V Machine elements (Maschinenelemente)

1 Limits and fits (Grenzmaβe und Passungen)

1.1 Measurement and inspection (Messen und Lehren)

In the past, it was the practice to make each component to ***precise dimensions*** and assemble the components to form the final product. Each ***dimension*** of the component was ***measured*** accurately using measuring instruments, and accepted only when the dimensions were extremely ***close*** to the ***prescribed dimensions***.

With the advent of ***mass production***, it was no longer possible to manufacture and measure each component to obtain an ***exact fit***. The dimensions of mass produced components varied from sample to sample and the ***measurement*** procedure had to be ***replaced*** by a different procedure called ***inspection***. The main feature of this inspection procedure was to check if each dimension of a

The inspection procedure is ***simpler*** than the measurement procedure and can be accomplished for example by using ***limit gauges.*** These gauges ensure that the dimensions of a component always lie between ***prescribed limits.***

This procedure guaranteed the ***interchangeability*** of components, regardless of when and where the components were produced. Soon ***international standards*** became ***desirable*** and ***necessary,*** and it has become the practice for manufacturers to adopt the **ISO Standards** detailed below in Section 1.3.

1.2 Basic quantities (Grundbegriffe)

Some of the basic quantities used when choosing suitable limits and fits for

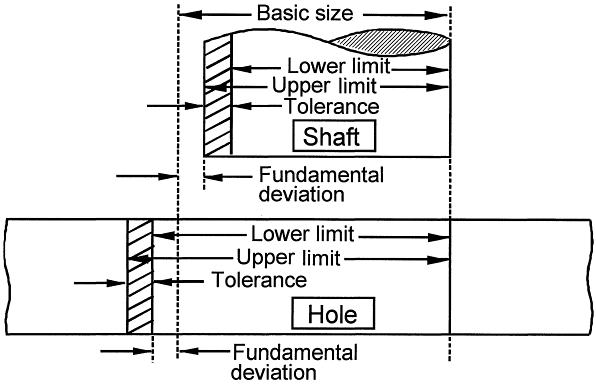


Fig 5.1. Basic quantities related to the fit of a shaft and a hole

1.3 ISO standards for limits and fits (ISO Toleranzsysteme)
The ISO standards are based on the two following items:
(1) Fundamental tolerance (2) Fundamental deviation

1.3.1 Fundamental tolerance grades (Grundtoleranzgrade)
The fundamental tolerance is specified in terms of 20 ***tolerance grades***. Each tolerance grade has a ***number*** assigned to it. The numbers assigned are 01, 0, and 1 to 18. The actual ***magnitude of the tolerance*** depends on both the ***tolerance grade*** and the ***basic size***. The basic sizes vary from 1mm to 3150 mm and are divided into 21 groups.
The tolerance grade which is to be used can be ***chosen freely*** by the designer depending on the ***accuracy*** to which the work has to be carried out. The smaller numbers correspond to ***smaller tolerances***, while the larger numbers correspond to ***larger tolerances*** assuming that the basic size remains the same. Tolerances on components should be chosen to be ***as large as possible***. This is because small tolerances require expensive manufacturing and measuring equipment, and lead to a higher percentage of ***rejected components***. The tolerance grades which are suitable for different types of applications are shown in Fig 5.2.

1.3.2 Fundamental deviation (Grundabmaβ)
The fundamental deviation determines the ***type of fit*** obtained when a shaft is mated to a hole. If we have a hole that is close to the basic size, then the ***greater*** the fundamental deviation of the shaft, the ***coarser*** will be the fit between hole and shaft. The fundamental deviations are indicated by the following letters:

For holes: A B C D E F G H J JS K M N P R S T U V W X Y Z ZA ZB ZC
For shafts: a b c d e f g h j js k m n p r s t u v w x y z za zb zc

The fundamental deviation is ***different*** for each of these letters and is illustrated in Fig 5.3. The letters JS for holes and js for shafts correspond to tolerance boundaries which are symmetrical relative to the zero line.

