis.
- Empirical Relationship Formulation: Develop empirical correlations for YS, US, str. coefficient, and strain hardening exponent.
- Initial Prop. Estimation: Apply these newly developed empirical relationships to estimate initial values for the aforementioned mat. Prop. of the unknown mat.
- TrueStress-Strain Curve Generation: Use the estimated values of H and n to construct the intermediate points of the truestress-truestrain curve, bridging the gap between the yield and ultimate str.
- Iterative Simulation and Curve Alignment: Perform finite element simulations using the derived material properties to generate a load-deflection curve. Subsequently, execute multiple iterations of these simulations, adjusting parameters such as YS and US. The insights gained from the prior sensitivity analysis will guide this iterative process, aiming to precisely match the simulated curve with the experimentally obtained SPT load-deflection curve.

- Final Mat. Prop. Characterization: The ultimate values of the mat. parameters, obtained after successfully aligning the simulated and experimental curves, will be established as the definitive prop. of the unknown mat.

## 3.2 Experimental setup

### 3.2.1 Experimental setup For SPT

The Small Punch Test (SPT) is composed of a punch, upper and lower dies, and specific fixtures that lock these elements to the loading machine. Transducers for load and displacement, also measuring data with precision, are included in the system. The setup can gather a higher level of data accuracy.

From the data collection perspective, a miniature sample is grasped on the borderline of the dies. The upper concave face of the specimen is displaced vertically and pulled into a centre hole. A hemispherical punch is mounted on the machine tool spindle; it vertically pushes the specimen until it fails. During this time, the load on the specimen and its movement are carefully marked to study metal displacement.

The essential components of the SPT system include:

- Miniature test specimens
- Punch holders, upper and lower dies, and hemispherical-tipped punches
- Fixtures for secure attachment to the test frame
- Precision loading system
- Load cells for accurate force measurement
- Laser displacement sensors and LVDTs for precise displacement tracking
- Direct recording and display mechanisms for load and displacement values.

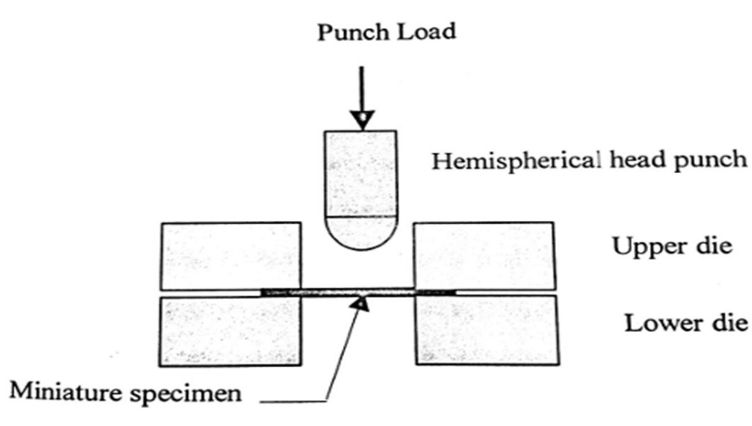


Fig.3.1: Schematic diagram of SPT apparatus with hemispherical-headed punch [20]

### 3.2.2 SPT Setup and Accessories

The main goal of SPT was to perform punch tests at temperatures starting at room temperature in order to get the load-displacement curve. A punch, a die holder to secure the upper and lower dies together, and lower and upper dies make up the SPT arrangement. A circular band that was 2 mm wide and securely clamped between the top and bottom dies and the die holder allowed the test to be conducted on a tiny specimen. Following the coaxial passage of the hemispherical punch through the upper die, the specimen's flat face is drawn through the centre aperture by applying a load. The punch's displacement and delivered force were precisely measured until the specimen broke.

The testing system's many parts and add-ons are listed below:

➢Small punch test specimens

➢ Setup consisting of lower & upper dies, Hapsimetric punch and die holder

➢ A load cell on a software-controlled test apparatus allows for precise punch displacement measurement.

➢ A PC to operate the testing equipment

➢ Attached to the test machine is an electronically controlled specimen heating furnace.

➢ Using argon gas to create an environment of inert gas

Nishant[20] performed the SPT experiment using a computer-controlled Zwick machine KAPPA 50SS, which has a 50KN capability. The upper and lower dies are securely clamped by the dies holder, an attachment that uses four M5 Allen screws spaced equally. Its construction provided for the seating arrangement of the die set.(20)

Circular plates made up the majority of the top and lower dies, which were secured together with die holders and four evenly spaced clamping screws at the edge. Based on the dies holder's exterior dimensions, the die set's outer dimensions were chosen" The lower die was counter-drilled to 6 mm after a 2.5 mm central hole was designed into its bottom surface. In order to accept specimens of the same diameter, this was further counter drilled to 8 mm. A 20 mm outside diameter projecting portion and a 6 mm diameter hole were machined into the upper die to match the lower die's counter-bored cavity.[20]

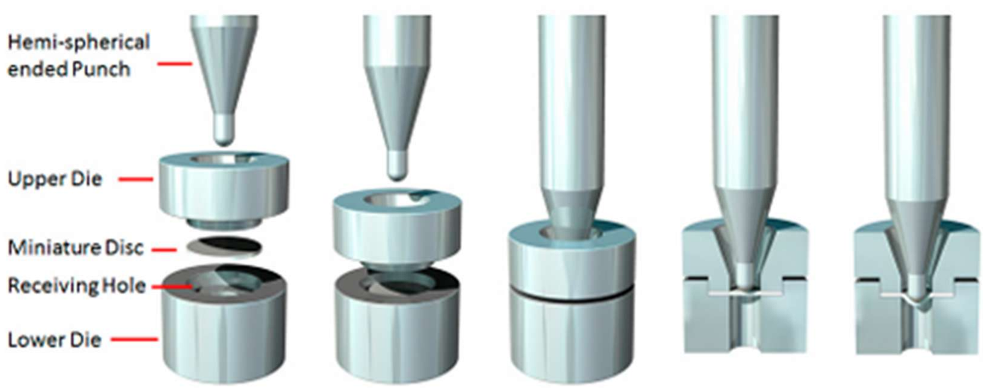


Fig. 3.2 Schematic representation of the SPT method [20]

### 3.3 Testing Methodologies and Equipment Design.

Modern tiny punch testing methods that are most commonly used use specimens that are 8 mm in diameter and 0.5 mm in thickness, while square specimens measuring 10 mm by 10 mm have been reported in the literature. A comprehensive fixture design comprising an upper and lower die, a ball with a diameter of 2.5 mm, and a rod that is 100 mm long and 2.5 mm in diameter was built by the National Institute of Standards and Technology (NIST). The punch is formed by the rod and ball working together to advance into the specimen that is held in the die.

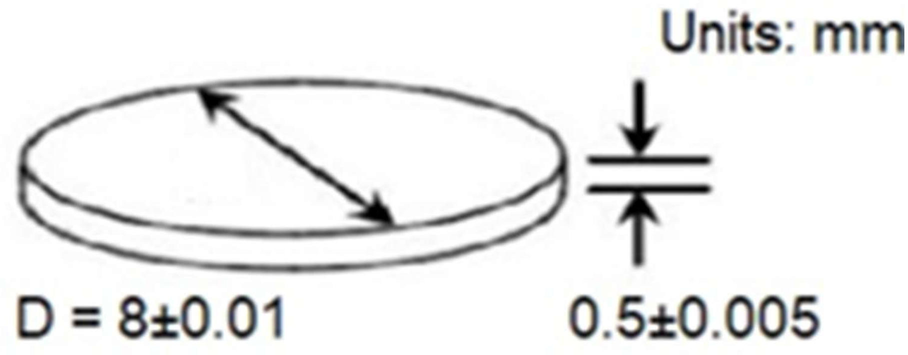


Fig 3.3 Specification of the Specimen[21]

NIST's experimental arrangement integrates a universal electro-mechanical test machine with a 5 kN load cell and an extensometer. The latter is placed on one column of the machine to capture relative movement between the actuator and the frame for a punch in the vicinity of the punch. This situation allows clear capture of force and displacement, which are critical in subsequent data evaluation.

Small punch tests usually yield force-displacement curves with five distinct regions: elastic region, local bending into membrane, transition stress regime, membrane stress regime, and final failure region. These characteristic regions form the basis for empirical correlations for the estimation of conventional mechanics.

### 3.4 Correlations and Data Analysis Methods

The formulation of empirical relations to estimate mechanical properties is one of the most important steps in developing the small punch testing technique. The relationship between tensile yield stress (σy) and an elastic plastic transition force (Fe) is used in traditional methods.

$\sigma_y = \alpha Fe/h^2$……... (3.1)[20]

where α is a previously constant dimensionless coefficient and h is the specimen thickness.

However, more advanced correlation strategies have been developed due to the fact, as some studies showed, that α cannot be considered constant. The methods of correlation for the estimation of the ultimate strength have been developed to advanced levels, including those that utilize the intersection force (Apri) at the beginning of plastic instability correlation

$\sigma u = \beta_{ui} * Fi/h_0^2$……... (3.2) [20]

has been proposed, where $\beta ui=0.1828*$(3.3) for $R^2=0.87$. The intersecting force corresponds ui=1.1h0……...(3.4) [20] and punch displacement vi=1.29h0…… (3.5) [20] to specimen deflection.

### 3.5 Standard Tensile Test Process

An INSTRON-4206 testing apparatus with an environmental chamber has been used to perform quasi-static tensile tests. The specimens' measurements were in line with those specified in ASTM E8M-04, Fig. 3.2.[20] [22] In order to attain greater strain rates, this purposefully short gauge length has been employed. After ten minutes of heating, all tensile tests were conducted inside the testing machine's environmental chamber. An acquisition system was used to gather load and displacement data, which were then processed by a specialised computer program. After then, the original data was processed to determine the actual stress-strain relationships. With room temperature (26ºC) serving as a reference, tensile test temperatures have been restricted to 150ºC, 200ºC, and 260ºC since the recrystallisation phenomenon for aluminium alloys begins at about 300ºC [20][22]. For the purpose of providing three distinct initial strain rates of 0.001s-1, 0.01s-1, and 0.1s-1, cross-head speeds of 1.92mm/min, 19.2mm/min, and 192mm/min have been chosen [22].

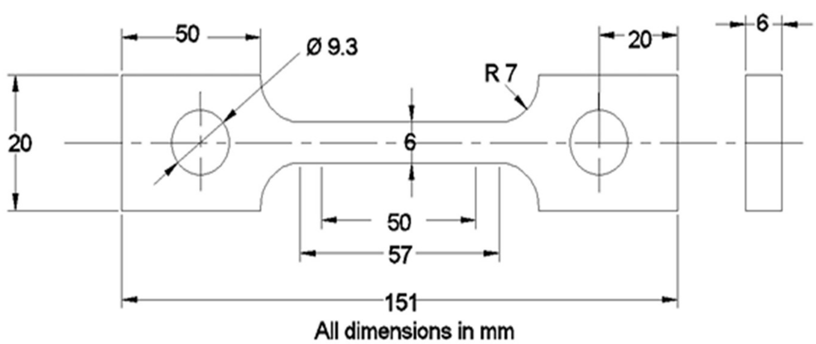

Fig 3.4 Tensile Test Specimen [22]

### 3.6 Finite Element Methodology

In this instance, an 8 mm diameter by 0.5 mm thick circular specimen is employed, and punching is done using a punch with a 2.5 mm nose diameter. The top and lower dies are likewise modelled with identical dimensions to Singh's dies used in SPT [11]. A 20 mm outer diameter and an 8 mm central hole are modelled for the lower die in order to suitably accommodate the specimen. To facilitate the simple passage of a hemispherical punch, the upper die is designed with an outer diameter of 20 mm and a central hole of 6 mm.

To closely resemble the real experiment, a three-dimensional model of the punch, dies, and miniature specimen has been created in the PART module. After discretising the model, 3-D iso-parametric elements are used in the MESH module to create the mesh. In this study, the small specimen is made using a solid 20 node quadratic brick element. On the other hand, solid 4 node linear brick elements have been employed for stiff objects (punch, lower and upper die). Hexahedra elements are used to discretise and simulate the tiny disc specimen. While there are 2428 elements and 2274 nodes in a punch, there are 2320 elements and 13197 nodes in a round disc.

