10.

Testing of Welded Joints
The basic test for determination of material behaviour is the tensile test.

Generally, it is carried out using a round specimen. When determining the strength of a welded joint, also standardised flat specimens are used. Figure 10.1 shows both standard specimen shapes for that test. A specimen is ruptured by a test machine while the actual force and the elongation of the specimen is measured. With these measurement values, tension \( \sigma \) and strain \( \epsilon \) are calculated. If \( \sigma \) is plotted over \( \epsilon \), the drawn diagram is typical for this test, Figure 10.2.

Normally, if a steel with a bcc lattice structure is tested, a curve with a clear yield point is obtained (upper picture). Steels with a fcc lattice structure show a curve without yield point.

The most important characteristic values which are determined by this test are: yield stress \( R_{el} \), tensile strength \( R_m \), and elongation \( A \).

To determine the deformability of a weld, a bending test to DIN EN 910 is used, Figure 10.3. In this test, the specimen is put onto two supporting rollers and a former is pressed through between the rollers. The distance of the supporting rollers is \( L_f = d + 3a \) (former diameter + three times specimen thickness).

The backside of the specimen (tension side) is observed. If a surface crack develops, the test will be stopped and the angle to which the specimen could be bent is measured. The
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test result is the bending angle and the diameter of the used former. A bending angle of 180° is reached, if the specimen is pressed through the supporting rollers without development of a crack. In Figure 10.3 specimen shapes of this test are shown. Depending on the direction the weld is bent, one distinguishes (from top to bottom) transverse, side, and longitudinal bending specimen. The tension side of all three specimen types is machined to eliminate any influences on the test through notch effects. Specimen thickness of transverse and longitudinal specimens is the plate thickness. Side bending specimens are normally only used with very thick plates, here the specimen thickness is fixed at 10 mm.

A determination of the toughness of a material or welded joint is carried out with the notched bar impact test. A cuboid specimen with a V-notch is placed on a support and then hit by a pendulum ram of the impact testing machine (with very tough materials, the specimen will be bent and drawn through the supports). The used energy is measured. Figure 10.4 represents sample shape, notch shape (Iso-V-specimen), and a schematic presentation of test results.
Three specimens are tested at each test temperature, and the average values as well as the range of scatter are entered on the impact energy-temperature diagram (AV T curve). This graph is divided into an area of high impact energy values, a transition range, and an area of low values. A transition temperature is assigned to the transition range, i.e. the rapid drop of toughness values. When the temperature falls below this transition temperature, a transition of tough to brittle fracture behaviour takes place.

As this steep drop mostly extends across a certain area, a precise assignment of transition temperature cannot be carried out. Following DIN 50 115, three definitions of the transition temperature are useful, i.e. to fix T Ü to:

1.) a temperature where the level of impact values is half of the level of the high range,
2.) a temperature, where the fracture area of the specimen shows still 50% of tough fracture behaviour
3.) a temperature with an impact energy value of 27 J.

Figure 10.5 illustrates a specimen position and notch position related to the weld according to DIN EN 875. By modifying the notch position, the impact energy of the individual areas like HAZ, fusion line, weld metal, and base metal can be determined in a relatively accurate way.

Figure 10.6 presents the influence of various alloy elements on the AV T - curve. Three basically different influences can be seen. Increasing manganese contents increase the impact values in the area of the high level and move the transition temperature to lower values. The values of the low levels remain unchanged, thus the steepness of the drop becomes clearer with increasing Mn-content. Carbon acts exactly in the opposite way. An increasing carbon content increases the transition temperature and lowers the values of the high level, the steel becomes more brittle. Nickel decreases slightly the values of the high level, but increases the
values of the low level with increasing content. Starting with a certain Nickel content (depends also from other alloy elements), a steep drop does not happen, even at lowest temperature the steel shows a tough fracture behaviour.

In Figure 10.7, the $A_V$-T – curves of some commonly used steels are collected. These curves are marked with points for impact energy values of $A_V = 27$ J as well as with points where the level of impact energy has fallen to half of the high level. It can clearly be seen that mild steels have the lowest impact energy values together with the highest transition temperature. The development of fine-grain structural steels resulted in a clear improvement of impact energy values and in addition, the application of such steels could be extended to a considerably lower temperature range.

With the example of the steels St E 355 and St E 690 it is clearly visible that an increase of strength goes mostly hand in hand with a decrease of the impact energy level. Another improvement showed the application of a thermomechanical treatment (controlled rolling during heat treatment). The application of this treatment resulted in an increase of strength and impact energy values together with a parallel saving of alloy elements. To make a comparison, the $A_V$-T - curve of the cryogenic and high alloyed steel X8Ni9 was plotted onto the diagram. The material is tested
under very high test speed in the impact energy test, thus there are no reliable findings about crack growth and fracture mechanisms.

