ferrite, which is a body centered cubic structure $(\alpha - iron)$. Excess carbon is rejected and forms iron carbide known as pearlite. Pearlite strongly increases hardness, strength of steel but reduces ductility.

If steel temperatures are rapidly lowered such that diffusion of carbon does not occur, bainite or martensite (see Section 3.1 for definitions) will form. These products cause steel to be harder, stronger but less ductile.

The process of tempering, which is a controlled raising of the steel's temperature, will cause carbon, trapped in the martensite, to diffuse to produce bainite or pearlite. Ductility and toughness are improved and are accompanied by a reduction in strength and hardness.

Steel when heated to a temperature between 127ºC (260ºF) and 160ºC (320ºF), depending on chemical composition, increases in yield and ultimate tensile strengths by as much as 25% above normal temperature values. However, ductility and fracture toughness are reduced.

The yield and tensile strengths of steel, at temperatures above approximately 160ºC (320ºF), begin to decrease such that, at a temperature of approximately 220ºC (430ºF), the physical properties are about the same as at normal temperature. At 650ºC (1200ºF), the steel decreases in volume (shrinks) as it changes its molecular structure $(\alpha - iron\ to\ \gamma - iron)$. The yield and ultimate strengths become very low with no strength at around 1200ºC (2200ºF).

3.4 ROLLING PRACTICE

With structural steels, the main objective is to produce fine grained steel since reducing grain size lowers the ductile brittle transition temperature, improves toughness and increases yield strength. When the steel is rolled, plastic deformation takes place due to atoms slipping along planes and the material is work hardened. The presence of heat can appreciably modify the tendency for work hardening during rolling. The temperature at which rolling occurs, which can significantly affect steel properties, may be summarized as follows:

- Deformation above 1000℃ (1830°F) produces course grain.
- Deformation carried out between 900℃ (1650°) and 1000℃ (1830°F) can lead to fine grains.
- Deformation carried out between 840°C (1540°F) and 900℃ (1650°F) causes austenite to form elongated grains.
- Deformation carried out below 840℃ (1540°F) can increase the brittle to ductile transition temperature.

Consideration of the above is used in steel mills to control desired steel properties.

3.5 CARBON & FERRITIC ALLOYS

The elements in steel including alloys and impurities may be summarized as follows:

Carbon

Carbon (up to 0.8%) is the main element in the formation of steel causing hardness and strength to be increased with increasing content. The greater the carbon content, the more difficult the steel is to weld.

Increase in Carbon also lowers the transformation temperature and increases Martensite (brittle structure). Higher carbon content tends to increase the risk of hydrogen induced cracking (H.I.C.) due to welding and reduces fracture toughness. Carbon increases strength and decreases ductility and weldability. It both controls the maximum attainable hardness and contributes substantially to hardenability. Carbon has a moderate tendency to segregate.

Manganese

Manganese, when combined with low sulphur content to form manganese sulphides, tends to reduce solidification cracking occurring at elevated temperature. Manganese also strengthens steel by solid solution hardening and grain refinement, which leads to increased fracture toughness.

Chromium

Chromium improves steel quality including higher toughness in the heat affected zone and higher hardness.

Niobium

Niobium raises the recrystalization temperature which helps to give a finer grain structure.

Phosphorous

Phosphorous tends to increase strength and hardness but decreases ductility and toughness. It is considered as an impurity but sometimes is added for atmospheric corrosion resistance. It has a strong tendency to segregate.

Titanium (nitride)

Titanium provides a means of controlling grain size at rolling.

Vanadium

Vanadium works at lower rolling temperatures [around 700°C (1290ºF)] to control grain size thus increasing strength and toughness.

Boron

Small amounts of Boron (0.0005%) increases hardenability and is used only in aluminum killed steels (see Chapter 4, Section 4.1.2(ii), Flux Core Arc Welding on hardenability of welds). It is effective with low oxygen and nitrogen steels to lower transition temperature.

Copper

Copper is used in structural steels for weathering resistance.

Molybdemum

Molybdemum improves corrosion resistance and improves resistance to solidification cracking.

Nickel

Nickel improves strength and toughness.

Silicon

Silicon (usually around 0.35% but can be much lower) is primarily a deoxidizing and scavenging agent. Silicon tends to reduce ductility.

Sulphur

Sulphur is primarily an impurity which significantly reduces the fracture toughness of steel. Its content needs to be kept low. One of the reasons for adding manganese is to form manganese sulphides improving the quality of the steel.