The lower die has precisely the same 1080 nodes and is discretised into 1080 components. Likewise, the upper die has 939 nodes and 956 discretised components. The rigid punch is given a reference point, and the hemispherical headed punch is represented as a distinct rigid component. Additionally, lower and upper dies are made as distinct, stiff components, and each one is given its own reference point. The material and associated characteristics assigned to the tiny disc in the PROPERTY module are identical to those of the conventional uniaxial tensile test. The ASSEMBLY module brings the stiff punch and tiny disc into point contact with one another.

To replicate the small punch test as closely as feasible, lower and higher dies are positioned at the bottom and top of the punch, respectively. Both stiff punches, dies, and micro discs now have the appropriate boundary conditions. With the exception of the axial direction, the stiff punch's reference point displacement is limited in all directions. The punch is given a 1 mm downward movement. Assigning a downward force of 700 N to the upper die compensates for the six screws that are present between the dies and the resulting contact force. With the exception of the punch movement direction, the top die is limited in all other degrees of freedom.

This has limited all six degrees of freedom because the bottom die is stationary. The simulation operates in the Static-General mode, which is defined by the STEP module. The INTERACTION module is utilised to define the surface-to-surface interaction between the top surface of the micro disc (SLAVE surface) and the hemispherical surface 31 (MASTER surface) of the rigid punch. Furthermore, surface-to-surface interaction determines the top surface of the specimen and the lower surface of the higher die, for example, the bottom surface of the specimen and the top surface of the lower die. Following that, a job is created and submitted for simulation. The tiny punch test curve is then contrasted with the load vs. displacement curve from the Visualisation module.

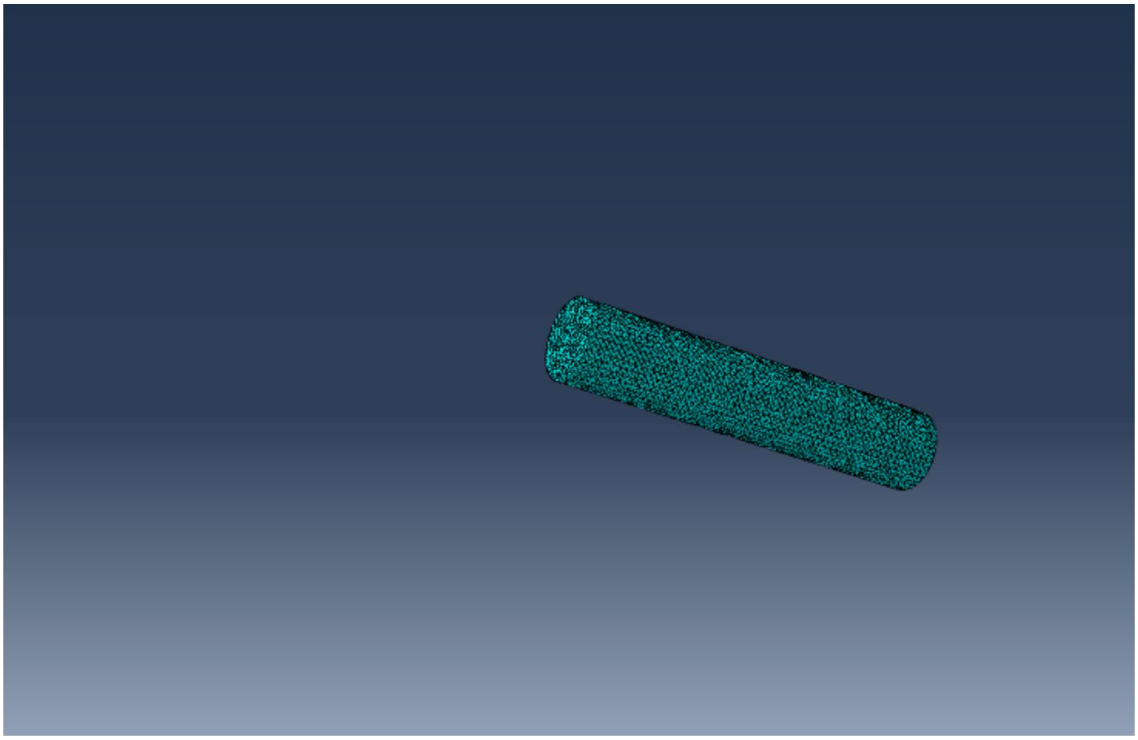

Fig.3.5 Meshed Hemispherical Punch

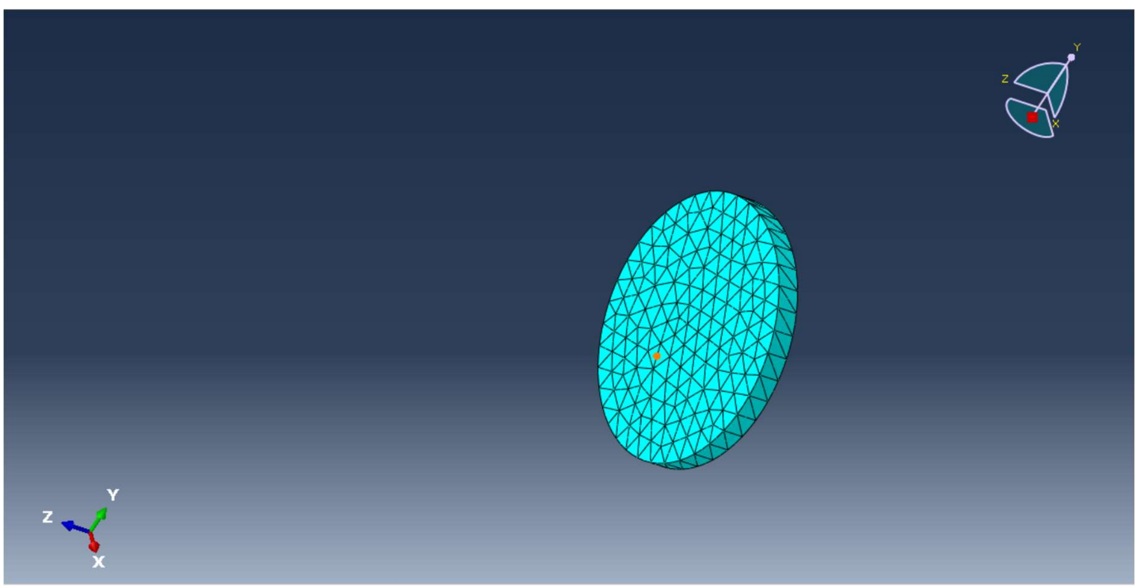


Fig.3.6 Meshed Specimen Disc

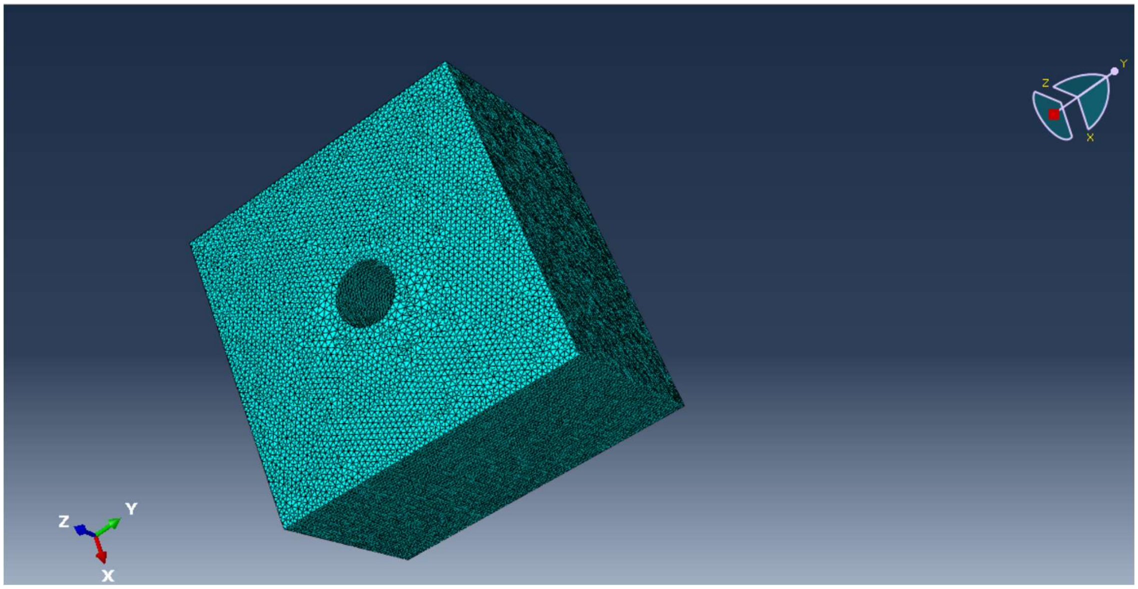

Fig3.7 The Die Complex for holding the Specimen and Punch

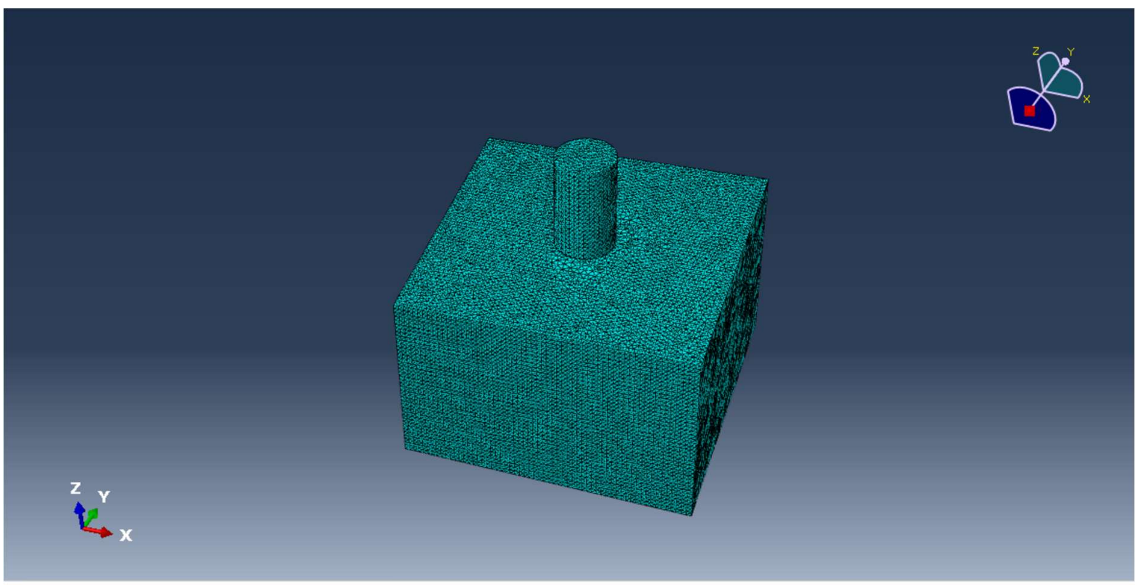

Fig 3.8 Assembly depicting the specimen (hidden between the dies), punch, lower and upper die

### 3.7 Mechanical Properties of the AL 6082

AL 6082, which belongs to the 6000 or 6xxx series, is a notable member of the wrought[23] aluminum-magnesium-silicon class. It is categorised as a medium-strength alloy, is well known for its remarkable resistance to corrosion [24], and is the strongest alloy in the 6000 series [23][24]. Because of its strong mechanical profile, it has been classified as a structural alloy and has gradually replaced alloy 6061 in a wide range of demanding applications.[23]The deliberate addition of a significant manganese content to its chemical[24] composition is essential because it efficiently regulates the grain structure[24], which directly contributes to the alloy's improved strength properties.[23]

Table 3.1. Chemical composition of 6082 aluminium alloy(wt%) [22]

| Si | Fe | Cu | Mn | Mg | Zn | Ti | Cr | Others |
|---|---|---|---|---|---|---|---|---|
| 0.7-1.3 | 0.5 | 0.1 | 0.4-1 | 0.6-1.2 | 0.2 | 0.1 | 0.25 | 0.1 |