Figure 10.8 shows two commonly used specimen shapes for a fracture mechanics test to determine crack initiation and crack growth. The lower figure to the right shows a possibility how to observe a crack propagation in a compact tensile specimen. During the test, a current I flows through the specimen, and the tension drop above the notch is measured.

As soon as a crack propagates through the material, the current conveying cross section decreases, resulting in an increased voltage drop. Below to the left a measurement graph of such a test is shown. If the force F is plotted across the widening V, the drawn curve does not indicate precisely the crack initiation. Analogous to the stress-strain diagram, a decrease of force is caused by a reduction of the stressed cross-section. If the voltage drop is plotted over the force, then the start of crack initiation can be determined with suitable accuracy, and the crack propagation can be observed.

Another typical characteristic of material behaviour is the hardness of the workpiece. Figure 10.9 shows hardness test methods to Brinell (standardised to DIN 50 351) and Vickers (DIN 50 133). When testing to Brinell, a steel ball is pressed with a known load.
to the surface of the tested workpiece. The diameter of the resulting impression is measured and is a magnitude of hardness. The hardness value is calculated from test load, ball diameter, and diameter of rim of the impression (you find the formulas in the standards). The hardness information contains in addition to the hardness magnitude the ball diameter in mm, applied load in kp and time of influence of the test load in s. This information is not required for a ball diameter of 10 mm, a test load of 3000 kp (29420 N), and a time of influence of 10 to 15 s. This hardness test method may be used only on soft materials up to 450 BHN (Brinell Hardness Number).

Hardness testing to Vickers is analogous. This method is standardised to DIN 50133. Instead of a ball, a diamond pyramid is pressed into the workpiece. The lengths of the two diagonals of the impression are measured and the hardness value is calculated from their average and the test load. The impressions of the test body are always geometrically similar, so that the hardness value is normally independent from the size of the test load. In practice, there is a hardness increase under a lower test load because of an increase of the elastic part of the deformation.

Hardness testing to Vickers is almost universally applicable. It covers the entire range of materials (from 3 VHN for lead up to 1500 VHN for hard metal). In addition, a hardness test can be carried out in the micro-range or with thin layers.

Figure 10.10 illustrates a hardness test to Rockwell. In DIN 50103 are various methods standardised which are based on the same principle.

With this method, the penetration depth of a penetrator is measured.
At first, the penetrator is put on the workpiece by application of a pre-test load. The purpose is to get a firm contact between workpiece and penetrator and to compensate for possible play of the device.

Then the test load is applied in a shock-free way (at least four times the pre-force) and held for a certain time. Afterwards it is released to reach minor load. The remaining penetration depth is characteristic for the hardness. If the display instrument is suitably scaled, the hardness value can be read-out directly.

All hardness test methods to Rockwell use a ball (diameter 1.5875 mm, equiv. to 1/16 Inch) or a diamond sfero-conical penetrator (cone angle 120°) as the penetrating body. There are differences in size of pre- and test load, so different test methods are scaled for different hardness ranges. The most commonly used scale methods are Rockwell B and C. The most considerable advantage of these test methods compared with Vickers and Brinell are the low time duration and a possible fully-automatic measurement value recognition. The disadvantage is the reduced accuracy in contrast to the other methods. Measured hardness numbers are only comparable under identical conditions and with the same test method. A comparison of hardness values which were determined with different methods can only be carried out for similar materials. A conversion of hardness values of different methods can be carried out for steel and cast steel according to a table in DIN 50150. A relation of hardness and tensile strength is also given in that table.

All the hardness test methods described above require a coupon which must be taken from the workpiece and whose hardness is then determined in a test machine. If a workpiece on-site is to be tested, a dynamical hardness test method will be applied. The advantage of these methods is that measurements can be taken on completed constructions with handheld units in any position. Figure 10.11 illustrates a
hardness test using a Poldi-Hammer. With this (out of date) method, the measurement is carried out by a comparison of the workpiece hardness with a calibration piece. For this purpose a calibration bar of exactly determined hardness is inserted into the unit, which is held by a spring force play-free between a piston and a penetrator (steel ball, 10 mm diameter). The unit is put on the workpiece to be tested. By a hammerblow to the piston, the penetrator penetrates the workpiece and the calibration pin simultaneously. The size of both impressions is measured and with the known hardness of the calibration bar the hardness of the workpiece can be determined. However, there are many sources of errors with this method which may influence the test result, e.g. an inclined resting of the unit on the surface or a hammerblow which is not in line with the device axis. The major source of errors is the measurement of the ball impression on the workpiece. On one hand, the edge of the impression is often unsharp because of the great ball diameter, on the other hand the measurement of the impression using magnifying glasses is subjected to serious errors.