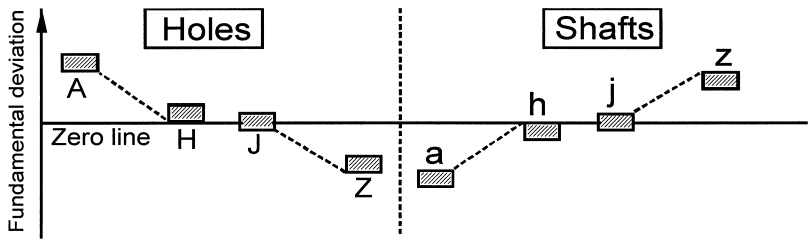


Fig 5.3 Position of the tolerance boundaries for holes and shafts

1. A ***hole*** is described by an appropriate capital letter followed by a number denoting the tolerance grade e.g H7
2. A ***shaft*** is described by an appropriate small letter followed by a number denoting a tolerance grade e.g. p6
3. A ***fit*** is described by writing the hole symbol followed by the symbol for the shaft e.g. H7/p6

1.3.3 Types of fits (Passungsarten)

1. **Fit** (Passung) – The term fit refers to the ***difference*** between the ***size of the hole*** and the ***size of the shaft*** when both members have the same basic size.
2. **Clearance fit** (Spielpassung) – A clearance fit is obtained when the ***low limit*** of a ***hole*** exceeds the ***high limit*** of a ***shaft*** which is to mate with the hole.
3. **Interference fit** (Übermaβpassung) – An interference fit is obtained when the high limit of the hole is ***smaller*** than the low limit of the shaft.
4. **Transition fit** (Übergangspassung) – In a transition fit there can be either a ***clearance*** or an ***interference*** between shaft and hole. In practice the tolerances for transition fits are ***very small,*** and both the hole and shaft are around the middle limit. Any interference that exists will be slight, and ***hand pressure*** is usually sufficient to push the shaft into the hole.

1.3.4 Systems of fits (Passungssysteme)

In order to keep ***manufacturing*** and ***inspection costs low***, industry has largely adopted either a ***hole basis system*** (based on a constant hole size) or a ***shaft basis system*** (based on a constant shaft size).

1.3.5 Fundamental deviations for H holes and h shafts
(Grundabmaβe für H Bohrungen und h Wellen)

All H holes and h shafts have zero deviation. The ***lower limit*** for H holes is the same as the ***basic size***. For shafts, the ***upper limit*** is equal to the ***basic size***.

1.3.6 Hole basis system (Passungssystem Einheitsbohrung)

In the hole basis system only ***H holes*** are used. As mentioned above, the ***fundamental deviation*** for all H holes is ***zero***. For a given H hole, ***shafts*** with the ***right fundamental deviation*** can be chosen to give any ***desired fit***.

1.3.7. Shaft basis system (Passungssystem Einheitswelle)

In the shaft basis system, only ***h shafts*** are used. Corresponding to a given h shaft, holes with the ***right fundamental deviation*** can be chosen to give any ***desired fit***.

1.3.8 Choice of suitable tolerance grades for holes on a hole basis system
(Auswahl von Einheitsbohrungen)

For ordinary work only ***six grades of holes*** are usually required as listed below:

H6 Internal grinding or honing	H9 Boring with a worn lathe
H7 High quality boring, broaching	H10 Good quality drilling
H8 Boring with a lathe, reaming	H11 Standard drilling

1.3.9 Some preferred fits using the hole basis system (Auswahl von Paβtoleranzfeldern)

(a) Clearance fits

1. Loose running fit	H7/d8, H8/d10, H11/d11
2. Easy running fit	H6/e7, H7/e8, H8/e9
3. Running fit	H6/f6, H7/f7, H8/f8
4. Close running fit	H6/g5, H7/g6, H8/g7
5. Location fit (not for running)	H6/h5, H7/h6, H8/h7

(b) Transition fit		**(c) Interference fit**	
1. Push fit	H6/j5, H7/j6	1. Light press fit	H6/p5. H7/p6
2. Easy keying fit	H6/k5, H7/k6	2. Press fit	H6/s5, H7/s6
3. Drive fit	H7/n6, H8/n7	3. Shrink fit	H6/u5, H7/u6

2 Rivets and riveted joints (Niete und Nietverbindungen)

Riveting is mainly used when it is necessary to join two or more metal sheets (or other components) ***permanently***. Although it has been ***replaced*** to a ***large extent*** by ***welding***, it has however many ***advantages*** over welding. Among these are that the

- microstructure of the metal remains unchanged
- it is possible to join different types of materials.
- on-site riveting is possible.
- process is easily controlled.