Table3.2. Mechanical Properties of AL 6082[29]

| Temper Grade | 6082 Soft 0 | 6082-T4 | 6082-T6 | 6082-T651 |
|---|---|---|---|---|
| **Temper Description** | Untempered | Solution heat treatment and naturally aged | Solution heat treatment and artificial aging | Like T6 but is also stress relieved by stretching |
| **Hardness (Vickers)** | 35 | 65 | 95 | 90 |
| **Density (kg/m3)** | 2700 | 2700 | 2700 | 2700 |
| **Tensile Strength (Yield) (MPa)** | 60 | 110 | 250-260 | 240 |
| **Tensile Strength (Ultimate) (MPa)** | 130 | 205 | 290-310 | 275 |
| **Elongation at Break (%)** | 27 | 14 | 10 | 6-9. |
| **Shear Strength (MPa)** | 85 | 126 | Not Listed | Not Listed |
| **Melting Point (°C)** | 585 – 650 | 585 – 650 | 585 – 650 | 585 – 650 |
| **Specific Heat Capacity (J/kg·K)** | 896 | 896 | 896 | 896 |
| **Modulus of Elasticity (GPa)** | 70 | 70 | 70 | 70 |
| **Thermal Conductivity (W/mK·)** | 150 – 170 | 150 – 170 | 150 – 170 | 150 – 170 |
| **Coefficient of Thermal Expansion (10-6/K)** | 23.4 | 23.4 | 23.4 | 23.4 |

AL6082 is processed through methods such as extrusioncold and hotstamping androlling however as a wroughtalloy not suitable for casting applications [23] while forging and cladding are technically feasible these are not common practices for this particular alloy[23]it is important to note that al 6082 cannotbe work-hardened instead its strengthis commonly augmented through heat treatments whichproduce varioustempers eg t6 t651 that enhancestrength albeit often with a corresponding reduction in ductility [23] for machining operations al 6082 in t5 or t6 exhibits favorable machinability facilitating the formation of tight swarfcoils when chipbreakers are employed [23] thealloy demonstrates good weldability brazeability corrosionresistance and formability although it is recognized that the strength within weldzone may experience a reduction [23]for applicationsinvolving bending orforming the -o ort4 are generally to optimize material.

The conversion relations so used are –

$\sigma_t = \sigma_{nom} (1 + \varepsilon_{nom})$…..(3.6)

$\varepsilon_t = \ln (1 + \varepsilon_{nom})$-……(3.7)

$\varepsilon_{tpl} = \varepsilon_t - \sigma_t/E$…………(3.8)

where σnom and εnom are the nominal stress and strain from a normal tensile test, and E is Young's modulus. Likewise, εtpl represents actual plastic strain, while σt & εt represent true stress and strain.

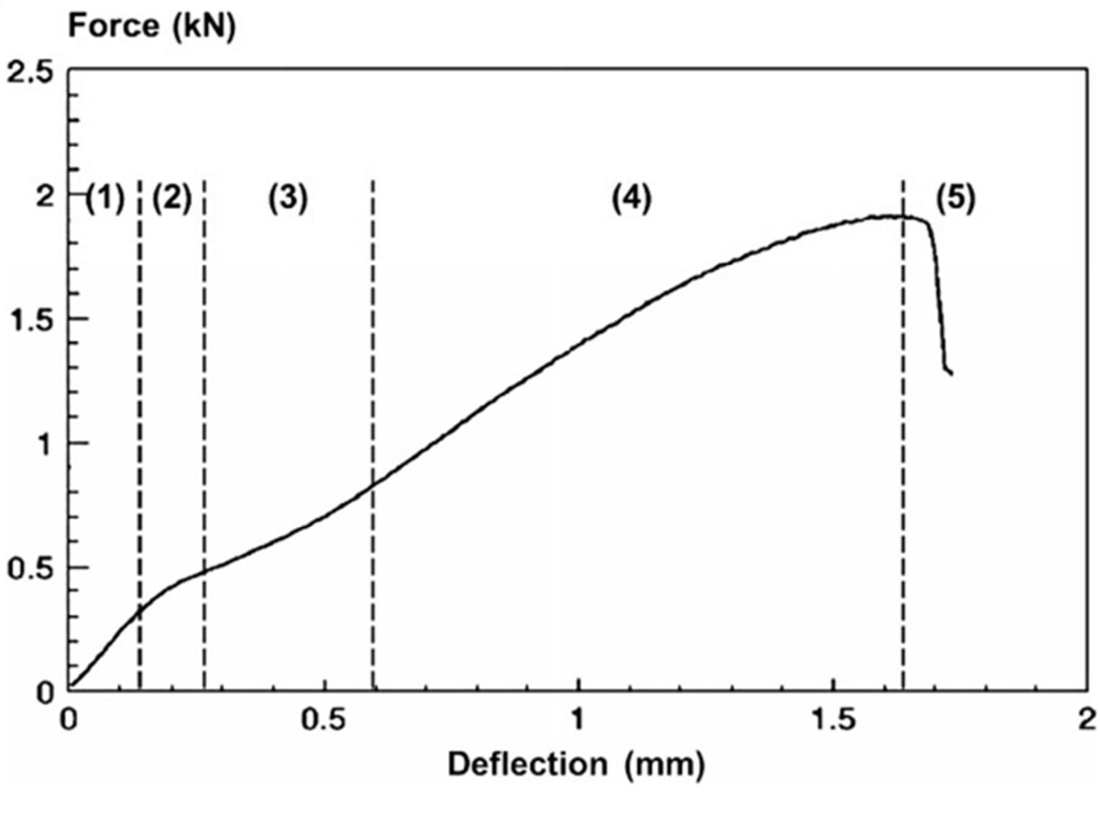


Fig 3.9 Force – Deflection for normal specimen [22]

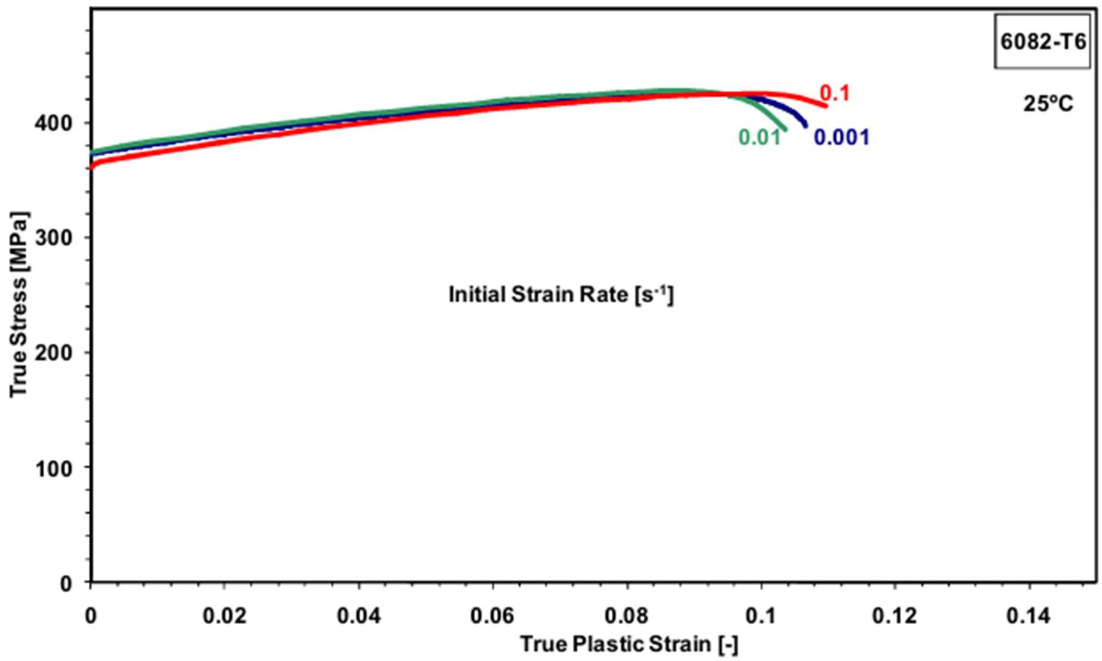


Fig.3.10 True stress-True strain curves for 6082-T6 alloy.

### 3.7.1 Microstructural properties

Before being chemically etched and examined under an optical microscope, samples from the uniaxially tested specimens were prepared from the [17] maximum elongation[26] area in order to conduct the microstructure study[26]. The Leica DM IRM Each specimen has two batches of samples prepared for the microstructural research [26]: one batch for the examination of the precipitates and another batch for the analysis of the grains and grain boundaries. Grain boundaries were observed using 18 fluoboric acid in water, while the precipitates were observed using 05 hydrofluoric acid in water [17]. The analysis of the first batch of samples is summarised in Fig. 3.10. It displays 6082 alloy micrographies for various treatment scenarios and [17][26][27] distorted at various test temperatures.Observations reveal that the microstructure of the alloy has not significantly changed under either of the heat treatment settings [17][26].[26] [16]Since the forming temperature in the material is too low to initiate any phase transformation 3, there is no discernible effect of the temperature and strain rate in the examined range [26].Due to the fact that mg2si precipitates are more diluted in the -al matrix, which causes material hardening and a reduction in ductility, [26][26] have very little effect on the 6082 microstructure. The [17][26] micrographies also display a lower mass percentage of the precipitates for the t6 condition.

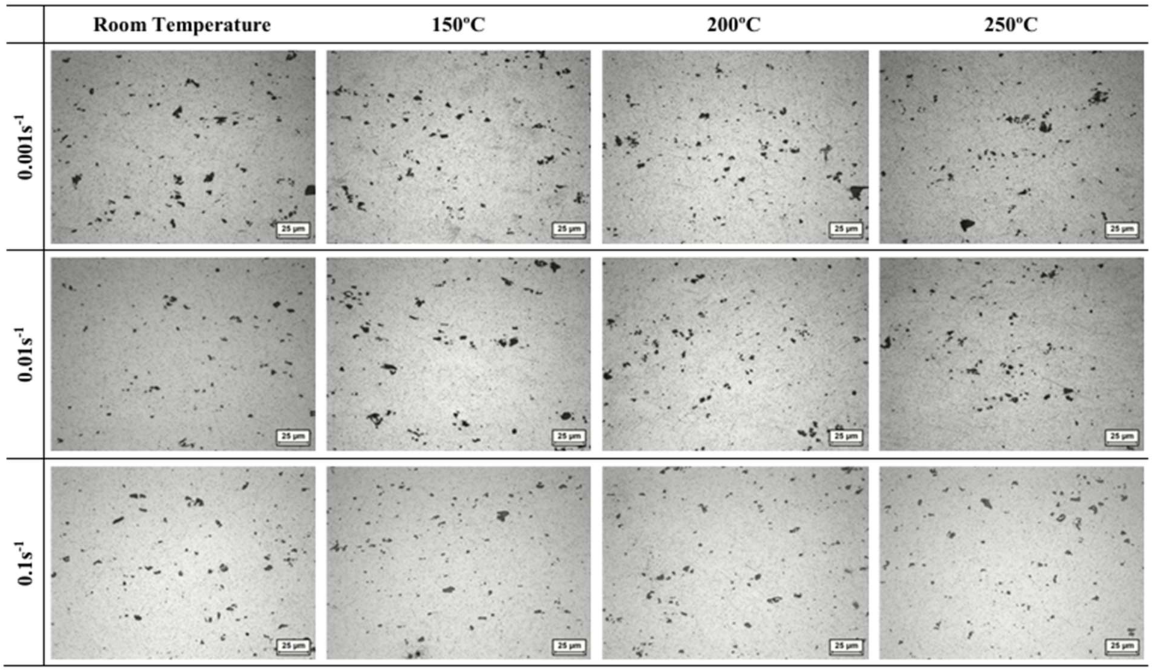


Fig 3.11 6082-T6 alloy microstructure evolution with temperature and strain rate 0.5%HF,500X

### 3.8 Mechanical Properties of the Cr-Mo steel

The Mechanical Properties of Cr-Mo Steel is given in the figure below

| 35CrMo Chemical composition(mass fraction)(wt.%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Chemical | | | Min.(%) | | | | Max.(%) | | |
| C | Si | Mn | P | S | Cr | Ni | Mo | V | Ta |
| 0.32-0.40 | 0.17-0.37 | 0.40-0.70 | | | 0.80-1.10 | | 0.15-0.25 | | |
| W | N | Cu | Co | Pb | B | Nb | Al | Ti | Other |
| | | | | | | | | | |