Figure 10.12 shows a modern measurement method which works with ultrasound and combines a high flexibility with easy handling and high accuracy. Here a test tip is pressed manually against a workpiece. If a defined test load is passed, a spring mechanism inside the test tip is triggered and the measurement starts. The measurement principle is based on a measurement of damping characteristics in the steel. The measurement tip is excited to emit ultrasonic oscillations by a piezoelectric crystal. The test tip (diamond pyramid) penetrates the workpiece under the test pressure caused by the spring force. With increasing penetration depth the damping of the ultrasonic oscillation changes and consequently the frequency. This change is measured by the device. The damping of the ultrasonic oscillation depends directly on penetration depth thus being a measure for material hardness. The display can be calibrated for all commonly used measurement methods, a measurement is carried out quickly and easily.

![Mobile Ultrasonic Hardness Test](image)
Measurements can also be carried out in confined spaces. This measurement method is not yet standardised.

To test a workpiece under oscillating stress, the fatigue test is standardised in DIN 50100. Mostly a fatigue strength is determined by the Wöhler procedure. Here some specimens (normally 6 to 10) are exposed to an oscillating stress and the number of endured oscillations until rupture is determined (endurance number, number of cycles to failure). Depending on where the specimen is to be stressed in the range of pulsating tensile stresses, alternating stresses, or pulsating compressive stresses, the mean stress (or sub stress) of a specimen group is kept constant and the stress amplitude (or upper stress) is varied from specimen to specimen, Figure 10.13. In this way, the stress amplitude can be determined with a given medium stress (prestress) which can persist for infinite time without damage (in the test: $10^7$ times). Test results are presented in fatigue strength diagrams (see also DIN 50 100). As an example the extended Wöhler diagram is shown in Figure 10.13. The upper line, the Wöhler line, indicates after how many cycles the specimen ruptures under tension amplitude $\sigma_a$.
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The damage line indicates analogously, when a damage to the material starts in form of cracks. Below this line, a material damage does not occur.

Test methods described above require specimens taken out of the workpiece and a partly very accurate sample preparation. A testing of completed welded constructions is impossible, because this would require a destruction of the workpiece. This is the reason why various non-destructive test methods were developed, which are not used to determine technological properties but test the workpiece for defects. Figure 10.14 shows...
two methods to test a workpiece for surface defects.

Figure 10.15 illustrates the principle of radiographic testing which allows to identify also defects in the middle of a weld. The size of the minimum detectable defects depends greatly on the intensity of radiation, which must be adapted to the thickness of the workpiece to be radiated. As the film with documented defects does not permit an estimation of the plate thickness, a scale bar must be shown for estimation of the defect size.

For that purpose, a plastic template is put on the workpiece before radiation which contains metal wires with different thickness and incorporated metallic marks, Figure 10.16. The size of the thinnest recognisable wire indicates the size of the smallest visible defect. Radiation testing provides information about the defect position in the plate plane, but not about the position within the thickness depth. A clear advantage is the good documentation ability of defects.

An information about the depth of the defect is provided by testing the workpiece with ultrasound. The principle is shown in Figures 10.17 and 10.18 (principle of a sonar).

The display of original pulse, backwall and defect echo is carried out with an oscilloscope.
This method provides not only a perpendicular sound test, but also inaccessible regions can be tested with the use of so called angle testing heads, Figure 10.19.

Figures 10.20 and 10.21 show schematically the display of various defects on an oscilloscope. A correct interpretation of all the signals requires great experience, because the shape of the displayed signals is often not so clear.

Figure 10.22 illustrates the potential of metallographic examination. Grinding and
etching with an acid makes the microstructure visible. The reason is that depending on structure and orientation, the individual grains react very differently to the acid attack thus reflecting the light in a different way. The macrosection, i.e. without magnification, gives a complete survey about the weld and fusion line, size of the HAZ, and sequence of solidification. Under adequate magnification, these areas can still not be distinguished precisely, however, an assessment of the developed microstructure is possible.

