



Machine Design Series: Material Properties (Course #1)

An Online Continuing Education Course for Engineers

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Introduction

Machine Design is a synthesis of art and engineering principles to construct, develop and manufacture machinery or machine parts to satisfy customer requirements. Design principles help engineers convert their concepts into physical shape and form when properly applied to the case at hand. The machine development could be for a brand-new idea, an innovative product or to modify an existing design to enhance the machine's or its parts' functionality. Established design principles and engineering procedures need to be applied in the proper sequence to convert an idea into engineering drawings which are then manufactured. For the successful design of any machine, the basic materials used for the machine must be strong enough to withstand external and internal forces and environmental conditions. Material properties determine the physical behavior of any machine. Hence, a machine designer must be very conversant with the physical properties of the material used to develop the machine. Materials also determine the cost of the machine. An engineer must focus on the material properties to design and produce a cost-effective machine. The ultimate objective of any design is to satisfy customer requirements in the end. Any machine must satisfy the following basic characteristics:

- Functionality
- Deformation, stiffness, and rigidity
- Strength
- Weight optimization
- Life
- Accuracy
- Quality
- Reliability

To satisfy these requirements, machinery analysis such as stress and strain analysis, stiffness and rigidity calculations, reliability determination, and weight and accuracy optimization, must be done. For all these analyses, any engineer must apply established design formulations that require the material properties to start with. The assumed structure, or conceptual shape and form, must withstand the applied loads to satisfy the required criterion. An engineer must understand how to apply engineering equations which will need the engineering material properties. So, understanding the effects of material properties on the machine's behavior and its life is critical to the success of any machine design. For any successful design, any engineer must understand dynamics, mechanism, strength of materials, theory of elasticity, vibration, etc. Moreover, the published material properties or data depend on the experimentation of these properties such as elastic modulus, ultimate strengths, Poisson's ratio, thermal

properties, etc. The published material properties are statistical by nature. Hence, an engineer has to be very particular about selecting proper material properties that will be used in the calculation to determine the machine behavior under applied loads.

Any machine design process can be divided into several critical phases to manage the overall design process. These steps can be applied in sequence to reduce the cost of the design and development process. The steps to design any machine should consist of the following four stages: Conceptual, Development, Analysis, and Verification

Conceptual Phase:

- Create functional requirements
- Create problem statements
- Develop assumptions of design
- Obtain environmental operating conditions of the design
- Identify cost and time requirements
- Understand manufacturing limitations

Development Phase:

- Develop external and internal forces, moments, and torque
- Select mechanism, joints, materials, and their properties
- Create conceptual shape and form of the design

Analysis:

- Develop an analysis plan to satisfy the requirements
- Perform stress and strain analysis
- Perform rigidity and stiffness analysis
- Perform Life Calculations
- Perform Reliability Analysis
- Perform weight optimization
- Finalize the conceptual plan into a workable design

Verification:

- Develop a test verification plan
- Perform Verification for the design
- Verify the outcome with requirements
- Finalize cost analysis
- Finalize the design

Each step is critical to the success of the design. Predominantly, the selection of material is even more important since the analysis phase is most important to determine the life, reliability, and strength of the machine which will satisfy the requirements. Moreover, the determination of realistic assumptions

for the design is also very important to have a cost-effective design that will satisfy customer requirements which are the ultimate objective of any successful design.

During the analysis phase, the selection of proper material and its strengths are fundamental to the quality and accuracy of analysis results. Selection of proper material out of large possibilities is a challenge for the engineer. The material selection primarily depends on the loads, life and cost requirements, and manufacturing capability available. The selection of material properties also depends on elastic modulus, ultimate strengths, thermal properties, corrosive strengths, etc. The experience of the engineer is critical here for the selection of materials for various elements of the design. There are various properties of any material that are critical for stress, strain, and life calculations. The selection of materials also depends on assembly requirements and the manufacturing capability available. Properties such as ultimate strengths, elongation, thermal coefficients, etc. vary for the same material depending on hardness, manufacturing methods, and heat treatment procedures applied to the material. All the components in any machine must be working in unison to give rise to any particular property of the machine.

