MAHAKAL INSTITUTE OF TECHNOLOGY, UJJAIN

Approved By: All India Council of Technical Education (New Delhi)

DEPARTMENT OF MECHANICAL ENGINEERING

LAB MANUAL

Name of Student : ……………………..

Name of Lab : Advance Machine Design

Subject Code : ME- 8001

Branch : Mechanical Engineering

Year/Sem : IV/VIII

Affiliated to Rajiv Gandhi Prodyogiki Vishwavidyalaya, Bhopal (MP)

INDEX

S. No.	Name of Experiment	Date	Sign	Remark
1.	Fundamentals of technical system and system approach			
2.	Study of phases and interaction of design process			
3.	Study of Design based on reliability			
4.	Design based on theory of elasticity and Numerical practice			
5.	Design based on theory of Plasticity and Numerical practice			
6.	Study of design based on tribology			
7.	Study of friction mechanisms and different kinds of friction.			
8.	Study of different kinds of wear and design changes as per wear mechanisms.			
9.	Study of different kind of lubricant used to design machine component			
10.	Study of various type of strain gauges and wire resistance gauges			

List of Experiments
Advance Machine Design (ME- 8001)

1. Fundamentals of technical system and system approach
2. Study of phases and interaction of design process
3. Study of Design based on reliability
4. Design based on theory of elasticity and Numerical practice
5. Design based on theory of Plasticity and Numerical practice
6. Study of design based on tribology
7. Study of friction mechanisms and different kinds of friction
8. Study of different kinds of wear and design changes as per wear mechanisms
9. Study of different kind of lubricant used to design machine component
10. Study of various type of strain gauges and wire resistance gauges

Lab Manual

ADVANCE MACHINE DESIGN (ME-8001)

Total number of Experiments: 10
Total number of Turns: 12

S. No.	Name of Experiment	Turns needed to complete
1.	Fundamentals of technical system and system approach	1
2.	Study of phases and interaction of design process	1
3.	Study of Design based on reliability	1
4.	Design based on theory of elasticity and Numerical practice	2
5	Design based on theory of Plasticity and Numerical practice	2
6	Study of design based on tribology	1
7	Study of friction mechanisms and different kinds of friction	1
8	Study of different kinds of wear and design changes as per wear mechanisms	1
9	Study of different kind of lubricant used to design machine component	1
10	Study of various type of strain gauges and wire resistance gauges	1

Distribution of Lab Hours:	**1 Hour – 40 Minutes**
Explanation of Experiment:	**20 Min.**
Performance of Experiment:	**50 Min.**
File Checking:	**10 Min.**
Attendance:	**05 Min.**
Viva/Quiz:	**05 Min.**
Solving of Queries:	**10 Min.**

DEPLOYMENT OF THE EXPERIMENT:

Turn	Deployment
1.	Introduction of Lab & explanation of Script
2.	Experiment No.1
3.	Experiment No.2
4.	Experiment No.3
5.	Experiment No.4
6.	Experiment No.4
7.	Experiment No.5
8.	Experiment No.5
9.	Experiment No.6
10.	Experiment No.7
11.	Experiment No.8
12.	Experiment No.9
13.	Experiment No.10

BATCH DISTRIBUTION:

(Per Batch of 30 Students)

REFERENCE BOOKS:

S. No.	Title of the Book	Authors	Publication
1.	Fracture Mechanics	TL Anderson	CRC Press
2.	Engineering Design	G.E. Dieter	Pearson
3.	Strain gauge primer	CC Peery & HR Lissener	McGraw- Hill

EXPERIMENT NO. 1

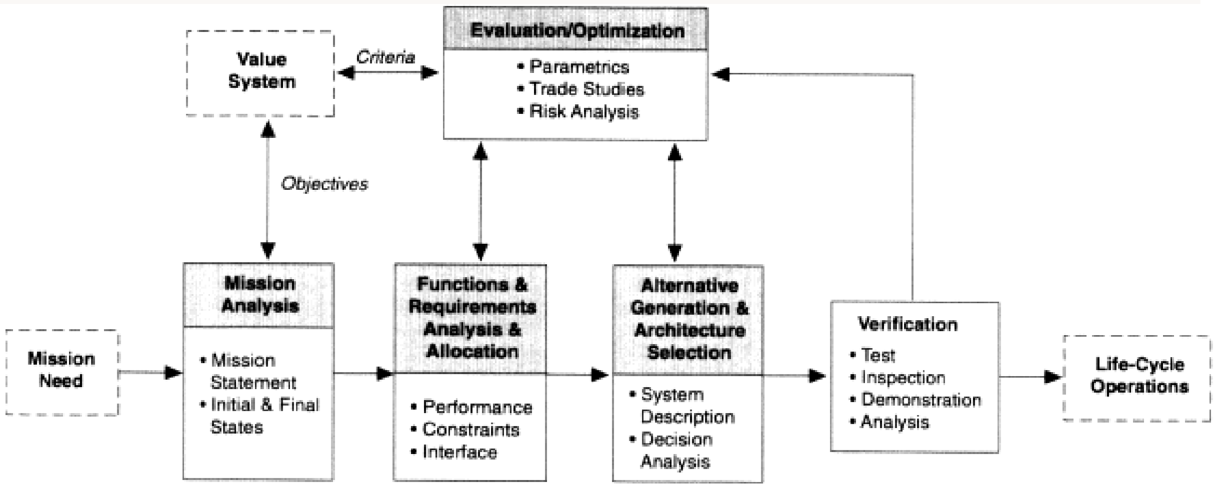
OBJECTIVE: Study of Fundamental of technical system and approach

Fundamental of technical system
Whether you are a backend developer, product manager or technical manager, everyone needs to know how to build reliable, scalable and maintainable applications. No one expects a developer or product manager to design a new storage engine. However, it is expected from the said folks, to appropriately describe load and operating performance parameters of their applications. They are also expected to cobble together various data systems like storage, caching, stream processing, search, retrieval and batch processing, and design a resilient system.

The Systems Engineering Process

Systems engineering, essentially an application of systems analysis to the design and procurement of hardware systems to accomplish specific ends, can be an effective tool of management when well defined and consistently implemented. The essential products of the systems engineering process and their programmatic use are described in this section.

The systems engineering process involves the top-down development of a system's functional and physical requirements from a basic set of mission objectives. The purpose is to organize information and knowledge to assist those who manage, direct, and control the planning, development, and operation of the systems necessary to accomplish the mission (Sage, 1992). The system's physical requirements lead to the specific hardware components that must be acquired or developed to perform the identified functions. The systems engineering process should be conducted in a way that includes consideration of alternative system configurations. The result should be a set of traceable requirements that may be used in design and procurement and in system verification and validation, a baseline description of the physical system, and a baseline description of the operational concept. This should also include a set of documented interfaces to ensure compatibility of different parts of the system as they are developed. The process being used in the Tank Waste Remediation System (TWRS) program at Hanford follows from what is described above; it is illustrated in Figure 1



Several terms used in systems engineering are defined below for the convenience of the reader. *Traceability* imposes the conditions that the interdependencies among physical and functional requirements be made explicit and that each requirement be trackable longitudinally through the entire systems engineering process and through the system' s full life cycle (Eisner, 1997). *System verification* is a two-step process to assure, first, that system design successfully captures the full set of system requirements, and second, that the system hardware and software fully implement the design. *System validation* is the process of assuring that, once the system is developed, its operational concept will meet the original system requirements (Sage, 1992).

Baseline descriptions, both of design of the physical system and of the functions the system is supposed to perform, once built, are essential to the process of modifying the system as new information or experience is obtained. *Configuration management and change control* are important quality assurance steps that ensure changes to the baseline occur in a planned manner and are thoroughly documented, so that implications for system performance are understood. The direction of desirable changes is specified through *configuration control* (Sage, 1992). The system's initial baseline description is also referred to as its *conceptual architecture*.

The systems engineering process provides value to the development, management, and implementation of a large program by ensuring:

- orderly definition of a system through top-down development of functions and requirements;
- clear distinction between design requirements developed by the program/project (potentially modifiable) and externally imposed constraints (not easily subject to modification);
- top-down consideration and evaluation of alternative solutions and designs, and
- completeness and traceability for design of system elements and interfaces, for configuration and change control, and for the system verification and validation plan(s).

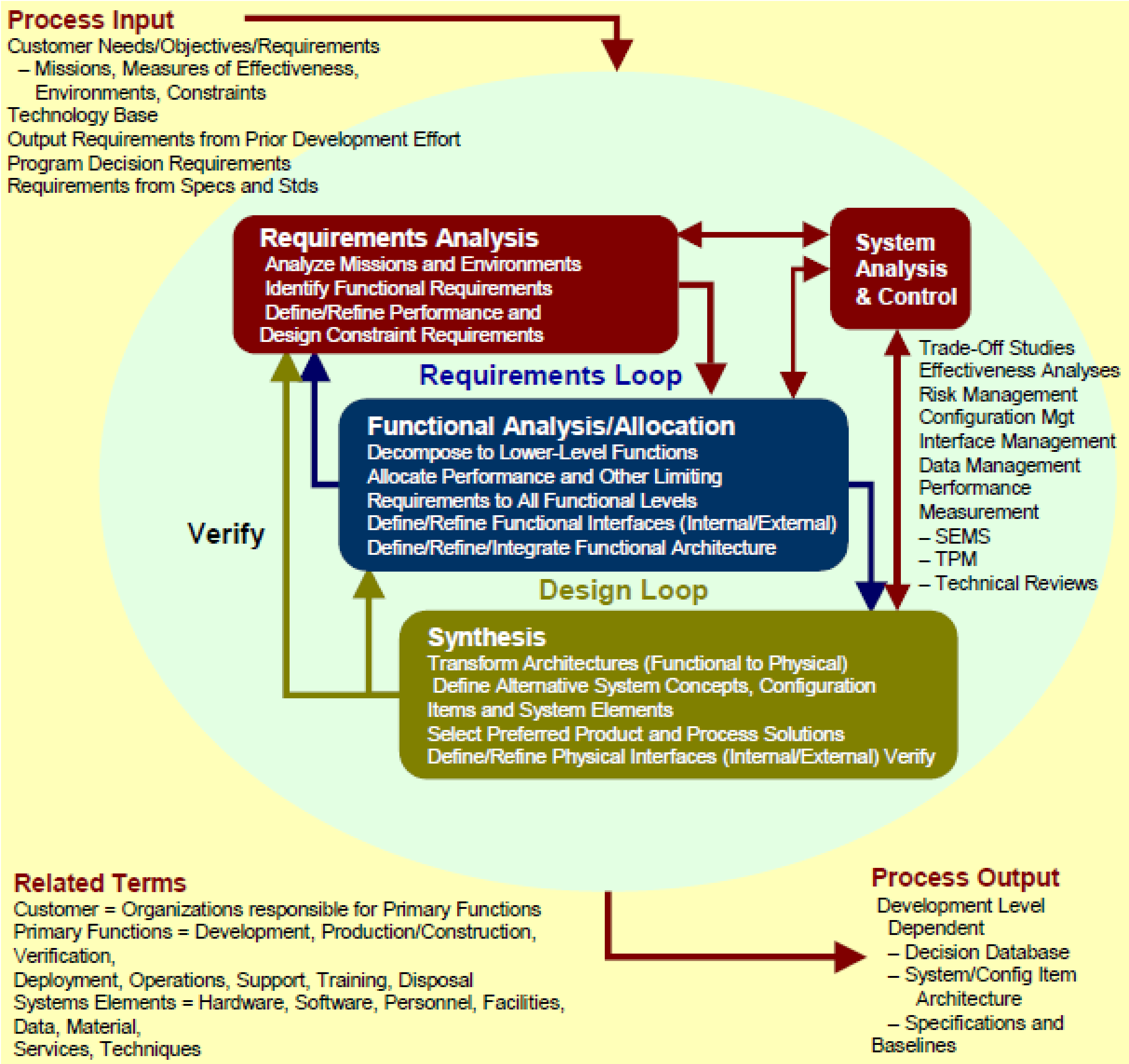
This value of the systems engineering process may be realized in a number of ways, including:

- increased ability to estimate system life-cycle costs,
- reduced redesign due to consideration of the entire system throughout its development,
- increased ability to effect design changes and retrofits due to clear traceability of requirements, design features, and configuration control, and
- increased probability of achieving the best technical de-

The Systems Engineering Process is a comprehensive, iterative and recursive problem solving process, applied sequentially top-down by integrated teams. It transforms needs and requirements into a set of system product and process descriptions, generate information for decision makers, and provides input for the next level of development. The process is applied sequentially, one level at a time, adding additional detail and definition with each level of development. [1]

The four (4) steps that comprise the SE Process are:

- Step 1: Requirements Analysis
- Step 2: System Analysis Control
- Step 3: Functional Analysis/Allocation
- Step 4: Design Synthesis
    - Process Input, Requirements Loop, Design Loop, Process Output & Verify



SMC Systems Engineering Handbook – Systems Engineering Process –

AcqTips:

- There is no one standard definition or systems engineering process. It's a collection of ways and means across many disciplines. Best practices, guidebooks and lessons learned are a great source of systems engineering knowledge.
- Each program is different so there is no one process that perfectly fits. It's the job of the systems engineer to modify the process to meets their programs needs the most

References:

-] Space and Missile Systems Center (SMC) "Systems Engineering Primer & Handbook" – 29 April 2005
- Defense Acquisition Guidebook (DAG) – Chapter 4
- DAU Systems Engineering Fundamentals Guide – Jan 2001
- NASA Systems Engineering Handbook (large 9 Mb file)

EXPECTED VIVA QUESTIONS:

Q.1 What is system engineering ?

Q.2 What is process output and process input ?

Q.3 What is the fundamental of system?

NAME OF FACULTY:

SIGNATURE:

DATE:

EXPERIMENT NO. 2

OBJECTIVE: Study of phases and interaction of design process

Engineering design is the method that engineers use to identify and solve problems. It has been described and mapped out in many ways, but all descriptions include some common attributes:

Engineering design is a process. This powerful approach to problem solving is flexible enough to work in almost any situation. Engineers learn important information about both the problem and possible solutions at each step or phase of the process.

Learn about different models of engineering design.

Engineering design is purposeful. The process always begins with an explicit goal. If it were a journey, it would be one with a specific destination – not a random sightseeing trip.

Engineering design is "design under constraint." Designers must choose solutions that include the most desired features and fewest negative characteristics. But they must stay the limitations of the given scenario, which could include time, cost, and the physical limits of tools and materials.

Engineering design is systematic and iterative. It is a process that includes steps that can be repeated, although not always in the same order. Steps include things like planning, modeling, testing, and improving designs.

Engineering design is a social, collaborative enterprise. This process is often done in small teams that include people with different kinds of knowledge and experience. Designers are continuously communicating with clients, team members, and others.

How are engineering design and science inquiry different?

Science is commonly described as the study of the natural world through observation and experimentation. In PreK-12 settings, it usually refers to "natural" sciences: physics, chemistry, biology, and earth, space, and environmental sciences. Like engineers, scientists also use a reasoning process to solve problems: scientific inquiry.

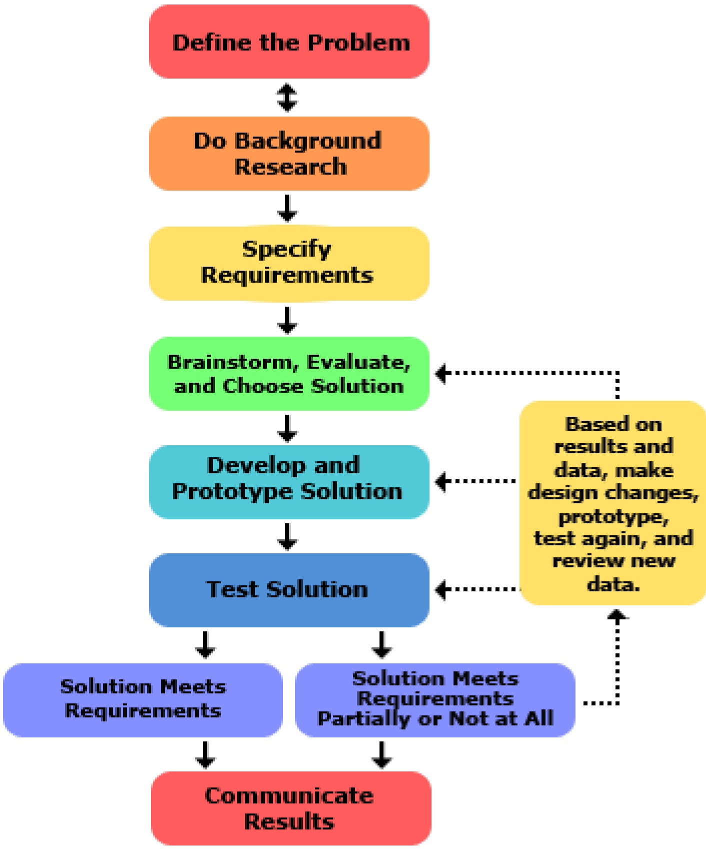
Science inquiry and engineering design use similar cognitive tools such as brainstorming, reasoning by analogy, mental models, and visual representations. Scientists use these tools to ask questions about the world around us and try to deduce rules that explain the patterns we see. Engineers use them to modify the world to satisfy people's needs and wants.

"Scientists discover the world that exists; engineers create the world that never was."
Theodore von Karman, co-founder of NASA's Jet Propulsion Laboratory

In the real world today, engineering and science cannot be neatly separated. Scientific knowledge informs engineering design, and many scientific advances would not be possible without technological tools developed by engineers.

The Engineering Design Process

The engineering design process is a series of steps that engineers follow to come up with a solution to a problem. Many times the solution involves designing a product (like a machine or computer code) that meets certain criteria and/or accomplishes a certain task. This process is different from the Steps of the Scientific Method, which you may be more familiar with. If your project involves making observations and doing experiments, you should probably follow the Scientific Method. If your project involves designing, building, and testing something, you should probably follow the Engineering Design Process. If you still are not sure which process to follow, you should read Comparing the Engineering Design Process and the Scientific Method. This diagram shows the steps of the engineering design process, and the table below describes each step in more detail:



Engineers do not always follow the engineering design process steps in order, one after another. It is very common to design something, test it, find a problem, and then go back to an earlier step to make a modification or change to your design. This way of working is called **iteration**, and it is likely that your process will do the same!

Steps of the Engineering Design Process

Define the Problem. The engineering design process starts when you ask the following questions about problems that you observe:

- What is the problem or need?
- Who has the problem or need?
- Why is it important to solve?

[Who] need(s) [what] because [why].

Do Background Research: Learn from the experiences of others — this can help you find out about existing solutions to similar problems, and avoid mistakes that were made in the past. So, for an engineering design project, do background research in two major areas:

- Users or customers

- Existing solutions

Specify Requirements: Design requirements state the important characteristics that your solution must meet to succeed. One of the best ways to identify the design requirements for your solution is to analyze the concrete example of a similar, existing product, noting each of its key features.

Brainstorm Solutions: There are always many good possibilities for solving design problems. If you focus on just one before looking at the alternatives, it is almost certain that you are overlooking a better solution. Good designers try to generate as many possible solutions as they can.

Choose the Best Solution: Look at whether each possible solution meets your design requirements. Some solutions probably meet more requirements than others. Reject solutions that do not meet the requirements.

Develop the Solution: Development involves the refinement and improvement of a solution, and it continues throughout the design process, often even after a product ships to customers.

Build a Prototype: A prototype is an operating version of a solution. Often it is made with different materials than the final version, and generally it is not as polished. Prototypes are a key step in the development of a final solution, allowing the designer to test how the solution will work.

Test and Redesign: The design process involves multiple iterations and redesigns of your final solution. You will likely test your solution, find new problems, make changes, and test new solutions before settling on a final design.

Communicate Results: To complete your project, communicate your results to others in a final report and/or a display board. Professional engineers always do the same, thoroughly documenting their solutions so that they can be manufactured and supported.

EXPECTED VIVA QUESTIONS:

Q.1 What is Engineering design?

Q.2 What is Engineering design process?

Q.3 Define steps of design process?

