5. MECHANICAL BONDING

Nails, screws, rivets, bolts, clamps and fasteners are ubiquitous in engineering systems and constitute by far the most versatile class of joining methods. These range from the nailing of two wooden planks to the bolting in place of an engine head, and from the rivetting of boiler plate to the zip fastener of a winter jacket. Cup and cone ground glass seals, described in the Introduction, are mechanical joints. So are the velcro, hook and felt, fabric fasteners which have effectively replaced the metal "pop-fastener". Figure 5.1 illustrates some of this wide variety, and in this chapter we will examine some of the principles involved in the design and fabrication of mechanical bonds and joints.

In particular, we will expand the discussion of stress concentration in mechanical assemblies and the role of residual stress in preserving the integrity of an assembly. We will analyse the requirements for seals and gaskets and describe some ways in which these requirements are met in practice. The role of friction as a positive factor in stabilizing a joint will be discussed, together with some negative aspects of friction. The role of coatings in controlling frictional properties will be described, as well as some of the possible corrosion problems associated with mechanical joining processes.

Examples will be given of both permanent and demountable mechanical joining systems, ranging from ultra-high vacuum seals to orthopaedic implants.

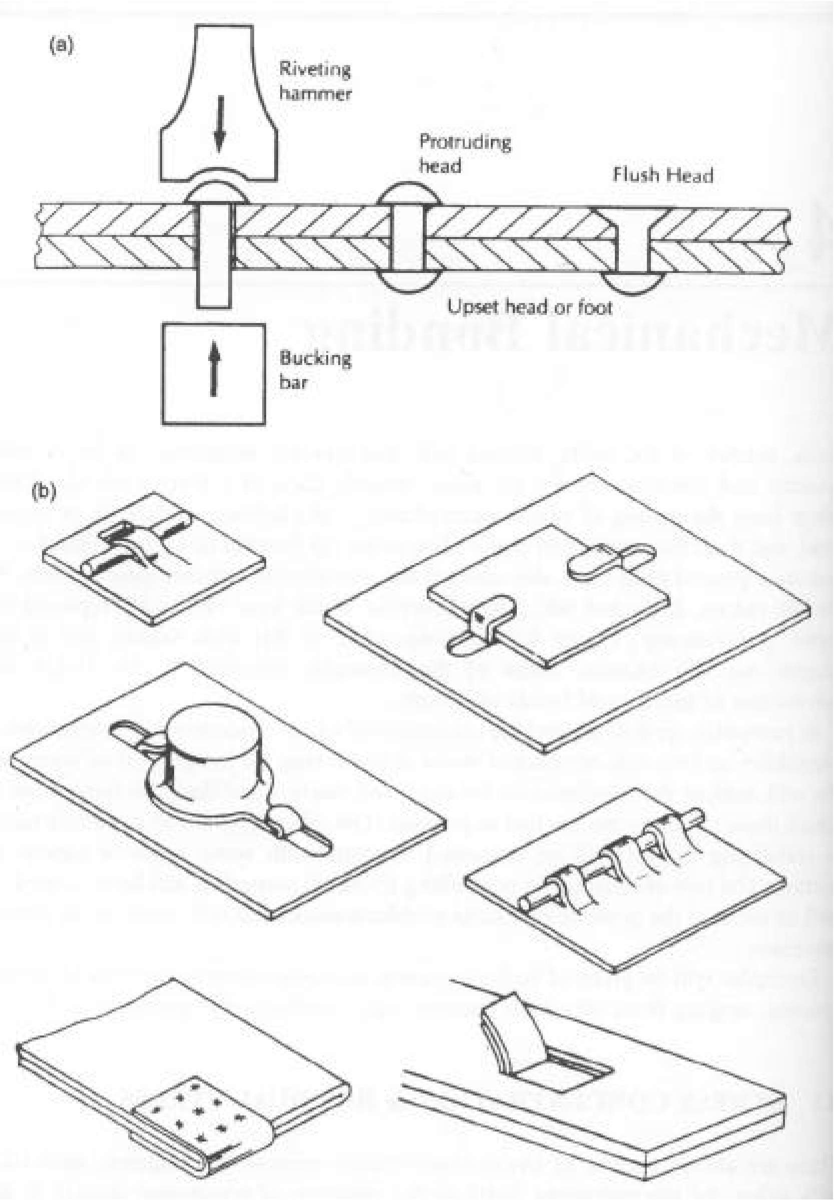

Fig 5.1
Some examples of mechanical fastening.
a) Rivetting
b) Tabs.

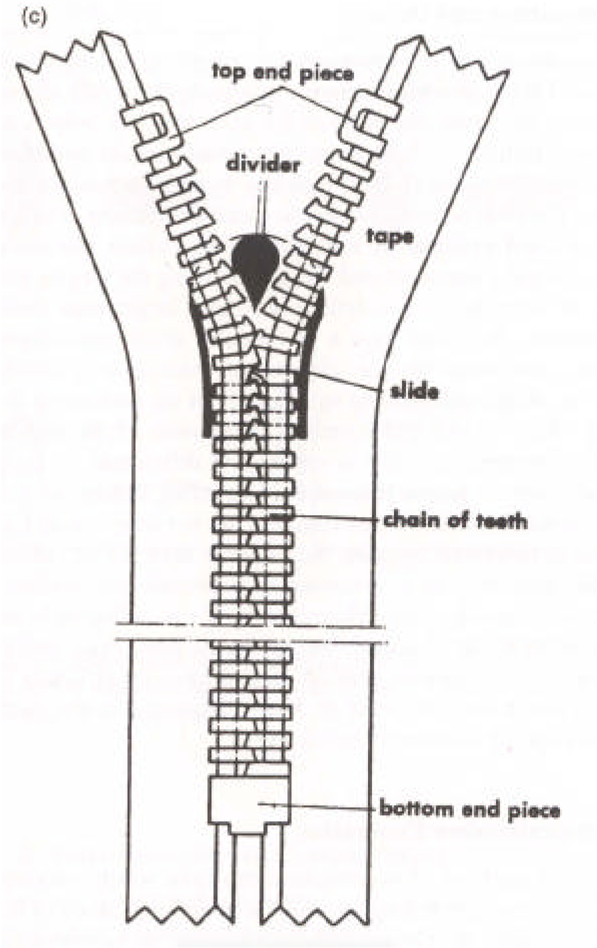

Fig 5.1 continued.
Some examples of mechanical fastening.