1.1 Learning Objects: The primary objectives for this course are as follows:

- Nature and definitions of Material Properties for various common engineering materials used in mechanical design
- Application and selection of engineering material properties for the purpose of machine design
- Differentiate between strength-related and non-strength-related properties for common engineering materials
- Theory and Testing stress-strain diagrams for steel materials
- Dynamic Strength of material under repeated external loading
- Thermal Properties of engineering materials used for mechanical design

2. Material Properties

The selection of material could be defined in two primary categories: Physical properties and non-technical properties. The physical properties of any material consist of values such as Young's modulus. Ultimate strengths, rupture strengths, toughness, hardness values, density, thermal coefficients and thermal conductivity, corrosion resistance, etc. On the other hand, non-technical properties could consist of manufacturability, machinability, castability, malleability, etc. The fundamental properties of any material could be subdivided into the following:

Strength-Related Properties:

- Young's Modulus
- Poisson's Ratio
- Elastic Limits
- Bulk Modulus

- Rupture strength
- Impact Strength
- Ultimate strengths
- Endurance Limit

Non-Strength Related Properties:

- Resilience
- Hardness
- Toughness
- Ductility
- Brittleness
- Frictional Coefficient
- Thermal Expansion Coefficient

Strength: Material strengths are different for different types of loadings. For the tensile or compressive type of loads, elastic limits, ultimate strengths, and Poisson’s ratio could be used. Impact strength could be determined by resilience values or toughness values. Endurance strength is dictated by the endurance limit for the material. The stiffness of the structure or rigidity of the structure depends on the elastic or shear modulus of the material. The definition of such properties is given in the next section for more clarity.

3. Stress and Strain Diagram

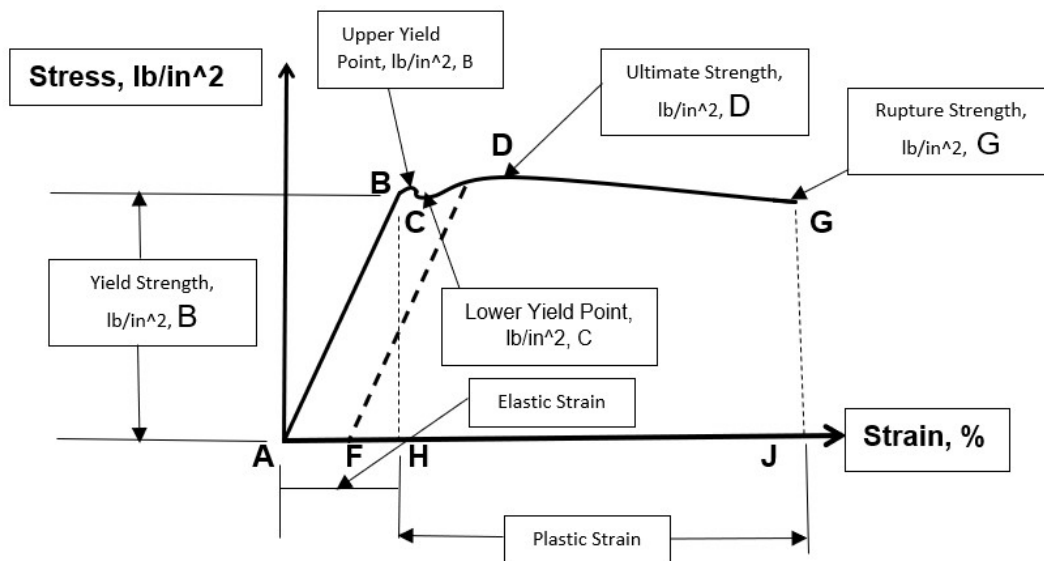


Fig. 1 Stress-Strain Diagram for Ductile Steel (Not to Scale)

