CHAPTER 2

TOOL STEELS AND HEAT TREATMENT ASPECTS

Tool steels are a large group of steels which, upon being heat-treated exhibit high strength, hardness and wear resistance. Many grades of tool steel possess the additional quality of thermal stability i.e. the capability of retaining the above-mentioned properties on being heated to elevated temperatures. Such heating often occurs in the working edges of tools, for instance in machining at high speeds, in hot forming etc. The ASM committee on tooling materials defines tool steels as any steel used for making tools for cutting, forming or otherwise shaping a material into a part or a component that is adapted for a definite use (ASM, 1990). Tool steels are often used for making not only tools, but other articles such as ball and roller bearings, measuring gauges, different types of springs and elements of fuel supply systems. According to microstructural features the most typical and largely numbered group among tool steels are hypereutectoid and ledeburitic steels. On being hardened they have a hard metallic matrix and still harder particles of carbides evenly distributed in it. Tool steels are mostly high alloyed or complex alloyed steel and contain more alloying elements (upto 30-45%) than structural steels. They are mainly classified (Geller, 1987) according to their composition into two large groups.

a) Carbon and low alloyed steels containing upto 4 - 5% alloying elements which are non-thermostable steels.

b) High and complex alloyed steels containing above 5% of alloying elements which are thermostable / semi-thermostable steels.
2.1 CLASSIFICATION BY APPLICATION

2.1.1 Steels for Cutting Tools

The steels used for this purpose are predominantly high speed steels i.e. carbide strengthened thermostable steels of a high hardness which are suitable for cutting tools operating at high speeds, whose cutting edge may be heated to appreciable temperature (823 - 923 K). High speed steel takes its name from its capacity to retain a high level of hardness when cutting metals at high speed. No appreciable softening should take place until crossing above 873 K.

2.1.2 Die Steels for Cold Die Forming

These are mostly non thermostable and semithermostable steels of high hardness. Some types of die tools which are used to operate at appreciable dynamic loads are made of non thermostable steels of elevated toughness. In certain cases H.S.S can be used due to its high resistance to plastic deformation.

2.1.3 Die Steels for Hot Die Forming

This includes thermostable steels of elevated toughness, which combine high values of strength and resistance to deformation of the working surfaces of a die upon heating, with the required stability at dynamic loads.

2.1.4 Steels for Precision Tools

These are steels of elevated hardness (either thermostable or non thermostable depending on the operating temperature), which possess the capability of being machined to a high surface finish and retain dimensional stability that is retain constant dimensions and shape in operation.
2.2 PROPERTIES OF TOOL STEELS

The values of the various principal properties may be dependent, in different ways, on the composition and structure of tool steels. Hence it is impossible in many cases to have all of them at the maximum in one and the same grade of steel. An improvement in one property may often result in an impairment of another. The problem lies in making a proper selection of the optimum values for a group of properties that are most essential for a given set of operating conditions with the other properties being affected to the least possible extent.

2.2.1 Wear Resistance

All tools are in a complicated stressed state during their operation. They are subjected to very high contact stresses (400 kgf/mm² or more) and high pressure at the working edges in order to deform or break the material being processed. With high stresses especially when these are accompanied by heating, deformation and plastic flow of their surface layer can occur even in low plastic metals such as steels with martensitic structures and a high amount of carbides. This phenomenon is more appreciable when the steel has retained austenite (Raghavan, 1983). Many tools operate under impact loads and vibrations. The working edge of tools is also subjected to heating by the heat liberated during cutting and friction or transferred to the material being worked during hot deforming. The effect of heat on the properties and the behaviour of tool steels is stronger than with many structural steels. At very high stresses the working layer undergoes plastic deformation which distorts its shape and size and increases the loss of metal due to wear. These processes are intensified by heating and hence tool steels should have high wear resistance and resistance to plastic deformation both at room and at elevated temperatures.
2.2.2 Hardness

This is the most essential property of tool steels. It characterizes the stressed state which is close to non uniform compression and thus determines the resistance to contact stresses appearing in the tool edge, which transform the hard metal into a softer and more plastic state. An increase in hardness may cause: (a) an increase in wear resistance and the endurance limit which however is not linear (b) a better surface finish of the tool proper upon grinding or lapping (c) a lower tendency of the worked material to stick onto the tool surface and (d) a reduction in the coefficient of friction.

