The damage of materials is the progressive physical process by which they break. The mechanics of damage is the study, through mechanical variables, of the mechanisms involved in this deterioration when the materials are subjected to loading. At the microscale level this is the accumulation of microstresses in the neighborhood of defects or interfaces and the breaking of bonds, which both damage the material. At the mesoscale level of the representative volume element this is the growth and the coalescence of microcracks or microvoids which together initiate one crack. At the macroscale level this is the growth of that crack. The two first stages may be studied by means of damage variables of the mechanics of continuous media defined at the mesoscale level. The third stage is usually studied using fracture mechanics with variables defined at the macroscale level.

When studying engineering materials such as metals and alloys, polymers and composites, ceramics, rocks, concrete, and wood, it is very surprising to see how such materials, which have different physical structures, are similar in their qualitative mechanical behavior. All show elastic behavior, yielding, some form of plastic or irreversible strain, anisotropy induced by strain, cyclic hysteresis loops, damage by monotonic loading or by fatigue, and crack growth under static or dynamic loads. This means that the common mesoscopic properties can be explained by a few energy mechanisms that are similar for all these materials. This is the main reason it is possible to explain material behavior successfully with the mechanics of continuous media and the thermodynamics of irreversible processes, which model the materials without detailed reference to the complexity of their physical microstructures.

1.1 Physical Nature of the Solid State and Damage

1.1.1 Atoms, Elasticity and Damage

All materials are composed of atoms, which are held together by bonds resulting from the interaction of electromagnetic fields. Elasticity is directly related to the relative movement of atoms. The physical study of the properties of an atomic lattice leads to the theory of elasticity, but a much easier way is to write the mathematical constitutive equations directly at the mesoscale level using the property of reversibility of strain, which implies a one-to-one relationship, and eventually incorporate the properties of linearity and isotropy.

When debonding occurs, this is the beginning of the damage process. For example, metals are organized in crystals or grains: a regular array of atoms except on many
lines of dislocations where atoms are missing. If a shear stress is applied, the dislocations may move by the displacement of bonds, thus creating a plastic strain by slip without any debonding as shown in Figure 1.1.

If the dislocation is stopped by a microdefect or a microstess concentration, it creates a constrained zone in which another dislocation may be stopped. This second process cannot occur without a debonding damage as shown in Figure 1.2. Several arrests of dislocations nucleate a microcrack. Other damage mechanisms in metals are intergranular debonding and decohesion between inclusions and the matrix.

All these mechanisms create plastic microstrains.

- In polymers, damage occurs by the breakage of bonds that exist between the long chains of molecules.
- In composites damage is the debonding between the fibers and the polymeric matrix.
- In ceramics it is mainly microdecohesions between the inclusions and the matrix.
- In concrete, the early damage mechanism is also a decohesion between aggregates and the cement with the complex influence of water.
- In wood, the weak point where damage occurs is the bonding of the celulosic cells.

In all cases elasticity is directly influenced by the damage, since the number of atomic bonds responsible for elasticity decreases with damage. This coupling,

![Figure 1.1. Elementary plastic strain by slip due to dislocation movement](image)

![Figure 1.2. Elementary damage by nucleation of a microcrack due to an accumulation of dislocations (after D. Krajcinovic)](image)