Disadvantages are that:

- the material is weakened by holes, weak joints,etc.
- working times are longer

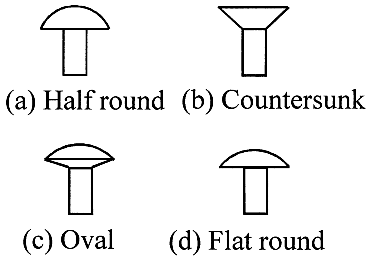


Fig 5.4 Some types of rivet heads

Riveting is still used to make firm and ***leakproof joints*** in ships, aircraft, steel containers, boilers, etc. In addition to its use in joining steel sheets, it is also used to join materials like copper, aluminium and their alloys.

2.1 Types of rivets (Nietformen)

Some of the types of rivets used are shown in Fig 5.4. Rivets with a ***half round*** head are the ***most frequently*** used, but ***countersunk rivets*** must be used for joints that need to have a ***flush surface***.

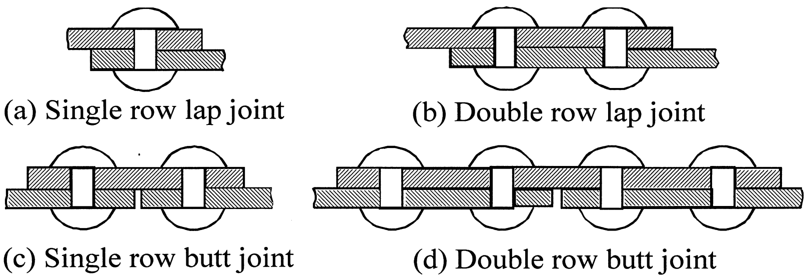


Fig 5.5 Some types of riveted joints

2.2 Types of riveted joints (Nietverbindunsarten)

Two types of joints are usually used, ***lap joints*** and ***butt joints***. Lap joints are used in boiler and container construction, while butt joints are used in steel construction. Some examples of the types of joints used are shown in Fig 5.5.

3 Screws and screw joints (Schrauben und Schraubenverbindungen)
Metal sheets and components can be joined by screws in several different ways as shown in Fig 5.6.

1) **Bolts and nuts** (Schrauben und Muttern) are used when both sides of the components to be joined are ***accessible*** (Fig 5.6(a)). If the parts are subject to vibration, an additional part like a ***spring washer*** or a ***lock nut*** is required to prevent the nut from becoming loose.
2) **Set screws** (Stellschrauben) are used (Fig 5.6(b)) when the use of a bolt and nut is not possible. Set screws with normal heads can be used, but it is often necessary to use set screws with ***countersunk heads***. Such screws are called ***socket screws*** (Fig 5.6(c)) and have a hole of ***hexagonal form*** in the head of the screw, enabling them to be tightened efficiently.
3) **Studs** (Stiftschrauben) are used for example (Fig 5.6(d)), when joining parts to ***cast iron components***. Cast iron has a low tensile strength and ***excessive tightening*** of a set screw into a cast iron thread can cause the ***thread to be damaged***. In this case the studs are screwed into the casting first, and the tightening is accomplished by using ***mild steel nuts***. Any ***damage*** caused will be to the nut or stud and not to the casting. Studs can be used to effect ***gas-tight*** and ***water-tight*** joints in cases when ***heavy pressures*** are present. A good example of the use of studs is their use for holding down a ***cylinder head*** on a ***cylinder block*** of an internal combustion engine. A ***thin gasket*** is placed between the metal surfaces to make the joint gas and water-tight.

3.1 Screws, bolts and nuts (Schrauben und Muttern)
Screws together with bolts and nuts, are the most convenient devices used for the ***nonpermanent*** joining of materials and components. A screw is the term used for a device (like a wood screw) ***used alone*** for joining two parts. Bolts and nuts on the other hand are ***used as a pair***. The usage of terms is clearly different from that in German where the term ***Schraube*** is used for both a screw as well as a bolt.
A screw joint is made by screwing an external screw thread on an internal screw thread. The screw thread is therefore the ***basis*** of the ***joining process***. There are many different kinds of screws, each made to a ***definite specification***. Some of the terms used in defining the specification of a screw are given below.