Fig.3.12 Chemical Composition of Cr-Mo Steel[30]

| 35CrMo Physical Properties | | |
|---|---|---|
| Tensile strength | 115-234 | σb/MPa |
| Yield Strength | 23 | σ 0.2 ≥/MPa |
| Elongation | 65 | δ5≥ (%) |
| ψ | - | ψ≥ (%) |
| Akv | - | Akv≥/J |
| HBS | 123-321 | - |
| HRC | 30 | - |

Fig 3.13 Mechanical Properties of Cr-Mo Steel[30]

| 35CrMo Mechanical Properties | | |
|---|---|---|
| Tensile strength | 231-231 | σb/MPa |
| Yield Strength | 154 | σ 0.2 ≥/MPa |

Fig 3.14 Mechanical Properties of Cr-Mo Steel.1[30]

| | | |
|---|---|---|
| Elongation | 56 | δ5≥(%) |
| ψ | - | ψ≥(%) |
| Akv | - | Akv≥/J |
| HBS | 235-268 | - |
| HRC | 30 | - |

Fig 3.15 Mechanical Properties of Cr-Mo Steel.1[30]

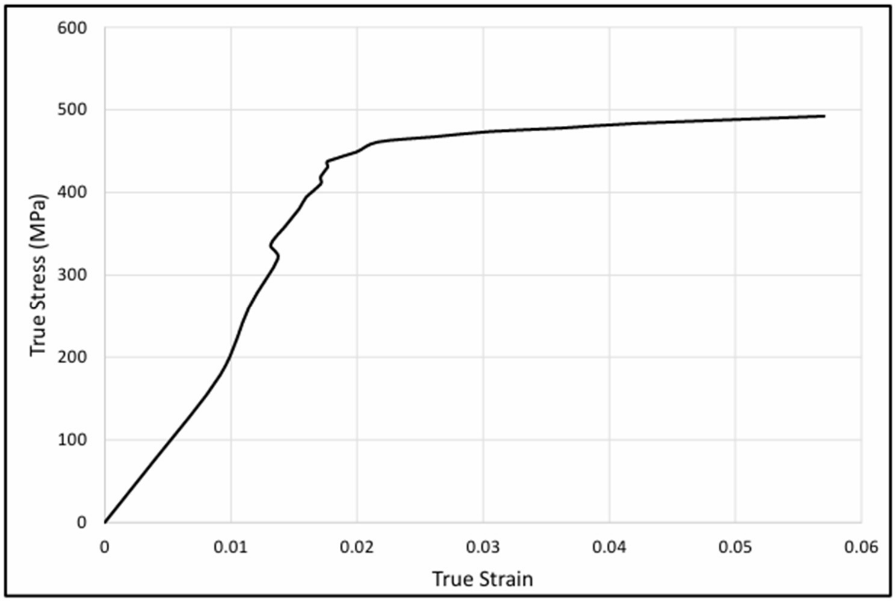


Fig 3.16 True Stress-True Strain Curve for 5Cr0.5Mo-RT[20]

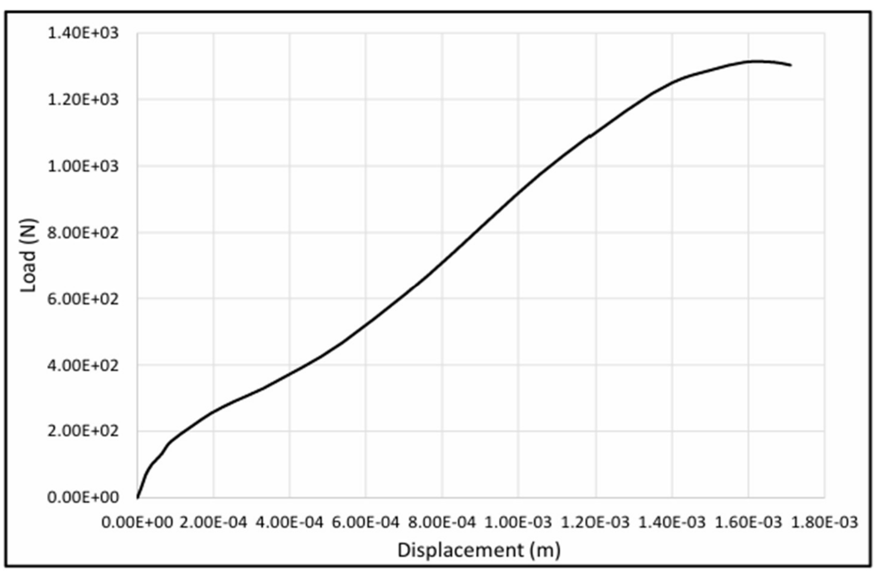


Fig 3.17 Load-Displacement Curve for 5Cr0.5Mo-RT[30]

# CHAPTER 4

# RESULTS AND DISCUSSION

### 4.1 Introduction

The tiny punch test uses a smaller specimen shaped like a circular disc to replicate the actual SPT procedure. Direct finite element analysis is performed on a range of materials using the ABAQUS/CAE tool. The entire procedure or procedures needed for the FE analysis on ABAQUS are described in Section 4.4.

In the property section, we may define material properties like density, Young's modulus, and poisson's ratio by selecting the ELASTIC option. Since AL6082 is the material in question, its elastic material properties are defined as follows: 69 GPa, 2710 Kg/m3, and 0.33. The post yields behaviour in ABAQUS is defined by the PLASTIC option. The true stress is defined by the data pair in the PLASTIC option as a function of the true plastic strain. The beginning yield stress and matching initial plastic strain, which should both be zero, are specified in the first data pair.

Plastic strains in the material are unlikely to be represented in the strain data from the materials test that are used to characterise the plastic behaviour. Rather, they are the material's overall stresses. The elastic strain, which is calculated by dividing the real stress by the Young's modulus, is subtracted from the overall strain value to determine the plastic strain. The following table displays the average data.

Table 4.1. True Stress and True Plastic strain value for AL6082 [17].

| True Plastic Stain | True Plastic Stress [MPa] strain rate: $0.1s^{-1}$ |
|---|---|
| 0 | 375 |
| 0.01 | 395 |
| 0.02 | 405 |
| 0.03 | 410 |
| 0.04 | 415 |
| 0.05 | 418 |
| 0.06 | 420 |
| 0.07 | 422 |
| 0.08 | 420 |
| 0.09 | 415 |
| 0.1 | 405 |
| 0.11 | 395 |