c) A zip fastener.

5.1 STRESS CONCENTRATION & RESIDUAL STRESS

There are always regions of stress concentration present in a material, associated with either the microstructure itself or the presence of processing defects in the material (inclusions, porosity or microcracks). It is convenient to distinguish between three different length scales when discussing stress concentrations and residual stresses, micro, meso and macro. On the microstructural scale, variations in stress may be associated with elastic or plastic anisotropy of the individual grains. If the normal to a grain boundary corresponds to a direction of high stiffness (high elastic modulus) in one grain, but to a direction of low stiffness in the neighbouring grain then, when a load is applied normal to the boundary, the elastic discontinuity will give rise to shear stresses at the edge of the boundary facet and parallel to the boundary. Hard, second phase particles, in a precipitation- or dispersion-hardened alloy, are also sites of stress concentration in the matrix phase, and in such regions the stress in a uniaxially-loaded specimen is triaxial rather than uniaxial.

5.2 MECHANICAL JOINING SYSTEMS

The simplified mechanical joining systems described below are intended to illustrate some of the factors which determine the selection of an assembly method for a mechanical joint.

5.2.1 Lock Seams

Lock seams made from sheet metal are ubiquitous. To be completely effective the lock seam must be sealed, and this may be done either with solder (as in a paint can) or by an organic resin (as in some long-life food storage containers, especially in low pH applications, such as preserves and jams).