3.6 HEAT TREATMENT OF STEEL

Heat treatment tends to relieve internal stresses and remove coarseness of grain and can have significant influence on the properties of welded material. Types of heat treatment are described as follows:

Annealing

The purpose of annealing is to soften the steel, relieve internal stresses and reduce the coarseness of grain. Annealing comprises heating steel to close to the upper critical temperature (phase change from δ-iron to γ-iron, see Section 3.1). Typically the material is heated to above 670°C (1240°F) for many hours (24 – 30 hours) and then slowly cooled (4 – 5 days) usually in a furnace to allow the material to be stress free. Annealing can provide stress relieving but is not usually effective in improving fracture toughness.

Normalizing

Normalizing consists of heating the steel to approximately 38ºC (100°F) above the upper critical temperature. The process is similar to annealing, with regard to heating rates, except the material is heated to 870°C (1600°F) and the material is then cooled in still air. Since the steel material is cooled more rapidly than the annealing process, it results in greater strength but less ductility. According to Stout (1987) heating steel to 870°C (1600°F) and controlling cooling (similar to the annealing process) can significantly improve fracture toughness characteristics and reduce nil-ductility temperatures.

Quenching

The process of quenching is used to provide hard steels. The steel is heated to above the critical temperature and held for sufficient time to change the structure. It is then quenched in oil (sometimes water) such as not to change the microstructure of the steel. The rate of cooling is important to establish desired properties and can be affected by the alloy content. The resulting hardened steel can be very brittle.

Tempering

Tempering is carried out after quenching to reduce the brittleness of steel. The steel is heated to below the critical temperature, held, then cooled slowly to provide the required properties. Tempering is carried out in oil, salt or lead baths and also in furnaces controlled by fans circulating air. The combination of quenching and tempering can produce the best combination of strength and notch ductility. For further discussion on the effects of thermal changes, see Section 3.3.

3.7 TENSION & HARDNESS TESTS

Tension tests are usually carried out on small circular or rectangular specimens and are carried out at a slow rate (see Section 3.12 on discussion on loading rates). The specimens are machined such that the section effectively tested has a smaller area than the end segments. The end segments are threaded to be engaged in grips. In the U.S.A., ASTM Standard A370 is normally applied for tension testing.

Hardness tests, of which there are several types (Scleroscope, Brinell, Vickers, Rockwell) typically involve impact applied to the steel. Although essentially these tests are to determine the ability of the material to deform, attempts at correlating the data with ultimate tensile strength have been made.

The **Scleroscope Hardness Test** involves a hammer and a rounded diamond tip dropped from a fixed height. The hardness is determined from the rebound height and measured according to the Mohs hardness scale. Very hard steels have a Mohs hardness of about 7.

The **Brinell Hardness Test** involves a steel ball, 10mm (3/8 inch) in diameter, applied with a large force. The Brinell Hardness number (HB) is determined from the applied force divided by the curved surface area of the indentation. Typical HB numbers for steels vary from 200 (soft) to 500 (hard).

The **Vickers Hardness Test** is similar to the Brinell test except that the indenter is in the shape of a pyramid with a diamond point. The Vickers Hardness Number (HV) is obtained from the applied force divided by the surface area of the pyramid like depression. Vickers Hardness Numbers for steel are similar to Brinnell Hardness Numbers.

The **Rockwell Hardness Test** utilizes a cone shaped diamond point on steel ball. Different sizes are used for different materials. In this case, the depth of the indentation is measured.

Although hardness tests have been used to estimate ultimate tensile strengths, they can also be used to assess variation in steel properties and potential for steel cracking due to application of heat when welding.

3.8 STEEL PROPERTIES

Steel, tested with either a circular or a rectangular cross section, displays an elasto plastic behavior. In the elastic range, the strain is fully recoverable. As is well known, the rate of increase of stress with increase in strain is called Young's modulus. As the load is increased, the strain becomes nonlinear and permanent plastic deformation occurs (see Figure 2.17a) eventually resulting in necking of the specimen. Normally, increasing stress is required to produce increasing strain causing **strain hardening**. Yield strength is generally measured at 0.2 percent strain. The rate at which stress increases with plastic strain is called the **Strain-Hardening Modulus**. The steel hardens to a peak value (ultimate tensile strength) then usually decreases until the specimen fails. If a specimen is unloaded, after being strained into the strain hardening region and is then immediately reloaded, it returns to the stress strain curve. However, the ductility at fracture will be reduced by the magnitude of residual strain.

If the specimen is left for several days until it is reloaded, it may return to a stress strain curve above the original curve resulting in higher tensile strength. This phenomenon, which is known as **Strain Aging,** also results in increase in strain hardening but with decrease in ductility. Although, usually tensile and compressive strengths of steel are about the same, as mentioned in Chapter 2, Section 2.3.3, when steel is first deformed in tension, then deformed in compression, the compressive strength is lower than if only tested in compression. This property, known as the Bauschinger Effect, also occurs when compression is first applied and when the load is reversed into tension.