NAME OF FACULTY:

SIGNATURE:

DATE:

EXPERIMENT NO. 3

OBJECTIVE: Study of Design based on reliability

Design for Reliability: Overview of the Process and Applicable Techniques

Design for Reliability (DFR) is not a new concept, but it has begun to receive a great deal of attention in recent years. What is DFR? What are the ingredients for designing for reliability, and what is involved in implementing DFR? Should DFR be part of a Design for Six Sigma (DFSS) program, and is DFR the same as DFSS? In this article, we will try to answer these questions and, at the same time, we will propose a general DFR process that can be adopted and deployed with a few modifications across different industries in a way that will fit well into the overall Product Development Process. The Synthesis applications can be used together based on the DFR approach.

What is Design for Reliability (DFR)?

All reliability professionals are familiar with the terms *Weibull Analysis* and/or *Life Data Analysis*. In fact, for many, these analysis techniques have become almost synonymous with reliability and achieving high reliability. The reality, though, is that although life data analysis is an important piece of the pie, performing just this type of analysis is not enough to achieve reliable products. Rather, there are a variety of activities involved in an effective reliability program and in arriving at reliable products. Achieving the organization's reliability goals requires strategic vision, proper planning, sufficient organizational resource allocation and the integration and institutionalization of reliability practices into development projects.

Design for Reliability, however, is more specific than these general ideas. It is actually a process. Specifically, DFR describes the entire set of tools that support product and process design (typically from early in the concept stage all the way through to product obsolescence) to ensure that customer expectations for reliability are fully met throughout the life of the product with low overall life-cycle costs. In other words, DFR is a systematic, streamlined, concurrent engineering program in which reliability engineering is weaved into the total development cycle. It relies on an array of reliability engineering tools along with a proper understanding of when and how to use these tools throughout the design cycle. This process encompasses a variety of tools and practices and describes the overall order of deployment that an organization needs to follow in order to design reliability into its products.

Why is DFR Important?

Why should a company commit resources for deploying a DFR process? The answer to this question is quite simple... warranty costs and customer satisfaction. Field failures are very costly. One case in point is the recently publicized Xbox issue, which has cost Microsoft more than a billion dollars in warranties (aside from loss of business and market share).

Clearly, in order to be profitable, an organization’s products must be reliable, and reliable products require a formal reliability process. Three important statements summarize the best practice reliability philosophy of successful companies:

> 1) Reliability must be designed into products and processes using the best available science-based methods.
>
> 2) Knowing how to calculate reliability is important, but knowing how to achieve reliability is equally, if not more, important.
>
> 3) Reliability practices must begin early in the design process and must be well integrated into the overall product development cycle.

Understanding when, what and where to use the wide variety of reliability engineering tools available will help to achieve the reliability mission of an organization. And this is becoming more and more important with the increasing complexity of systems as well as the complexity of the methods available for determining their reliability. System interactions, interfaces, complex usage and stress profiles need to be addressed and accounted for. With such increasing complexity in all aspects of product development, it becomes a necessity to have a well defined process for incorporating reliability activities into the design cycle. Without such a process, trying to implement all of the different reliability activities involved in product development can become a chaotic situation, where different reliability tools are deployed too late, randomly, or not at all, resulting in the waste of time and resources as well as the occurrence of problems in the field.

Managers and engineers have come to this realization and a push for a more structured process has been seen in recent years. The circumstances are very similar to what happened with the "Quality Assurance" discipline back in the 1980s, which spawned successful processes such as *Six Sigma* and *Design for Six Sigma* (DFSS). It is thus only natural for organizations to look to these existing processes and sometimes even try to include reliability in them. However, although Six Sigma and DFSS have been quite successful in achieving higher quality, reducing variation and cutting down the number of non-conforming products, the methodologies are primarily focused on product *quality* and many organizations are starting to realize that they do not adequately support the achievement of high *reliability*. Therefore, these organizations are starting to put more emphasis on the separate, although often complementary, techniques of Design for Reliability.

Since the distinctions between reliability and quality, and consequently between DFR and DFSS, are often still poorly understood, it is worthwhile to address this topic briefly in the next few sections before presenting the overall process and the specific techniques that comprise DFR.

Distinction Between Reliability and Quality

First, let us start with some basic clarifications. Traditional *quality control* assures that the product will work after assembly and as designed. Whereas *reliability* provides the probability that an item will perform its intended function for a designated period of time without failure under specified conditions. In other words, reliability looks at *how long* the product will work as designed, which is a very different objective than that of traditional quality control. Therefore, different tools and models apply to reliability that do not necessarily apply to quality and vice versa. This is exemplified by the following comparison of DFSS (focused on quality) and DFR (focused on reliability).

Distinction Between DFSS and DFR

Design for Six Sigma emerged from the Six Sigma and the Define-Measure-Analyze-Improve-Control (DMAIC) quality methodologies, which were originally developed by Motorola to systematically improve processes by eliminating defects. Unlike its traditional Six Sigma/DMAIC predecessors, which are usually focused on solving existing manufacturing issues (i.e., "fire fighting"), DFSS aims at avoiding manufacturing problems by taking a more proactive approach to problem solving and engaging the company efforts at an early stage to reduce problems that could occur (i.e., "fire prevention"). The primary goal of DFSS is to achieve a significant reduction in the number of nonconforming units and production variation. It starts from an understanding of the customer expectations, needs and *Critical to Quality* issues (CTQs) before a design can be completed. Typically in a DFSS program, only a small portion of the CTQs are reliability-related, and therefore, reliability does not get center stage attention in DFSS. DFSS rarely looks at the long-term (after manufacturing) issues that might arise in the product.

On the other hand, Design for Reliability is a process specifically geared toward achieving high long-term reliability. This process attempts to identify and prevent design issues early in the development phase, instead of having these issues found in the hands of the customer. As mentioned previously, a variety of tools are used in order to accomplish this objective. These tools are different than those used in DFSS, even though there is some overlap. Figure 1 illustrates the different tools used in DFSS and DFR, as well as the overlap between the two. As you can see from this graphic, the types of tools used in DFR are based on modeling the life of the product, understanding the operating stresses and the physics of failure. The common area between DFSS and DFR includes tools such as *Voice of the Customer* (VOC), *Design of Experiments* (DOE) and *Failure Modes and Effects Analysis* (FMEA), which are essential elements in any kind of product improvement program.

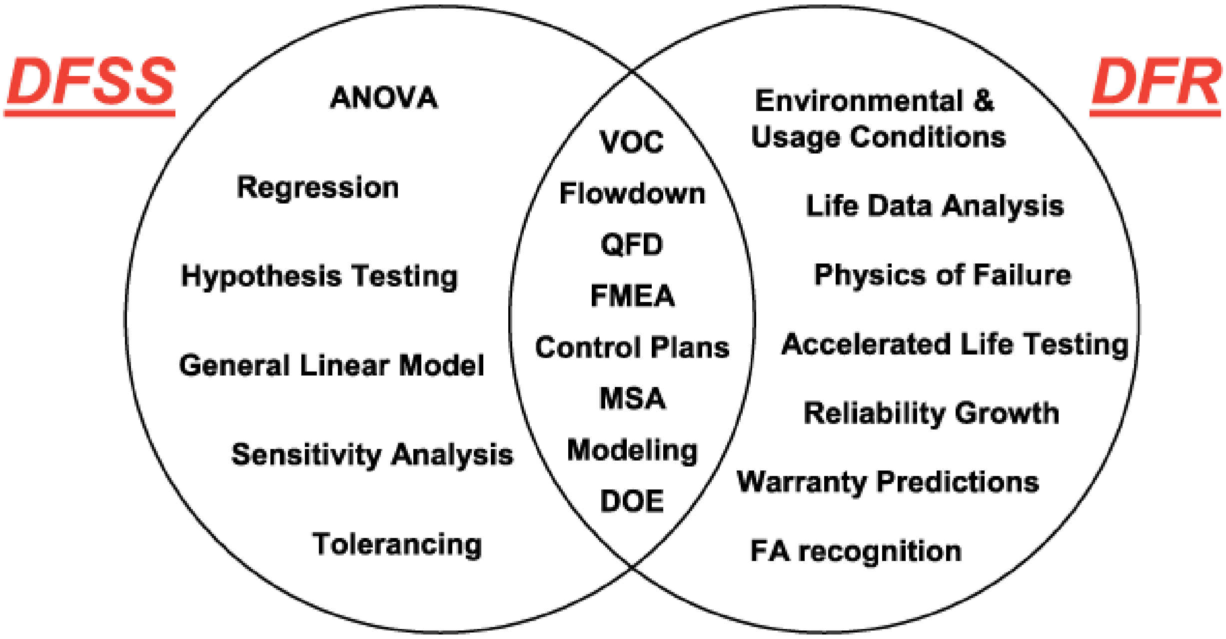


Figure 1: Tools used in DFSS and DFR

Proper Relationship Between Reliability and Quality

As the previous sections demonstrate, there is a clear distinction between the goals and tools employed to assure *quality* versus those employed to analyze and improve *reliability*. Of course, there are also many natural affinities between the two disciplines and it is understandable that many organizations have traditionally combined both quality and reliability under the same umbrella. In some cases, when the organization clearly understands the distinction between quality and reliability and applies the appropriate tools for both objectives, this combination can be appropriate and effective. However, when there is not a clear understanding of the essential differences in the tools involved, this can lead to very poor outcomes resulting from the improper use of tools and data. The rest of this article attempts to distinguish the specific processes and techniques that are necessary to ensure a product's reliability by presenting a high-level overview of a general DFR process.

The DFR Process

The *Stress-Strength Interference* principle states that a product fails when the stress experienced by the product exceeds its strength (as shown in Figure 2). In order to reduce the failure probability (and thus increase the reliability), we must reduce the interference between stress and strength. A structured process, such as the DFR process presented in this article, is needed in order to achieve this. The proposed process can be used as guide to the sequence of deploying the different tools and methods involved in a program to ensure high reliability. This process can be adapted and customized based on your specific industry, your corporate culture and other existing processes within your company (such as Six Sigma and/or DFSS). In addition, the sequence of the activities within the DFR process will vary based on the nature of the product and the amount of information available. It is important to note that even though this process is presented in a linear sequence, in reality some activities would be performed in parallel and/or in a loop based on the knowledge gained as a project moves forward. Figure 3 presents a summary of the full process and the ways in which techniques may interact.

In order to make this DFR process general enough, and applicable to different industries, we decided to break the process down into six key activities, which are: 1) Define, 2) Identify, 3) Analyze and Assess, 4) Quantify and Improve, 5) Validate and 6) Monitor and Control. By dividing the process into these activities, we can identify and group the different tools, and provide a roadmap that can easily be followed, as well as easily mapped into a Product Development Process (Concept, Design, Assurance, Manufacturing and Launch).

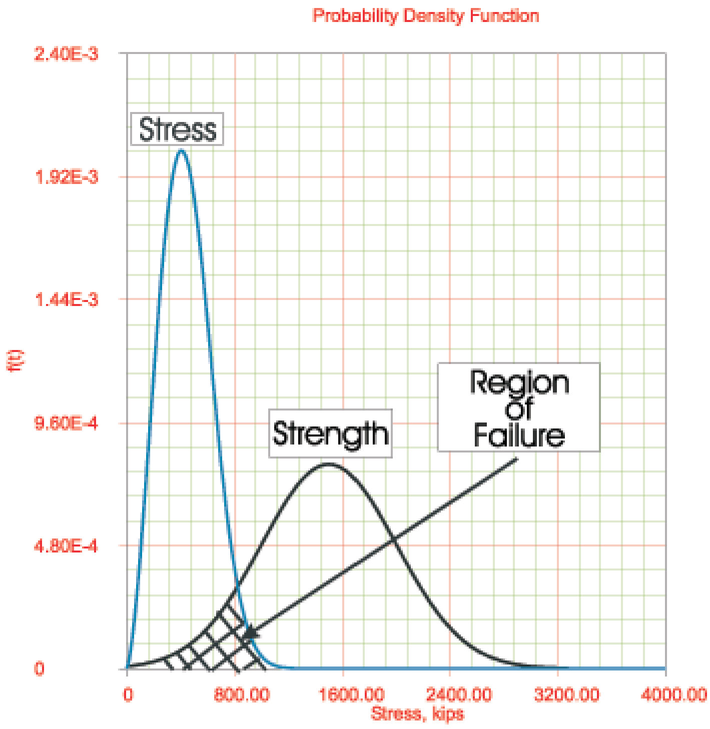


Figure 2: Illustration of Stress-Strength Interference

Define

The purpose of this stage is to clearly and quantitatively define the reliability requirements and goals for a product as well as the end-user product environmental/usage conditions. These can be at the system level, assembly level, component level or even down to the failure mode level.

Determining the usage and environmental conditions is an important early step of a DFR program. Companies need to know what it is that they are designing for and what types of stresses their products are supposed to withstand. The conditions can be determined based on customer surveys, environmental measurement and sampling.

Requirements can be determined in many different ways, or through a combination of those different ways. Requirements can be based on contracts, benchmarks, competitive analysis, customer expectations, cost, safety, best practices, etc. Some of the tools worth mentioning that help in quantifying the "voice of the customer" include *KANO models*, *affinity* *diagrams* and *pair-wise comparisons*. Of particular interest to DFR are the requirements that are *Critical to Reliability* (CTR). While the emphasis of DFSS is on satisfying the Criticality to Quality issues (CTQs), which are typically not reliability-related, DFR focuses specifically on the reliability aspects of a product.

The system reliability requirement goal can be allocated to the assembly level, component level or even down to the failure mode level. Different allocation techniques are available, such as *Equal*, *AGREE*, *Feasibility*, *ARINC*, *Repairable Systems Allocation* and the cost-based *RS-Allocation* methods (which are supported by ReliaSoft BlockSim software).

Once the requirements have been defined, they must be translated into design requirements and then into manufacturing requirements. A commonly used methodology is the *Quality Function Deployment* (QFD) approach using what is commonly called the *House of Quality* tool. This is a systematic tool to translate customer requirements into functional requirements, physical characteristics and process controls.

Identify

In this stage, a clearer picture about what the product is supposed to do starts developing. It is important to understand how much change is introduced with this new product. A product can be an upgrade of an existing product, an existing product that is introduced to a new market or application, a product that is not new to the market but is new to the company or it could be a completely new product that does not exist in the market. With more design or application change, more reliability risks are introduced to the success of the product and company.

A thorough change point analysis should reveal changes in design, material, parts, manufacturing, supplier design or process, usage environment, system's interface points, system's upstream and downstream parts, specifications, interface between internal departments, performance requirements, etc. A formal methodology called *Change Point Analysis* can be used to examine what changes, if any, have taken place. The purpose of this exercise is to identify and prioritize the *Key Reliability Risk* items and their corresponding *Risk Reduction Strategy*. Designers should consider reducing design complexity and maximizing the use of standard (proven) components.

A good tool to assess risk early in the DFR program is the FMEA. FMEAs identify potential failure modes for a product or process, assess the risk associated with those failure modes, prioritize issues for corrective action and identify and carry out corrective actions to address the most serious concerns. A properly applied *Design FMEA* (DFMEA) takes requirements, customer usage and environment information as inputs and, through its findings, initiates and/or informs many reliability-centered activities such as *Physics of Failure*, *System Analysis*, *Reliability Prediction*, *Life Testing* and *Accelerated Life Testing*.

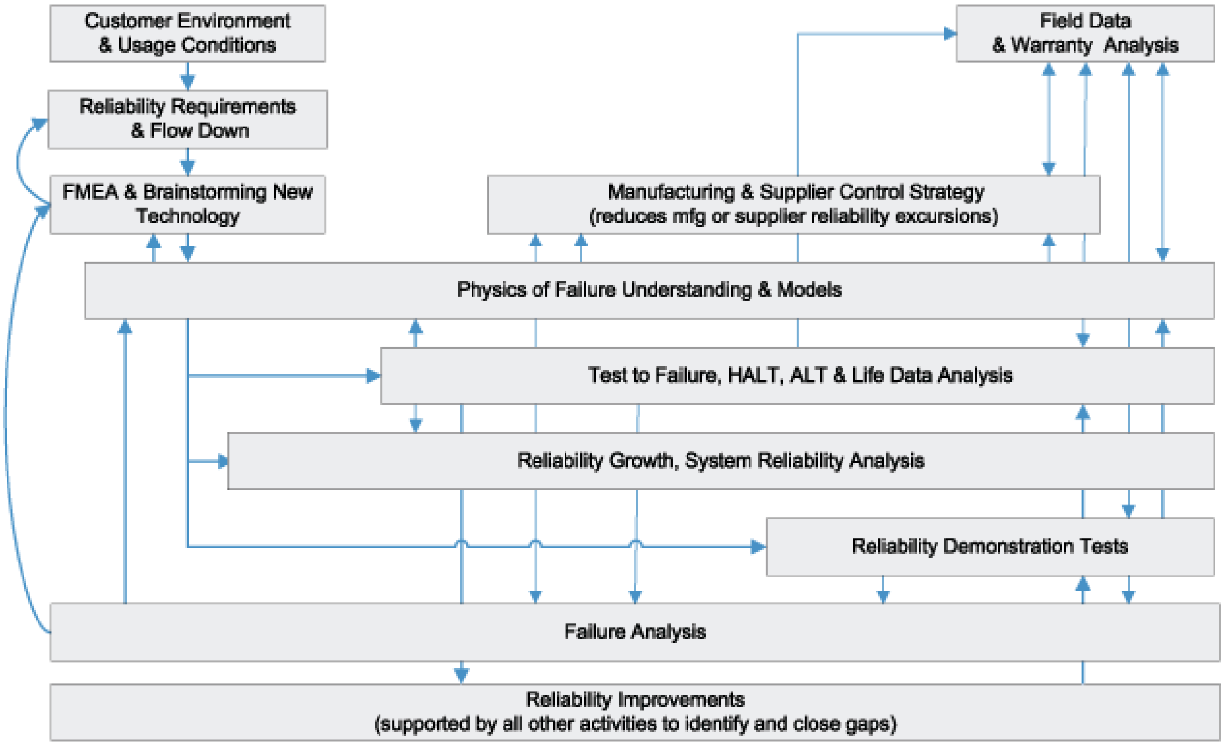


Figure 3: DFR Process

Analyze and Assess

It is highly important to estimate the product's reliability, even with a rough first cut estimate, early in the design phase. This can be done with estimates based on engineering judgment and expert opinion, *Physics of Failure* (PoF) analysis, simulation models, prior warranty and test data from similar products/components (using life data analysis techniques) or *Standards Based Reliability Prediction* (using common military or commercial libraries, such as MIL-217, Bellcore and Telcordia, to come up with rough MTBF estimates or to compare different design concepts when failure data is not yet available).

PoF analysis provides much needed insights into the failure risks and mechanics that lead to them (especially when actual test data is not available yet). PoF utilizes knowledge of life-cycle load profile, package architecture, material properties, relevant geometry, processes, technologies, etc, to identify potential *Key Process Indicator Variables* (KPIVs) for failure mechanisms. It can also be used to identify design margins and failure prevention actions as well as to focus reliability testing.

Quantify and Improve

In this stage, we will start quantifying all of the previous work based on test results. By this stage, prototypes should be ready for testing and more detailed analysis. Typically, this involves an iterative process where different types of tests are performed, the results are analyzed, design changes are made, and tests are repeated. A wide array of tools are available for the reliability engineer to uncover product weaknesses, predict life and manage the reliability improvement efforts. The following is a summary of the most commonly used tools.

Design of Experiments (DOE) provides a methodology to create organized test plans to identify important variables, to estimate their effect on a certain product characteristic and to optimize the settings of these variables to improve the design robustness. Within the DFR concept, we are mostly interested in the effect of stresses on our test units. DOEs play an important role in DFR because they assist in identifying the factors that are significant to the life of the product, especially when the physics of failure are not well understood. Knowing the significant factors results in more realistic reliability tests and more efficient accelerated tests (since resources are not wasted on including insignificant stresses in the test).

With testing comes data, such as failure times and censoring times. Test results can be analyzed with *Life Data Analysis* (LDA) techniques to statistically estimate the reliability of the product and calculate various reliability-related metrics with a certain confidence interval. Applicable metrics may include reliability after a certain time of use, conditional reliability, B(X) information, failure rate, MTBF, median life, etc. These calculations can help in verifying whether the product meets its reliability goals, comparing designs, projecting failures and warranty returns, etc.