1) The angle of a screw thread is the angle between the ***two inclined faces*** of the screw thread Fig 5.7 (a).
2) The pitch is the distance measured between ***any point*** on a thread and the ***corresponding point*** on the next thread when measured parallel to the axis of the screw Fig 5.7 (a).
3) The major diameter is the ***external diameter*** of the screw, and the minor diameter is the core or ***smallest diameter*** of the screw.

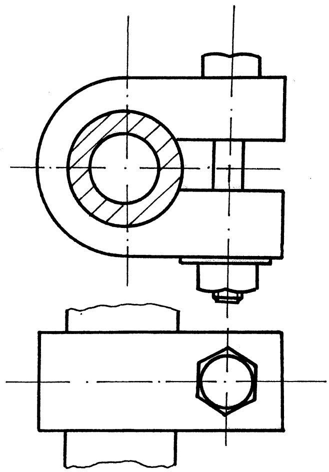


Fig 5.6 (a) Use of bolts and nuts

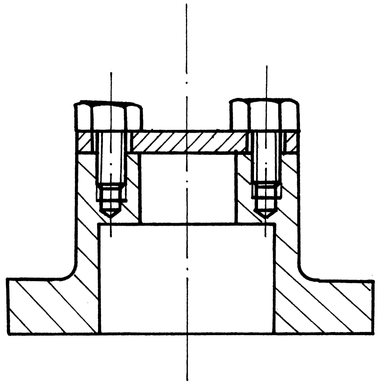


Fig 5.6(b) Use of set screws

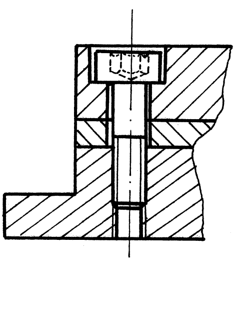


Fig 5.6 (c) Use of socket screws

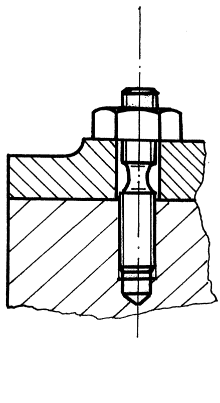


Fig 5.6 (d) Use of studs

4) The depth of engagement is the radially measured distance over which the two mating ***screw threads overlap*** (Fig 5.7 (b)).
5) One distinguishes between ***left hand*** and ***right hand*** screws depending on ***which way*** they have ***to be rotated***, when fastening takes place.

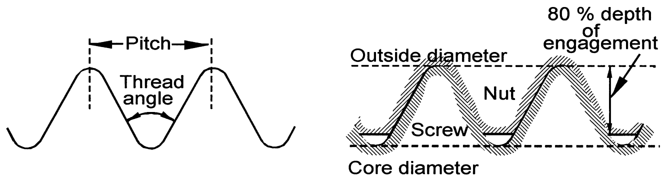


Fig 5.7(a) Angle of a screw thread (b) Depth of engagement

3.2 Types of screw threads (Gewindearten)

Many types of screw threads have been used in the past, but with increasing international cooperation, ***two types*** of screw threads are ***predominantly used*** for most purposes today. These are the ISO ***metric screw thread*** and the (American) ***unified*** (inch) ***screw threads***. In addition to these, other screw threads are used for ***special purposes*** like in the construction of ***drive*** and ***feed shafts*** for machines and machine tools.

3.2.1 Unified screw threads ((American) Unified Gewinde)

These screw threads are mainly used in the U.S and Canada. The ***basic profile*** of the unified screw thread is the same as that for the ISO metric thread. The series of unified threads that are available are:

1) Coarse series	UNC	or	UNRC
2) Fine series	UNF	or	UNRF
3) Extra fine series	UNEF	or	UNREF
4) Constant pitch series	UN	or	UNR
5) Other selected combinations	UNS	or	UNRS

The following features are worth noting.