As mentioned previously, the varying processes of making steel can have significant influences on the properties of steel. The processes causes grain refinement and elongation of grains in the rolling direction resulting in anisotropic properties (unequal properties in at least two directions) particularly with regard to ductility and fracture toughness. Thus the steel properties, with regard to ductility and fracture toughness, in the transverse or through thickness direction, can be significantly less than for the longitudinal direction.

Some variations in properties with regard to structural shapes, include the following:

- Mill Test Results (MTR) higher than minimum specified ASTM A36 up to 338 MPa (49 ksi) [SSPC (1994)].

- Notable variation in yield strength, fracture toughness and ductility across rolled sections. Beedle and Tall (1959) reported yield strengths 4-7% higher in the web than in the flanges and similarly Galambos and Ravindra (1978). Engelhardt et al (1996) reported significant strength variations within 89mm (3.5 inches) from the center of the web. Byefield and Nethercot (1997) also reported higher yield strengths obtained from the web due to finer grain structure and higher carbon content than the flanges. Bartlett et al (2003), regarding the mechanical properties of

ASTM A992 steel, found that the mean ratio of flange yield strength to web yield strength to be 0.953 and consistent with the findings of Galambos and Ravindra (1978). It is interesting to note that Withey (1928) found similar characteristics of property variation in the 1920s.

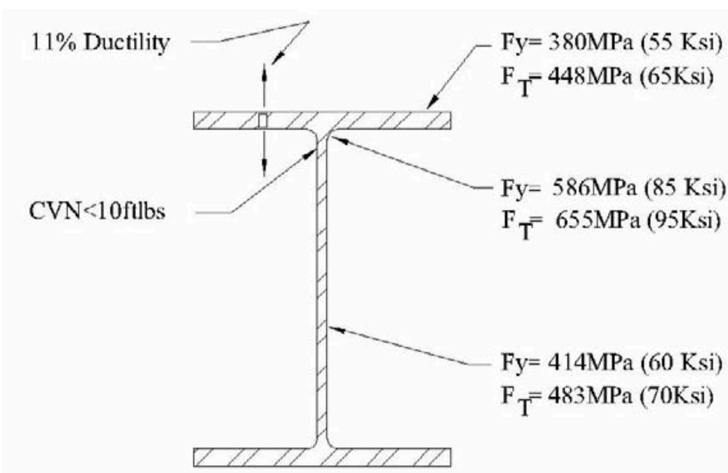
- Tests reported by Sarkinnen (1998) showed low ductility (only 11%) and low toughness in through thickness tests. Sarkinen's results are illustrated in Figure 3.9. These results indicate the anisotrophy of steel in terms of ductility and toughness particularly with regard to through thickness properties.

- Significant variation has been found in the "K" area region of some wide flange members. This is discussed in Section 3.9.

- Low toughness in Hollow Steel Sectionsat the seam weld and corner regions. This is discussed in Section 3.10.

- Significant increases in yield strength occur due to higher strain rate. See Section 3.12.

The effects of temperature on yield and tensile strengths are described in Section 3.3. It should be mentioned that the modulus of elasticity also decreases significantly commencing at a temperature of about 100ºC (212ºF).

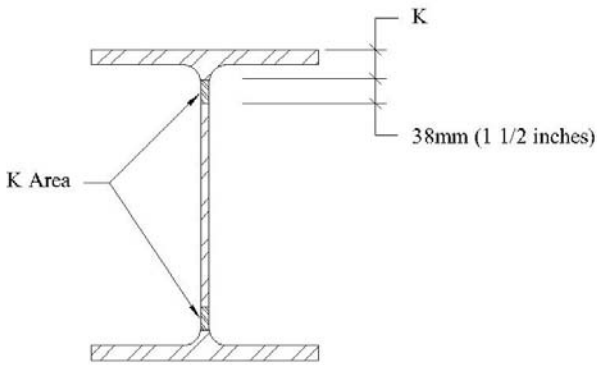


Wide Flange Member Properties

Figure 3.9

3.9 TOUGHNESS & DUCTILITY IN WIDE FLANGE MEMBERS

The K area is defined as the region of the web that extends from the tangent point of the web and the flange-web fillet [K dimension in AISC (2005)] to a distance of 38mm (1½ inches) into the web beyond the K dimension (see Figure 3.10). Around 1995, concern for low toughness and ductility in the K area of wide flange members was expressed by the industry. During fabrication on some projects, involving welding of continuity and/or double plates in wide flange members at moment frame connections, fractures occurred. Some fractures originated at the toe of the fillet, between the section flange and web extending into the web area. Some full scale tests on welded moment resisting beam column connections for the SAC project (see Chapter 1, Section 1.2.11) resulted in failures due to fractures running along the K area. Similar fractures were noted in some wide flange columns of existing buildings following the 1994 Northridge earthquake. [Maranian (1997)].