As an alternative to testing under normal use conditions and LDA, *Quantitative Accelerated Life Testing* (QALT) can also be employed to cut down on the testing time. By carefully elevating the stress levels applied during testing, failures occur faster and thus failure modes are revealed (and statistical life data analysis can be applied) more quickly.

Highly Accelerated Tests (HALT/HASS) are qualitative accelerated tests used to reveal possible failure modes and complement the physics of failure knowledge about the product. However, data from qualitative tests cannot be used to quantitatively project the product's reliability.

A very important aspect of the DFR process also includes performing *Failure Analysis* (FA) or *Root Cause Analysis* (RCA). FA relies on careful examination of failed devices to determine the root cause of failure and to improve product reliability. This is where the engineers come face-to-face with the failure, see what a failure actually looks like and study the processes that lead to it. FA provides better understanding of physics of failure and can discover issues not foreseen by techniques used prior to testing (such as FMEA). FA helps with developing tests focused on problematic failure modes. It can also help with selecting better materials and/or designs and processes, and with implementing appropriate design changes to make the product more robust.

System Reliability Analysis with *Reliability Block Diagrams* (RBDs) can be used in lieu of testing an entire system by relying on the information and probabilistic models developed on the component or subsystem level to model the overall reliability of the system. It can also be used to identify weak areas of the system, find optimum reliability allocation schemes, compare different designs and to perform auxiliary analysis such as availability analysis (by combining maintainability and reliability information).

Fault Tree Analysis (FTA) may be employed to identify defects and risks and the combination of events that lead to them. This may also include an analysis of the likelihood of occurrence for each event.

Reliability Growth (RG) testing and analysis is an effective methodology to discover defects and improve the design during testing. Different strategies can be employed within the reliability growth program, namely: test-find-test (to discover failures and plan delayed fixes), test-fix-test (to discover failures and implement fixes during the test) and test-fix-find-test (to discover failures, fix some and delay fixes for some). RG analysis can track the effectiveness of each design change and can be used to decide if a reliability goal has been met and whether, and how much, additional testing is required.

Validate

The activities described thus far should continue until the design is considered to be "acceptable." In the Validate stage, a *Demonstration Test* can be used to make sure that the product is ready for high volume production. Statistical methods (such as *Parametric Binomial* and *Non-Parametric Binomial*) can be used to develop a test plan (i.e., a combination of test units, test time and acceptable failures) that will demonstrate the desired goal with the least expenditure of resources.

Suppliers also present another area of risk that needs to be addressed in a DFR program and, therefore, procedures should be developed to assist and control the suppliers. Continuous sampling of units for testing and QALT and LDA analysis is highly desirable throughout manufacturing to estimate the reliability of the product and assess whether the reliability goal is still expected to be met.

Monitor and Control

Process FMEAs (PFMEAs) can be used to examine the ways the reliability and quality of a product or service can be jeopardized by the manufacturing and assembly processes. *Control Plans* can be used to describe the actions that are required at each phase of the process to assure that all process outputs will be in a state of control. *Factory Audits* are necessary to ensure that manufacturing activities (such as inspections, supplier control, routine tests, storing finished products, Measurement System Analysis and record keeping) are being implemented according to requirements.

The manufacturing process is also prone to deviations. The reliability engineer ought to communicate to the production engineer the specification limits on the KPIVs that would define a "reliability conforming" unit. The production engineer is then responsible for ensuring that the manufacturing process does not deviate from the specifications. Here, we start seeing more aspects of reliability engineering discipline merge with quality engineering. *Statistical Process Control* (SPC) methods can be useful in this regard.

Burn-in and *Screening* are DFR tools that can be useful in preventing infant mortality failures, which are typically caused by manufacturing-related problems, from happening in the field. Deciding on the appropriate burn-in time can be derived from QALT and/or LDA. Also, manufacturability challenges might force some design changes that would trigger many of the DFR activities already mentioned.

Does the DFR process end here, though? The answer is a definite No. Continuous monitoring and field data analysis are necessary in order to observe the behavior of the product in its actual use (and abuse) conditions, and use the gained knowledge for further improvements or in future projects. In other words, we need to close the loop, review the successful activities as well as the mistakes, and ensure that the lessons learned are not lost in the process. Tools such as *Failure Reporting, Analysis and Corrective Action Systems* (FRACAS) can assist in capturing the knowledge gained, as well as the necessary data, and can be deployed throughout the Product Development Cycle.

Conclusion

In this article, we attempted to give an overall picture as to what Design for Reliability is, and we proposed a process to follow for implementing DFR. The proposed process is general enough to be easily adopted by different kinds of industries and to fit into the overall Product Development Process. It is important to note that certain methods, tools and/or principles are called upon in multiple parts of this process. A stage might require different tools; also, a specific tool may be used in multiple stages.

In general, the DFR methodology can bring a reliable product to market using a process focused on designing out or mitigating potential failure modes prior to production release, based on an understanding of the physics of failure, testing to discover issues and statistical analysis methods for reliability prediction. DFR can open up many opportunities for companies who want to move beyond securing a basic offering to the marketplace to creating a true competitive advantage in which reliability plays a critical role for customer satisfaction.

EXPECTED VIVA QUESTIONS:

Q.1 What is reliability?

Q.2 Define design aspects based on reliability?

Q.3 What do you mean by DFR process?

NAME OF FACULTY:

SIGNATURE:

DATE:

EXPERIMENT NO. 4

OBJECTIVE: Design Based On Theory of Elasticity

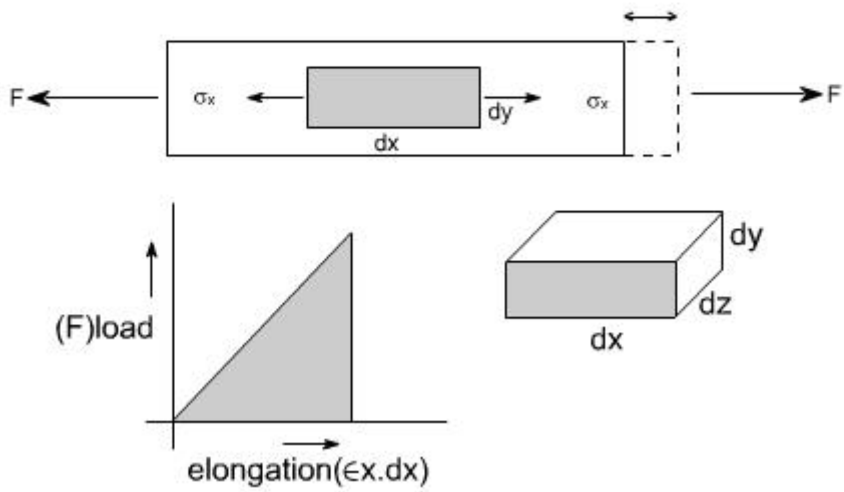
THEORIES OF ELASTIC FAILURE

While dealing with the design of structures or machine elements or any component of a particular machine the physical properties or chief characteristics of the constituent materials are usually found from the results of laboratory experiments in which the components are subject to the simple stress conditions. The most usual test is a simple tensile test in which the value of stress at yield or fracture is easily determined.

However, a machine part is generally subjected simultaneously to several different types of stresses whose actions are combined therefore, it is necessary to have some basis for determining the allowable working stresses so that failure may not occur. Thus, the function of the theories of elastic failure is to predict from the behavior of materials in a simple tensile test when elastic failure will occur under any conditions of applied stress.

A number of theories have been proposed for the brittle and ductile materials.

Strain Energy: The concept of strain energy is of fundamental importance in applied mechanics. The application of the load produces strain in the bar. The effect of these strains is to increase the energy level of the bar itself. Hence a new quantity called strain energy is defined as the energy absorbed by the bar during the loading process. This strain energy is defined as the work done by load provided no energy is added or subtracted in the form of heat. Some times strain energy is referred to as internal work to distinguish it from external work ‘W'. Consider a simple bar which is subjected to tensile force F, having a small element of dimensions dx, dy and dz.



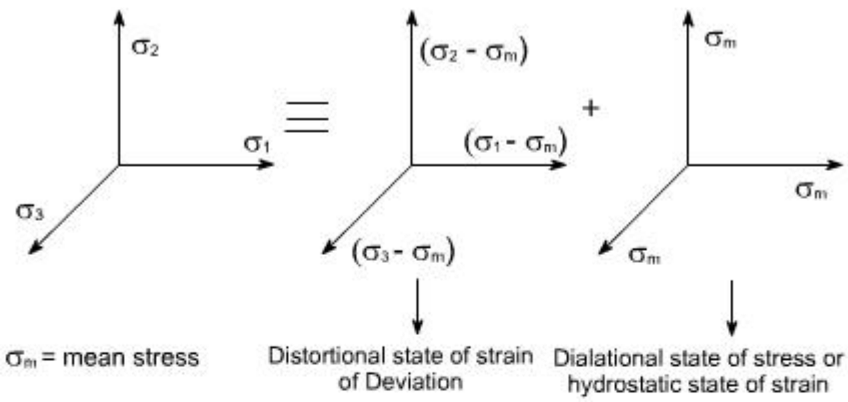
The strain energy U is the area covered under the triangle

$$U = \frac{1}{2} F . \in_x . d_x$$
$$= \frac{1}{2} \sigma_x . dydz . dx \in_x$$
$$= \frac{1}{2} \sigma_x . \in_x . dxdydz$$
$$= \frac{1}{2} \sigma_x \left(\frac{\sigma_x}{E} \right) . dxdydz$$
$$\boxed{\frac{U}{volume} = \frac{1}{2} \frac{\sigma_x^2}{E}}$$

A three dimension state of stress respresented by s_1, s_2 and s_3 may be throught of consisting of two distinct state of stresses i.e Distortional state of stress

Deviatoric state of stress and dilational state of stress

Hydrostatic state of stresses.



$$\sigma_m = \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{3}$$

Thus, The energy which is stored within a material when the material is deformed is termed as a strain energy. The total strain energy U_r

$$U_T = U_d + U_H$$

U_d is the strain energy due to the Deviatoric state of stress and U_H is the strain energy due to the Hydrostatic state of stress. Futher, it may be noted that the hydrostatic state of stress results in change of volume whereas the deviatoric state of stress results in change of shape.

Different Theories of Failure : These are five different theories of failures which are generally used

(a) Maximum Principal stress theory (due to Rankine)

(b) Maximum shear stress theory (Guest - Tresca)

(c) Maximum Principal strain (Saint - venant) Theory

(d) Total strain energy per unit volume (Haigh) Theory

(e) Shear strain energy per unit volume Theory (Von – Mises & Hencky)

In all these theories we shall assume.

s_{Yp} = stress at the yield point in the simple tensile test.

s_1, s_2, s_3 - the three principal stresses in the three dimensional complex state of stress systems in order of magnitude.

(a) Maximum Principal stress theory :

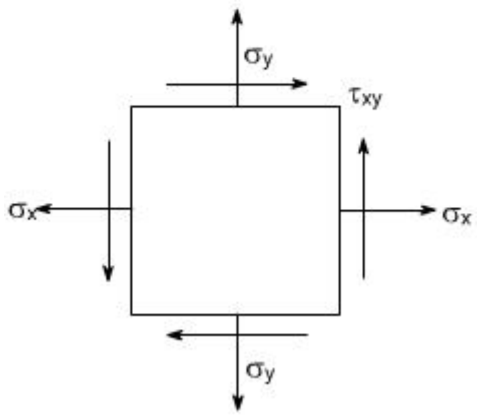
This theory assume that when the maximum principal stress in a complex stress system reaches the elastic limit stress in a simple tension, failure will occur.

Therefore the criterion for failure would be

$s_1 = s_{yp}$

For a two dimensional complex stress system s_1 is expressed as

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4.\tau_{xy}^2}$$
$$= \sigma_{yp}$$

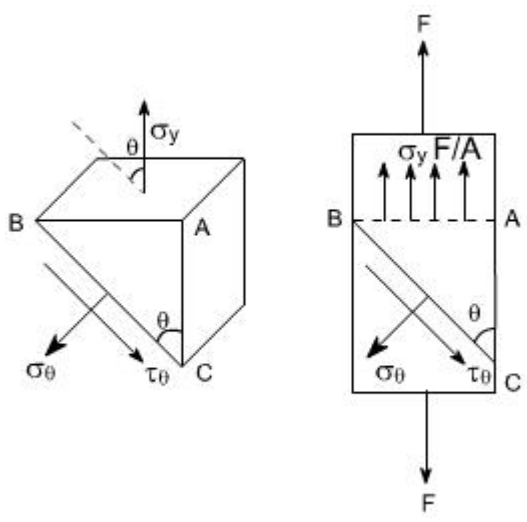


Where s_x, s_y and t_{xy} are the stresses in the any given complex stress system.

(b) Maximum shear stress theory:

This theory states that teh failure can be assumed to occur when the maximum shear stress in the complex stress system is equal to the value of maximum shear stress in simple tension.

The criterion for the failure may be established as given below :



For a simple tension case

$$\sigma_\theta = \sigma_y \sin^2\theta$$

$$\tau_\theta = \frac{1}{2}\sigma_y \sin 2\theta$$

$$\tau_\theta \big|_{max^m} = \frac{1}{2}\sigma_y \quad \text{or}$$

$$\tau_{max^m} = \frac{1}{2}\sigma_{yp}$$

whereas for the two dimentional complex stress system

$$\tau_{max^m} = \left(\frac{\sigma_1 - \sigma_2}{2}\right)$$

where σ_1 = maximum principle stress

σ_2 = minimum principal stress

$$\text{so} \quad \frac{\sigma_1 - \sigma_2}{2} = \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4\tau^2 xy}$$

$$\frac{\sigma_1 - \sigma_2}{2} = \frac{1}{2}\sigma_{yp} \Rightarrow \sigma_1 - \sigma_2 = \sigma_y$$

$$\Rightarrow \sqrt{(\sigma_x - \sigma_y)^2 + 4\tau^2 xy} = \sigma_{yp}$$

becomes the criterion for the failure.

(c) Maximum Principal strain theory :

This Theory assumes that failure occurs when the maximum strain for a complex state of stress system becomes equals to the strain at yield point in the tensile test for the three dimensional complex state of stress system.

For a 3 - dimensional state of stress system the total strain energy U_t per unit volume in equal to the total work done by the system and given by the equation

$$U_t = 1/2\sigma_1 \in_1 + 1/2\sigma_2 \in_2 + 1/2\sigma_3 \in_3$$

substituting the values of $\in_1, \in_2$ and $\in_3$

$$\in_1 = \frac{1}{E}\left[\sigma_1 - \gamma(\sigma_2 + \sigma_3)\right]$$

$$\in_2 = \frac{1}{E}\left[\sigma_2 - \gamma(\sigma_1 + \sigma_3)\right]$$

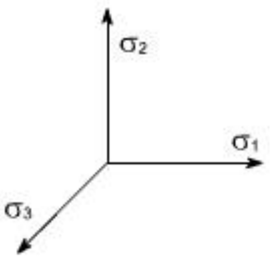
$$\in_3 = \frac{1}{E}\left[\sigma_3 - \gamma(\sigma_1 + \sigma_2)\right]$$

Thus, the failure criterion becomes

$$\left(\frac{\sigma_1}{E} - \gamma\frac{\sigma_2}{E} - \gamma\frac{\sigma_3}{E}\right) = \frac{\sigma_{yp}}{E}$$

or

$$\boxed{\sigma_1 - \gamma\sigma_2 - \gamma\sigma_3 = \sigma_{yp}}$$



(d) Total strain energy per unit volume theory :

The theory assumes that the failure occurs when the total strain energy for a complex state of stress system is equal to that at the yield point a tensile test.

$$\frac{1}{2E}\left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\gamma(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1)\right] = \frac{\sigma_{yp}^2}{2E}$$

Therefore, the failure criterion becomes

$$\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\gamma(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1) = \sigma_{yp}^2$$

It may be noted that this theory gives fair by good results for ductile materials.

(e) Maximum shear strain energy per unit volume theory :

This theory states that the failure occurs when the maximum shear strain energy component for the complex state of stress system is equal to that at the yield point in the tensile test.

$$\frac{1}{12G}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]=\frac{\sigma_{yp}^2}{6G}$$

Where G = shear modulus of regidity

Hence the criterion for the failure becomes $\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]=2\sigma_{yp}^2$

As we know that a general state of stress can be broken into two components i.e,

(i) Hydrostatic state of stress (the strain energy associated with the hydrostatic state of stress is known as the volumetric strain energy)

(ii) Distortional or Deviatoric state of stress (The strain energy due to this is known as the shear strain energy)

As we know that the strain energy due to distortion is given as

$$U_{distortion}=\frac{1}{12G}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]$$

This is the distortion strain energy for a complex state of stress, this is to be equaled to the maximum distortion energy in the simple tension test. In order to get we may assume that one of the principal stress say (σ_1) reaches the yield point (σ_{yp}) of the material. Thus, putting in above equation $\sigma_2 = \sigma_3 = 0$ we get distortion energy for the simple test i.e

$$U_d=\frac{2\sigma_1^2}{12G}$$

Futher $\sigma_1 = \sigma_{yp}$

Thus, $\boxed{U_d=\frac{\sigma_{yp}^2}{6G}}$ for a simple tension test.

EXPECTED VIVA QUESTIONS:

Q.1 What is theory of elasticity?

Q.2 What is elastic failure?

Q.3 Describe theories of failure?

NAME OF FACULTY:

SIGNATURE:

DATE:

EXPERIMENT NO. 5

OBJECTIVE: Design based on theory of Plasticity and Numerical practice

Introduction to Plasticity

The theory of linear elasticity is useful for modeling materials which undergo small deformations and which return to their original configuration upon removal of load. Almost all real materials will undergo some **permanent** deformation, which remains after removal of load. With metals, significant permanent deformations will usually occur when the stress reaches some critical value, called the **yield stress**, a material property.

Elastic deformations are termed **reversible;** the energy expended in deformation is stored as elastic strain energy and is completely recovered upon load removal. Permanent deformations involve the dissipation of energy; such processes are termed **irreversible**, in the sense that the original state can be achieved only by the expenditure of more energy.

The **classical theory of plasticity** grew out of the study of metals in the late nineteenth century. It is concerned with materials which initially deform elastically, but which deform **plastically** upon reaching a yield stress. In metals and other crystalline materials the occurrence of plastic deformations at the micro-scale level is due to the motion of dislocations and the migration of grain boundaries on the micro-level. In sands and other granular materials plastic flow is due both to the irreversible rearrangement of individual particles and to the irreversible crushing of individual particles. Similarly, compression of bone to high stress levels will lead to particle crushing. The deformation of micro-voids and the development of micro-cracks is also an important cause of plastic deformations in materials such as rocks.

A good part of the discussion in what follows is concerned with the plasticity of metals; this is the 'simplest' type of plasticity and it serves as a good background and introduction to the modelling of plasticity in other material-types. There are two broad groups of metal plasticity problem which are of interest to the engineer and analyst. The first involves relatively small plastic strains, often of the same order as the elastic strains which occur. Analysis of problems involving small plastic strains allows one to design structures optimally, so that they will not fail when in service, but at the same time are not stronger than they really need to be. In this sense, plasticity is seen as a material **failure**[1].

The second type of problem involves very large strains and deformations, so large that the elastic strains can be disregarded. These problems occur in the analysis of metals manufacturing and forming processes, which can involve extrusion, drawing, forging, rolling and so on. In these latter-type problems, a simplified model known as **perfect plasticity** is usually employed (see below), and use is made of special **limit theorems** which hold for such models.

Plastic deformations are normally **rate independent,** that is, the stresses induced are independent of the rate of deformation (or rate of loading). This is in marked

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contrast to classical **Newtonian fluids** for example, where the stress levels are governed by the *rate* of deformation through the viscosity of the fluid.

Materials commonly known as "plastics" are not plastic in the sense described here. They, like other polymeric materials, exhibit **viscoelastic** behaviour where, as the name suggests, the material response has both elastic and viscous components. Due to their viscosity, their response is, unlike the plastic materials, **rate-dependent**. Further, although the viscoelastic materials can suffer irrecoverable deformation, they do not have any critical yield or threshold stress, which is the characteristic property of plastic behaviour. When a material undergoes plastic deformations, i.e. irrecoverable and at a critical yield stress, and these effects *are* rate dependent, the material is referred to as being **viscoplastic**.