1) Both the UN and UNR threads have the same have the same profile which is identical to that of the ISO metric threads.
2) The term UN thread applies to both the internal and external threads, while the term UNR applies only to the external threads.
3) External UN threads may have either flat or rounded crests and roots.
4) Internal UN threads must have rounded roots, but may have flat or rounded crests.
5) Internal UN threads must have rounded roots.

3.2.2. ISO metric threads (Metrisches ISO Gewinde)

As mentioned before, the profile of the ISO metric thread is the same as the unified thread. There are a number of metric thread series, some of which are mentioned below.

1) **ISO metric series** – Covers thread diameters from 1mm to 68 mm. Intended for use in all types of bolts and nuts and other types of mechanical fasteners.
2) **ISO metric fine thread series** – Covers thread diameters from 1mm to 300mm. Used for mechanical fasteners, for ensuring ***water-tight*** and ***gas-tight*** joints, for measuring instruments, etc.
3) **ISO metric saw tooth thread** – The saw tooth thread has a thread angle of 33°. The unsymmetrical thread form makes ***unsymmetrical loading*** possible. Used in the construction of collett chucks for lathes and milling machines.
4) **ISO metric acme thread** (trapezoidal form) – Covers thread diameters from 8mm to 300mm. Used in drives for machine tools, vices, valves, presses, etc.

3.2.3 Other types of threads (Andere Gewindearten)

1) **Whitworth pipe threads –** This thread has an angle of 55 degrees and is used in pipes and pipe parts where ***effective sealing*** is important.
2) **Round screw thread –** These threads have a thread angle of 35 degrees together with ***rounded roots*** and ***crests***. Used for example in clutch spindles.

3.2.4 Types of screws, bolts and nuts (Schraubenarten und Mutterarten)

1) **Different types of heads -** In addition to having different types of screw threads, screws can also have different types of heads. Some of the types of heads which are used are shown in Fig 5.8.
2) **Taper screws –** Screws which have a ***tapering form*** are not used with a nut. Examples of these are ***wood screws*** and hardened ***self-tapping screws*** used to join metals. The self-tapping screws are able to cut a thread in the metal when they are screwed in.
3) **Nuts –** Nuts can also have different forms. Some of the available forms are shown in Fig 5.9.
4) **Thread inserts** – Thread inserts are used with materials like soft metals, plastics and wood where the thread ***strips off*** or is ***easily damaged***. They can also be used to repair damaged screw threads.
5) **Locking devices –** Locking devices are often necessary to prevent screws and bolts from becoming loose. Some of the devices that can be used are own in Fig 5.10.