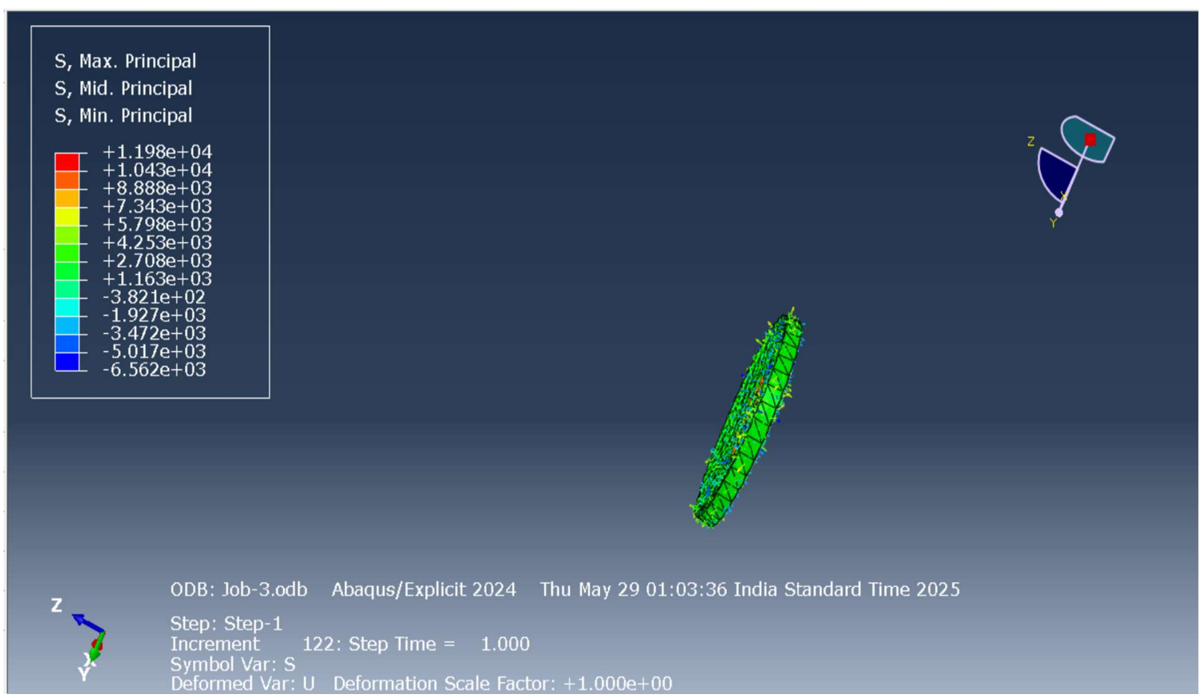

Fig 4.1 Max. Principal, Mid. Principal, Min. Principal stress on the specimen

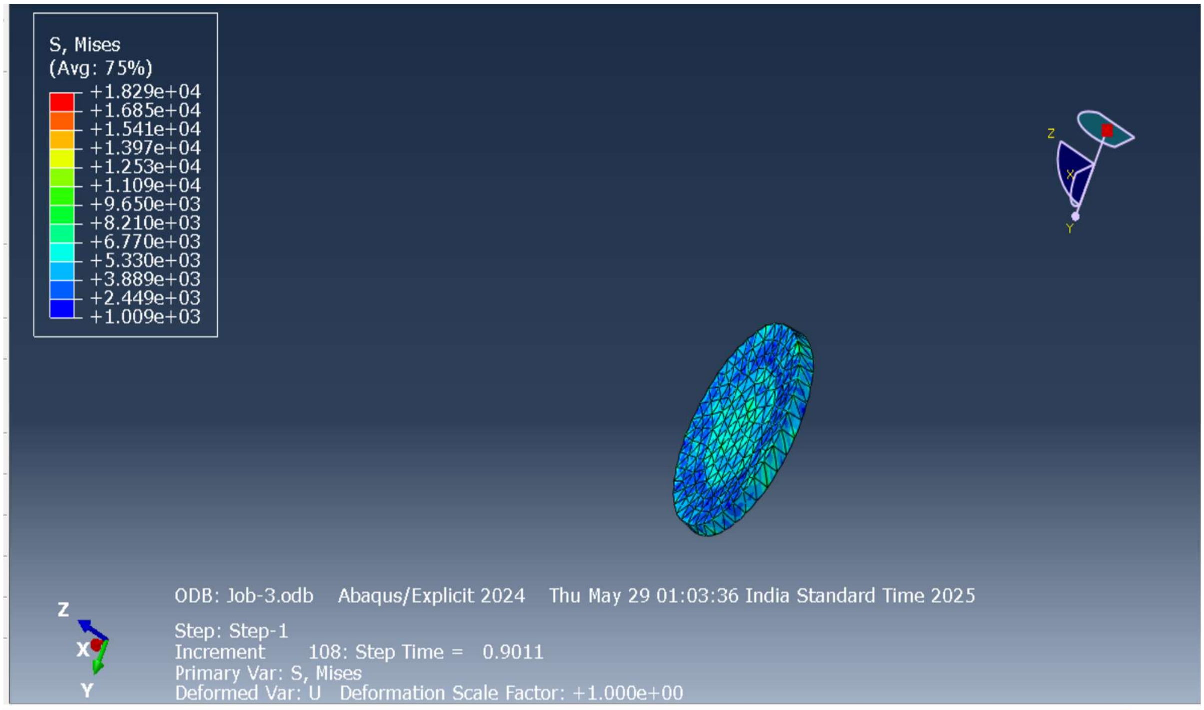


Fig 4.2 Von Mises stress on the Specimen

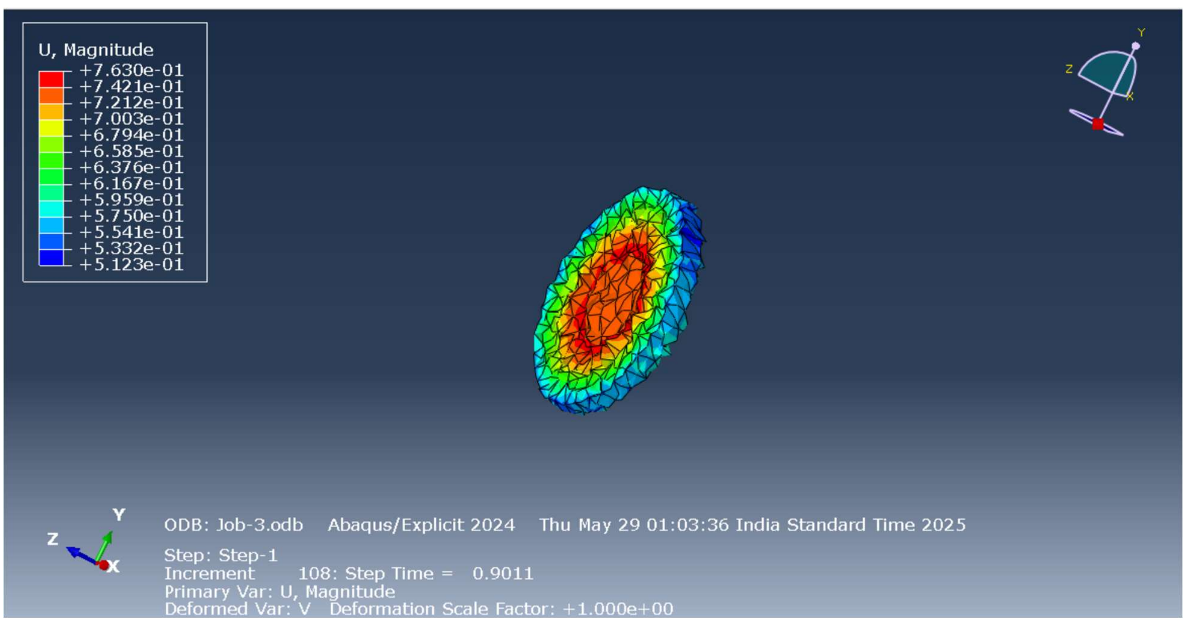


Fig 4.3 Displacement magnitude on the specimen on Deformed Contour

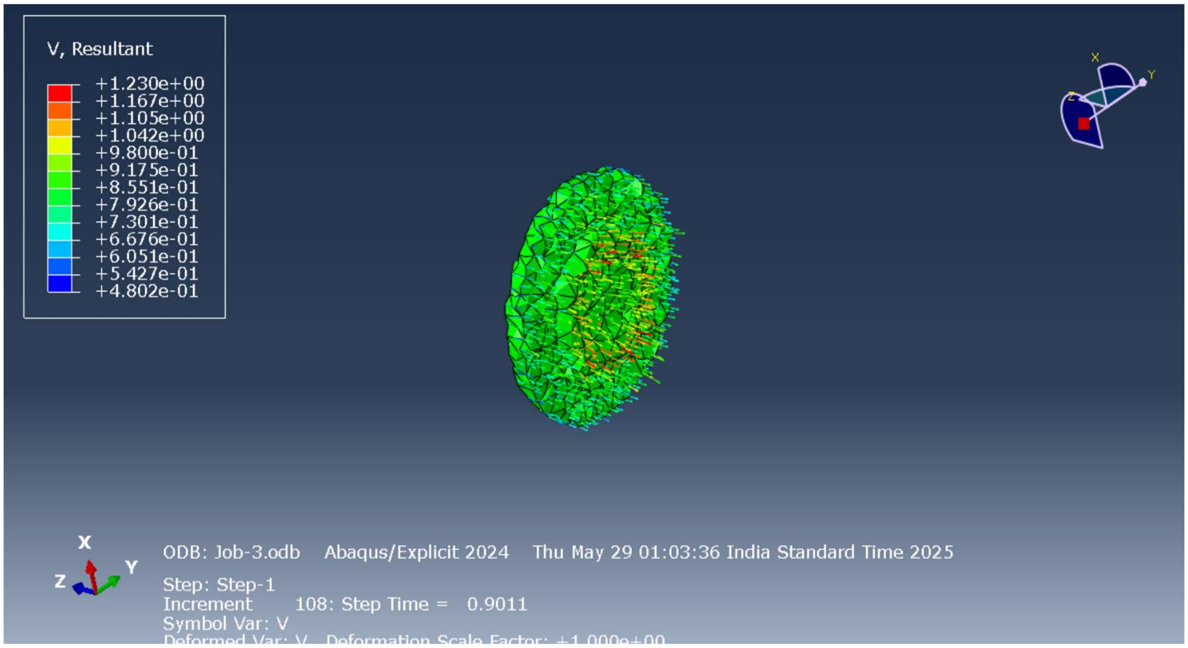


Fig4.4 Magnitude of Velocity Vector on the specimen

| Step | Increment | Total Time | WALL Time | Step Time | Stable Time Inc | Kinetic Energy | Total Energy |
|---|---|---|---|---|---|---|---|
| 1 | 10 | 0.0578149 | 37 | 0.0578149 | 0.00870833 | 1.29278e+06 | 1.28791e+06 |
| 1 | 15 | 0.101357 | 47 | 0.101357 | 0.00870833 | 1.29821e+06 | 1.28803e+06 |
| 1 | 21 | 0.153607 | 59 | 0.153607 | 0.00870833 | 1.307e+06 | 1.28801e+06 |
| 1 | 27 | 0.205857 | 71 | 0.205857 | 0.00870833 | 1.31456e+06 | 1.28795e+06 |
| 1 | 33 | 0.258106 | 82 | 0.258106 | 0.00870833 | 1.31527e+06 | 1.28794e+06 |
| 1 | 38 | 0.301648 | 94 | 0.301648 | 0.00870833 | 1.31521e+06 | 1.28793e+06 |
| 1 | 44 | 0.353898 | 107 | 0.353898 | 0.00870833 | 1.31507e+06 | 1.28793e+06 |
| 1 | 50 | 0.406148 | 121 | 0.406148 | 0.00870833 | 1.31479e+06 | 1.28793e+06 |
| 1 | 56 | 0.458398 | 135 | 0.458398 | 0.00870833 | 1.31463e+06 | 1.28792e+06 |
| 1 | 61 | 0.50194 | 149 | 0.50194 | 0.00870833 | 1.31431e+06 | 1.28792e+06 |
| 1 | 67 | 0.55419 | 161 | 0.55419 | 0.00870833 | 1.31414e+06 | 1.28792e+06 |
| 1 | 73 | 0.60644 | 177 | 0.60644 | 0.00870833 | 1.31384e+06 | 1.28792e+06 |
| 1 | 79 | 0.65869 | 193 | 0.65869 | 0.00870833 | 1.31356e+06 | 1.28791e+06 |
| 1 | 84 | 0.702232 | 205 | 0.702232 | 0.00870833 | 1.31336e+06 | 1.28791e+06 |
| 1 | 90 | 0.754314 | 217 | 0.754314 | 0.00849502 | 1.31317e+06 | 1.28791e+06 |
| 1 | 96 | 0.804625 | 230 | 0.804625 | 0.00823791 | 1.31292e+06 | 1.28791e+06 |
| 1 | 102 | 0.853529 | 244 | 0.853529 | 0.00800738 | 1.31264e+06 | 1.28791e+06 |
| 1 | 108 | 0.901052 | 258 | 0.901052 | 0.00777076 | 1.31234e+06 | 1.28791e+06 |
| 1 | 115 | 0.954684 | 273 | 0.954684 | 0.00750556 | 1.31202e+06 | 1.2879e+06 |
| 1 | 122 | 1 | 288 | 1 | 0.00729516 | 1.3118e+06 | 1.2879e+06 |