Plasticity theory began with Tresca in 1864, when he undertook an experimental program into the extrusion of metals and published his famous yield criterion discussed later on. Further advances with yield criteria and plastic flow rules were made in the years which followed by Saint-Venant, Levy, Von Mises, Hencky and Prandtl. The 1940s saw the advent of the classical theory; Prager, Hill, Drucker and Koiter amongst others brought together many fundamental aspects of the theory into a single framework. The arrival of powerful computers in the 1980s and 1990s provided the impetus to develop the theory further, giving it a more rigorous foundation based on thermodynamics principles, and brought with it the need to consider many numerical and computational aspects to the plasticity problem.

Observations from Standard Tests

In this section, a number of phenomena observed in the material testing of metals will be noted. Some of these phenomena are simplified or ignored in some of the standard plasticity models discussed later on.

At issue here is the fact that any model of a component with complex geometry, loaded in a complex way and undergoing plastic deformation, must involve material parameters which can be obtained in a straight forward manner from simple laboratory tests, such as the tension test described next.

The Tension Test

Consider the following key experiment, the **tensile test**, in which a small, usually cylindrical, specimen is gripped and stretched, usually at some given rate of stretching (see Part I, §5.2.1). The force required to hold the specimen at a given stretch is recorded, Fig. 8.1.1. If the material is a metal, the deformation remains elastic up to a certain force level, the yield point of the material. Beyond this point, permanent plastic deformations are induced. On unloading only the elastic deformation is recovered and the specimen will have undergone a permanent elongation (and consequent lateral contraction).

In the elastic range the force-displacement behaviour for most engineering materials (metals, rocks, plastics, but not soils) is linear. After passing the elastic limit (point *A* in Fig. 8.1.1), the material "gives" and is said to undergo plastic **flow**. Further increases in load are usually required to maintain the plastic flow and an increase in displacement; this phenomenon is known as **work-hardening** or **strain-hardening**. In some cases, after an initial plastic flow and hardening, the force-displacement curve decreases, as in some soils; the material is said to be **softening**. If the specimen is unloaded from a plastic state (*B*) it will return along the path *BC* shown, parallel to the original elastic line. This is **elastic recovery**. The strain which remains upon unloading is the permanent plastic deformation. If the material is now loaded again, the force-displacement curve will re-trace the unloading path *CB* until it again reaches the plastic state. Further increases in stress will cause the curve to follow *BD*.

Two important observations concerning the above tension test (on most metals) are the following:

(1) after the onset of plastic deformation, the material will be seen to undergo negligible volume change, that is, it is **incompressible**.
(2) the force-displacement curve is more or less the same regardless of the rate at which the specimen is stretched (at least at moderate temperatures).

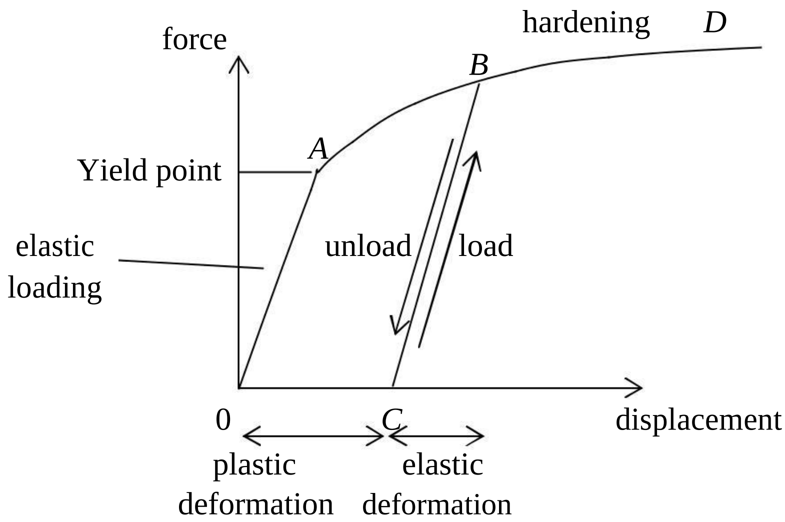


Figure : force/displacement curve for the tension test

Nominal and True Stress and Strain

There are two different ways of describing the force F which acts in a tension test. First, normalising with respect to the *original* cross sectional area of the tension test specimen A_0 , one has the **nominal stress** or **engineering stress**,

$$_{n} \qquad \frac{F}{A_0}$$

Alternatively, one can normalise with respect to the *current* cross-sectional area A, leading to the **true stress**,

$$\frac{F}{A}$$

in which F and A are both changing with time. For very small elongations, within the elastic range say, the cross-sectional area of the material undergoes negligible change and both definitions of stress are more or less equivalent.
Similarly, one can describe the deformation in two alternative ways. Denoting the original specimen length by l_0 and the current length by l, one has the **engineering strain**

$$\frac{l \ \ l_0}{l_0}$$

Alternatively, the **true strain** is based on the fact that the "original length" is continually changing; a small change in length dl leads to a **strain increment** $d\ dl / l$ and the total strain is *defined* as the accumulation of these increments:

$$_{t} \qquad \int_{l_0}^{l} \frac{dl}{l} \qquad \ln \frac{l}{l_0}$$

The true strain is also called the **logarithmic strain** or **Hencky strain**. Again, at small deformations, the difference between these two strain measures is negligible. The true strain and engineering strain are related through

$$_{t} \qquad \ln 1$$

Using the assumption of constant volume for plastic deformation and ignoring the very small elastic volume changes, one has also {▲Problem 3}

$$\ln \frac{l}{l_0} \, .$$

The stress-strain diagram for a tension test can now be described using the true stress/strain or nominal stress/strain definitions, as in Fig. 8.1.2. The shape of the nominal stress/strain diagram, Fig. 8.1.2a, is of course the same as the graph of force versus displacement (change in length) in Fig. 8.1.1. *A* here denotes the point at which the maximum force the specimen can withstand has been reached. The *nominal stress* at *A* is called the **Ultimate Tensile Strength** (UTS) of the material. After this point, the specimen "necks", with a very rapid reduction in cross -sectional area somewhere about the centre of the specimen until the specimen ruptures, as indicated by the asterisk.
Note that, during loading into the plastic region, *the yield stress increases*. For example, if one unloads and re-loads (as in Fig. 8.1.1), the material stays elastic up until a stress higher than the original yield stress *Y*. In this respect, the stress-strain curve can be regarded as a yield stress versus strain curve.

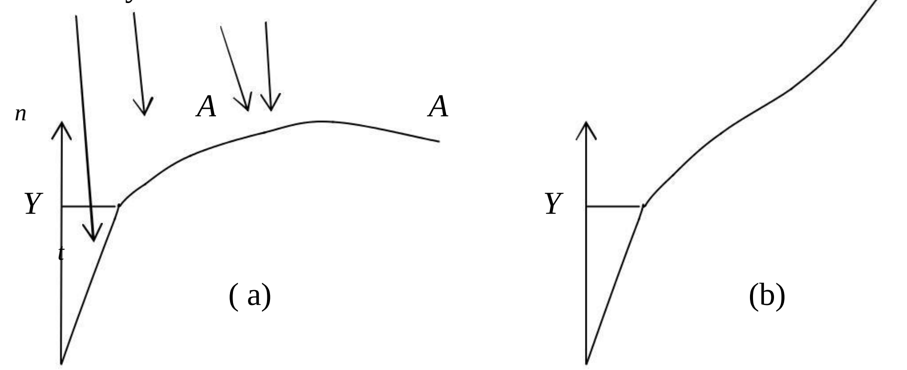


Figure : typical stress/strain curves; (a) engineering stress and strain, (b) true stress and strain

Compression Test

A compression test will lead to similar results as the tensile stress. The yield stress in compression will be approximately the same as (the negative of) the yield stress in tension. If one plots the true stress versus true strain curve for both tension and compression (absolute values for the compression), the two curves will more or less coincide. This would indicate that the behaviour of the material under compression is broadly similar to that under tension. If one were to use the nominal stress and strain, then the two curves would not coincide; this is one of a number of good reasons for using the *true* definitions.

The Bauschinger Effect

If one takes a virgin sample and loads it in tension into the plastic range, and *then* unloads it and continues on into compression, one finds that the yield stress in compression is *not* the same as the yield strength in tension, as it would have been if the specimen had not first been loaded in tension. In fact the yield point in this case will be significantly *less* than the corresponding yield stress in tension. This reduction in yield stress is known as the **Bauschinger effect**. The effect is illustrated in Fig. 8.1.3. The solid line depicts the response of a real material. The dotted lines are two extreme cases which are used in plasticity models; the first is the **isotropic hardening** model, in which the yield stress in tension and compression are maintained equal, the second being **kinematic hardening**, in which the total elastic range is maintained constant throughout the deformation.

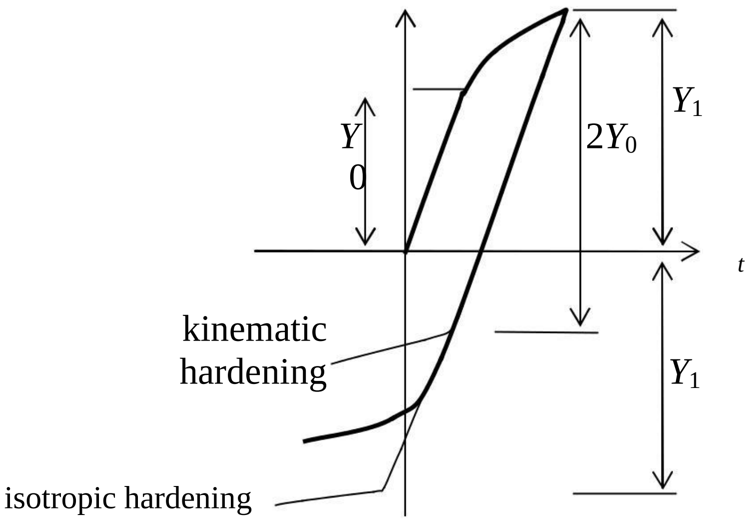


Figure : The Bauschinger effect

The presence of the Bauschinger effect complicates any plasticity theory. However, it is not an issue provided there are no reversals of stress in the problem under study.

Hydrostatic Pressure

Careful experiments show that, for metals, the yield behavior is independent of hydrostatic pressure. That is, a stress state $_{xx}\ _{yy}\ _{zz}\ p$ has negligible effect on the yield stress of a material, right up to very high pressures. Note however that this is not true for soils or rocks.

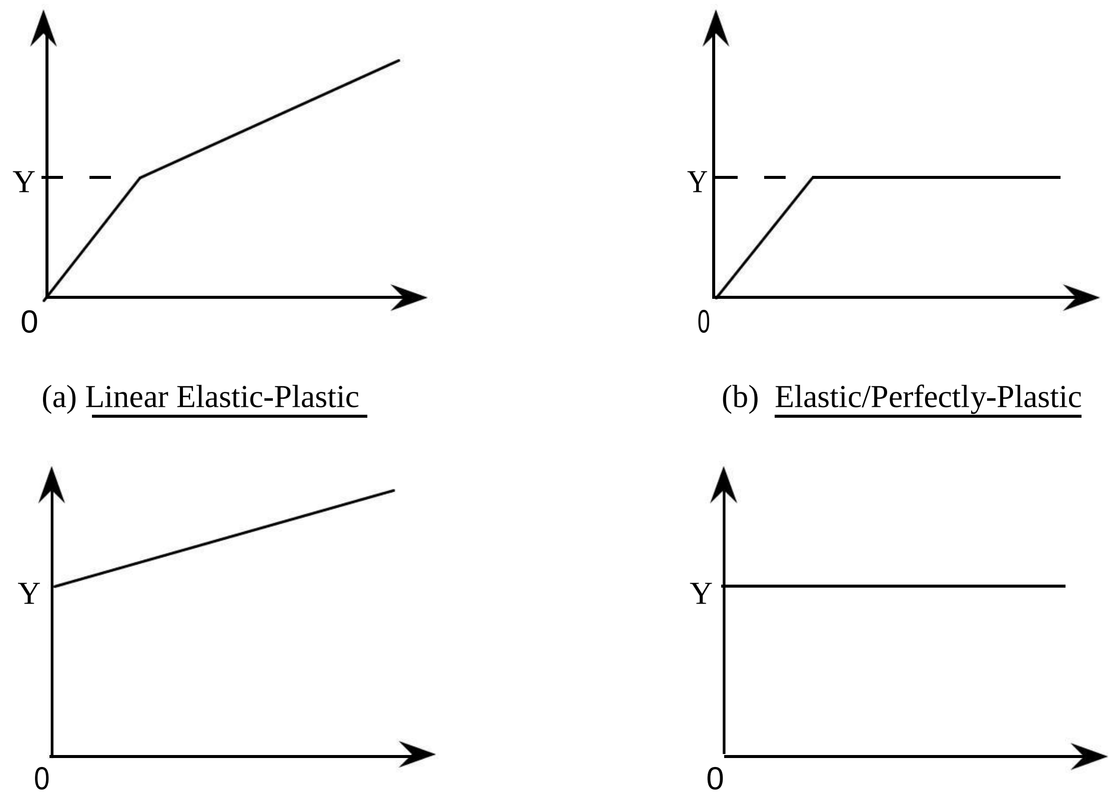
Assumptions of Plasticity Theory

Regarding the above test results then, in formulating a basic plasticity theory with which to begin, the following assumptions are usually made:

(1) the response is independent of rate effects
(2) the material is incompressible in the plastic range
(3) there is no Bauschinger effect
(4) the yield stress is independent of hydrostatic pressure
(5) the material is isotropic

The first two of these will usually be very good approximations, the other three may or may not be, depending on the material and circumstances. For example, most metals can be regarded as isotropic. After large plastic deformation however, for example in rolling, the material will have become anisotropic: there will be distinct material directions and asymmetries.

Together with these, assumptions can be made on the type of hardening and on whether elastic deformations are significant. For example, consider the hierarchy of models illustrated in Fig. 8.1.4 below, commonly used in theoretical analyses. In (a) both the elastic and plastic curves are assumed linear. In (b) work-hardening is neglected and the yield stress is constant after initial yield. Such **perfectly-plastic** models are particularly appropriate for studying processes where the metal is worked at a high temperature – such as hot rolling – where work hardening is small. In many areas of applications the strains involved are large, e.g. in metal working processes such as extrusion, rolling or drawing, where up to 50% reduction ratios are common. In such cases the elastic strains can be neglected altogether as in the two models (c) and (d). The **rigid/perfectly-plastic** model (d) is the crudest of all – and hence in many ways the most useful. It is widely used in analyzing metal forming processes, in the design of steel and concrete structures and in the analysis of soil and rock stability.



(a) Linear Elastic-Plastic (b) Elastic/Perfectly-Plastic

(c) Rigid/Linear Hardening (d) Rigid-Perfectly-Plastic

Figure 8.1.4: Simple models of elastic and plastic deformation

The Tangent and Plastic Modulus
Stress and strain are related through *E* in the elastic region, *E* being the Young's modulus, Fig. 8.1.5. The **tangent modulus** *K* is the slope of the stress-strain curve in the plastic region and will in general change during a deformation. At any instant of strain, the *increment* in stress *d* is related to the *increment* in strain *d* through[2]

$$dKd$$

[2] the symbol here represents the true strain (the subscript *t* has been dropped for clarity); as mentioned, when the strains are small, it is not necessary to specify which strain is in use since all strain measures are then equivalent

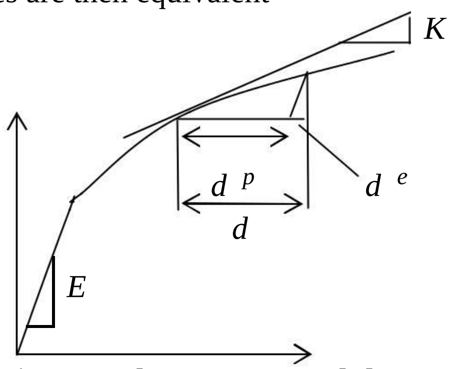


Figure : The tangent modulus

After yield, the strain increment consists of both elastic, ^{e}, and plastic, $d^{\;p}$, strains:

$$d \quad d^{\;e} \quad d^{\;p}$$

The stress and plastic strain increments are related by the **plastic modulus** *H*:

$$dH\,d^{\;p}$$

and it follows that {▲Problem 4}

$$\underline{1} \quad \underline{1} \quad \underline{1}$$

K E H

Friction Block Models

Some additional insight into the way plastic materials respond can be obtained from friction block models. The rigid perfectly plastic model can be simulated by a Coulomb friction block, Fig. 8.1.6. No strain occurs until reaches the yield stress *Y*. Then there is movement – although the amount of movement or plastic strain cannot be determined without more information being available. The stress cannot exceed the yield stress in this model:

| |

The linear elastic plastic model with linear strain hardening incorporates a second, hardening, spring with stiffness *H*, in parallel with the friction block, Fig. 8.1.8. Once the yield stress is reached, an ever increasing stress needs to be applied in order to keep the block moving – and elastic strain continues to occur due to further elongation of the free spring. The stress is then split into the yield stress, which is carried by the moving block, and an **overstress** *Y* carried by the hardening spring.

Upon unloading, the block "locks" – the stress in the hardening spring remains constant whilst the free spring contracts. At zero stress, there is a negative stress taken up by the friction block, equal and opposite to the stress in the hardening spring.

The slope of the elastic loading line is *E*.

EXPECTED VIVA QUESTIONS:

Q.1 What is plasticity?

Q.2 Explain stress strain curve?

Q.3 What is yield stress?

NAME OF FACULTY:

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EXPERIMENT NO. 6

OBJECTIVE: Study of design based on tribology

What is Tribology ?

• Tribology is derived from the Greek word “Tribos”. Meaning of Tribos is Rubbing.

• Tribology is a science that deals with friction, lubrication and wear in all contacting pairs.

• Tribological knowledge helps to improve service life, safety and reliability of interacting machine components; and yields substantial economic benefits.

Few Examples requiring tribological knowledge :

Let us consider few failed machine components, failure of which could had been avoided using tribological knowledge.

Example 1 : Seal

As shown in Fig. 1.1 carbon graphite seal is employed to avoid leakage of steam from rotary joints of paper industry. Failure of this component occurs due to adhesive wear. Adhesive wear causes uneven surface that leads to reduction in mechanical contact area. For same imposed load, reduction in mechanical contacts, increases the level of stress and hence chances of failure.

Fig. 1.1: Carbon graphite seal.

Example 2: Cam

Example 2 is related pitting wear on the cam surface(as shown in Fig. 1.2). Cams are used to transmit rotary motion in reciprocating motion. These components are subjected to jerks in sliding distance, which leads to form some pits on the cam surface. Creation of pits on cam surface increases noise pollution and reduces mechanical performance. Understanding the mechanism of pit formation helps to estimate the life of component and find methods to reduce such pitting failures.

Fig. 1.2: Pitting of cam surface.

Example 3: Journal Bearings

The following figures(Fig. 1.3(a) and Fig. 1.3(b)) are examples of two journal bearing. Left hand side is photograph of centrally grooved engine journal bearing. It appears that bearing is worn out due to foreign particles. Right hand side is a photograph of an aluminum bearing subjected to heavy load, which causes shaft surface to run over bearing inner surface. In these examples of journal bearing, wear increases the clearance between shaft and bearing and leads to reduction in load support capacity of the bearing. Often such failures occur in absence of sufficient lubricant hydrodynamic film thickness due to relatively low speed. Learning tribology cultivates an understanding that at low speeds, the main purpose of oil is the lubrication and high viscosity oil will be preferred to low viscosity oil, while at high speeds the major purpose of oil is to act as a coolant and low viscosity lubricants are preferred to carry away frictional heat of operation. Here lubrication is a secondary consideration.

Fig. 1.3(a): Abrasive wear and Fig. 1.3(b): Rubbing wear

Example 4: Magnetic Bearing

Magnetic bearings are known as non-contact levitation. In the figure given below(Fig. 1.4) a repulsive type permanent magnetic bearing is shown. Due to improper design and external noise factors, bearing failed within three hours of operation at relative speed of 115 rpm.