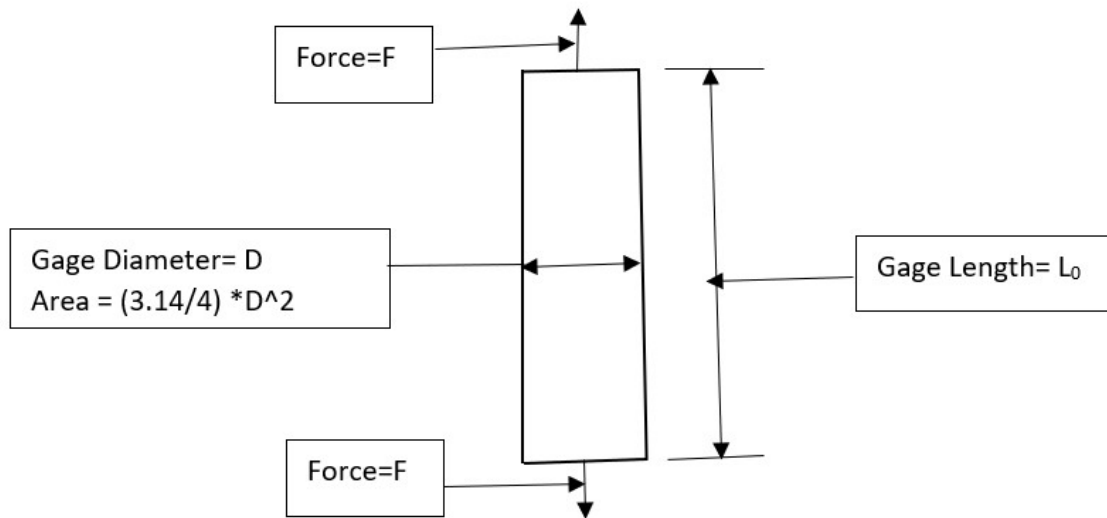


Fig. 2 Coupon Details for Stress-Strain Test (Not to Scale)

The stress-strain diagram, shown in Fig1.1, is obtained for a steel coupon specimen under static and adjustable tensile loading in a tensile machine. The tensile load is applied very slowly at both ends of the specimen very slowly to the main static equilibrium at any point of loading.

As per ASTM (American Standards of Testing Materials), E8, the tensile load is continuously changed to maintain a constant strain rate which is typically about 0.05 in/in/min. The strain is measured by an extensometer attached to gauge the length of the specimen. For most engineering materials, the curve has a linear portion at the beginning (From A to B in Fig 1.1). This is called the elastic portion of the curve. This is called the elastic portion because, when the load is removed, the specimen will go to its original length without any initial deformation. The strain of the specimen up to the yield point is called elastic strain as shown in the diagram (From A to B of the curve). At point B, material flows plastically up to the point of rupture, Point E of the curve. So, from point B to point E, strain is called plastic strain. During the plastic zone, the material changes its axial dimension without increasing the applied load. This is called the plastic flow of the material. The stress level at point G is called the rupture strength of the material. This typical stress-strain diagram, Fig. 1, is exhibited by ductile material, structural steel when loaded as described earlier (See Fig. 2).

Since finding the exact proportion limit for the material is very difficult to determine, in 1906, the International Congress for Testing Materials at Brussel defined the proportional limit as the stress in the material for a permanent set of 0.001 percent. The yield point in Fig. 1 is a very important characteristic of any structural material. At this point, the material yields to the load i.e., the material starts to flow plastically when the elastic limit is crossed. The stress at the yield point is called yield point stress for the material. For mild steel, the yield point could happen at about 2% elongation of the gauge length. The position of the upper yield point, Point B in Fig. 1 is affected by the speed of the applied load, and the