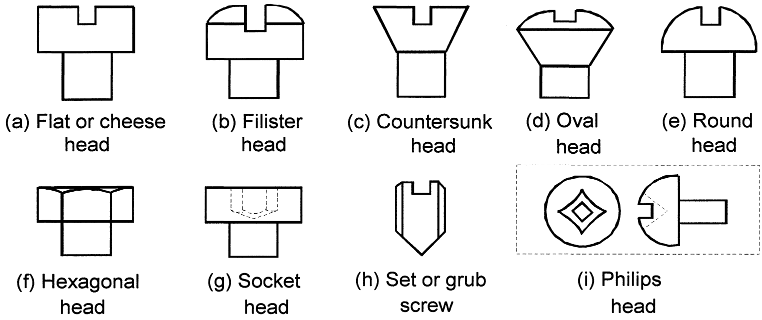


Fig 5.8 Some types of screw heads

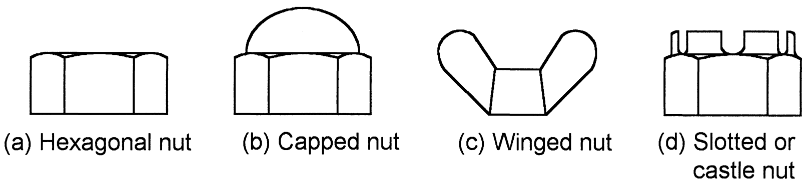


Fig 5.9 Some types of nuts

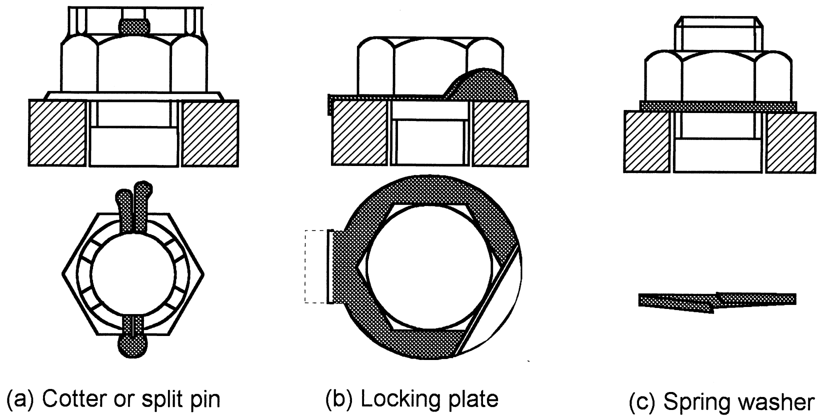


Fig 5.10 Some types of locking devices

4 Pins (Stifte)

4.1 Uses of pins (Verwendung von Stiften)

Pins are ***removable fasteners***. They are used are used as ***locating devices*** and as fasteners for the ***transmission*** of ***small torques***.

4.1.1 Locating pins (Paβstifte)

Locating pins are used to locate (or secure) the ***position*** of two components relative to each other. They facilitate the ***precise assembly*** of components and prevent ***sideways movement*** due to lateral (sideways) forces.

4.1.2 Fastening pins (Befestigungsstifte)

Fastening pins are used to hold components together firmly so that they can ***transmit forces*** and ***couples*** without becoming loose.

4.1.3 Overload protection pins (Abscherstifte)

Overload protection pins are used to ***prevent damage*** when components are subjected to ***excessive forces*** or ***torques***. If the forces or torques exceed certain values, the ***pin breaks*** thereby ensuring that no damage is caused.

4.2 Types of pins (Stiftformen)

Pins can be classified according to their ***shape*** or ***form*** as cylindrical pins, taper pins, roll pins, spiral pins, grooved pins, etc.

4.2.1 Cylindrical pins (Zylinderstifte)

Cylindrical pins are used as ***locating pins*** to join parts when ***strength*** and ***accuracy*** are important, and when the parts that are joined need to be rarely separated.

4.2.2 Taper pins (Kegelstifte)

Taper pins are usually made with a standard taper of 1: 50. The hole is usually ***bored*** to the smallest diameter of the pin and then ***enlarged*** with a ***taper reamer*** until the pin projects 4 mm above the hole when inserted by hand. The pin is then hammered in until it is firmly fixed in the hole. The pin is ***elastically deformed*** in this process and creates a strong joint which however is not strong enough to resist shocks.

4.2.3 Roll pins (Spannstifte)

These are ***hollow cylindrical pins*** which have a ***slit*** along their length. They are made of spring steel and heat treated before use. The outer diameter of the pin is larger than the hole and becomes ***compressed*** when driven into the hole. These can be used to join components and to ensure resistance against lateral forces.

4.2.4 Spiral pins (Spiral-Spannstifte)

These are rolled in the form of a ***spiral cylinder*** from heat treated spring steel The outer diameter is slightly larger than the hole. The pins are rolled elastically tighter when driven into the hole. These pins (due to their elastic properties) are particularly suitable for use in joints which are ***subjected to shocks.***

4.2.5 Grooved pins (Kerbstifte)

Grooved pins usually have ***three grooves*** along part or the whole of their length. These are used in joints where ***great accuracy*** is ***not required***, and where the joints are rarely separated.

5 Axles and shafts (Axen und Wellen)

5.1 Axles (Axen)

Axles are used as ***mountings*** and ***supports*** for wheels, pulleys, levers etc. and are mainly subjected to ***bending loads***. They are ***not used*** for the ***transmission*** of ***torques***. Axles can be used in a ***fixed position*** as for example in cranes. They can also be used as ***moving components*** as for example in trains and other vehicles.

5.2 Shafts (Wellen)

Shafts are rotating machine elements which carry gear wheels, pulleys, couplings, etc. They are used to transmit torques and are subjected to both ***bending*** and ***torsional*** stresses. Shafts are of different types like for example fixed rigid shafts, shafts with joints in them and flexible shafts.