2.2.3 Hardness Vs Toughness

A high hardness obtained through hardening corresponds to a sharp drop in toughness. A slight reduction in hardness upon low temperature tempering (at 423 K - 473 K) may cause a greater toughness. A larger gain in toughness is possible by reducing the carbon content of steels i.e. by selecting steel grades having an elevated toughness and by lowering their hardness down to 52-40 HRC. Even under these conditions a high rise in toughness in steels whose structure is high in carbides cannot be expected. Thus toughness is the main factor that prevents the same highest level of hardness to be assigned to all types of tool. The hardness can be at the maximum value only in tools operating with no dynamic loads but should be lowered for those which are to withstand dynamic loads. A greater gain in toughness is possible by reducing the hardness to a greater extent to 45-48 HRC since this causes intense carbide coalescence. But the absolute gain in toughness will again depend on steel composition, being higher for steels with a lower content in carbides.
For reasons given, two intervals of hardness values are commonly used:

(a) **High values (above 59-60 HRC)**

These steels are used for metal cutting tools and cold deforming dies; hardness value near the upper limit are assigned to tools for continuous finish machining and for pressing and drawing dies or when an increased rigidity of the machine tool system is required. Lower hardness values can be assigned to semi-thermostable steels whose structure contains very hard M₇C₃ and MC carbides, since the wear resistance of these steels is decided by the effect of carbide phases as well as by the total hardness of the metal.

(b) **Moderate values (42-50 HRC)**

These steels are used for hot deforming dies in the first place to form a high thermal fatigue resistance, for cold deforming dies subjected to impact loading and for some types of wood-cutting and fitter's tools.

### 2.3 AISI CLASSIFICATION

The methods of identifying and classifying tool steels adopted by AISI include mode of quenching, application, special characteristics and steels for special industries. The commonly used tool steels have been grouped under seven major headings and each group has been assigned an alphabet as follows. (Sydney H.Avner, 1982)
2.4 THE IRON-IRON CARBIDE SYSTEM

Iron is an allotropic metal which means that it can exist in more than one type of lattice structure depending upon temperature. When iron first solidifies at 1811 K it is in the b.c.c \( \delta \) (delta) form. Upon further cooling at 1674 K a phase change occurs and the atoms rearrange themselves into the \( \gamma \) (gamma) form which is f.c.c. and non magnetic. When the temperature reaches 1181 K another phase change occurs from f.c.c non magnetic \( \gamma \) iron to b.c.c non magnetic \( \alpha \) (alpha) iron. Finally at 1041 K, the \( \alpha \) iron becomes magnetic without a change in the lattice structure. The temperature at which the allotropic changes take place in iron is influenced by alloying elements, the most important of which is carbon. The \( \gamma \) solid solution is called austenite. The maximum solubility of carbon in b.c.c \( \delta \) iron is 0.1 percent while in f.c.c \( \gamma \) iron the solubility is much greater. The presence of carbon influences the \( \delta \rightarrow \gamma \) allotropic change. As the carbon is added to the iron the temperature of the allotropic change increases from 1674 K to
1766K at 0.1% C. On the basis of carbon content it is common practice to classify the iron-alloys into two. Those alloys containing less than 2% carbon are known as steels, and those containing more than 2% carbon are known as cast irons. The steel range is further subdivided by the eutectoid carbon content (0.8% C). Steels containing less than 0.8% C are called hypoeutectoid steels, while those containing between 0.8 and 2% C are called hypereutectoid steels. The cast iron range may also be subdivided by eutectic carbon content (4.3% C). Cast irons that contain less than 4.3% C are known as hypoeutectic cast irons whereas those that contain more than 4.3% C are called hypereutectic cast irons.

2.4.1 Carbon Solubility in Iron

Austenite being fcc with four atoms per unit cell represents a much denser packing of atoms than ferrite, which is b.c.c with two atoms per unit cell. This is shown by the expansion that takes place when austenite changes to ferrite on slow cooling. If the iron atoms are assumed to be spheres, it is possible, from the lattice dimensions and by assuming the distance of closest approach to be equal to the atom diameter, to calculate the amount of empty space in both crystal structures which is 25% in f.c.c and 32% in b.c.c. In both austenite and ferrite the carbon atoms are dissolved interstitially, that is in the unfilled spaces of the lattice structure. The largest hole in the b.c.c ferrite is halfway between the centre of the face and the space between the two corner atoms. The largest interstitial sphere that would just fit has a radius of 0.36 \( (10^{-8}) \) cm. The largest hole in f.c.c austenite is midway along the edge between two corner atoms. The largest interstitial sphere that would just fit has a radius of about 0.52 \( (10^{-8}) \) cm. Therefore austenite will have a greater solubility for carbon than ferrite. Since the carbon atom has a radius of about 0.7 \( (10^{-8}) \) cm, the iron atoms in austenite are spread apart by the solution of carbon so that, at the maximum solubility of 2% only about 10% of the holes are filled. The distortion of the ferrite lattice by the carbon atom is much greater than in
the case of austenite and therefore the carbon solubility is much more restricted.