Fig. 4.5 Incremental values of total energy and kinetic energy with time

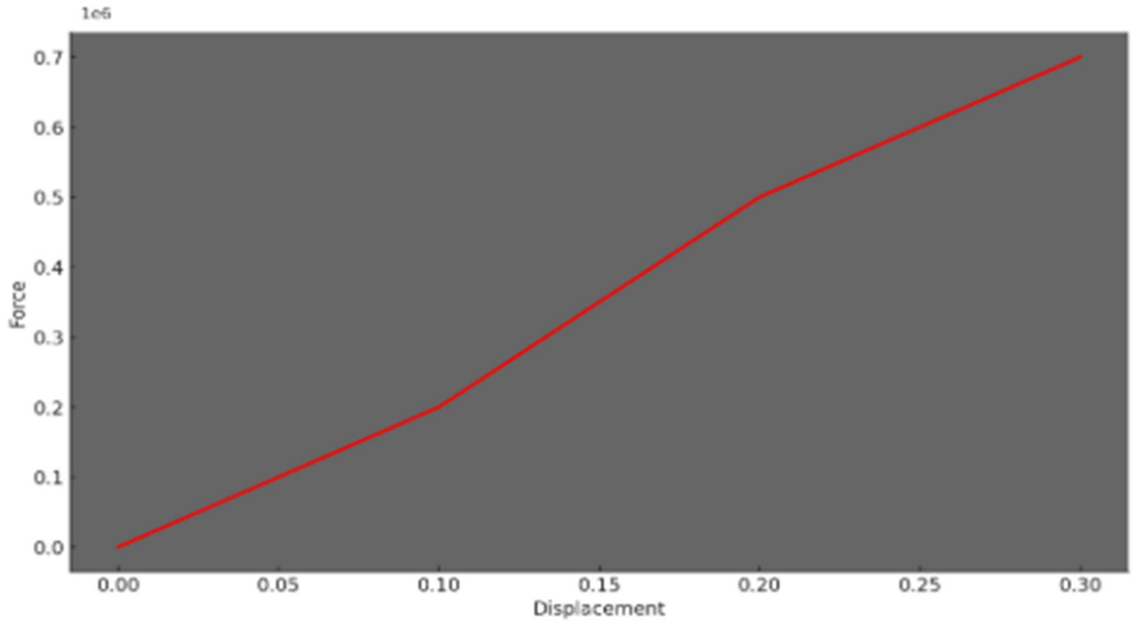


Fig. 4.6 Force vs Displacement curve for AL 6082

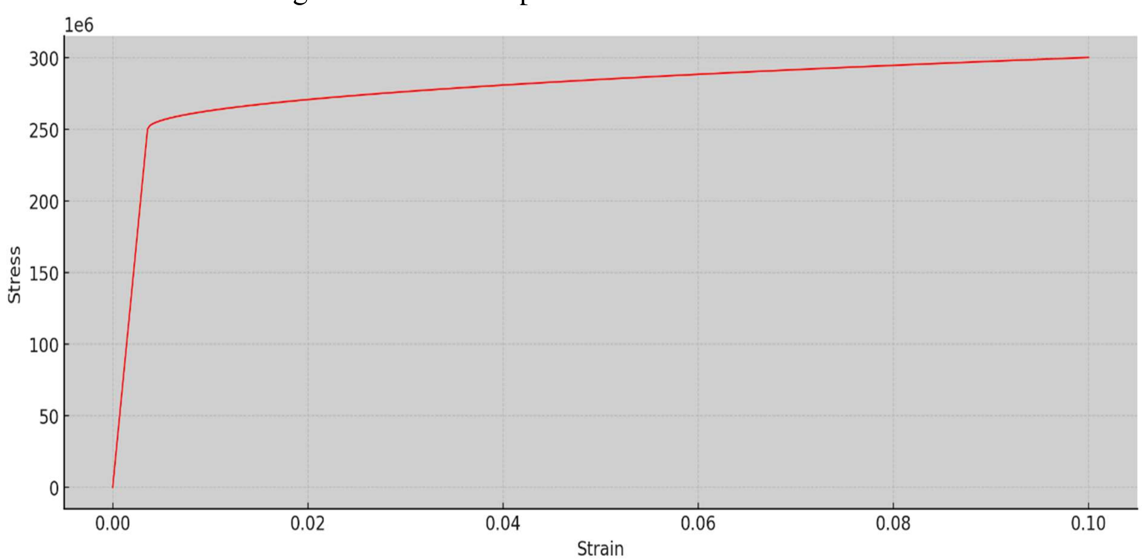


Fig. 4.7 Stress vs Strain Curve for AL 6082

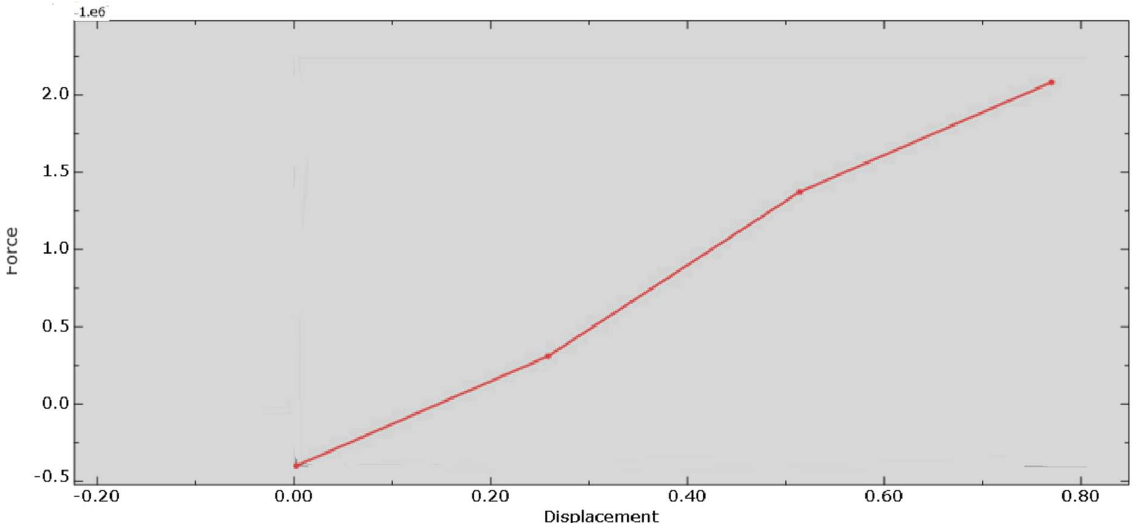

Fig 4.8 Force vs displacement curve for Cr-Mo Steel

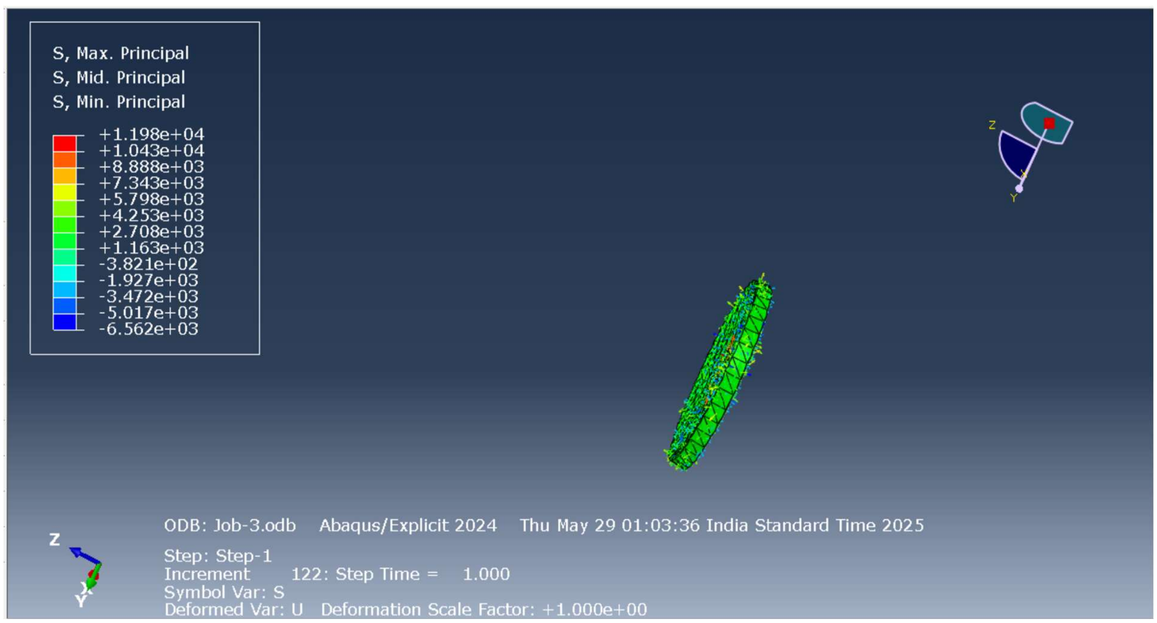


Fig 4.9 Max. Principal, Mid. Principal, Min. Principal stress on the specimen Cr-Mo steel

# CHAPTER 5

# CONCLUSION AND FUTURE WORK

## 5.1 Conclusion

### 5.1.1 Conclusion

Using the Small Punch Test (SPT) and Finite Element Method (FEM) on Al6082 and Cr-Mo steel, the thorough study of the design and implementation of a hybrid setup for assessing the mechanical properties of service-exposed materials has produced significant insights and created a strong foundation for advanced material characterisation. Assessing the integrity and remaining life of components functioning under challenging service circumstances is made easier with this integrated approach.

### 5.1.2 The Hybrid SPT-FEM Framework for Service-Exposed Materials

The hybrid SPT-FEM approach's main strength is its capacity to offer thorough material characterisation in situations when conventional techniques are impractical or unattainable.

### 5.1.3 Reaffirming the Efficacy of Small Punch Testing for In-Service Characterisation

One essential miniature testing technique that has been repeatedly verified is the Small Punch Test (SPT). Important mechanical characteristics including fracture toughness, ductile-to-brittle transition temperature, and tensile qualities are all well estimated by it.1. Its ability to examine service-exposed components in-situ, especially in situations when material extraction is severely constrained, is what makes it so valuable. Without sacrificing the component's structural strength, SPT's intrinsic non-destructive or semi-destructive character enables accurate assessment of material integrity and remaining service life.

Usually 8 mm in diameter and 0.5 mm thick, SPT uses small disc specimens that are loaded centrally by a spherical punch. Mechanical qualities can be derived from the characteristic parameters provided by the force/deflection curve that results.1. This feature is particularly useful for important applications in industries where it is not practical to extract larger bulk material volumes for traditional uniaxial tensile testing, such as nuclear power generating and steam power plants.3 For metallic materials, especially steels, the force/deflection test record shows five different regions: final failure, membrane stress regime, local bending moving to a membrane stress regime, departure from linearity, and elastic. Critical metrics such as ultimate tensile stress (connected to maximal force) and yield stress (associated with a change in slope) can be determined from these locations.

The strategic evolution of SPT for ductile materials is an important finding in its development. The primary difference between the Miniature Disc Bend Test (MDBT) and the Small Punch Test is the level of constraint placed on the specimens; MDBT specimens are merely supported, whereas SPT specimens are clamped between two dies.5. SPT is specifically suited for ductile materials because of this purposeful engineering improvement in the clamped arrangement. Significant plastic deformation occurs in ductile materials, and the clamped configuration enables a more thorough recording of the material's entire load-displacement response by creating a membrane stress regime. This reflects an ongoing improvement of miniature testing methods to satisfy particular material characterisation requirements and is essential for comprehending the intricate mechanical behaviour of numerous in-service components.

### 5.1.4 Leveraging Finite Element Method for Comprehensive Mechanical Property Determination

A fundamental numerical method for resolving complicated differential equations used in engineering and mathematical modelling, including fluid dynamics, heat transfer, and structural analysis, is the Finite Element Method (FEM). Its fundamental idea is to break down a big, complicated system into smaller, simpler finite components, then put together the behavioural equations of each component to create a bigger system of algebraic equations that represents the problem as a whole.

The practical use of FEM, known as finite element analysis (FEA), greatly lessens the need for costly physical prototypes and labour-intensive experimental testing. This makes it possible for engineers to precisely forecast component behaviour under a variety of loading scenarios and virtually optimise designs. Among the benefits of FEM are its capacity to capture localised effects inside a structure, combine different material properties, and accurately depict complex geometries. When it comes to SPT, FEM simulations are essential for deciphering the intricate, multiaxial stress and strain states that form inside the tiny specimen. These states are very challenging to determine using only empirical methods. Additionally, FEM makes it possible to forecast the course of deformation and damage within the material and makes it easier to design and use complex constitutive models.

The incorporation of FEM is a substantial departure from material characterisation that is solely empirical. Even though empirical correlations are frequently used to extrapolate traditional mechanical qualities from SPT data, they are typically not generalisable and are intrinsically restricted to the particular material, geometry, and testing conditions from which they were obtained.One On the other hand, FEM-driven inverse analysis is a more basic, physics-based method. A deeper comprehension of the material's basic behaviour is made possible by the extraction of intrinsic material constitutive parameters, which makes predictions that can be applied to a wider variety of loading scenarios and geometries.9. This shift greatly increases the prediction potential of the characterisation method by going beyond simply correlating observed phenomena to comprehending the underlying mechanisms and, most importantly, forecasting behaviour under unexpected settings.

### 5.1.5 Synergistic Advantages of the Hybrid Approach in Assessing Material Integrity

By successfully fusing the strong analytical capabilities of FEM, such as complex stress state analysis, accurate material parameter optimisation, and advanced damage prediction, with the practical benefits of SPT, such as minimal material extraction and applicability for in-situ assessment, the hybrid SPT-FEM framework represents a potent synergy. The inherent drawbacks of each technique when applied separately are skilfully addressed by this integrated methodology, such as SPT's conventional reliance on perhaps shaky empirical correlations for complicated material behaviours or FEM's vulnerability to mesh distortion during significant deformations.

By successfully fusing the strong analytical capabilities of FEM, such as complex stress state analysis, accurate material parameter optimisation, and advanced damage prediction, with the practical benefits of SPT, such as minimal material extraction and applicability for in-situ assessment, the hybrid SPT-FEM framework represents a potent synergy. The inherent drawbacks of each technique when applied separately are skilfully addressed by this integrated methodology, such as SPT's conventional reliance on perhaps shaky empirical correlations for complicated material behaviours or FEM's vulnerability to mesh distortion during significant deformations.

The hybrid SPT-FEM approach's capacity to calculate an in-service material's conserved mechanical strength in its in-situ state in order to determine its suitability for service 3, as well as its use for life extension studies and remnant life evaluation, has significant implications. Through the use of this integrated technology, basic material constitutive and damage characteristics may be extracted from small in-situ samples and subsequently input into high-fidelity FEM models. By making it easier to create "digital twins" of crucial parts, this feature enables proactive, predictive maintenance plans. In the management of high-value assets within critical infrastructure, engineers can greatly improve reliability, decrease downtime, and save a significant amount of money by simulating the remaining useful life under anticipated service loads by understanding the real-time, localised degradation of materials. As a result, asset management has shifted from being reactive to being predictive.

Table 4: Advantages and Limitations of Individual SPT and FEM, and Their Hybrid Combination

| Method | Advantages | Limitations |
|---|---|---|
| Small Punch Test (SPT) | Effective for characterising localised material qualities, it requires little material extraction, is appropriate for in-situ or semi-destructive applications, is economical for initial screening, has well-established empirical correlations, and has standards for some applications. | For materials that are highly anisotropic, the biaxial loading mode may present challenges. Conventional reliance on empirical correlations may result in results that are weaker or material-specific, sensitive to adopted best practices and testing parameters, usually lacking complete stress-strain curves, and significantly impacted by friction between the punch and specimen. |
| Finite Element Method (FEM) | It can accurately manage complex geometries and disparate material properties, eliminate the need for costly physical prototypes, anticipate complex material behaviour under a range of pressures, and offer comprehensive insights into localised stress and strain fields. | The model's assumptions and simplifications, the difficulty of meshing complex geometries (particularly those with sharp corners), the difficulty of accurately modelling materials (including nonlinearities and time-dependent properties), the computationally demanding nature of simulations, and the possibility of mesh distortion in problems involving very large deformations all affect the results. |
| Hybrid SPT-FEM | Improves the prediction of damage initiation and fracture propagation, permits robust inverse analysis for determining basic constitutive parameters, greatly increases the accuracy of correlations between small- | Requires complex inverse analysis algorithms, accurate friction coefficient determination can affect results, highly detailed models (such as those that incorporate deformable dies) can be computationally expensive, |

| | | |
|---|---|---|
| | scale and conventional properties, and offers a strong framework for remnant life assessment and fitness-for-service evaluations. It also successfully gets around the inherent limitations of individual methods.4. | and strong validation against bulk-scale experimental data is still essential for industrial acceptance.11. |

### 5.1.6. Insights from Al6082 Characterization

Through the use of the hybrid SPT-FEM framework, Al6082's mechanical response and degradation mechanisms under a range of service-exposed situations have been better understood.