Fig. 1.4: Wear scar due to edge loading

Example 5: Multi-row Roller Bearing

Cracking of outer ring is shown in Fig. 1.5. Here cracking means deep cracks which breaks outer ring in number of pieces. Such failure occurs due to faulty manufacturing and wrong assembly of roller bearing. Tribological relations help estimating increase in contact stresses due to misalignment of shaft and improper mounting of bearing surfaces. Hence an approximation on reduction in service life can be estimated.

Fig. 1.5: Failure of large size roller bearing

Example 6: Gear

A pit on the surface of gear tooth is shown in Fig. 1.6. The pit generally occurs due to excessive contact stress. Understanding the effect of contact stress helps in developing an equation for estimation of perspective gear life.

Fig. 1.6(a): Gear teeth removed from gear.

Fig. 1.6(b): Pits on gear teeth.

Studies of fluid film bearings, rolling element bearings, seals, gears, cams, and brakes are some of the applications in which tribology is required.

Basic knowledge gained by Tribology course is very useful for industries related to power, steel, cement, oil etc. Practicing such knowledge in problems ranging from house hold appliances to large size ships earns great economic benefits. Therefore tribology course is often named as : "Industrial Tribology", "Applied Tribology".

History of Tribology

Details of the history of tribology are given by : Dowson[1]. Few notable points are :-

• September 1964 -- Conference on Lubrication in Iron and Steel Works in Cardiff (UK). Realization of considerable losses due to lack of knowledge related friction and wear of machine components.

• After this realization UK Minister of State for science formed a committee to investigate the education, research and the need of industry related to lubrication.

• Committee after deliberations concluded that only lubrication engineering could not provide complete solution to deal with friction and wear of machine components. An interdisciplinary approach embracing solid and fluid mechanics, chemistry, and material science is essential. Since there was no word for such new concept, a new name "Tribology" was coined in 1966.

• After 1966, the word "Tribology" has been used for :

1. Basic mechanisms governing interfacial behavior.
2. Basic theories quantifying interfacial mechanisms.
3. Solutions to friction and wear problems.

• Major breakthrough in tribological science came in 1981 with development of "Scanning tunneling microscope"(STM)[2] and systematic theory based on "Contact mechanics". Such developments provided tools to predict and estimate the behaviour of a single asperity contact.

• Subsequent development of Atomic Force Microscope(AFM)[2] in 1985 allowed measurement (surface topography, friction force) of all engineering surfaces. Atomic Force Microscope can be used for studies of adhesion, scratching, wear, lubrication, surface temperatures and measurements of elastic/plastic mechanical properties.

• The developments of tip-based microscopes (STM & AFM) and computational techniques for simulating tip-surface interactions and interfacial properties, have allowed systematic investigations for interfacial problems. Modifying and manipulating surface microstructure provide a bridge between science and engineering.

Need of Tribology as subject :

• Friction, wear and lubrication have been taught in many science and engineering classes at a rudimentary level. It means empirically derived trends (friction force is proportional to loading force, static friction is greater than kinetic friction, viscous friction in a fluid is proportional to the normal contact force, etc.) are often used as the only predictive tools available. These approaches have the drawbacks of being predictive only over a limited range of parameters. Since the under-laying physical mechanisms are not well understood, often one does not even know which are the important parameters or over what range the observed trends are valid. This poor predictive power has led the field of tribology being perceived in many scientific quarters.

• Most tribological phenomenon are inherently complicated and interconnected, making it necessary to understand the concepts of TRIBOLOGY in details.

• Integration of knowledge from multifaceted disciplines(solid mechanics, fluid mechanics, material science, chemistry etc) is essential and therefore a seprate subject is required.

• Solid Mechanics: Focus is on expressions of contact stresses/deformations and surface temperatures due to rolling/sliding.

• Fluid Mechanics: Study of lubricant film formed between various geometric shapes of rolling/sliding surfaces.

• Material Science: Focus is on atomic and micro scales mechanisms whereby solid surface degradation or alteration occurs during relative motion.

• Chemistry: Deals with reactivity between lubricants and solid surfaces.

• Thermodynamics: Heat and mass transfer in fluids and bounding solids.

EXPECTED VIVA QUESTIONS:

Q.1 What is Tribology?

Q.2 What is importance of tribology in engineering?

Q.3 What are the example of tribology?

NAME OF FACULTY:

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EXPERIMENT NO. 7

OBJECTIVE: Study of friction mechanisms and different kinds of friction

FRICTION

Friction is the tangential resistance to motion. The occurrence of friction is a part of everyday life. It is needed so that we have control on our walking. On the other hand, in most of running machines friction is undesirable (energy loss, leading to wear of vital parts, deteriorating performance due to heat generation) and all sorts of attempts (i.e. using low friction materials, lubricating surfaces with oil or greases, changing design so that sliding can be reduced) have been made to reduce it.

Often coefficient of friction(μ) is considered a constant value for a pair of material. In addition, the value of μ is accounted much lesser than 1.0. In practice μ greater than 1.0, as shown in Table 2.1, has been observed. Generally coefficients of friction depend on parameters such as temperature, surface roughness and hardness.

Table 2.1: Coefficient of friction for various metals sliding on themselves.

Aluminum	1.5
Copper	1.5
Gold	2.5
Iron	1.2
Platinum	3
Silver	1.5

Fig. 2.1 indicates that under dry lubricant conditions, μ ranges between 0.1 to 1.0 for most of the materials. Very thin lubrication reduces coefficient by 10 times.

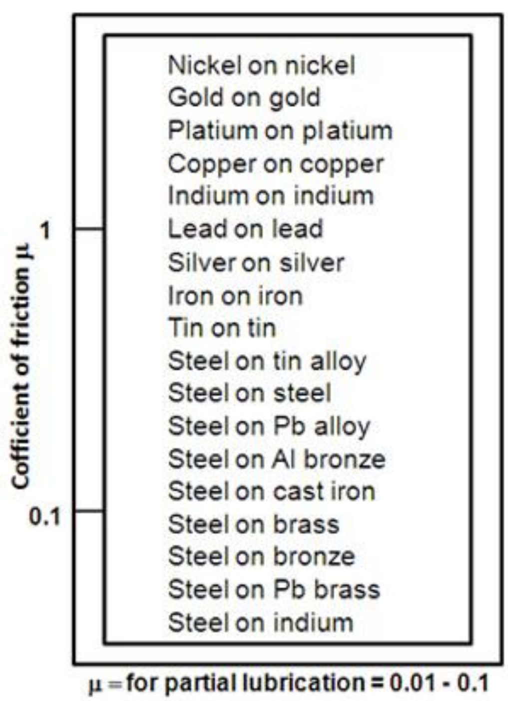

Fig. 2.1: Coefficient of friction for various metals.

Generally, adhesion(Fig. 2.2) increases the friction. So, while selecting metal pairs, low adhesion metal pairs must be selected to reduce friction force. Similiar material pair must be avoided as similar materials have higher tendency of adhesion.

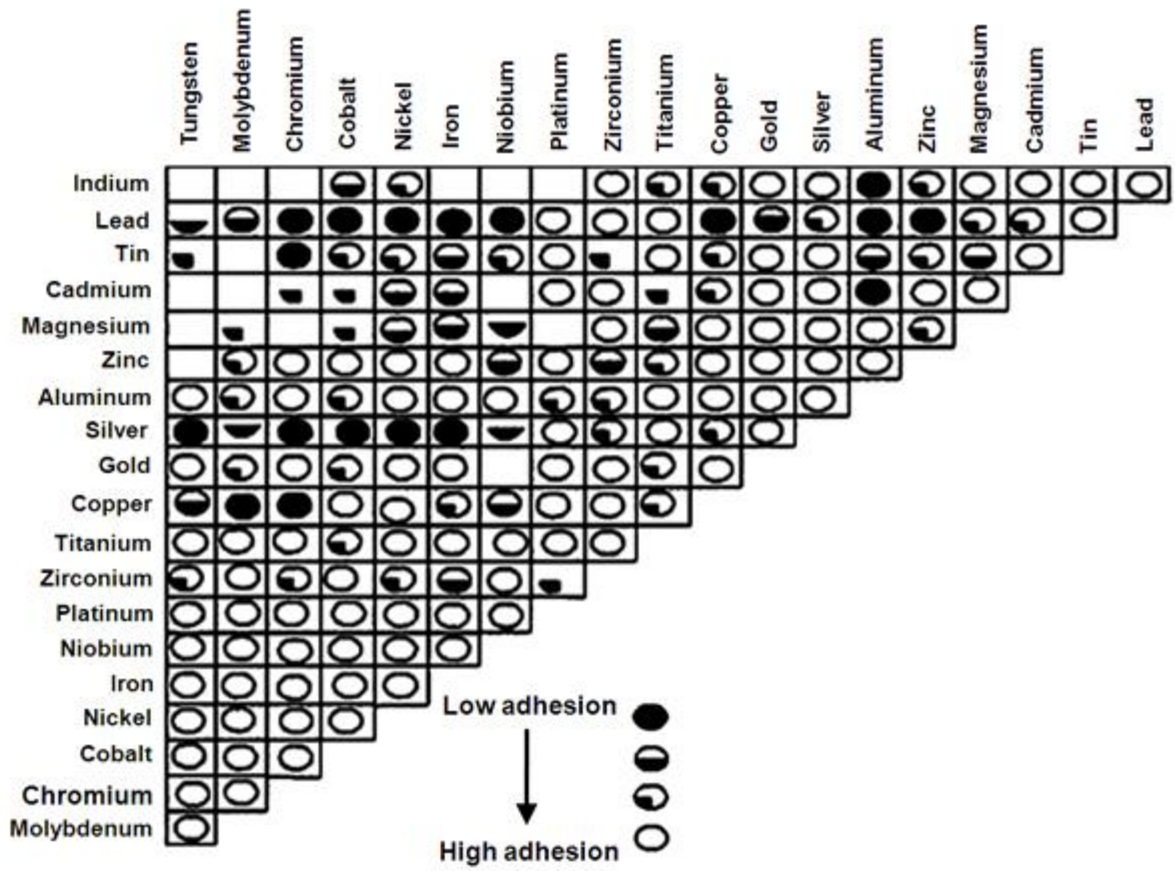

Fig. 2.2: Adhesive Friction among various materials.

Static & Kinetic Frictions :

Before starting friction mechanisms, it is necessary to define static and kinetic friction. Let us consider a block on the surface getting pushed by a tangential force F. On application of 20 N load, block does not move. This second point on the graph(Fig. 2.3) shows that on application of 40 N, still block does not move. There is static force equilibrium between application force and friction force. On application of 50 N load, block just start sliding. At this point of load application friction force remains equal to 50 N, but friction resistance decreases subsequently to 40 N. In other words, static friction is higher than kinetic friction. Table 2.2 shows few published results of static/kinetic coefficient of friction. This table indicates that coefficient of friction is statistical parameter. It is difficult to obtain same value under various laboratory conditions. Further, there is a possibility of substantial decrease in kinetic friction relative to static friction. Stick-slip is a phenomenon where the instantaneous sliding speed of an object does not remain close to the average sliding speed. Stick-slip is a type of friction instability.

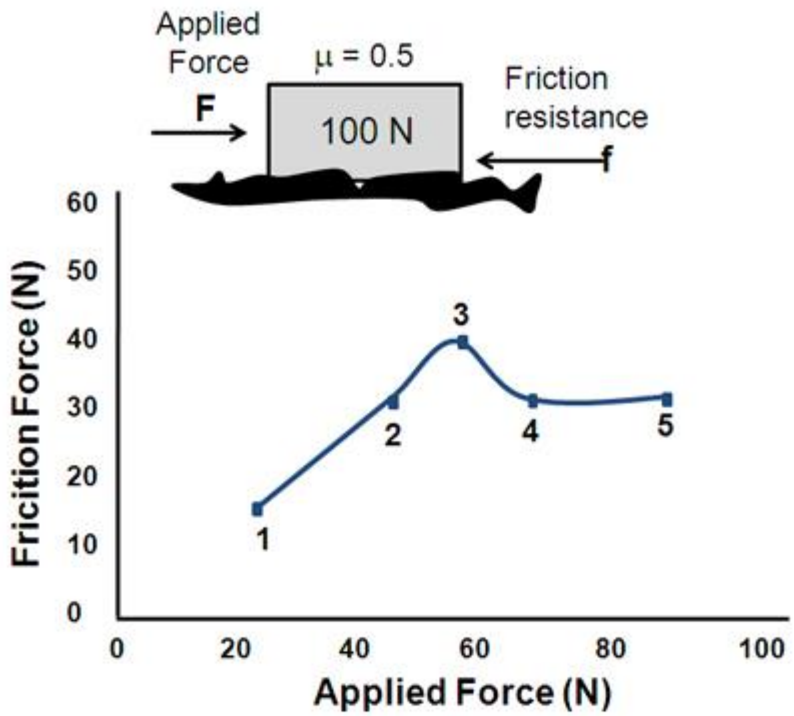

Fig. 2.3: Difference between the static and kinetic friction may initiate 'stick-slip'.

Table 2.2: μ for wood-on-wood reported in various articles.

Listed material combination	μ_s	μ_k
Wood on wood	0.25 – 0.5	0.19
Wood on wood (dry)	0.25 – 0.5	0.38
Wood on wood	0.30 – 0.70	---
Wood on wood	0.6	0.32
Wood on wood	0.6	0.5
Wood on wood	0.4	0.2
Oak on oak (para. to grain)	0.62	---
Oak on oak(perp. To grain)	0.54	0.48
Oak on oak(fibers parallel)	0.62	0.48
Oak on oak(fibers crossed)	0.54	0.34
Oak on oak(fibers perpendicular)	0.43	0.19

A friction is statistical parameter depends on a number of variable. There is a need to understand science of friction.

To understand the effect of material pair, role of lubrication, and environmental factors let us start with dry friction. The dry friction is also known as solid body friction and it means that there is no coherent liquid or gas lubricant film between the two solid body surfaces. Four theories given by Leonardo da Vinci, Amonton, Coulomb and Tomlison for dry lubrication are explained in following paragraph.

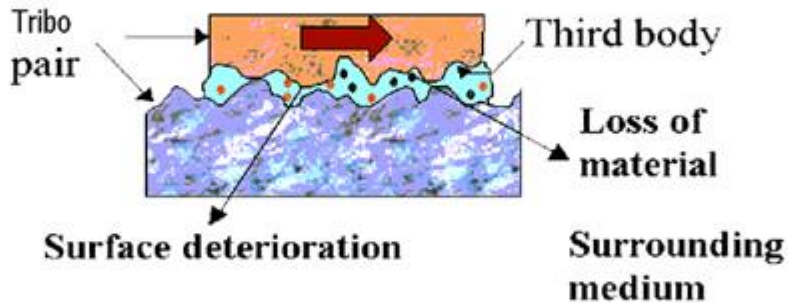

Fig. 2.4: Amonton`s work.

Leonardo da vinci(Earliest experimenter, 1452-1519) :

As per Leonardo, “Friction made by same weight will be of equal resistance at the beginning of movement, although contact may be of different breadths or length”.

“Friction produces the double the amount of effort if weight be doubled”. In other words, F α W.

G.Amontons, 1699 : The friction force is independent of the nominal area (F ≠ A) of contact between two solid surfaces. The friction force is directly proportional F α N to the normal component of the load. He considered three cases(Fig. 2.4) and showed that friction force will vary as per the angle of application of load. As per Amontons μ = 0.3 for most of materials.

C.A.Coulomb 1781 (1736-1806) :

• Clearly distinguished between static & kinetic frictions. Friction due to interlocking of rough surfaces.

• Contact at discrete points $\mu_{static} \geq \mu_{kinetic}$.

• f ≠ func(A).

• f ≠ func(v).

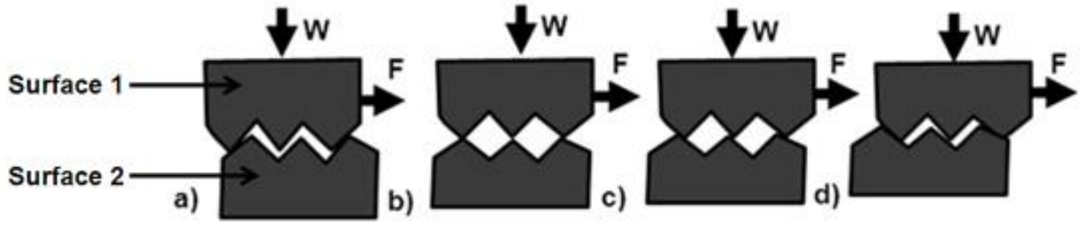

Fig. 2.5: Coulomb friction model.

As per coulomb friction force is independent of sliding speed. But this law applies only approximately to dry surfaces for a reasonable low range of sliding speeds, which depends on heat dissipation capabilities of tribo-pairs.

TOMLINSON's Theory of Molecular attraction, 1929 :

Tomlison based on experimental study provided relation between friction coefficient & elastic properties of material involved.

$$f = 1.07 * [\theta_I + \theta_{II}]^{2/3}$$

where E is young modulus, Mpsi

Where θ is

$$\theta = \frac{3.E + 4.G}{G(3.*E + G)}$$

where G is modulus in shear, Mpsi

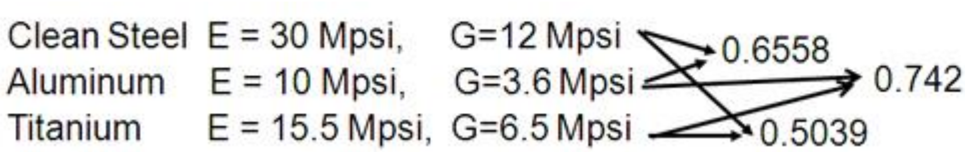

Fig. 2.6: Examples on Tomlison formula.

As per Tomlison due to molecular attraction between metal, cold weld junctions are formed. Generally load on bearing surface is carried on just a few points. These are subjected to heavy unit pressure, and so probably weld together. Adhesion force developed at real area of contact.

Fig. 2.6 provides illustration related to Tomlison`s friction formula. This figure indicates f = 0.6558 for clean steel and aluminium, f = 0.742 for aluminium and titanium, and f = 0.5039 for clean steel and titanium.

Scientific Explanation of Dry Friction :

There are two main friction sources: Adhesion and Deformation. Force needed to plough asperities of harder surface through softer. In lubricated tribo-pair case, friction due to adhesion will be negligible, while for smoother surfaces under light load conditions deformation component of friction will be negligible.

Fig. 2.7 demonstrates the adhesion (cold weld) between two surfaces. Some force, F_a, is required to tear the cold junction. Fig. 2.8 demonstrates the deformation process. It shows a conical asperity approaching to a softer surface. To move upper surface relative to lower surface some force is required.

- Two friction sources : Deformation and Adhesion.
- Resulting friction force (F) is sum of two contributing (F_a & F_d) terms.
- Lubricated tribo-pair case -- negligible adhesion.
- Smoother surfaces under light load conditions – Negligible deformation.

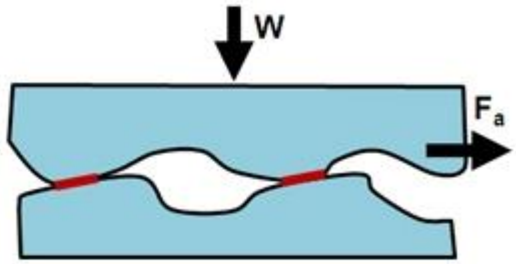

Fig. 2.7: Adhesion

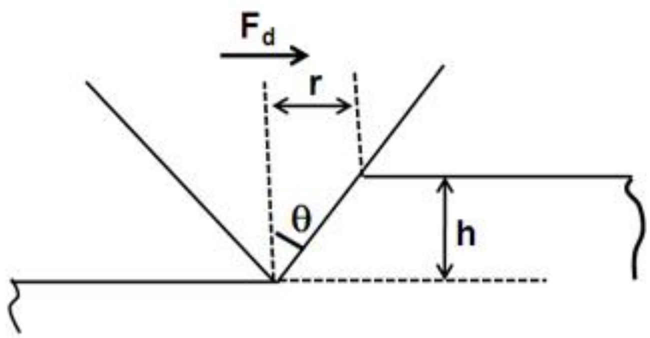

Fig. 2.8: Abrasion(Deformation)[1]

EXPECTED VIVA QUESTIONS:

Q.1 Define Friction and type of friction?

Q.2 What is Coefficient of friction and its value?

Q.3 What is Dry friction?