K Area

Figure 3.10

The significant differences in the properties at the K area and other areas of the section apparently are due to cold roller straightening (known as rotary or roller straightening) of the sections. Cold roller straightening is necessary as wide flange members, after cooling down, often have bows that exceed [ASTM A6]. The Rotary straightening method is carried out continuously and the rollers apply cold working which also includes the area between the web and flanges of wide flange members. The contact stresses cause the mechanical properties in the K area to become stronger but less tough and less ductile.

Rotary or roller straightening is used primarily for lighter members typically less than 223 kg/m (150 lb/ft). Heavier sections use the gag straightening procedures which involves deforming each member as a simple beam and not imposing significant contact stresses.

Issues on the K area may be summarized as follows:

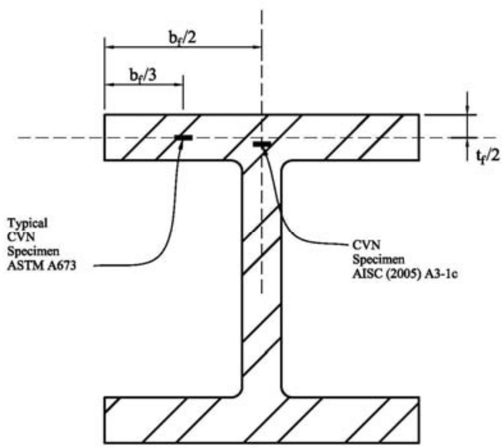
- Low ductility
- Low toughness
- Prevalent in members under 223 kg/m (150 pounds/ft.)

Gag straightening, which is typically used on heavier members, gives improved properties. This is because gag straightening is applied to short lengths of the member and does not tend to work harden the K area.

Application of controlled heating and quenching can improve the properties and some steel wide flange members are produced with these supplementary processes.

AISC (2005) requires Charpy Vee Notch tests (CVN) to be carried out in the core area as shown in Figure 3.11 in order to ensure adequate toughness properties in this area. This is required for columns in seismic lateral resisting systems in the United States [AISC (2005)].

It was first recommended by Yee et al (1998) to keep the welding of the stiffener (continuity) plates well away from the K area. This is now an AISC requirement for Seismic Design (AISC Seismic 2005).



Charpy Vee Notch Specimen
Locations Specified in ASTM A673 and AISC-LRFD

Figure 3.11

3.10 TOUGHNESS IN HOLLOW STEEL SECTIONS

There has been concern for low toughness in hollow steel sections (HSS) particularly following the Northridge California 1994 Earthquake. As mentioned in Chapter 1, Section 1.1.9, Figures 1.7a, 1.7b and 1.7c from the 1994 Northridge Earthquake show rupture of braces appearing to initiate from the corners. Similar types of failures occurred in tests of a two-story special concentric braced frame using rectangular hollow steel sections carried out at the University of California Berkeley by Uriz and Mahin in 2004 [SEAOSC (2005)]

A steel tube post being erected on a project in Alaska fractured along its length when hit with a sledge hammer when being erected (see Figure 3.12). The cause of the cracking is unknown. However, low temperature and low toughness in the corners of the tube appear likely causes. This failure appears similar to the fractured girder that occurred in Belgium in 1934 (see Chapter 1, Section 1.1.4). Figure 3.13 shows a crack in a tube supporting a stair discovered several years after construction. The circumstances of the cracking are not known.

Kosteski et al (2005) carried out Charpy V-Notch (CVN) testing on HSS sections manufactured in North America, South America (Brazil) and Europe (France, Germany and Finland) primarily to assess variations in toughness characteristics in the sections following concerns for an advisory given in AWS D1.1 (2004). The advisory in AWS (2004) discusses that for ASTM A500 (cold formed), hollow sections, products manufactured to this section may not be suitable for those applications such as dynamically loaded welded structures, etc., where low temperature notch toughness properties may be important. Furthermore, they advise that special investigation or heat treatment may be required if this product is applied to tubular T, Y and K connections. A similar statement is made in ASTM A500 [ASTM A500 (2001)].

Kosteski et al carried out 557 CVN tests on coupons taken from various locations around the cross section at temperatures from approximately -75ºC (-103ºF) to 50ºC (122ºF) to obtain the complete toughness – temperature transition curve for each location. Locations included the weld seam. The HSS sections, from which the CVN specimens were taken, included cold formed (Canada and Finland), cold formed and stress relieved (Canada and France), hot rolled (Germany), hot rolled then cold-shaped (Brazil).