5.2.2 Screws & Bolts

In spite of their poor ductility and their tendency to promote corrosion by acting as strong cathodes, brass screws and bolts continue to find diverse applications, for example as major components of domestic electrical equipment. The primary reason is their good machinability, which is also a consequence of their limited ductility.

Alternative methods of mechanical assembly are being substituted for brass nuts and bolts, even though nickel plating reduces corrosion susceptibility by reducing the electrode potential with respect to steel. One reason is the cost of the alloy, but another is the susceptibility of brass to environmentally-assisted crack growth: stress corrosion cracking. This phenomenon is associated with the development of either intergranular or transgranular microcracking at the site of a stress concentration and in the presence of moisture.

Steels provide by far the widest range of screws and bolts, including high tensile strength, heat-treatable alloy steels, and the precipitation-hardened, high strength stainless steels (the PH steels) for corrosion resistant applications. Electroplated steel bolts are a cheaper alternative to the PH steels, if they are capable of surviving the application without localized corrosion or spalling of the coating. As in other engineering applications, the primary advantages of steel are its cost effective strength and toughness and these have to be set against its primary disadvantage - susceptibility to degradation by corrosion.

5.2.3 Rivets

A rivet is pushed into a locating hole in the two components to be joined and cold-headed (upset-forged) to form the join. Sufficient compressive elastic energy must be stored in the components to ensure that the rivet is placed in tension by stress relaxation when the compressive forging pressure is released. The rivetting process is illustrated schematically in Fig. 5.2. The quality of the final rivetted structure depends sensitively on the preparation of the hole and the control of the punch pressure cycle. A wide range of rivet designs is available, in which a compromise is sought between the strength of the assembled joint, the required ductility of the rivet material and the control of the forging process. Assuming the rivet to be elastic to the yield stress, to have the same compliance as the material being joined, and no workhardening beyond the yield stress, then the compressive load required to forge a rivet of radius r is just: $F_c = \pi r^2 \sigma_y$. If the compressive load is increased beyond this point the elastic energy is stored in the joint assembly (Fig. 5.2). The situation can be analysed approximately. As the compressive load is released, the sign of the stress in the rivet is reversed, placing it in tension. If the forging force exceeds $3F_c$, then the relaxation process will place the rivet under a tensile stress which exceeds its yield stress, and reverse plastic flow will occur. The residual tensile stress in the rivet increases linearly from zero to σ_y as the forging force increases from F_c to $3F_c$, The tensile strength perpendicular to the rivetted joint will be a maximum when the forging force is the minimum required for general yielding, $F= F_c$, so that the rivet experiences no prestress, but the tensile strength parallel to the joint is improved by the tensile residual stress in the rivet, since the frictional force at the interface reduces the stress concentration at the rivet by assisting load transfer to the components (Fig. 5.3). The optimum cold-heading conditions thus depend on the expected stresses in service, and will be somewhere in the range $F_c < F < 3F_c$. A more accurate analysis of the mechanical performance of a rivetted joint is outside the scope of this text.

The importance of rivetted structures dates from the earliest days of the industrial revolution, in the construction of boilers for steam engines and, later, in the construction of steel-hulled ships. Welded structures to a large extent superseded rivetted plate in the ship-building industry after the 1939-45 World War, but for many years rivetted assemblies have dominated the airframe industry, in which the material of first choice is a wrought aluminium alloy. Today aluminium rivetted airframe structures are being challenged in some areas, by adhesive lap-joints. In many applications a rivetted join is in competition with a modified lap-joint, which combines the lock-seam design with an adhesive. This combination both seals the join and prevents excessive stress concentration, by distributing the load over a larger contact area. The main limitation on the lock-seam remains the requirement for ductility of the sheet (which must be bent to a radius of the order of the thickness).