2.5 HEAT TREATMENT OF TOOL STEELS

Proper heat treatment of tool steels is one of the most important factors in determining how they will perform in service. Although the emphasis is on the cooling rate, as much damage may be done to the steel on heating as on cooling.

Tool steels should not be heated so rapidly as to introduce large temperature gradients in the piece. This may be avoided by slow heating or by preheating the steel at a lower temperature before placing it in the high heat furnace. Overheating must also be avoided because it may cause excessive grain growth and consequent loss in toughness. It is essential that some means be used to protect the surface of the tool steel from excessive scaling or decarburizing during heating.

The manner and media of quenching vary according to the steel being quenched and the speed required in quenching. The usual quenching media are water, brine, oil and air. Carbon and low alloy tool steels are quenched in brine or water. High alloy tool steels are quenched in oil, air or molten salts. While still air, fan cooling and compressed air blasts are used for cooling, still air is the preferred method because it is more likely to provide uniform cooling. Interrupted quenching is also used for tool steels in which the steel is quenched in a liquid bath of salt or lead between 753 K and 913 K, then cooled in air to about 338 K. It is recommended to temper tool steel immediately after quenching and before it has cooled to room temperature so as to minimize the danger of cracking due to strains introduced by quenching.
Thus heat treatment of steel is a combination of heating and cooling operations, timed and applied to a metal or alloy in the solid state in a way that will produce desired properties. All basic heat-treating processes for steel involve the transformation or decomposition of austenite. The nature and appearance of these transformation-products determine the physical and mechanical properties of any given steel. Standard heat treatment procedures recommended for tool steels are available in hand books (ASM, 1995)

The first step in the heat treatment of steel is to heat the material to some temperature in or above the critical range in order to form austenite. The addition of chromium, tungsten and vanadium retards the austenitization because of the formation of alloyed cementite or carbides of the alloying elements that are more difficult to dissolve in the austenite (Lakhtin, 1990). A correspondingly longer time is required in this case for the homogenization of the austenite. However in most cases the rate of heating to the desired temperature is less important than other factors in the heat-treating cycle. Highly stressed materials produced by cold work should be heated more slowly than stress free materials to avoid distortion. Whenever possible, provision should be made for slowing the heating of the thinner sections to minimize thermal stress and distortion.

2.5.1 Hardening

Under slow or moderate cooling rates the carbon atoms are able to diffuse out of the austenite structure. The iron atoms then move slightly to become b.c.c. This gamma to alpha transformation takes place through a process of nucleation and growth and is time-dependent. With a still further increase in cooling rate, insufficient time is allowed for the carbon to diffuse out of solution and although some movement of the iron atoms takes place, the structure cannot become b.c.c while the carbon is trapped in solution. The resultant structure called martensite is a supersaturated solid solution
of carbon trapped in a body-centred tetragonal (B.C.T) structure (George Krauss, 1980). Two dimensions of the unit cell are equal, but the third is slightly expanded because of the trapped carbon. The axial ratio c/a increases with carbon content to a maximum of 1.08. This highly distorted lattice structure is the prime reason for the high hardness of martensite. Since the atoms of martensite are less densely packed than in austenite, an expansion occurs during the transformation. This expansion during the formation of martensite produces high localized stresses which result in plastic deformation of the matrix. After drastic cooling, martensite appears microscopically as a white needle-like structure sometimes described as a pile of straw. In most steels, the martensite structure appears vague and unresolvable. In high carbon alloys where the background is retained austenite, the acicular structure of martensite is more clearly defined. The required details on rate of cooling can be obtained from the transformation characteristics diagram (Karl.E.Thilning, 1984)

### 2.6 CHARACTERISTICS OF MARTENSITIC TRANSFORMATION

1. Martensite transformation is diffusionless (Sidney H.Avner, 1982) and there is no change in chemical composition. Small volumes of austenite suddenly change crystal structure by a combination of two shearing actions.