#### 5.1.6.1 Understanding Mechanical Response and Degradation Mechanisms in Al6082

A well-known heat-treatable Al-Mg-Si alloy in the 6xxx series, Al6082 finds widespread use in crucial structural applications in the automotive, aviation, and marine sectors. Its remarkable blend of strength, formability, and corrosion resistance accounts for its extensive use. Precipitation strengthening, which is accomplished by careful solution heat treatment and ensuing ageing procedures, can greatly increase the mechanical strength of Al6082.

Unfortunately, the recrystallisation action of traditional hot working techniques frequently causes coarse grains to form in Al6082, which negatively affects the material's strength and overall service life.16 By limiting aberrant grain formation, novel processing techniques like the continuous casting direct rolling (CCDR) approach have demonstrated promise in halting this undesired material degeneration.16 The mechanical characteristics of Al6082 are significantly impacted by particular heat treatments (T4 and T6), according to empirical research: Higher elongation is usually obtained with T4 therapy, however superior strength is imparted with T6 treatment. Interestingly, the T6R4 condition (T6 heat treatment followed by cold rolling) has better toughness than the T4R4 condition and can reach strengths of up to 400 MPa.16 Due to work hardening, cold rolling, a crucial operation, typically results in increased strength and hardness, but frequently at the expense of decreased elongation.16 Abnormal grain growth can result from recrystallisation, especially secondary recrystallisation, which is known to shorten fatigue life and strength in engineering applications.16 On the other hand, deliberate cold-working deformation and suitable heat treatment (such as T6) can efficiently refine grains and encourage the development of precipitates with a nanoscale size. By preventing dislocations from aggregating and encouraging a more homogeneous microstructure, this procedure aids in the restoration of elongation and fracture toughness.

A crucial consideration when evaluating materials exposed to service is that microstructural deterioration frequently happens locally or heterogeneously rather than consistently throughout the component. By combining FEM's ability to represent the intricate stress states and material reactions within these particular microstructures with

SPT's ability to sample very small, localised locations, the hybrid SPT-FEM technique provides a unique capability. This makes it possible to precisely probe and comprehend how localised microstructural alterations, like those brought on by heat treatment or cold rolling, affect the overall mechanical behaviour. In contrast to bulk property measurements, this offers a more precise and detailed evaluation of material health and is crucial for precisely forecasting localised deterioration and failure in actual service situations.

### 5.1.7 Contribution of Hybrid SPT-FEM to Al6082 Service Life Prediction

A crucial consideration when evaluating materials exposed to service is that microstructural deterioration frequently happens locally or heterogeneously rather than consistently throughout the component. By combining FEM's ability to represent the intricate stress states and material reactions within these particular microstructures with SPT's ability to sample very small, localised locations, the hybrid SPT-FEM technique provides a unique capability. This makes it possible to precisely probe and comprehend how localised microstructural alterations, like those brought on by heat treatment or cold rolling, affect the overall mechanical behaviour. In contrast to bulk property measurements, this offers a more precise and detailed evaluation of material health and is crucial for precisely forecasting localised deterioration and failure in actual service situations. The hybrid technique also makes it easier to evaluate the subtle effects of microstructural alterations on the tensile strength and hardness of Al6082, such as severe plastic deformation or grain size refinement brought on by cryogenic treatment. Accurately forecasting the material's long-term performance and remaining useful life in demanding applications depends on the data obtained from this method.

It is commonly known that forecasting service life and making important financial decisions about component replacement, rehabilitation, or repair depend heavily on an understanding of mechanical properties.21 The hybrid SPT-FEM framework's special strength is its capacity to carry out in-situ characterisation 3 of real service-exposed material that has experienced degradation in the real world. The behaviour of the component under future service demands can be simulated by incorporating this localised, real-world data into an advanced FEM model. This essentially makes it possible to create a "digital twin" of the component's current state, offering incredibly precise estimates of how long it will still be usable. This feature improves dependability and optimises maintenance programs by going beyond basic property determination and marking a substantial advancement towards sophisticated predictive asset management.

It is commonly known that forecasting service life and making important financial decisions about component replacement, rehabilitation, or repair depend heavily on an understanding of mechanical properties.21 The hybrid SPT-FEM framework's special strength is its capacity to carry out in-situ characterisation 3 of real service-exposed material that has experienced degradation in the real world. The behaviour of the component under future service demands can be simulated by incorporating this localised, real-world data into an advanced FEM model. This essentially makes it possible to create a "digital twin" of the component's current state, offering incredibly precise estimates of how long it will still be usable. This feature improves dependability and optimises

maintenance programs by going beyond basic property determination and marking a substantial advancement towards sophisticated predictive asset management.

### 5.2 Future Work

Refining current models, expanding material and environmental applicability, and combining cutting-edge computational and experimental approaches will be the main goals of the hybrid SPT-FEM methodology's ongoing development.

#### 5.2.1 Advancements in FEM Modeling and Inverse Analysis

Future developments in FEM modelling will focus on enhancing inverse analysis methods' precision, effectiveness, and resilience:

- **Sophisticated Optimization Algorithms:** Higher success rates and more overall efficiency in parameter estimation will result from replacing existing optimisation methods, like Nelder-Mead, with more advanced and effective alternatives that enable the application of boundary conditions for each constant.
- **Enhanced Damage and Failure Prediction:** It is essential to enhance the model's capacity to forecast necking behaviour and ductile damage. If necking and fracture in SPT specimens are extensively experimentally analysed, this may include modifying mesh settings or further optimising other behavioural aspects.
- **Realistic Boundary Conditions:** A more precise evaluation of the influence of equipment compliance will be possible if the punch and dies are included in the FEM model as deformable solids rather than rigid entities. Although this raises the computational cost, it can be lessened by efficiency gains (such as 90° rotation models). In a same vein, adding more material characteristics for the dies and punch will improve the overall system compliance image.
- **Improved Friction Coefficient Determination:** A more precise evaluation of the influence of equipment compliance will be possible if the punch and dies are included in the FEM model as deformable solids rather than rigid entities. Although this raises the computational cost, it can be lessened by efficiency gains (such as 90° rotation models). In a same vein, adding more material characteristics for the dies and punch will improve the overall system compliance image.
- **Physics-Based Rupture Criteria:** Future studies will try to create and apply more physics-based rupture criteria, perhaps using sophisticated damage models, to precisely forecast material failure, going beyond unphysical visco-plastic collapse criteria.
- **Comprehensive Creep Data Integration:** Addressing the limitation that creep data often covers only a limited stress range, future FEM models will need to incorporate creep models capable of covering a very large stress and strain range, handling relaxation, and accurately predicting rupture.

#### 5.2.2. Expanding Material and Environmental Applicability

The hybrid SPT-FEM structure may find wider use in a variety of materials and demanding service conditions.

- **Wider Material Range Analysis:** For testing irradiated materials in crucial applications like nuclear fusion reactors, it is especially crucial to expand the research to examine a larger spectrum of materials beyond ductile steels, including brittle samples.
- **Characterization in Aggressive Environments:** It will be crucial to continue developing and validating SPT procedures for materials exposed to harsh conditions, like those that cause hydrogen embrittlement. In order to determine threshold stress based just on SPT tests with little experimental scatter, models must be calibrated.
- **High-Temperature Creep Characterization:** Future research will focus on creating reliable physics-based computational models that can forecast creep and fracture behaviour over short and long service periods, particularly for welded joints where microstructural degradation may occur, for materials that function under creep conditions, such as Cr-Mo steel. The impact of different parameters on creep behaviour will continue to be examined through systematic experiments employing FEM.

#### 5.2.3. Integration with Advanced Technologies and Methodologies

The combination of SPT-FEM and new technologies will be used more and more in material characterisation in the future:

- **Artificial Intelligence and Machine Learning (AI/ML):** Creating and implementing AI-based algorithms, data-driven approaches, and autonomous workflows for material characterisation procedures is an important future direction. This comprises:
  - creating AI algorithms based on physics to increase analysis's reproducibility, efficiency, and robustness.
  - accelerating the extraction of conclusions from intricate microstructural data by applying AI algorithms to microscopy and image processing.
  - To speed up material design and research, high-throughput screening is combined with machine learning and first-principles computations.
- **Complementary Non-Destructive Testing (NDT) Techniques:** Even though SPT is semi-destructive, a more thorough material assessment may be obtained by combining it with strictly non-destructive techniques. Future developments in NDT will involve the creation of internal imaging equipment and the use of software for enhanced analysis that is based on complex mathematical algorithms and artificial intelligence. A comprehensive understanding of material integrity can be obtained by combining SPT-FEM with various NDT techniques, including as eddy current testing, magnetic particle testing, and ultrasonic testing (UT), which can identify defects, voids, and weld discontinuities.

- **Digital Twins and Predictive Maintenance:** The creation of "digital twins" of crucial components is made possible by the capacity to extract basic material constitutive and damage data from tiny, in-situ samples in conjunction with high-fidelity FEM models. By modelling remaining useful life under anticipated service loads, this will allow proactive, predictive maintenance procedures, improving reliability and lowering downtime..

### 5.2.4. Refinement of Experimental Procedures and Data Analysis

Analysis and validation of experimental data must be continuously improved:

- **Enhanced Data Analysis Scripts:** A single, all-inclusive software for curve analysis and pertinent estimations will be produced by enhancing Python scripts for evaluating experimental test results by including proof stress and UTS computations.

- **Addressing Overestimations:** To improve accuracy, more investigation is required into the overestimations seen in best practice proof stress estimates from SPT data.

**5.2.5 Direct Validation:** The quality assurance of SPT will be strengthened by the direct comparison of optimised Johnson-Cook results with bulk-scale behaviour made possible by the implementation of tensile test simulations for validation purposes.
The hybrid SPT-FEM framework will maintain its status as a vital instrument for advanced material characterisation by following these future paths, guaranteeing the dependability, safety, and prolonged service life of vital engineering components.

# REFERENCES


[1] Lucon E, Benzing JT, Derimow N, Hrabe N. *Small Punch Testing to Estimate the Tensile and Fracture Properties of Additively Manufactured Ti-6Al-4V. J Mater Eng Perform*. 2021;30(7):10.1007/s11665-021-05603-9. doi: 10.1007/s11665-021-05603-9. PMID: 34413624; PMCID: PMC8370038.

[2] Patel Pruthvishkumar Keshavlal, 2023.Investigation *of mechanical properties of in-service materials using small punch test". https://s3-ap-southeast-1.amazonaws.com/gtusitecirculars/uploads/Final%20Synopsis_454275.pdf*

[3] *Nuclear materials - CEA, accessed on May 29, 2026*, https://www.cea.fr/english/Documents/scientific-and-economic-publications/nuclear-energy-monographs/CEA_Monograph10_Nuclears-Materials_2019_GB.pdf

[4] Altstadt, E. & Ge, Hongen & Kuksenko, Viacheslav & Serrano, Marta & Houska, M. & Lasan, M. & Bruchhausen, Matthias & Lapetite, J.-M & Dai, Yong. (2015*). Critical evaluation of the small punch test as a screening procedure for mechanical properties. Journal of Nuclear Materials. 472. 10.1016/j.jnucmat.2015.07.029..*

[5] Subbaiah, Arunkumar. (2019). *Overview of Small Punch Test. Metals and Materials International. 26. 10.1007/s12640-019-00454-5.*

[6] Link, RE & Eskner, Mats & Sandström, Rolf. (2004). *Mechanical Property Evaluation Using the Small Punch Test. Journal of Testing and Evaluation - J TEST EVAL. 32. 10.1520/JTE11504*.

[7] Čížek, Petr & Kander, Ladislav & Stejskalová, Šárka. (2018). *Industrial applications of small punch test. Ubiquity Proceedings. 1. 13. 10.5334/uproc.13.*

[8] ASTM E3205-20 - iTeh Standards, *https://cdn.standards.iteh.ai/samples/106859/08fcae5927464b6c879cfd0fc82174f5/ASTM-E3205-20.pdf*

[9] Calaf-Chica, Jose & Bravo, P. & Preciado, Mónica & Ballorca-Juez, Daniel. (2019). A systematic FEM analysis of the influence of mechanical properties in the reliability of the correlation methods in the Small Punch Test. International Journal of Mechanical Sciences. 153-154. 299-309. 10.1016/j.ijmecsci.2019.02.013.