NAME OF FACULTY:

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EXPERIMENT NO. 8

OBJECTIVE: Study of different kinds of wear and design changes as per wear mechanisms.

Introduction of Wear

Undesirable removal of material from operating solid surface is known as wear. There are two definitions :

(1) Zero wear : Removal of material which causes polishing of material surfaces may be known as "Zero wear". It may increase performance. It is for betterment, so it is not undesirable.

Zero wear is basically a polishing process in which the asperities of the contacting surfaces are gradually worn off until a very fine, smooth surface develops. Generally, “polishing-in” wear is desirable for better life of tribo-pair. Fig. 3.1(a) shows polished surface of helical gear which occurs due to slow loss of metal at a rate that will have a little affect on the satisfactory performance within the life of the gears.

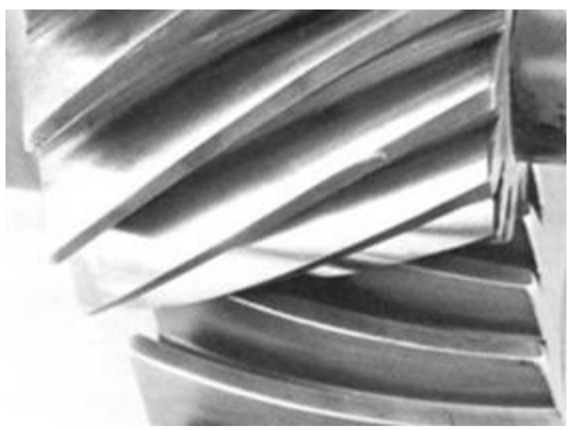


Fig. : Zero wear of helical gear.

(2) Measurable wear : Removal of material from surface that increases vibration; noise or surface roughness may be treated an "Measureable wear". Often we measure wear in volume/mass reduction. Undesirable removal of material occurs in measurable wear.

Measurable wear refers to a loss of material which must be counted to estimate the life of tribo-pair. The extent of measurable weardepends on the lubrication regime, the nature of the load, the surface hardness and roughness, and on the contaminants in the lubricating oil. A typical example of measurable wear in helical gear is shown in Fig. 3.1(b) which is typically known as pitting wear.

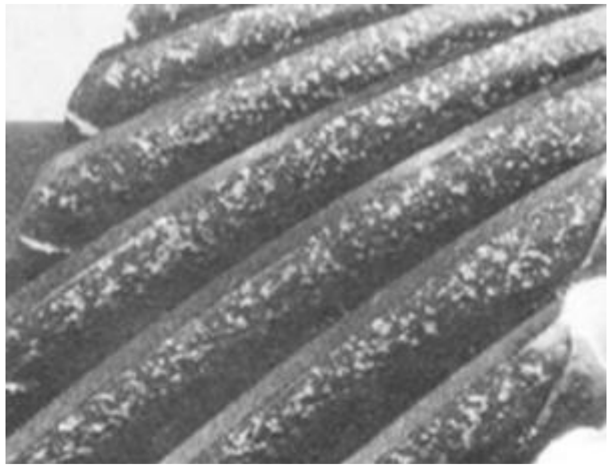


Fig. : Measurable wear of helical gear.

Pitting is a surface fatigue failure which occurs due to repeated loading of tooth surface and the contact stress exceeding the surface fatigue strength of the material. Material in the fatigue region gets removed and a pit is formed. The pit itself will cause stress concentration and soon the pitting spreads to adjacent region till the whole surface is covered with pits. Subsequently, higher impact load resulting from pitting may cause fracture of already weakened tooth. Sometimes impurities in materials provide nucleus for crack generation as shown in Fig. 3.1(c). Fig. 3.1(d) shows merger of generated cracks, which finally detaches from the surface as shown in Fig. 3.1(e). Such formation of pits (removal of material) comes undermeasurable wear.

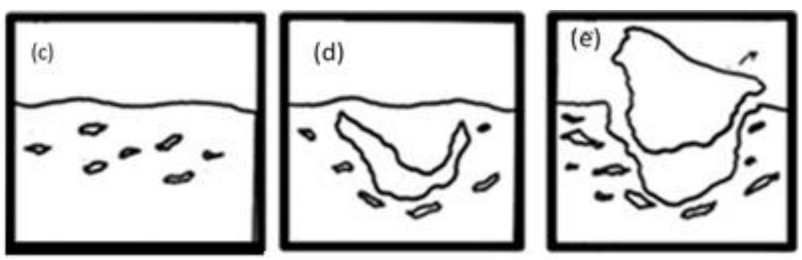


Fig. : Formation of pit.

Many time the change in surface profile alters the optimum value of clearance and reduces load capacity of machine components. Let us consider Fig. 3.2 of worn out rollers. Sliding to rolling ratio for these worn out rollers increase with wear rate and usage of rolling element bearing loses its purpose.

Fig. : Worn out rollers.

This Fig. 3.3 shows variation in bearing clearance due to abrasion of the bearing surface. With increase in bearing clearance load capacity of bearing decreases as shown in Fig. 3.4. X-axis of Fig. 3.4 represents radial clearance which is given by 0.1% of radius multiplied with the factor depicting increase in clearance due to wear.

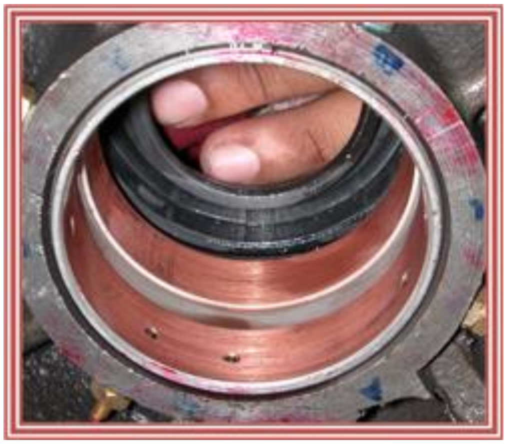


Fig. : Abrasion marks on bearing bore.

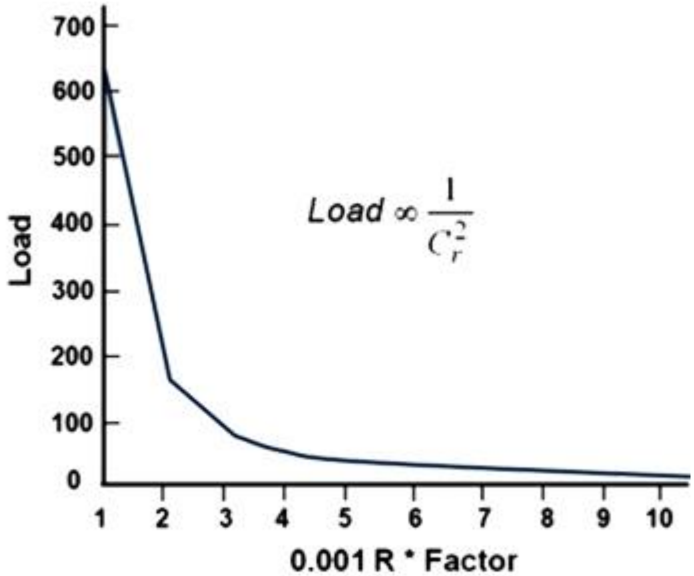


Fig. : Effect of clearence on load.

Removal of material from operating solid surfaces by solid particles depends upon Load, Velocity, Environment, and Materials. Removal of material from operating solid surface by Fluid (liquid/gas) depends upon Velocity, pressure, Environment and material.

As wear increases power losses increases, oil consumption increases, rate of component replacement also inreases. Ultimately, it reduces efficiency of the system. Therefore, as far as possible wear should be minimized.

Wear Mechanisms :

Wear can be classified based on the ways that the frictional junctions are broken, that is, elastic displacement, plastic displacement, cutting, destruction of surface films and destruction of bulk material. There are many types of wear mechanisms, but we shall discuss about common wear mechanisms, which are:

• Abrasive Wear : polishing, scouring, scratching, grinding, gouging.

• Adhesive Wear : galling, scuffing, scoring.

• Cavitation (interaction with fluid).

• Corrosive Wear (Chemical nature).

• Erosive Wear.

• Fatigue : delamination.

• Fretting Wear.

Adhesive Wear

Adhesive wear is very common in metals. It is heavily dependent on the mutual affinity between the materials. Let us take example of steel and indium [Fig. 3.5(a)]. When steel pin under load is pushed [Fig. 3.5(b)] in indium block, and subsequently retracted [Fig. 3.5(c)], a thin layer of indium transferred on the steel pin. Similar behavior is observed by pushing brass metal in indium metal. This behavior demonstrates the loss of indium material, which occurs due to high value of adhesive force between steel and indium. If steel pin is subjected to normal load as well as tangential load [Fig. 3.5(d)] then severe wear of indium material occurs. By introducing a thin layer of lubricant at the interface of indium and metal, the severe wear can be reduced to mild wear. Shear strength of lubricant layer is much smaller than shear strength of indium metal, therefore weak interface between steel and indium occurs which can be sheared easily and wear rate reduces to mild value.

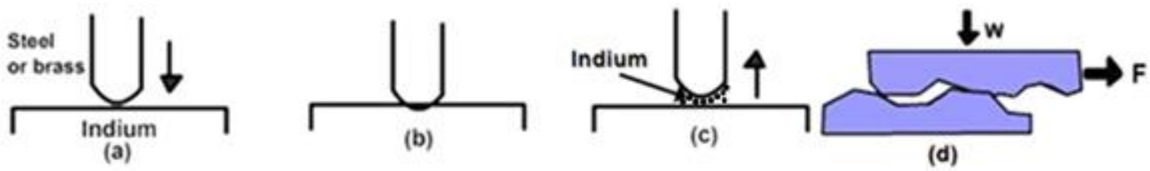


Fig. 3.5: Adhesive wear.

All theories which predict wear rates start from the concept of true area of contact. It is usually assumed that the true area of contact between two real metal surfaces is determined by the plastic deformation of their highest asperities. Severity of adhesive wear is based on the area of contact which is given by $A = W/H$. Here, W is load applied to press one surface over other surface and H is hardness of soft material. This expression provides appropriate results if whole load is supported due to plastic deformation of the surface. However, for elasto-plastic deformation, the expression needs to be slightly modified. ($A = (W/H)^n$ where ($2/3 < n < 1$). Here assumption is that higher asperities could be deformed plastically, while the lower contacting asperities are subject to within elastic limits. In addition, the adhesive wear will depend on the shear strength of friction junctions. This means total true area of contact consists of plastic and elastic asperity contacts and shear strength of the contacting asperities vary in shear strength and thus influence the rate of adhesive wear. If the junction is weaker than the material on either side of it, shearing occurs at the interface itself Fig. 3.6(a). There will be little surface damage and little wear. This situation occurs if sliding occurs within the surface oxide layer. If the junction is stronger than one of the metals, shearing will not occur at the interface but at a little distance within the softer metal [Fig. 3.6(b) and Fig. 3.6(c)]. This may lead to an enormous increase in wear rate.

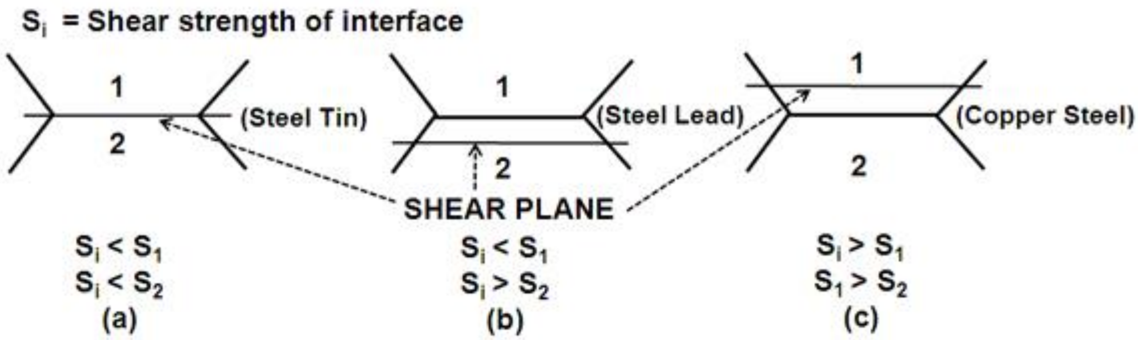
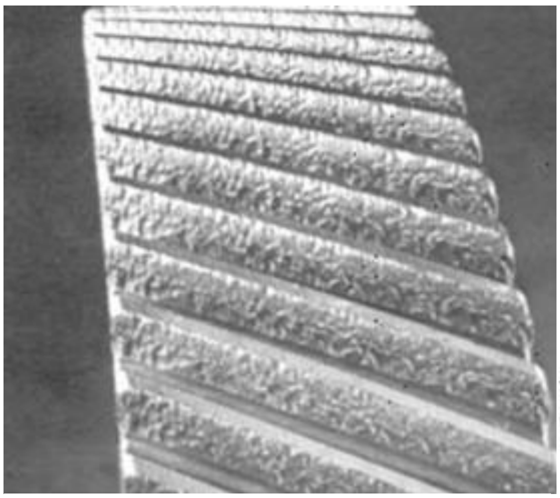


Fig. 3.6: Location of shear plane.

Abrasive Wear

Abrasive wear, sometimes called cutting wear, occurs when hard particles slide and roll under pressure, across the tooth surface. Hard particle sources are: dirt in the housing, sand or scale from castings, metal wear particles, and particles introduced into housing when filling with lube oil. Scratching is a form of abrasive wear, characterized by short scratch-like lines in the direction of sliding. This type of damage is usually light and can be stopped by removing the contaminants that caused it. Fig. 3.16(a) shows abrasive wear of a hardened gear.



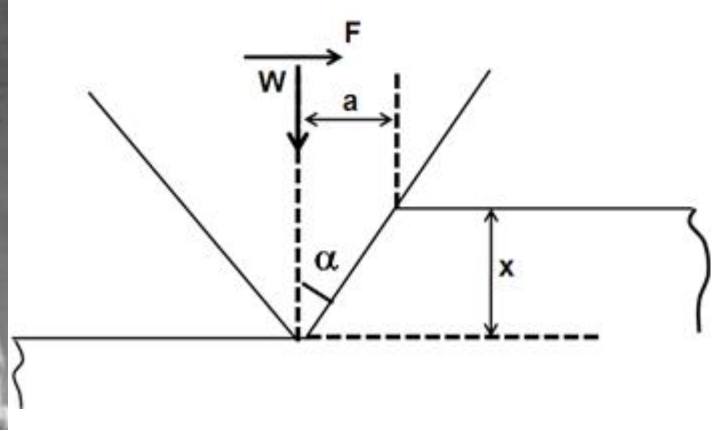


Fig. : Two-Body abrasion

Fig. : Abrasive wear of gear.

Abrasive wear is caused by the passage of relatively hard particles/asperities over a surface. Following are few well-known reasons of abrasive wear mechanisms :

- Micro-cutting : sharp particle or hard asperity cuts the softer surface. Cut material is removed as wear debris.

- Micro-fracture : generally occurs in brittle, e.g. ceramic material. Fracture of the worn surface occurs due to merging of a number of smaller cracks.

- Micro fatigue : When a ductile material is abraded by a blunt particle/asperity, the worn surface is repeatedly loaded and unloaded, and failure occurs due to fatigue.

- Removal of material grains : Happens in materials (i.e. ceramics) having relatively week grain boundaries.

Two other mechanisms, very similar to abrasive wear are :

- Erosive wear : Impact of particles against a solid surface is known as erosive wear.

- Cavitation wear : Localized impact of fluid against a surface during the collapse of bubbles is known as cavitation wear.

Basic modes of abrasive wear are classified as two body abrasion and three body abrasion.

Two – Body Abrasion :

This wear mechanism happens betweent two interacting asperities in physical contact, and one of it is harder than other. Normal load causes penetration of harder asperities into softer surface thus producing plastic deformations. To slide, the material is displaced/removed from the softer surface by combined action of microploughing & micro-cutting.

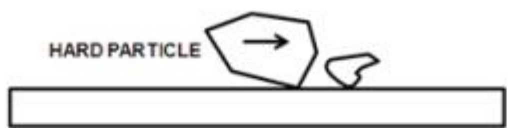


Fig. 3.18: Three-Body abrasion

Corrosive Wear

• Chemical reaction + Mechanical action = Corrosive wear

The fundamental cause of Corrosive wear is a chemical reaction between the material and a corroding medium which can be either a chemical reagent, reactive lubricant or even air. Understanding the mechanisms of corrosive is important to reduce this kind of wear. Let us consider a jaw coupling used for connecting shaft and motor, as shown in Fig. 3.20. This coupling is corroded, due to moist environment and its outer dimensions have increased. If we rub this coupling with fingers, brown colour debris will get detached from the coupling surface. In other words, after chemical reactions, mechanical action is essential to initiate corrosive wear.

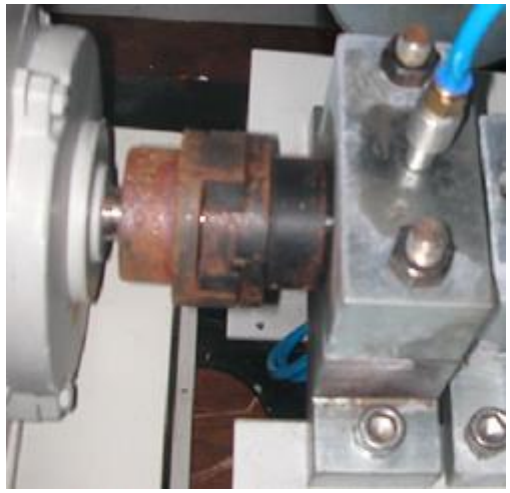


Fig. : Jaw coupling.

Stages of corrosive wear :

• Sliding surfaces chemically interact with environment (humid/industrial vapor/acid)

• A reaction product (like oxide, chlorides, copper sulphide)

• Wearing away of reaction product film.

The most corrosion films passivate (Fig. 3.21) or cease to grow beyond a certain thickness. This is favourable as corrosion process stops its own. But most corrosion films are brittle & porous, and mechanical sliding wears away the film. The formation and subsequent loss of sacrificial (Fig. 3.22) or short life-time corrosion films is the most common form of corrosive wear.

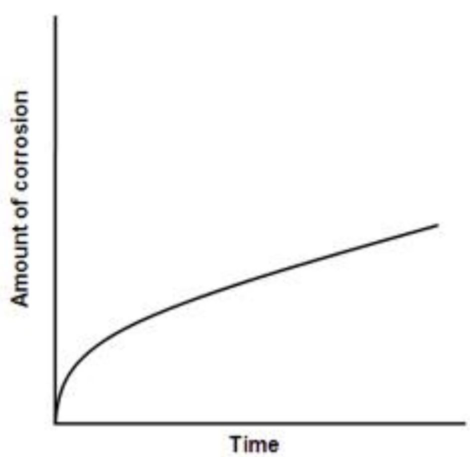


Fig. : Passivation of corrosion.

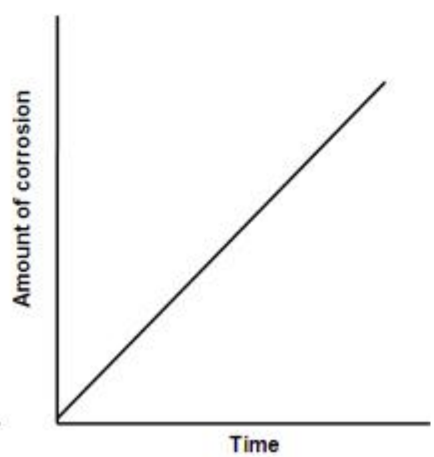


Fig : Continuous corrosion.

Sliding surfaces may wear by chemically reacting with the partner surface or the environment, or both. The oxide layers resulting from reactions with the environment are typically 10 microns thick, and they may have a protective role unless the thickness tends to grow during the cyclic contact process. If the oxide layer grows, it becomes liable to break in brittle fracture, producing wear particles. Hard, broken-off oxide particles may then profoundly affect subsequent wear life as abrasive agents. If soft, ductile debris results, it may form a protective layer on the surface.