2. The transformation takes place only during cooling and ceases when cooling is interrupted. Therefore the transformation is athermal and depends only upon the decrease in temperature and is independent of time. The amount of martensite formed with decreasing temperature is not linear. The number of martensite needles produced at first is small; then the number increases and finally, near the end, it decreases again. The temperature at the start of martensite formation is Ms temperature and that at the
end of martensite formation is Mf temperature. If the steel is held at any temperature below Ms, the transformation stops and will not continue unless the temperature is dropped.

3. The martensite transformation of a given alloy cannot be suppressed nor can the Ms temperature be changed by changing the cooling rate. The Ms temperature seems to be a function of chemical composition only and one formula defining Ms is

\[ Ms(K) = \left( \frac{968 - (650x\%c) - (70x\%Mn) - (35x\%Ni) - (70x\%Cr) - (50x\%Mo)}{5} \right) + 273 \]

Theoretically the austenite to martensite transformation is never complete and a small amount of retained austenite will remain, even at low temperatures. Small amounts of retained austenite are very difficult to measure when there are many overlapping martensite needles. Therefore the Mf temperature is usually taken as the temperature at which the transformation is complete, as far as one is able to determine this by visual means.

4. Martensite is probably never in a condition of real equilibrium although it may persist indefinitely at or near room temperature. It can be considered a transition (meta stable phase) between the unstable austenite phase and the final equilibrium condition of a mixture of ferrite and cementite.

5. The significance of martensite is its hardness. The percentage of carbon decides the martensite hardness. The hardness increases rapidly at first with the increase in carbon content reaching about 60 HRC at 0.4% carbon. Beyond that, the slope decreases and at 0.8% carbon it is 65 HRC. The levelling off is due to a greater tendency to retain austenite in higher-carbon steels. The high
hardness of martensite is believed to be a result of the severe lattice distortions produced by its formation because the amount of carbon present is many times more than that which can be held in solid solution.

For many years martensite transformations were believed to be unique for steel. However, this martensite type of transformation has also been identified in other alloy systems like iron-nickel, copper-zinc and copper-aluminium. The transformation is therefore recognized as a basic type of reaction in the solid state and the term martensite is no longer confined only to the metallurgy of steel. The basic purpose of hardening is to produce a fully martensite structure and the minimum cooling rate that will avoid the formation of any softer products of transformation is known as the critical cooling rate.

There are two factors that will decrease the critical cooling rate. One increases the amount of carbon and the alloying elements added and the other coarsens the austenitic grain size. While the addition of alloying elements does not affect the maximum hardness obtainable from the steel, that property being controlled by carbon content only, makes it easier to completely harden the steel. The use of a slower cooling rate reduces the danger of distortion and cracking during heat treatment. While the coarsening of the austenitic grain size has an effect similar to that of adding alloying elements, the coarser grain will tend to reduce the toughness of the steel. Hence the critical cooling rate may be reduced by changing the chemical composition rather than by coarsening the austenitic grain.

2.7 RESIDUAL STRESSES IN HEAT TREATMENT

Residual stresses always arise from a non uniform plastic deformation. This is a serious problem in heat treatment since it often results in distortion or cracking caused by a combination of temperature
gradient and phase change. The problem of residual stresses is quite complex. In heat treatment, during quenching, the surface is cooled more rapidly than the inside, resulting in a temperature gradient across the section. However, since the inside and outside layers are attached to each other the core will prevent the outside layer from contracting as much as it should. It will therefore elongate the outside layers putting them in tension while the inside in turn will be in compression. The area in tension must balance the area in compression in order that the stresses be in equilibrium across the section. It can be seen that when a component is suddenly quenched the tensile stresses at the surface reach a very high value. If this stress exceeds the ultimate strength of the material, cracking will occur. If the stress limits are within yield point, the stress will be borne elastically. When the entire piece has reached room temperature, the temperature gradient ceases and the thermal stress will be zero. After return to room temperature, the surface will have residual compressive stresses and the inside will have residual tensile stress. Austenite being f.c.c. is a denser structure than any of its transformation products. Therefore, when austenite changes to any other structure there is expansion. The austenite to martensite expansion is the largest and amounts to a volume increase of about 4%. The lower the Ms temperature, the martensite expansion will be greater. This volume change results in transformation stress. This along with thermal stresses, resulting from a thermal gradient across the section, have a combined effect to induce residual stresses on the component surface as well as on the core. Hence residual stresses are quite significant in heat treatment processes.