[10] Foletti, S. & Madia, M. & Cammi, Andrea & Torsello, G.. (2011). *Characterization of the behavior of a turbine rotor steel by inverse analysis on the small punch test. Procedia Engineering. 10. 3636-3643. 10.1016/j.proeng.2011.04.597..*

[11] Abendroth, Martin. (2017). *FEM Analysis of Small Punch Tests. Key Engineering Materials. 734. 23-36. 10.4028/www.scientific.net/KEM.734.23..*

[12] Zoe Jie,Chen Yechao,Li Shanshan,Huauang Xiang(2015). *Research on Material Stress Strain Curve Prediction Methods Based on Transfer Learning and Artificial Intelligence, https://doi.org/10.4271/2026-01-8317*

[13] Altstadt, E. & Ge, Hongen & Kuksenko, Viacheslav & Serrano, Marta & Houska, M. & Lasan, M. & Bruchhausen, Matthias & Lapetite, J.-M & Dai, Yong. (2015). *Critical evaluation of the small punch test as a screening procedure for mechanical properties. Journal of Nuclear Materials. 472. 10.1016/j.jnucmat.2015.07.029.*

[14] Jose Calaf-Chica(1), Mario Sánchez Palomar(2), Pedro Miguel Bravo Díez(3), Mónica Preciado Calzada(4). *Deviations in yield and ultimate tensile strength estimation with the Small Punch Test: numerical analysis of pre-straining and Bauschinger effect influence. Calaf-mm_2021.pdf;jsessionid=47654A29D323CF7C1D0863576C9A75FA*

[15] Victoria Brown *Finite Element Modelling of the Small Punch Test for Structure Critical Design(2020) Victoria Brown - Doctoral Thesis.pdf*

[16] Çakan, Betül Gülçimen, Soyarslan, Celal, Bargmann, Swantje and Hähner, Peter. *Experimental and Computational Study of Ductile Fracture in Small Punch Tests. https://ris.utwente.nl/ws/files/277301499/Gulcimen_cakan_2017_Experimental_and_computational_stud.pdf*

[17] FEM-Simulation Applications & quality assurance - ZEISS, *https://www.zeiss.com/metrology/en/explore/topics/fem-simulation.html*

[18] David Müzel, Sarah et al. "*Application of the Finite Element Method in the Analysis of Composite Materials: A Review." Polymers vol. 12,4 818. 4 Apr. 2020, doi:10.3390/polym12040818*

[19] Adebisi Alade, Adefemi, Ibrahim, Ahmed(2023). *Application of Finite Element Method for Mechanical Characterization of Wood and Reconstituted Lignocellulosic-Based Composites – A Review. https://doi.org/10.21926/rpm.2301003*

[20] Nishant. *Design of hybrid setup for determination of mechanical properties of service exposed materials using fem and small punch test(2015)*

[21] Lucon, Enrico & Benzing, Jake & Hrabe, Nik, 2020. *Development and Validation of Small Punch Testing at NIST. NIST Interagency/Internal Report 8303. https://doi.org/10.6028/NIST.IR.8303*

[22] Torca, Ireneo & Aginagalde, Andrea & Esnaola, Jon & Galdos, Lander & Azpilgain, Zigor & Garcia, Carlos. (2009). *Tensile Behaviour of 6082 Aluminium Alloy Sheet under Different Conditions of Heat Treatment, Temperature and Strain Rate. Key Engineering Materials. 423. 105-112. 10.4028/www.scientific.net/KEM.423.105*

[23] 6082-T6~T651 Plate. *https://www.aalco.co.uk/datasheets/Aluminium-Alloy_6082-T6~T651_148.ashx*

[24] 6082 aluminum suppliers T6 temper. *https://alu-cn.com/product/6082-aluminum-suppliers-t6-temper/*

[26] Peter Hähner, Celal Soyarslan, Betül Gülçimen Çakan, Swantje Bargmann, 2019, *Determining tensile yield stresses from Small Punch tests: A numerical-based scheme, Materials & Design, Volume 182, 107974, ISSN 0264-1275, https://doi.org/10.1016/j.matdes.2019.107974*.

[26] Pushpraj Singh, Raj Kumar Singh, Anil Kumar Das et al. *Optimization of Heat Treatment Cycle for Cast-Al6082 Alloy to Enhance the Mechanical Properties, 26 September 2023, PREPRINT (Version 1) available at Research Square [https://doi.org/10.21203/rs.3.rs-3363991/v1]*

[27] Xiao, H.-W., & Gao, Z.-J. (2012). *The Application of Scanning Electron Microscope (SEM) to Study the Microstructure Changes in the Field of Agricultural Products Drying. InTech. doi: 10.5772/35223*

[28] Wróbel, R., Scheel, P., Maeder, X. *et al. Microstructure formation in micron-scale thin-walled Hastelloy X samples fabricated with laser powder bed fusion. Prog Addit Manuf **9**, 361–373 (2024). https://doi.org/10.1007/s40964-023-00458-z*

[29] 6082 Aluminum Alloy-Everything You Need to Know – Enze. *https://www.enzemfg.com/6082-aluminum-alloy-everything-you-need-to-know/*

[30] Datasheet for Steel Grades Structure Steel 35CrMo. *35CrMo Chemical Composition, Mechanical Properties, Heat Treatment, 35CrMo Datasheets, 35CrMoSupplier*

# LIST OF PUBLICATION

| Title of paper | Name of Conference |
|---|---|
| Design of hybrid setup for determination of mechanical properties of service exposed materials using small punch test | Presented in ICARI-2025 |


ISBN- 978-93-341-6814-3

International Conference of Advance Research and Innovation (ICARI-2025)

February 2nd, 2025

Certificate of Participation

This is to certify that Dr./Mr./Ms. Shivam Shekhar presented/attended/volunteered paper entitled Design of Hybrid setup for determination of Mechanical properties of service exposed materials using a small Punch Test for "**International Conference of Advance Research and Innovation (ICARI-2025)**" organized by the International Journal of Advance Research and Innovation (www.ijari.org), held at Delhi State Center, Institution of Engineers (India), New Delhi, India, on January 28th, 2025.

Prof. Nand Kumar
Editor

Prof. RC Singh
Editor

Prof. Bhupendra Singh Chauhan
Editor in Chief

www.ijari.org

# DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Shahbad Daulatpur, Main Bawana Road, Delhi-42

## PLAGIARISM VERIFICATION

Title of the Thesis:

DESIGN OF HYBRID SETUP FOR DETERMINATION OF MECHANICAL PROPERTIES OF SERVICE EXPOSED MATERIALS USING SMALL PUNCH TEST AND FEM

Total No. of Pages:58

Name of the Scholar: Shivam Shekhar

Supervisor (s) :Dr Sanjay Kumar

Department Mechanical Engineering

This is to report that the above thesis was scanned for similarity detection. Process and outcome is given below:

Software used Turnitin Similarity Index: 8% , Total Word Count: 14117

Date:

**Candidate's Signature** **Signature of Supervisor(s)**

# Shivam Shekhar

## SHIVAM THESIS FINAL_31_05_25.pdf

Delhi Technological University

### Document Details

Submission ID

trn:oid:::27535:98659522

Submission Date

May 31, 2025, 12:13 PM GMT+5:30

Download Date

May 31, 2025, 12:14 PM GMT+5:30

File Name

SHIVAM THESIS FINAL_31_05_25.pdf

File Size

1.5 MB

58 Pages

14,117 Words

88,395 Characters

# 8% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

## Filtered from the Report

- Bibliography
- Quoted Text
- Small Matches (less than 10 words)

## Match Groups

**62** Not Cited or Quoted 8%
Matches with neither in-text citation nor quotation marks

**7** Missing Quotations 1%
Matches that are still very similar to source material

**0** Missing Citation 0%
Matches that have quotation marks, but no in-text citation

**0** Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

## Top Sources

6% Internet sources
3% Publications
5% Submitted works (Student Papers)

## Integrity Flags

**2 Integrity Flags for Review**

**Replaced Characters**
14 suspect characters on 4 pages
Letters are swapped with similar characters from another alphabet.

**Hidden Text**
43 suspect characters on 1 page
Text is altered to blend into the white background of the document.

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for you to review.

A Flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.

## Match Groups

- **62** Not Cited or Quoted 8%
  Matches with neither in-text citation nor quotation marks
- **7** Missing Quotations 1%
  Matches that are still very similar to source material
- **0** Missing Citation 0%
  Matches that have quotation marks, but no in-text citation
- **0** Cited and Quoted 0%
  Matches with in-text citation present, but no quotation marks

## Top Sources

6% Internet sources
3% Publications
5% Submitted works (Student Papers)

## Top Sources

The sources with the highest number of matches within the submission. Overlapping sources will not be displayed.

| | | | |
|---|---|---|---|
| 1 | Internet | dspace.dtu.ac.in:8080 | 1% |
| 2 | Publication | Torca, I., A. Aginagalde, J.A. Esnaola, L. Galdos, Zigor Azpilgain, and C. Garcia. "Te... | <1% |
| 3 | Internet | www.enzemfg.com | <1% |
| 4 | Submitted works | Delhi Technological University on 2019-06-03 | <1% |
| 5 | Internet | www.researchgate.net | <1% |
| 6 | Internet | repository.lcu.edu.ng | <1% |
| 7 | Internet | nvlpubs.nist.gov | <1% |
| 8 | Internet | kipdf.com | <1% |
| 9 | Internet | www.mdpi.com | <1% |
| 10 | Publication | Joshi, Aniket. "Evaluation and Optimisation of the Small Ring Test and its Amalga... | <1% |

11 Submitted works

National University of Ireland, Galway on 2018-10-14 <1%

12 Submitted works

University of Greenwich on 2025-03-30 <1%

13 Internet

cronfa.swan.ac.uk <1%

14 Internet

elibrary.tucl.edu.np <1%

15 Submitted works

atharvacoe on 2025-04-09 <1%

16 Publication

A. Pourferiedouni, S.G. Shabestari. "Microstructural analysis and mechanical prop... <1%

17 Internet

researchcommons.waikato.ac.nz <1%

18 Internet

5dok.net <1%

19 Submitted works

Middle East College of Information Technology on 2023-04-24 <1%

20 Submitted works

Coventry University on 2023-12-04 <1%

21 Submitted works

University of Sheffield on 2023-08-24 <1%

22 Internet

etheses.whiterose.ac.uk <1%

23 Internet

ir.lib.shimane-u.ac.jp <1%

24 Internet

www.coursehero.com <1%

25 Submitted works
University of Bristol on 2019-09-06 <1%

26 Internet
www.ijrest.net <1%

27 Submitted works
Bournemouth University on 2024-07-12 <1%

28 Submitted works
Delhi Technological University on 2019-05-25 <1%

29 Submitted works
Higher Education Commission Pakistan on 2009-07-21 <1%

30 Submitted works
Queensland University of Technology on 2022-04-30 <1%

31 Publication
Romy Welschen, Frideriki Naziris, Peter ten Pierick, Murthy Kolluri. "Small Punch ... <1%

32 Publication
S. H. Chan. "Transport Phenomena In Combustion, Volume 1 - Proceedings of the ... <1%

33 Submitted works
The Robert Gordon University on 2017-04-11 <1%

34 Submitted works
Universiti Teknologi Malaysia on 2025-01-20 <1%

35 Submitted works
University of New South Wales on 2023-10-22 <1%

36 Publication
Vladimir V. Skripnyak, Vladimir A. Skripnyak, Evgeniya G. Skripnyak. "Chapter 20 ... <1%

37 Internet
rc.library.uta.edu <1%

38 Internet
su-plus.strathmore.edu <1%

39 Internet

tu-freiberg.de <1%

40 Internet

www.nepjol.info <1%

41 Submitted works

IIT Delhi on 2014-04-01 <1%

42 Submitted works

University College London on 2023-08-29 <1%

43 Internet

etd.aau.edu.et <1%

44 Internet

link.springer.com <1%

45 Internet

repositorio.ipen.br <1%

46 Internet

umpir.ump.edu.my <1%