Fretting Wear

Fretting Wear coined in 1927 by Tomlinson. It refers to small amplitude(1 to 300 μm), with high frequency oscillatory movement mainly originated by vibration. This generally occurs in mechanical assemblies (press fit parts, rivet / bolt joints, strands of wire ropes, rolling element bearings), in which relative sliding on micron level is allowed. It is very difficult to eliminate such movements and the result is fretting. Fretting wear and fretting fatigue are present in almost all machinery and are the cause of total failure of some otherwise robust components.

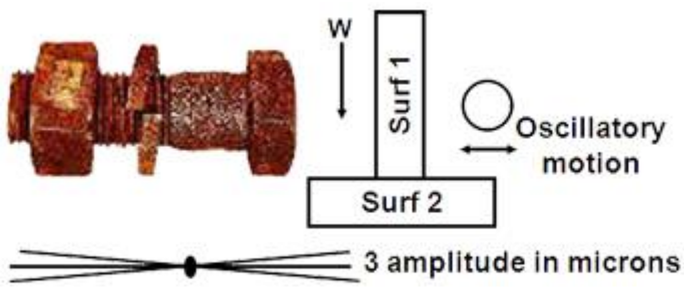


Fig. : Fretting wear.

Fretting occurs wherever short amplitude reciprocating sliding between contacting surfaces is sustained for a large number of cycles. The centre of the contact may remain stationary while the edges reciprocate with an amplitude of the order of 1 micron to cause fretting damage. One of the characteristic features of fretting is that the produced wear debris is often retained within the contact due to small amplitude sliding. The accumulating wear debris gradually separates both surfaces and, in some cases, may contribute to the acceleration of the wear process by abrasion. The process of fretting wear can be further accelerated by temperature. Reciprocating movements as short as 0.1 micron in amplitude can cause failure of the component when the sliding is maintained for one million cycles or more.

EXPECTED VIVA QUESTIONS:

Q.1 What is wear?

Q.2 Define the type of wear?

Q.3 How we can reduce wear problem?

NAME OF FACULTY:

SIGNATURE:

DATE:

EXPERIMENT NO. 9

OBJECTIVE: Study of different kind of lubricant used to design machine component

LUBRICATION
Importance of lubrication

It is known since ages that oils and greases reduce the friction between sliding surfaces, by filling the surface cavities and making the surfaces smoother. Action of liquids/greases known as lubrication. In other words, lubrication is a process by which the friction and wear rates in a moving contact are reduced by using suitable lubricant. Lubricant is a substance introduced between relatively moving parts to reduce friction (μ = 0.1 to 0.0001) and wear rate. The progress in scientific research indicated that reduction in friction occurs due to decrease in adhesion component of friction compared to abrasion component of friction. Almost every relatively moving component in an assembly requires lubricant.

Examples :

(1) A standard lock(Fig. 4.1) : On turning the key, the bolt slides into a notch on the door frame. Force required to turn key and move bolt will be reduced by lubrication.

Fig. 1: Simple lock and key.

(2) Window lifting mechanism(Fig. 4.2) : The windows in most of cars use linkages to lift the window glass. A small electric motor is attached to a worm gear to lift the window. For smooth functioning lubrication is used.

Fig. 2: Window lifting mechanism[1].

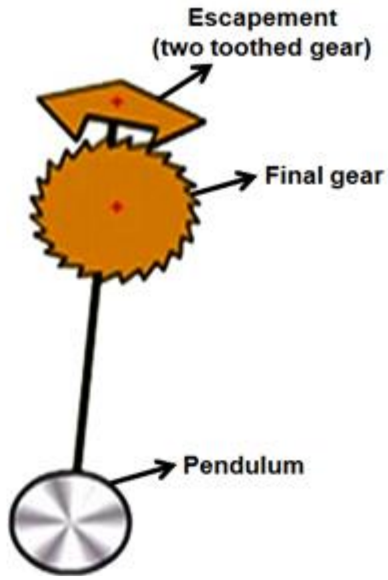


Fig. 3: Pendulum clock.

Sometimes the choice of lubricant type depends the properties of system. For example, in watches or instruments(Fig. 4.3), any lubricant type could meet the load and speed requirements, but because of need for low friction it is normal to use a very low viscosity oil. However, for open gears, wire ropes, or chains the major problem is to prevent the lubricant from being thrown off the moving parts, and it is necessary to use a thick bituminous oil or grease having special adhesive properties.

Advantages of lubrication in addition to reducing friction and wear rate are :

• Reducing instant failures.

• Reducing fatigue failure (Lubricant reduces the force required in tangential direction so reduces the Fatigue Failure)

• Reducing surface failures.

• Reducing stress concentration.

Applications of Lubricant :

1. Transmission parts.

2. Bearings.

3. Cams and followers.

4. Journals.

5. Seal faces.

6. Any situation involving metal to metal contact.

Lubricants are often classified as "Newtonian and "Non-Newtonian" fluids. This classification is on basis of relation between shear stress and shear strain rate(Fig. 4.4).

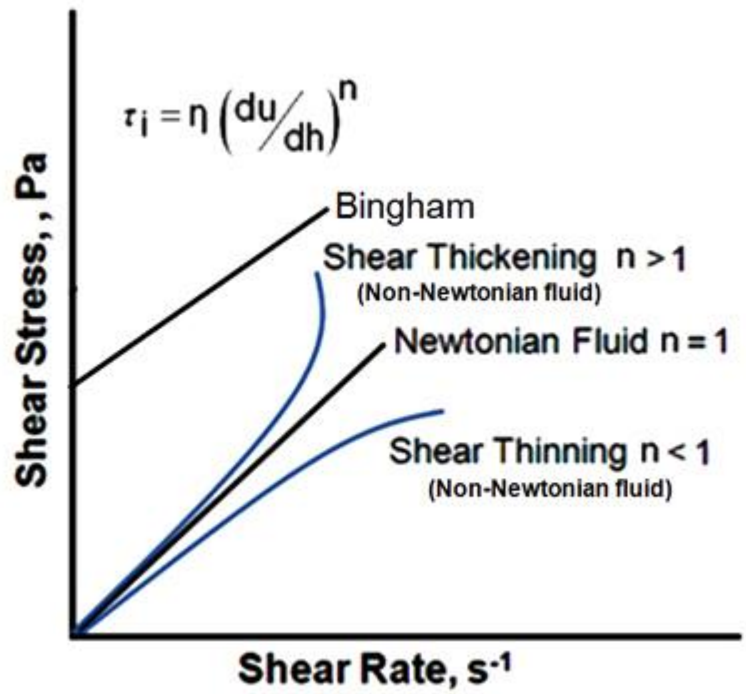


Fig. 4: Newtonian and non Newtonian fluid.

For Newtonian fluid, shear stress is given by Eq.(4.1)

$$\tau = \eta\dot{\phi} = \eta\frac{d\dot{x}}{dy} = \eta\frac{du}{dy}$$ ....**Eq.(4.1)**

In this relation, η is known as dynamic viscosity, which is one of the important lubrication parameters. Method of replenishing lubricant decides overall performance of the system.

What do we expect from lubricant :

Required lubricant properties are specific to applications. We expect some requirements from the lubricant which can be explained by consider few examples :
(1) Lubricant between cylinder liner and rings(Fig. 4.5).

Requirements are :

• Lubricant must form a film to separate the surfaces and reduce the friction between metal to metal contact in order to improve the efficiency of the system.

• Needs to adhere to the surfaces (attachment of thin lubricant layer on the surfaces).

• Must neutralize the corrosive products of combustion.

• Withstand high temperature inside the cylinder.

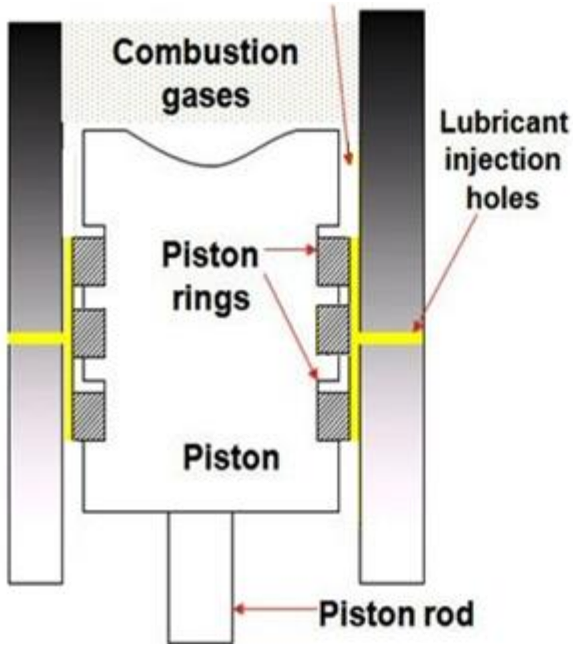


Fig. 5: Lubricant between cylinder liner and rings.

(2) Lubrication in journal bearings (Fig. 4.6) :

Requirements are :

• Lubricant should support heavy shaft and loads.

• Lubricant should avoid contact stresses.

• Lubricant should have ability to dampen vibrations.

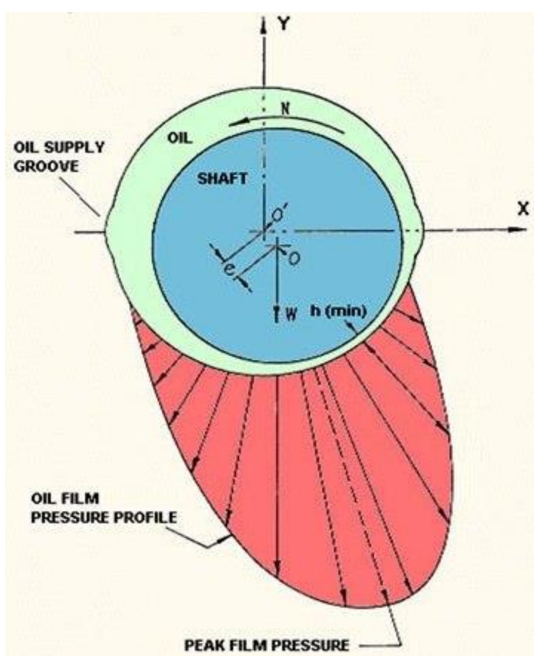


Fig. 6: Radial journal bearing hydrodynamic pressure profile.

Lubrication in bone joints:

Requirements are :

• Contain proteins that stick to cartilage layer resulting in smooth sliding.

• Coefficient of friction ~ 0.01.

• Minerals that nourish the cartilage cells.

• Increase viscosity with increase in applied pressure.

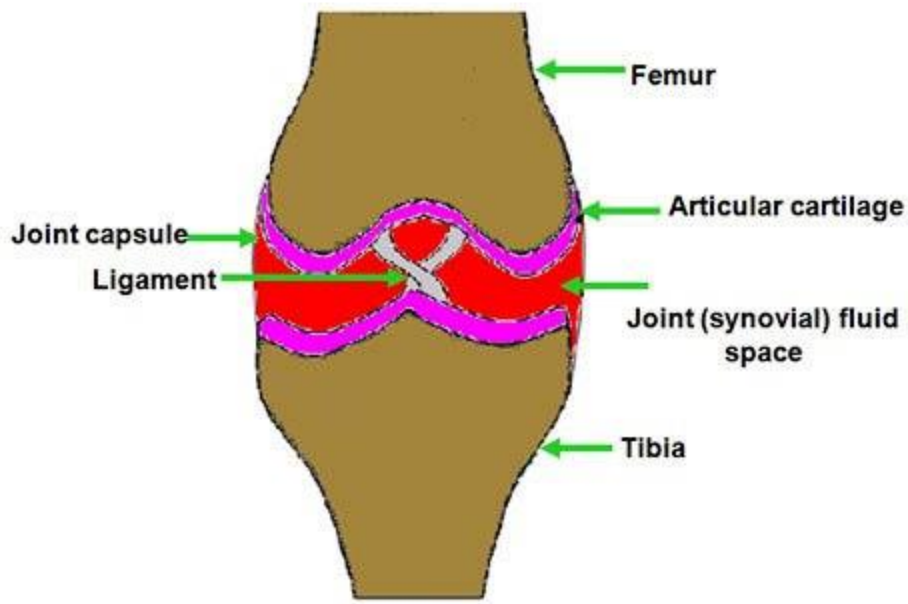


Fig. 7: Lubrication in bone joint.

Lubricant thickness between two solid surfaces must be thick to avoid wear, but thin enough to minimize lubricant shearing. In other words, lubrication can be thick or thin based on the application.

Thick & Thin Lubrications :

• Thick lubrication is governed by Reynolds theory. Thick lubrication is not advantageous because lesser the quantity of oil gives the lesser friction.

• Thin lubrication is far more complex. Requires scientific study at nano- to micro- level. From friction point of view, it is advantageous than thick lubrication.

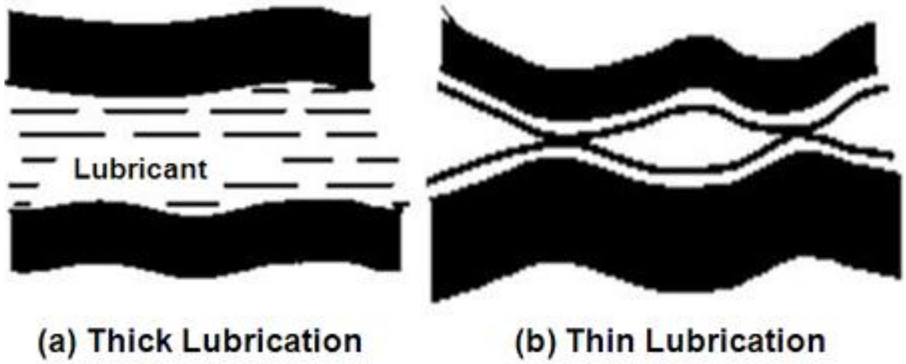


Fig. 8: Fluid film lubrication.

Lubrication Mechanisms :

Although fluid film lubrication relies heavily on fluid mechanics and kinematics, yet it is still ultimately a problem of two surfaces that are either in partial-contact or separated by a thin fluid film. Further, Reynolds equation that governs fluid film lubrication is based on the assumption of thin film. Therefore it is necessary to understand the importance of these lubrication mechanisms relative to the surface texture of tribo-pair. A dimensionless film parameter Λ (often referred as "specific film thickness") is used to classify the aforementioned four lubricant regimes. $R_{rms,a}$ is root mean square (rms) surface roughness of surface a, and $R_{rms,b}$ is rms surface roughness of surface b. Interestingly here rms value is used, while generally arithmetic avg. roughness is used. To clarify this, let us examine Fig. 4.8(a). From tribological point of view, a surface without any asperity but with a number of valleys (that retains lubricants and provide a room for debris collection) is always preferred. Measurement of average roughness imposes a linear penalty on all points whether a point is too close to nominal line or too far. However, rms roughness parameter uses square term. If there are three points: A one unit, B two units and C three units away from nominal line, RMS roughness parameter put penalty of one, four and nine on points A, B, C respectively. Therefore rms value is a better roughness parameter compared to average roughness.

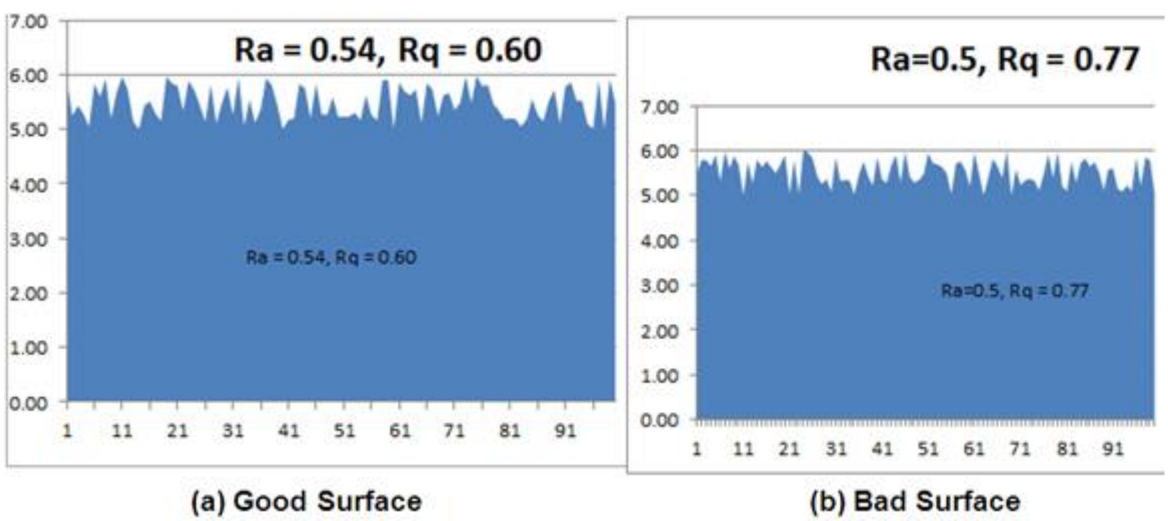


Fig. 8(a): Comparison between average and root mean square roughness.

Based on the value of dimensionless film parameter(Λ), Eq.(4.2) lubrication mechanisms are classified as follows :

• Boundary lubrication, $\Lambda < 1$

• Hydrodynamic lubrication, $\Lambda > 5$

• Mixed lubrication, $1 < \Lambda < 3$

• Elastohydrodynamic, $3 < \Lambda < 5$

Peak surface roughness is generally two to three times of the rms surface roughness. Therefore $\Lambda > 1$ does not indicate the clear separation between tribo-pair. This is a main reason to keep film parameter lesser than 3 but greater than 1 to identify mixed lubrication mechanism. To avoid any wear and minimize friction, a complete separation, between asperities of two relative moving surfaces is essential. This requires film parameter more than 3. Film parameter depends on film thickness and composite surface roughness of tribo-pair. Often foreign particles or wear debris changes the hydrodynamic/elastohydrodynamic lubrication to mixed or boundary lubrication mechanism, as shown in Fig. 9.

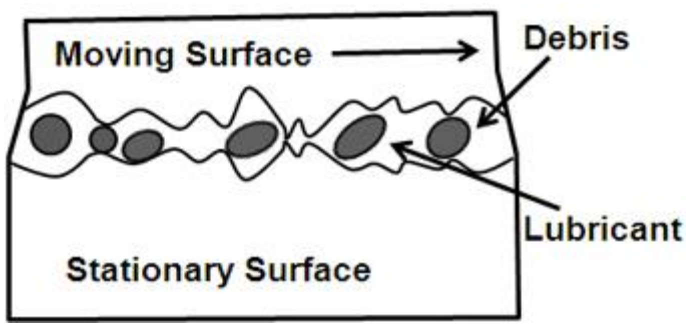


Fig. 9 : Foreign particles/wear debris shift hydrodynamic/elastohydrodynamic lubrication in boundary/mixed lubrication.

$$\Lambda = \frac{h_{\min}}{\sqrt{R_{rms,a}^2 + R_{rms,b}^2}} \quad \text{....Eq.(4.2)}$$

Applications of Tribology
Introduction

Tribology is required for equipments/machines of petrochemical, railway, automotive, agriculture, shipping, power generation, aerospace, military applications, electronic devices and almost all phase of life where motion under load is encountered. Most common machine elements (rolling or sliding) in those equipments/machines are :

• Bearings.

• Gears.

• Cams.

• Brakes.

• Seals.

The above tribo-elements have been classified based on their functionality.

Function of bearings is to support load, while the function of gears is to transmit power. Cams are required to convert rotary motion in reciprocating motion. Brakes are required to stop the motion. The function of seals is to minimize the leakage.

Fig. (a): Taper roller bearing.

Fig. (b): Ball bearings.

Fig. (c): Sliding bearing.

At micro level; gears, cams, brakes, and seals are bearings. Bearings means system which supports load. Gears, cams, brakes, and seals support load. Therefore they may be treated as bearing. When we start imagining about bearing, very common type bearing “rolling element bearing” appears(Fig. (a) and (b). Other kind of bearings are sliding contact(Fig. (c)) and sliding non-contact bearings.

Bearing Classifications based on Relative Motion :

• Rolling contact.

• Sliding.

Bearings are employed to separate rotating/sliding elements from relatively stationary components.

Bearing Classifications based on Direction of Load :

• Radial (Journal)

• Thrust.

• Conical/Taper.

Bearing Classifications based on lubrication system :

• Dry.

• Boundary lubricated.

• Elastohydrodynamic.