5.2.1 Rigid shafts (Starre Wellen)

These can be of many types like for example straight shafts, shafts with ***offsets*** in them like crankshafts, uniform shafts or shafts with ***reduced cross-section*** in certain places on the shaft. Shafts in machine tools called ***spindles*** are ***often hollow*** to accommodate chucks, tools, workpieces, etc.

5.2.2 Crankshafts (Kurbelwellen)

These are used to convert ***reciprocating motion*** into ***rotary motion*** as for example in ***engines*** or ***compressors*** with pistons in them.

5.2.3 Drive shafts (Getriebewellen)

These shafts often have their cross-sections reduced in certain places to enable machine elements like gear wheels, pulleys, bearings, couplings, etc. to be ***easily*** and ***accurately fitted*** on them.

5.2.4 Jointed shafts (Gelenkwellen)

These are used when the ***position*** of the end of a shaft ***can change*** as in the drive shafts of cars. The use of ***universal joints*** allows complete flexibility in these cases.

5.2.5 Flexible shafts (Biegsame Wellen)

These are used with small electrical devices which are fitted with high speed low torque motors. They are particularly useful when the position of the device driven by the motor (like a drill or a speedometer) ***changes its position*** often relative to the motor. The shafts are usually made of ***several strands*** of ***steel wire*** interwoven to give maximum flexibility. The interwoven strands are then protected by covering them with a ***metal*** (or other type of) ***sheath***.

5.3 Shaft to hub (or collar) connections (Welle-Nabe Verbindungen)

A shaft is mainly used to ***transmit rotary motion***. This is done ***through machine elements*** like gear wheels, pulleys, clutch plates, etc. which are mounted on the shaft. The ***connection*** between the ***shaft*** and the ***machine element*** which is responsible for the further transmission of the torque is called the ***shaft to hub (or collar)*** connection. The hub is the usually the ***inner surface*** (or other part) of the gear wheel or other machine element which fits on the shaft. Connections can be of two types (1) those that depend on ***frictional forces*** and (2) those that depend on ***mechanical fastening devices***.

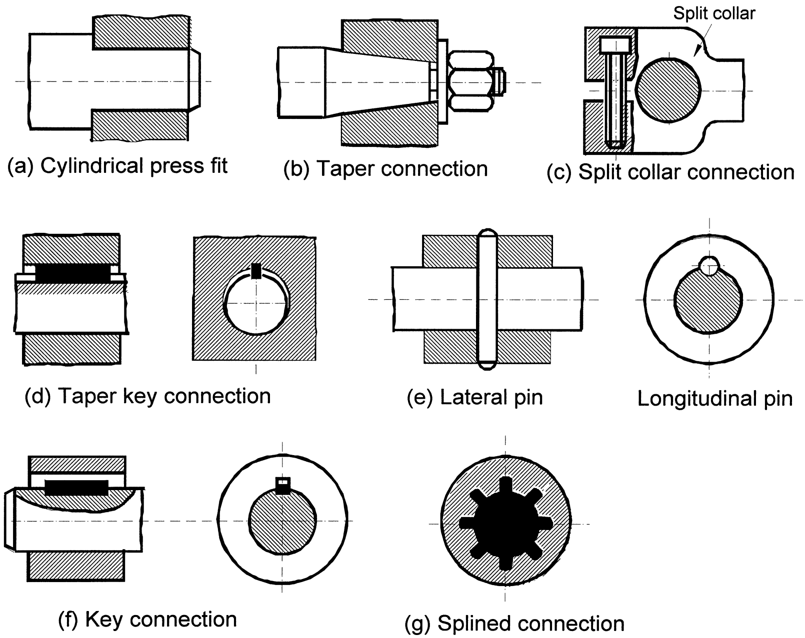


Fig 5.11 Shaft to hub connections

5.3.1 Shaft to hub connections which depend on frictional forces
(Reibschlüssige Nabenverbindungen)

(a) Cylindrical press fit connections (Zylindrischer Preβverbände)

This is a ***simple*** and ***cheap way*** of making shaft to hub connections (Fig 5.11(a)). The shaft has a very slightly larger diameter than the hole into which it fits. It can be pressed into the hole if sufficient force is used. Such a fit is called an ***interference fit*** (see p115). The fitting can also be done by ***heating the hub***, so that the hole expands allowing the hub (or collar) to be slipped easily over the shaft. On cooling the hub contracts, and grips the shaft firmly. Such connections are ***permanent*** and are able to transmit ***large***, ***variable*** and ***abruptly changing*** torques and forces. This type of connection can be used for gear wheels, pulleys, flywheels, couplings, etc.