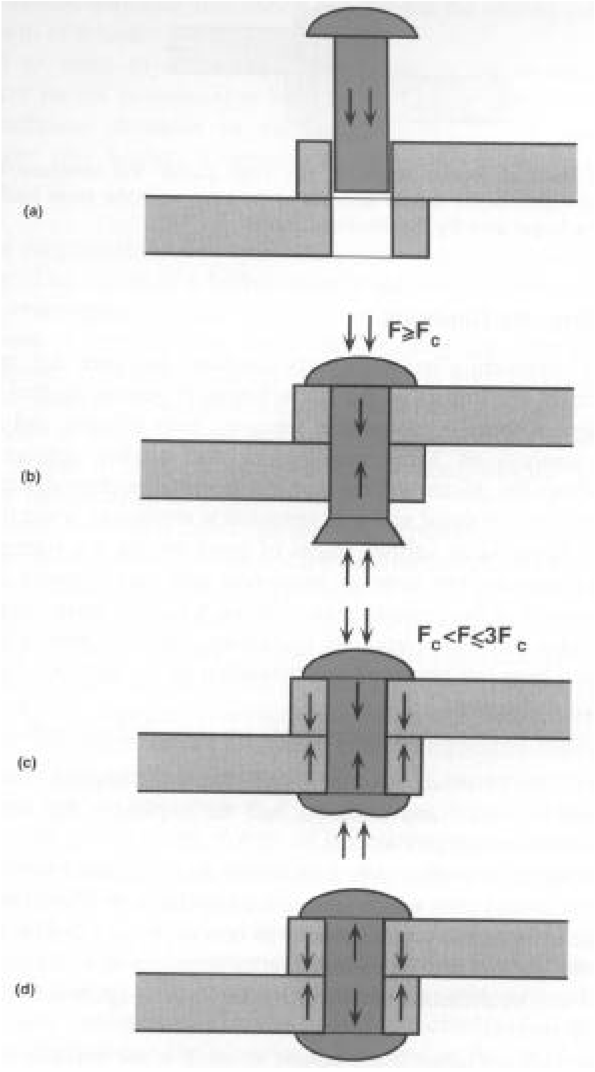

Fig. 5.2
Forming a rivetted joint.
a) The rivet is pushed into the locating holes in the sheet components.
b) Upset forging of the rivet is initiated when the applied force exceeds that required for general yielding.
c) The compressive force used to forge the rivet also places the components in compression.
d) Provided that the compressive force is not excessive, the residual tensile stress in the finished rivet will be below its yield stress.

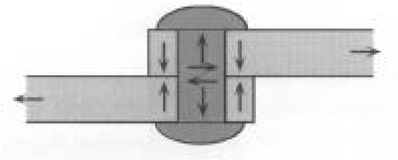

Fig. 5.3
The residual tensile stress in the rivet places the components in residual compression and improves the tensile strength of the joint since the shear load at the joint is distributed over a larger area by the frictional forces.

5.2.4 Orthopaedic Implants

The impact of engineering technology on medicine has been felt in three areas, which complement the impact of the life sciences in genetic control and pharmacology. The first of these is biomedical imaging, both invasive and non-invasive. Tomographic analysis of X-ray radiographic and nuclear magnetic resonance (NMR) data allows the doctor and the surgeon to visualize three-dimensional tissue structure in considerable detail and with remarkable resolution, while the ultrasound imaging of the foetus in its various stages of development is a commonplace. The second area of advance has been in transplant and microsurgery and has been extensively reported in the popular press, although heart bypass surgery and heart transplants are now considered 'routine' operations. The third area concerns us here and has followed from our improved understanding of the reaction of a living tissue to an implanted component.

Tissue reactions to implanted components are classified under three headings:

1. Incompatible: An ab-reaction of the tissue rejects the implant. The surrounding tissues become swollen and inflamed, and the implant is the site of pain and oedema. The wound refuses to heal.
2. Inert: The implant is coated, over a relatively short period of time, by a layer of epithelial (skin-like) cells which isolate the implant from the surrounding living tissue. Once isolated, the organism does its best to pretend that the implant is not present. If the implant is to be removed (after bone growth to repair a fracture, for example) it can be detached readily from the layer of epithelial cells, which are very loosely bonded.
3. Compatible: Cells of living tissue adhere strongly to the implant. Removal of the implant can only be achieved by cutting away the tissue, so that implant removal is accompanied by tissue damage.