An assessment of the distribution of alloy elements across the welded joint can be carried out by the electron beam micro-analysis. An example of such an analysis is shown in Figure 10.23. If a solid body is exposed to a focused electron beam of high energy, its atoms are excited to radiate X-rays. There is a simple relation between the wavelength of this radiation and the atomic number of the chemical elements. As the intensity of the radiation depends on the concentration of the elements, the chemical composition of the solid body can be concluded from a survey of the emitted X-ray spectrum qualitatively and quantitatively. A detection limit is about 0.01 mass % with this method. Microstructure areas of a minimum diameter of about 5 µm can be analysed. If the electron beam is moved across the specimen (or the specimen under the beam), the element distribution along a line across the...
solid body can be determined. Figure 10.23 presents the distribution of Ni, Cr, and Fe in the transition zone of an austenitic plating in a ferritic base metal. The upper part shows the related microsection which belongs to the analysed part. This microanalysis was carried out along a straight line between two impressions of a Vickers hardness test. The impressions are also used as a mark to identify precisely the area to be analysed.

The so called Strauß test is standardised in DIN 50914. It serves to determine the resistance of a weld against intergranular corrosion. Figure 10.24 shows the specimen shape which is normally used for that test. In addition, some details of the test method are explained.

Figure 10.25 presents a specimen shape for testing the crack susceptibility of welding consumables. For this test, weld number 1 is welded first. The 2. weld is welded not later than 20s in reversed direction after completion of the first weld. Throat thickness of weld 2 must be 20% below of weld 1. After cooling down, the beads are examined for cracks. If cracks are found in weld 1, the test is void. If weld 1 is free from cracks, weld 2 is examined for crack with magnifying glasses. Then weld 1 is machined off and weld 2 is cracked by bending the weld from the root. Test results record any
surface and root cracks together with information about position, orientation, number, and length. The welding consumable is regarded as ‘non-crack-susceptible’ if the welds of this test are free from cracks.

Figure 10.26 presents two proposals for self-stressing specimens for plate tests regarding their hot crack tendency. Such tests are not yet standardised to DIN.

There are various tests to examine a cold crack tendency of welded joints. The most important ones are the self-stressing Tekken test and the Implant test where the stress comes from an external source.

In the Tekken test which is standardised in Japan, two plates are coupled with anchor joints at the ends as a step in joint preparation see Figure 10.27. Then a test bead is welded along the centre line. After storing the specimen for 48 hours, it is examined for surface cracks. For a more precise examination, various transverse sections are planned. The value to be determined is the minimum working temperature at which cracks no longer occur. The specimen shape simulates the conditions during welding of a root pass.
The most commonly used cold crack test is the Implant test, Figure 10.28. A cylindrical body (Implant) is inserted into the bore hole of a support plate and fixed by a surface bead. After the bead has cooled down to 150°C the implant is exposed to a constant load. The time is measured until a rupture or a crack occurs (depending on test criterion ‘rupture’ or ‘crack’). Varying the load provides the possibility to determine the stress which can be born for 16 hours without appearance of a crack or rupture. If a stress is specified to be of the size of the yield point as a requirement, a preheat temperature can be determined by varying the working temperature to the point at which cracks no longer appear.

As explained in chapter ‘cold cracks’ the hydrogen content plays an important role for cold crack development. Figure 10.29 shows results of trials where the cold crack behaviour was examined using the Tekken and Implant test. Variables of these tests were hydrogen content of the weld metal and preheat temperature. The variation of the hydrogen content of the weld metal was carried out by different exposure to humidity (or rebaking) of the used stick electrodes. Based on the hydrogen content, the preheat temperature was increased test by test. Consequently, the curves of Figure 10.29 represent the limit curves for the related test. Specimens above these curves remain free from cracks, below these curves cracks are present. Evident for both graphs is that with increased preheat temperature considerably higher hydrogen contents are tolerated without any crack development because of the much better hydrogen effusion.

If both graphs are compared it becomes obvious that the tests produce slightly different findings, i.e. with identical hydrogen content, the determined preheat temperatures required for the avoidance of cracking, differ by about 20°C.
Figure 10.30 illustrates a method to measure the diffusible hydrogen content in welds which is standardised in DIN 8572. Figure a) shows the burette filled with mercury before a specimen is inserted. The coupons are inserted into the opened burette and drawn with a magnet through the mercury to the capillary side (density of steel is lower than that of mercury, coupons surface). Then the burette is closed and evacuated. The hydrogen, which effuses of the coupons but does not diffuse through the mercury, collects in the capillary. The samples remain in the evacuated burette 72 hours for degassing. To determine the hydrogen volume the burette is ventilated and the coupons are removed from the capillary side. The volume of the effused hydrogen can be read out from the capillary; the height difference of the two mercury menisci, the air pressure, and the temperature provide the data to calculate the norm volume under standard conditions. This volume and the coupons weight are used to calculate, as measured value, the hydrogen volume in ml/100 g weld metal. This is the most commonly used method to determine the hydrogen content in welded joints.

Figure 10.30