(b) Taper connections (Kegliger Preβverband)

These are easily removable connections in which an ***outer taper*** on the shaft fits into an ***inner taper*** in the hub (Fig 5.11(b)). They are pressed together using a nut or a screw. The ***axial forces*** which are brought into play give rise to ***large***

normal forces which hold the components together. Taper connections are capable of transmitting large, variable and abruptly changing torques. They can be used for the same applications which were mentioned for the cyindrical press connections. In addition they are also used in machine tool spindles and mounts for ball bearings.

(c) Clamp connections with split or slit collar (Geteilte Nabe)
These connections are ***easily removable*** and can be ***moved along the axis*** or ***rotated about the axis*** (Fig 5.11(c)). They are suitable for use with moderate torques. For use with larger torques an ***additional rectangular key*** should be [illegible]

The shaft and the hub have ***slots cut*** in them, and a key with a slope of 1:100 along the length is pressed into the slots (Fig 5.11(d)). This causes the ***axes*** of the shaft and the hub to be ***displaced***, so that they are ***pressed against each other***. The result is an increase in the friction between the shaft and the collar and which forces them to rotate together.

5.3.2 Shaft to hub connections that depend on mechanical devices (Formschlüssige Nabenverbindungen)

(a) Pin connections (Stiftverbindungen)
These are ***removable connections*** mostly suitable for the transmission of smaller

5.3.3 Axial locking devices (Wellensicherungen)
Many types of locking devices are available for preventing the ***axial movements*** of shafts and machine elements like ball bearings, bushes, pulleys, etc.

a) Locking rings (Sicherungsringe)
These are made of spring steel and are ***round in shape***. They exert uniform pressure round the circumference of a slot or recess.

(b) Snap rings (Springringe)
These are used where a ring of ***uniform cross-section*** is required.

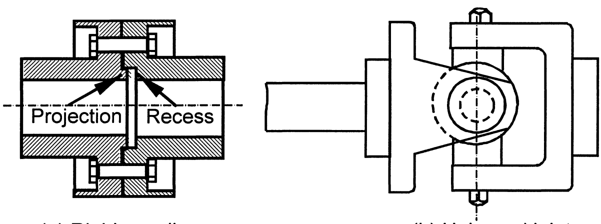
(c) Locking discs (Sicherungsscheibe)
These are used for small shafts in instruments and other devices.

(d) Cotter pins (Splint)
These are particularly useful in preventing bolts and nuts from ***becoming loose***.

(e) Adjusting ring or set collar (Stellringe)
These are used to ***limit the axial movement*** of shafts or to ***allow the sideways motion*** of moving elements like wheels and levers.

6 Couplings (Kupplungen)

The main purpose of a coupling is to transmit the torque from one shaft to another shaft (or to another drive element). There are many types of couplings.



(a) Rigid coupling (b) Universal joint

Fig 5.12 Some Couplings

6.1 Rigid couplings (Starre Kupplungen)
Rigid couplings make a ***firm connection*** between a shaft and another drive element. One form of rigid coupling is shown in Fig 5.12 (a). One of the shafts has a ***cylindrical projection*** which fits into a corresponding ***cylindrical recess*** on the other shaft. The shafts can be screwed together to be ***friction tight***. When the coupling has to be disconnected, the shafts must be moved apart in the axial direction.

6.2 Flexible inelastic couplings (Flexible unelastische Kupplungen)
These are required to connect shafts which are ***misaligned laterally*** or ***angularly***. **Universal joints** (Gelenkkupplungen) can be used where very large misalignments are present, and are particularly useful for connecting the ***engine*** of a vehicle to the ***final drive axle***. Two such joints are usually coupled through sliding ***splined drive*** shafts, to allow both ***longitudinal*** and ***lateral movement*** of the axle relative to the engine. One type of universal joint is shown in Fig 5.12(b).