Implant surgery introduces two new engineering requirements for any bonding process:

1. The time-dependence of post-surgical healing and the influence of the healing process on bond formation must be considered. A compromise is usually necessary between the immobilization of the patient following surgery and the need for suitable muscular stimulation to complete the healing process (such as the regrowth of a broken bone).
2. The need to avoid tissue incompatibility. This is the inverse of the usual requirement for the component to be stable in the environment (that is, it must exhibit sufficient corrosion or oxidation resistance). We now require the environment (the biological tissues) to be stable in the presence of the component!

We confine the present discussion to orthopaedic implants intended to repair the bony skeleton. The setting of a broken bone is achieved by fixing the two ends in position and encouraging natural bone growth processes to make the repair. The growth of bone is stimulated by stress, and loading the bone in compression encourages growth. However, if the applied load is too high, dissolution will occur (the bone will shorten). Dissolution of bony tissue will also occur if the bone is unstressed (calcium loss is a major problem for astronauts held in weightless orbit for extended periods of time). It follows that a 'working window' of compressive load exists for bone healing to occur.

The mechanical problem is then to fix the bone in position, but allow for sufficient compressive stress at the contact between the two fractured ends in order to promote growth of new bone. The commonest method of achieving this is by the use of metallic plates and screws, typically made from a high quality stainless steel or a titanium alloy. Both these materials are biochemically inert, and so can be removed relatively easily in a subsequent operation, once healing is complete, should this be considered medically desirable. However these metals also have a very much higher elastic modulus than bone, so that relaxation of the compressive load on the broken bone can occur at very small displacements (Fig. 5.4). In consequence, dissolution of the bone may replace bone growth at the fracture. To prevent this considerable attention has been given to the design of an isocompliant implant, with elastic properties approximating those of bone. Some plastic materials appear suitable, but have not yet gained wide acceptance.

The setting and fixing of broken bones is a task for traumatic (unplanned or emergency) surgery. The replacement of defective joints is undertaken in elective (planned) surgery. One of the commonest operations in orthopaedic elective surgery is that of hip-joint replacement. This is usually indicated if the meniscus which cushions the load applied to the hip-joint is damaged or destroyed. The operation involves replacing the joint with an artificial cup, set into the pelvic girdle, and a matching ball and shaft, inserted into the head of the femur (Fig. 5.5). Until recently the preferred materials were a high density polyethylene cup and a highly polished stainless steel ball mounted on a stainless steel stem. Today the stainless steel ball has been largely replaced by an alumina ball with a conical hole which fits over the stainless steel or titanium alloy shaft. The cup is cemented in place with a methacrylate resin which is formulated to retain its dimensions after molding (many such compounds shrink as cross-linking process proceeds). Unfortunately, the crosslinking of methacrylate is an exothermic chemical reaction and the heat evolved must be dissipated. Moreover, the reaction is accelerated if the methacrylate does heats up, and the heat evolved can kill the surrounding living tissue (necrosis).

The stem of the metal ball is forced into the shaft of the femur (the thigh bone) and held in place by a residual compressive radial stress. Here the problem is once again the high elastic modulus of the metal compared to the bone and its limited biocompatibility. Very little dissolution of the bony tissue is required before the compressive stress on the stem of the implant is relaxed. At the same time, the metal is inert, rather than biocompatible, leading to a weak bond at the metal-tissue interface. The cyclic bending stresses which act on the hip-joint during walking can result in rotation of the cup out of position or, worse, loosening of the stem of the implant in the femur shaft and eventual failure of the joint. One possible solution to this problem which has been clinically tested and approved is the development of a stem with a porous layer, formed by partial sintering of either packed metal fibres or a coarse metal powder (usually a titanium alloy) to the stem of the implant. The interstices in the porous surface layer are large enough to allow the ingrowth of bony tissue, together with the capillary blood supply needed to keep the tissue alive. Of course, such a joint is now strongly bonded to the bone, and replacement of the stem would be a major surgical undertaking.

A major problem in an artificial hip-joint is the wear which can occur at the interface between the ball and the plastic cup, especially if there is some misalignment of the joint. Both the wear damage and frictional losses are reduced by the combination of a polymer cup with an alumina ball and a metal stem.

It is worth recognizing that surgical procedures have to be performed on soft tissues of complex shape and in the presence of rather unstable viscous fluids. The dimensional tolerances which can be achieved are strongly dependent on the individual skills of the surgeon, and perfect alignment of the implant components is not easy.

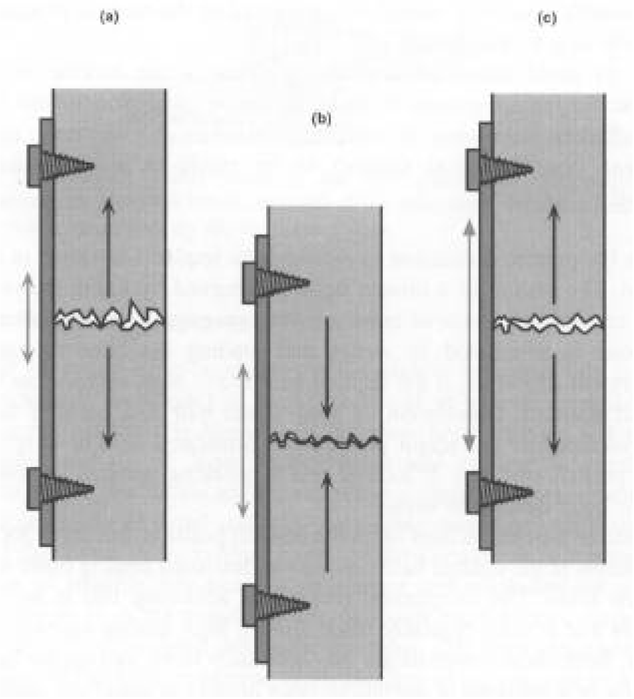

Fig. 5.4
A metal bone plate fixes the two halves of a fractured bone in contact until new bone has formed to repair the break.
a) If the tensile stress in the plate is insufficient, then the Compressive stress in the bone will be insufficient to promote growth and bone dissolution may occur.
b) There exists a window of compressive stress in the fracture contact area within which the growth of new bone is stimulated.
c) If the tensile stress in the metal plate is excessive, then the compressive stress in the contact area will again result in bone dissolution rather than new growth.

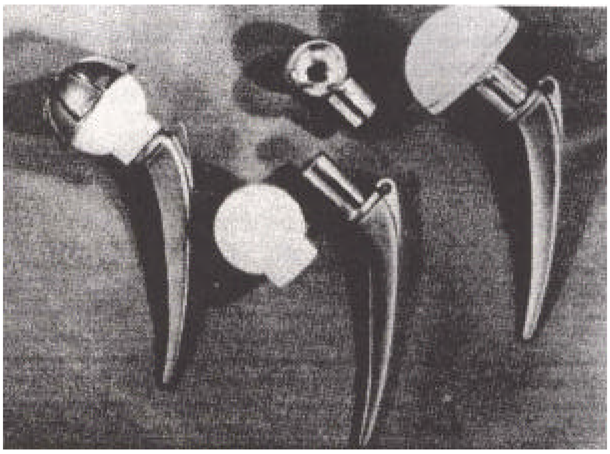

Fig. 5.5

An artificial hip joint has two components: the cup, which is set into the pelvic girdle; and the ball, whose stem is inserted into the head of the femur (the thigh bone).