• Hydrostatic.

• Aerostatic.

• Hydrodynamic.

• Aerodynamic.

• Squeeze Film.

A group of elasto hydrodynamic, hydrostatic, hydrodynamic, aerostatic, aerodynamic and squeeze film bearings are termed as “Fluid Film Lubricated Bearings”.

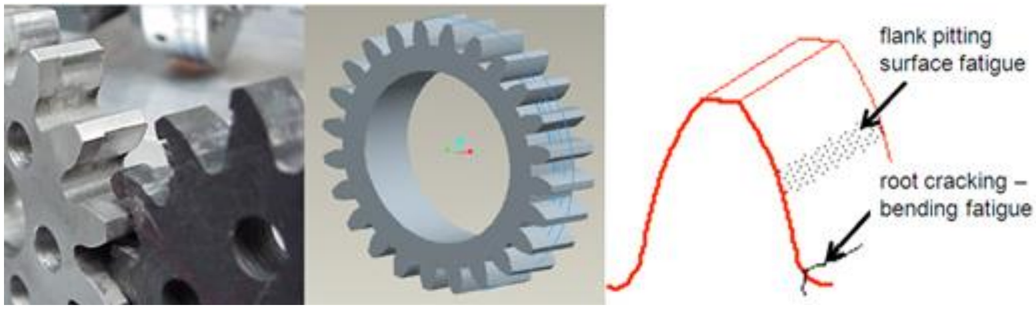


Fig. : Spur gear.

GEARS: When we imagine gears, a picture of wheel with teeth appears(Fig. 6.2). The tooth profile of these wheels is made to maintain the constant velocity ratio. The gears are used to amplify the torque from 1:1 to 40:1 ratio (i.e. involute). Often multistage of gears is used to increase the torque ratio.

Fig. : Various gear.

Spur gears, as shown in Fig. 6.2, are the simplest gears. Fig. 6.3 shows some gears.

Cams :

These components transmit rotary motion to reciprocating motion.

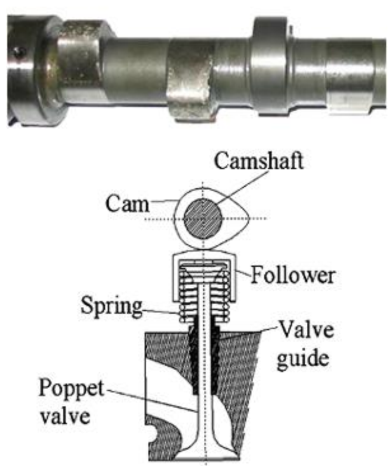


Fig. : Camshaft and cam-follower mechanism.

Elastohydrodynamic lubrication occurs in cam follower mechanisms Maximum pressure in these components may vary from 0.5 to 3 GPa.

Brakes: Basic principle of brakes(Fig. 6.5) depends on friction. So application of tribology is very essential in brakes.

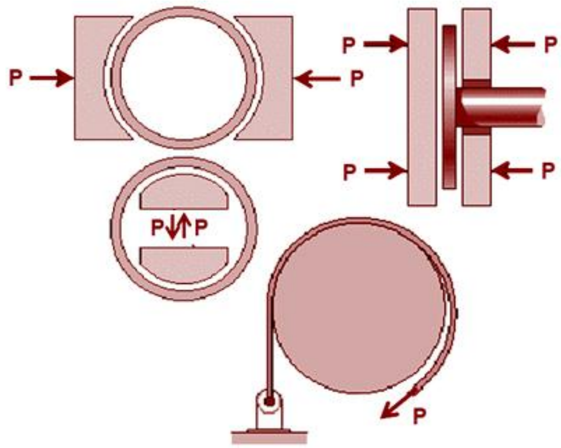


Fig. : Different types of brakes.

Seals :

There are mainly two types of seals :

1. **Contact seals**.

2. **Non-contact seals.**

Non - contact seals are prefered for high speed operation. Friction and wear play very important role in contact seals.

EXPECTED VIVA QUESTIONS:

Q.1 What is Lubrication?

Q.2 What are the type of lubricant?

Q.3 Define hydrodynamic and hydrostatic lubrication?

NAME OF FACULTY:

SIGNATURE:

DATE:

EXPERIMENT NO. 10

OBJECTIVE: Study of various type of strain gauges and wire resistance gauges

Introduction

Various means like mechanical, optical, acoustical, pneumatic or electrical can be used to measure deformation (strain) of an object. Earlier mechanical devices such as extension meter *(extensiometer)* were used to measure strain by measuring the change in length and comparing it to the original length of the object. However, mechanical strain gauges offer certain limitations like low resolutions. Besides they are bulky and difficult to use.

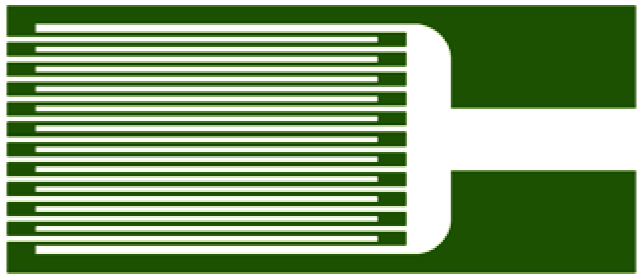
Further, capacitance and inductance-based strain gauges were introduced but these devices's sensitivity to vibration, their mounting requirements, and circuit complexity restricted their usage.

Next are the photoelectric gauges. These gauges use a light beam, two fine gratings, and a photocell detector to generate an electrical current proportional to strain. A photoelectric gauge can be as short as 1/16 inch but its usage proves to be extremely costly and delicate.

In 1938, the first bonded, metallic wire-type strain gauge was introduced. The metallic foil-type strain gauge is constructed of a grid of wire filament of approximately 0.001 in thickness, bonded directly to the strained surface by a thin layer of epoxy resin. When a load is applied to the surface, it gets strained and experiences a change in length. This resulting change in length is conveyed to the resistor and the corresponding strain is measured in terms of the electrical resistance of the foil wire, which varies linearly with strain. Other types of Strain Gauges are described below.

A strain gauge is a resistor used to measure strain on an object. When an external force is applied on an object, due to which there is a deformation occurs in the shape of the object. This deformation in the shape is both compressive or tensile is called strain, and it is measured by the strain gauge. When an object deforms within the limit of elasticity, either it becomes narrower and longer or it become shorter and broadens. As a result of it, there is a change in resistance end-to-end. The strain gauge is sensitive to that small changes occur in the geometry of an object. By measuring the change in resistance of an object, the amount of induced stress can be calculated. The change in resistance normally has very small value, and to sense that small change, strain gauge has a long thin metallic strip arrange in a zigzag pattern on a non-conducting material called the carrier, as shown below, so that it can enlarge the small amount of stress in the group of parallel lines and could be measured with high accuracy. The gauge is literally glued onto the device by an adhesive.

When an object shows physical deformation, its electrical resistance gets change and that change is then measured by gage.



Principle:

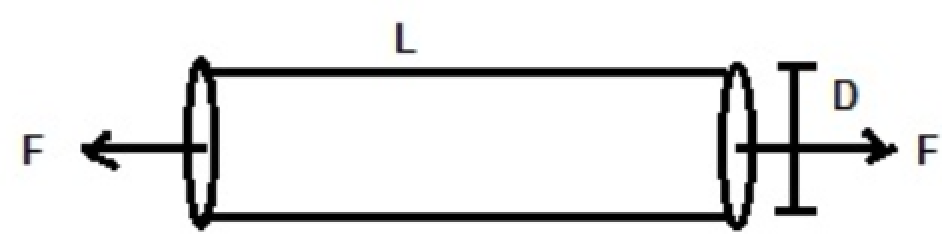
Resistance of a strained wire is more than the resistance of a un-strained wire of same dimensions. In other words, compression or expansion of a metal of given dimension alters the resistance of the metal. Mathematically,

$$R = \rho \frac{l}{A}$$

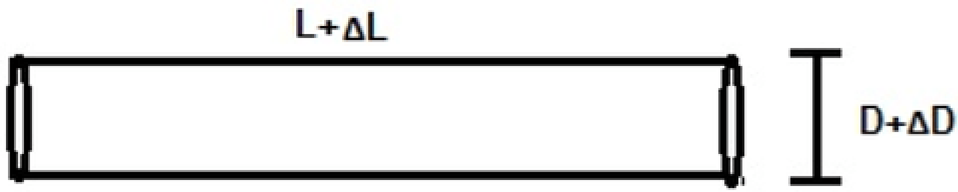
A change in length (l) or Cross sectional area (A) of the wire alters the resistance ®.

Gauge Factor

Consider a metal wire with length L and cross sectional area D with a force F applied on either ends.



The dimensions of the wire changes to L+ΔL and D+ΔD.



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Gauge factor is given as the ratio of change in electrical resistance R to the mechanical strain ε
Mechanical strain is defined as the ratio of change in dimension to the original dimension in which the strain is applied, in this case length.

Gauge factor = GF = (ΔR/R)/(ΔL/L) .

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta\rho/\rho}{\varepsilon} + 1 + 2v$$

where v is poisson’s ratio and ρ is resistivity. (Approximation factors reduce the length and area to 1+2V.)

Piezoreistive effect

It is the change in resistivity of a material when mechanical strain is applied. While the effect of this in the material is negligible, the gauge factor becomes dependent only on geometric factors so it is;
GF = 1+ 2V
However, most commonly used strain gauges work on piezoresistivity , eg: Constantan is material where piezoresistivity is around 20% of the GF.
For a video tutorial on **derivation of gauge factor** and its relation to poisson’s ratio click here 5

Gauge factor for different materials

Material	**Gauge Factor**
Metal foil strain gauge	2-5
Thin-film metal (e.g. constantan)	2
Single crystal silicon	-125 to + 200
Polysilicon	±30
Thick-film resistors	100
p-type Ge	102

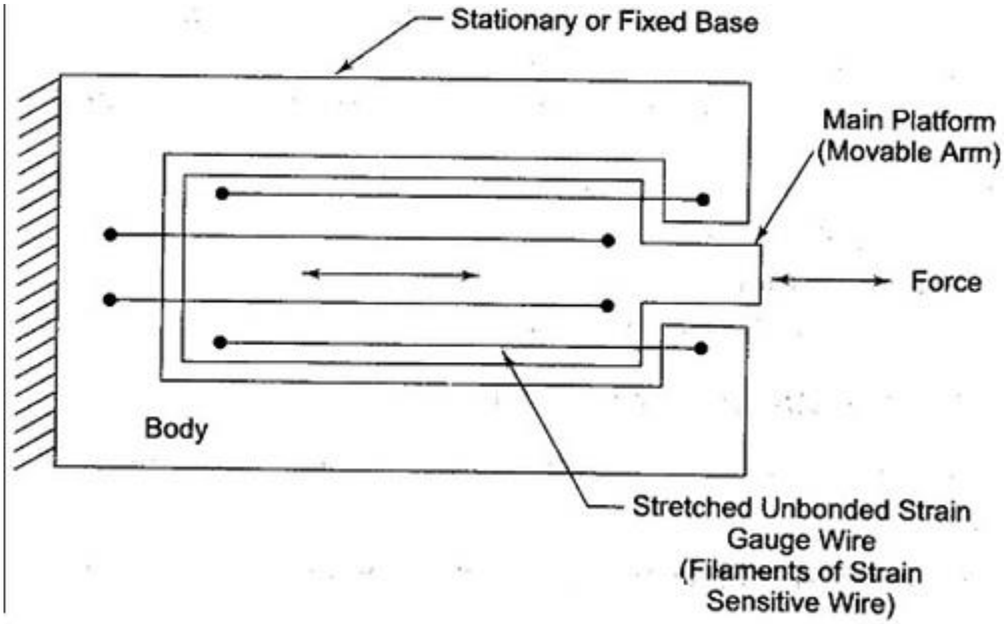
Types of Strain gauges

Strain gauges consist of very fine metallic wires that are arranged in a grid pattern attached to a flexible substrate called the **carrier**. The carrier is in close contact with the test subject so that any

pressure on the subject translates to the movement of the carrier which in turn leads to compression or expansion of the metal wires. The foil is shaped as a grid to increase the area over which the forces act, giving a reliable output.
These strain gauges are attached to arms of a Wheatstone bridge from which the voltage corresponding to the resistance change is measured. Depending on the design of the strain gauges they are classified into many types.

a. Unbounded Metal Strain gauge

The wire is not completely bonded with the carrier. It consists of a fixed body and a movable part. Metal wires connect these two parts and the movable part is in contact with the specimen.



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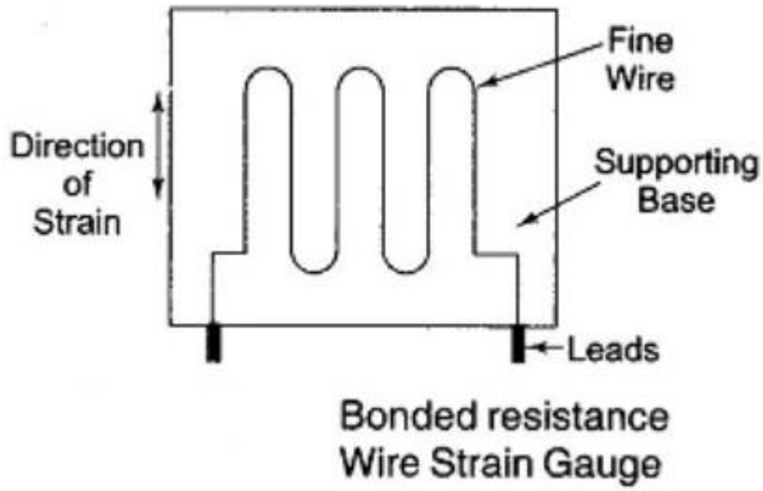
Application of unbounded metal strain gauge:

- Used in applications where there is a need for removable gauges.
- Force, Pressure and Acceleration are some quantities measured

Advantages of unbonded metal strain gauge: High Accuracy
Disadvantages of unbonded metal strain gauge: More space is occupied.

b. Bonded Metal wire Type

The metal wire is bonded to the carrier with epoxy. And the whole structure is attached to the specimen.



Advantages of bonded metal wire type strain gauge

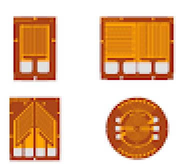
- Inexpensive
- Small
- Temperature dependence is less
- Very sensitive
- For vibrational sensing and load sensing (Static and dynamic Load)

Disadvantages of bonded metal wire type strain gauge

Susceptible to creep error. Since they are highly sensitive and directly bonded to the specimen, over time due to wear of the adhesive will reduce its accuracy.

c. Bonded metal foil strain gauge

Similar to the metal wire strain gauge, only foil is used in place of thin metallic wires. They are manufactured by photo-etching process. They can take different shapes rather than the comb like structure of the metal foil



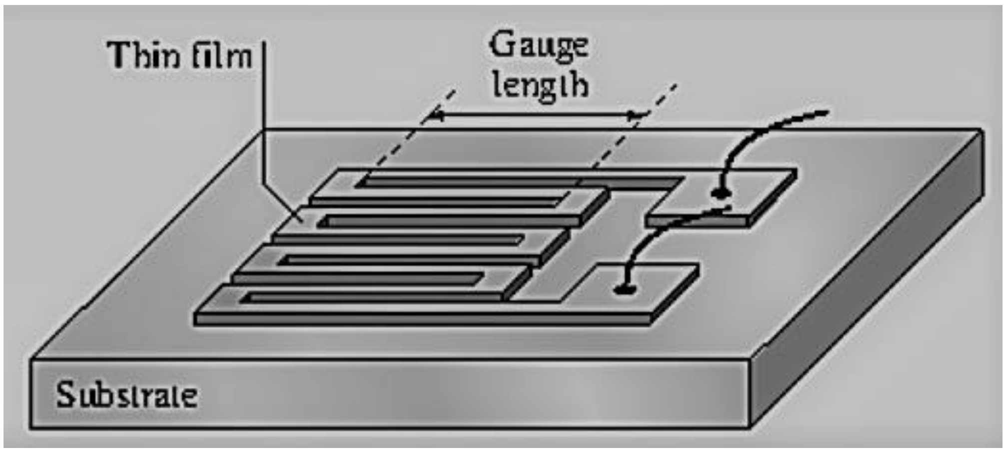
Advantages of Bonded metal foil strain gauge

- They have all the advantages of bonded metal wire strain gauge. In addition they reduce the transverse sensitive.
- They are much cheaper due to ease in manufacturing

d. Thin film strain gauge

This does not need adhesive. This is manufactured by deposition of a insulating layer followed by the deposition of the metal onto the specimen. Depending on the deposition technique, thin film strain gauges are of two types.

1. Vacuum deposition
2. Sputtering technique



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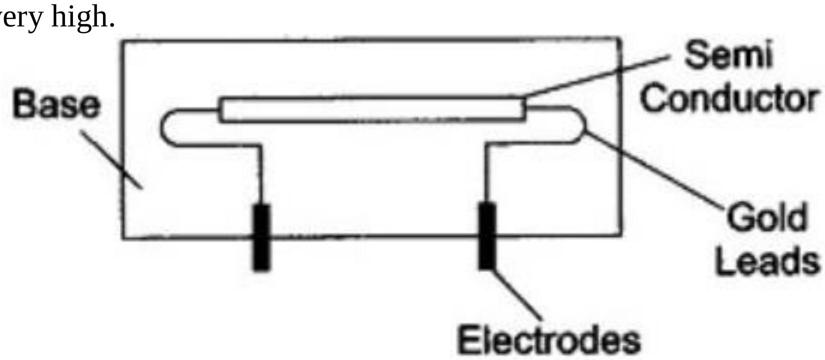
Advantages of Thin film strain gauge

Since there is molecular attachment, there is more stability and less susceptible to creep error.

e. Semiconductor Strain gauges.

Using deposition of semiconductors by semiconductor fabrication techniques of photo lithography and molecular beam epitaxy, they have high pezoresistive properties which means that the G.F is very high.



Semiconductor Strain Gauge

Advantages of Semiconductor Strain gauges

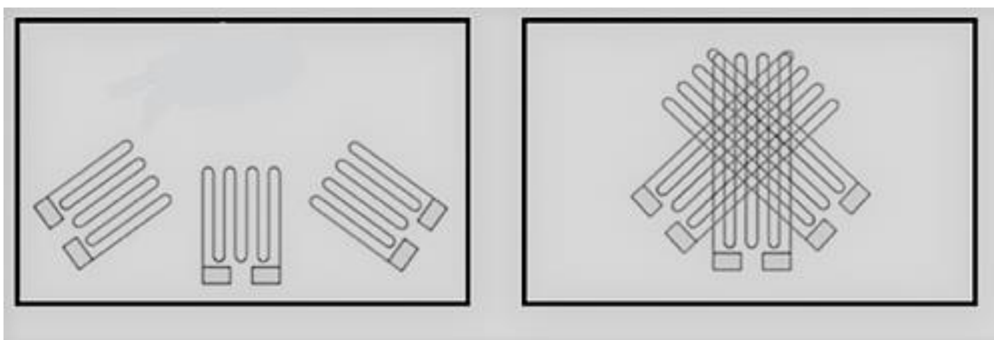
- Most sensitive
- Very cheap
- Strong output signal (high GF)
- No creep (no bonding)
- High pressure range

Disadvantages of Semiconductor Strain gauges

- Temperature sensitive (Semiconductors are highly sensitive to small variation in temperatures)
- Non linear output.

Rosette strain gauge

These are strain gauges that are designed to be multidirectional. Since unidirectional strain gauges can only measure the strain in the direction of its alignment, it does not provide detailed data.



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These strain gauges are connected in star or delta connections.

Temperature dependence of strain gauges

Resistance of the material changes due to temperature in addition to the strain and geometrical factors discussed above. In that case, the resistance change is given as

$$\frac{\Delta R}{R} = GF\varepsilon + \alpha\theta$$

In order to minimize the error due to temperature and creep, compensations are provided for the strain gauges when it is connected to the Wheatstone bridge.

EXPECTED VIVA QUESTIONS:

Q.1 What is the principle of strain gauge?

Q.2 What are the type of strain gauges?

Q.3 Define term: 1. photoelasticity

2. photoelastic bench

3. Electric wire resistance

4. Circuit sensitivity

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SIGNATURE:

DATE: