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Tool Steels

Christian Højerslev

Abstract On designing a tool steel, its composition and heat treatment parameters are chosen to provide a hardened and tempered martensitic matrix in which carbides are evenly distributed. In this condition the matrix has an optimum combination of hardness and toughness. The primary carbides provide resistance against abrasive wear and secondary carbides (if any) increase the resistance against plastic deformation.

Tool steels are alloyed with carbide forming elements (Typically: vanadium, tungsten, molybdenum and chromium) furthermore some steel types contains cobalt, which respectively raises the temperature at which martensite transformation initiates and at which the transformation is complete. Addition of alloying elements serves primarily two purpose (i) to improve the hardenabillity and (ii) to provide harder and thermally more stable carbides than cementite.

Assuming proper heat treatment, the properties of a tool steel strongly depends on which alloying elements are added and their respective concentrations.

Contents

1 Introduction

Tool steels are iron-based alloys with properties, which are different from those of carbon steels due to the presence of alloying elements. They belong to a large group of steels which, upon heat treatment exhibit high strength, high hardness and high wear resistance relative to other steel types.

Moreover, many tool steel types have good microstructural stability at elevated temperature (red hardness), and they retain their properties to an appreciable depth in the material (except steels belonging to Group W see section 5. 1).

Tool steels are widely applied e.g. as dies, moulds and cutting tools [6].

The purpose of this report is (i) to outline some general principles for heat treatment of tool steels, (ii) to give an overview of how typical alloying elements effect the properties of the correct heat treated tool steel, and (iii) to give an overview of the various types of tool steels.

2 Heat treatment of tool steels

In general, the purpose of heat treating tool steels is to achieve a homogeneous structure, consisting of a fully hardened and tempered matrix, which for most types contains evenly distributed (primary and secondary) carbides. Whether the preferred type of martensite is of lath- or plate-type, basically depends on whether toughness or high resistance against abrasive wear is desired [19].

If correct heat treatment is applied, the properties of a tool steel originate from the principal alloying elements and their respective amounts. Table 2. 1. provide qualitative information of which elements to chose to obtain some of the most important tool steel properties.

Table 2.1. Alloying elements for obtaining various tool steel properties

Characteristic	Elements(a)
Hot hardness	W, Mo, Co (with W or Mo), V, Cr, Mn
Wear resistance	V, W, Mo, Cr, Mn
Deep hardening	Mn, Mo, Cr, Si, Ni, V(b)
Minimum distortion	Mo (with Cr), Cr, Mn
Toughening by grain refinement	V, W, Mo, Mn, Cr

(a) Elements are arranged roughly in order of decreasing potency when added in usual amounts for the characteristic desired. (b) Provides deep hardening if austenitized at high enough temperature to dissolve vanadium carbide.

2.1 As delivered condition

The manufacturer of tool steels always delivers the steel in a fully annealed condition, unless the customer specifies other conditions. When fully annealed, the structure is spheroidite, i.e. the matrix is ferritic (bcc), and thereby soft, carbon is chemically bound in "spherical" carbides. In this condition, machining is easy.

The annealed condition is not suitable for tool application, and proper heat treatment must be applied after machining.

2.2 The heat treatment process

2.2.1 Austenitisation

Selection of the austenitisation temperature and time is a weighing of pros and cons. It is desirable to obtain homogeneous austenite as to achieve homogeneity in the hardened sample. Homogeneous austenite can be achieved by a relatively long holding time and a temperature as high as possible, but in the austenite region to enable fast diffusion. However, care must be taken to avoid grain growth.

TTA-diagrams (Time Temperature Austenite) can be used to select time and temperature. However, the kinetics of the austenite formation strongly depends on the microstructure from which the austenite grows, which locally may be severely varied, thus TTA-diagrams must be used with care. Alternatively, proper austenitisation time and -temperature might be provided by means of artificial neural network analysis [27].

At a sufficiently high temperature some carbides (which are present in the as delivered condition) dissolve whereby the amount of dissolved alloying elements and carbon in the matrix is enhanced. Even though both carbon and alloying elements in solid solution in austenite (expect for Al and Co) lower the M_s- and M_f temperatures, thus making it more difficult to obtain a fully martensitic structure upon cooling, the hardenability is often improved (see section 2.3.).

However, high temperature and long holding time promote grain growth, which results in a lower hardness of the hardened and tempered sample.

2.2.2 Quenching

Quenching is performed to achieve maximum hardness by transformation of austenite into martensite.

The cooling rate must be sufficiently high to form martensite with the same composition as austenite; hence, diffusion of carbon and alloying elements should be prevented during cooling. On the other hand the cooling rate should be sufficiently slow to avoid the introduction of internal stress causing undesired dimension changes (i.e. the introduced stresses must not exceed σ_y) or heat cracks.

As a rule of thumb heat cracks are avoided if the temperature difference between bulk and surface do not exceed 150 ° C (see figure 2.2.2.1.) [22].

Optimum cooling provides the same transformation rate throughout the sample.
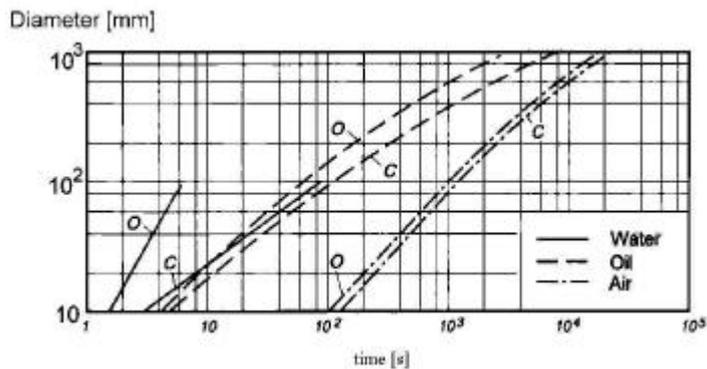
Figure 2.2.2.1. Time for cooling from 800- 500 °C for long cylindrical objects in different cooling media. O: 1 mm below the surface, C: The centre of the sample.

On selecting cooling media it is necessary to take the specimen dimension into account.

For a specimen of a simple geometry e.g. cylindrical or spherical it is possible to calculate cooling rates at various distances from the surface (see reference [21]). If the specimen geometry is complex it might be possible to determine cooling rates at various locations by either computer simulations or by conducted tests.

2.2.3 Tempering

The martensite formed by quenching is too brittle to use in a practical applica-tion, and therefore it must be tempered. Tempering is heating of the steel/martensite with the purpose of (i) changing the martensitic structure (bct) towards quasi-equilibrium where ferrite and carbides are formed by nucleation and growth, possibly with diffusion as the rate-determining step [8], (ii) relieving most of the undesired stresses introduced by quenching [6], and (iii) to transform retained austenite - if present - to ferrite and carbides.

To avoid undesired or to achieve desired, mostly diffusion controlled, trans-formations during tempering time and temperature must be considered [22], [6].

Highly alloyed tool steels (e.g. high-speed- and hot-work steels) often requires tempering at ~500- 600 °C for ~1 hour two or three times, at these temperatures substitutionally dissolved elements are mobile, and alloying element carbides can form (see section 4. 1.).

Low alloyed tool steels (e.g. low-alloy special-purpose- and water-hardening steels) are tempered at lower temperatures to avoid reduction in hardness and temper brittleness [22].

Tool steels, expect for plain carbon and low-alloyed tool steels, exhibit secon-dary hardening, which is usually ascribed to precipitation of secondary alloying carbides coherent with the matrix [19]. HREM investigations by Pippels and co-workers seem to support this.
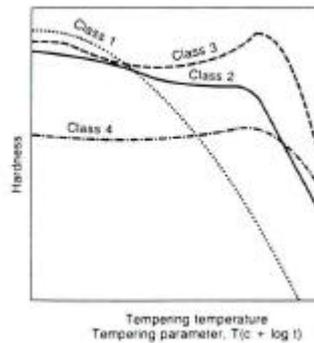
Figure 2.2.3.1. Principal appearance of tempering parameters as a function of hardness for tool ste els. The four different classes refers to: Class 1: Carbon- and low-alloy steels, class 2: Medium to high-alloy cold-work steels, class 3: Highly alloyed high-speed steels and class 4: Medium- to high-alloy hot-work die steels

High-speed- and hot work steels obtain their maximum hardness after secondary hardening [6], [10].

The hardness of tool steels as a function of tempering time can show one of the four curves given in figure 2.2.3.1. In practice many tool steels exhibit intermediate curves.

Typical steel types for the four different classes are [19]:

Class 1: Carbon- and low-alloy steels
Class 2: Medium to high-alloy cold-work steels
Class 3: Highly alloyed high-speed steels
Class 4: Medium- to high-alloy hot-work die steels

2.3 Influence of alloying elements

Adding of alloying elements to a Fe-C steel can effect the $\gamma \rightarrow \alpha$ transformation in three ways. It can change the homogeneity range for a given phase, it can change the nucleation rate of ferrite [25] and the kinetics of the growth of α [9].

All tool steels are alloyed with carbon and various strong carbide forming elements, and stoichiometrically considerations are made, to ensure a constitution of a tempered martensitic matrix (bcc) containing hard alloy carbides (~1800- 3000 HV) after proper heat treatment.

In the fully annealed (as delivered) condition, there is an optimal amount of alloy-carbides. Some of these are primary carbides, meaning that they do not (fully) dissolve during austenitisation.

On austenitisation secondary carbides decompose, thereby releasing alloying elements which are substitutionally dissolved in the iron lattice (austenite - fcc); carbon is dissolved interstitially. On cooling, these substitutionally dissolved carbide forming alloying elements improve the hardenability, ie. the ease at which martensite (bct) is formed, by reducing the rates of the diffusion controlled pearlite- and bainite[1] formations.

However, addition of all alloying elements, except for aluminium and cobalt, reduces the temperature, M_s at which martensite formation is initiated, and the temperature, M_f at which the martensite transformation is complete [23]. M_s and

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1 In this context bainite formation is (not entirely correct) reckoned a diffusion-controlled process.

M_f are either determined experimentally or estimated using the imperical formulae in equations (1) and (2). Consequently, depending on the dimensions of an austenitisised work-piece "fast" quenching may be required to achieve a full transformation of austenite to martensite even in highly alloyed steels. "Fast" quenching is undesired, since it enhances the level of internal stresses and thus risk for dimensional changes and/or cracking [2].

(1) M_s [°C] = 500 – 333C – 34Mn –35V - 20Cr – 17Ni –11Mo –10Cu –5W + 15Co +30Al

(2) M_f [°C] = M_s – 215

The element contents are expressed in wt-%. If molybdenum is present 1 wt-% Mo has the same effect on M_s as 5/11 wt-% W [21], [12].

Note, that only alloying elements dissolved in the matrix contribute to the expression in equation 1. Hence tool steels containing vanadium, tungsten/molybdenum as principal alloying elements often reduce the M_s- and M_f-temperature to a lesser extend than expected from equation 1, because part of these elements is bound as primary carbide and is therefore not dissolved in austenite.

An example to how the kinetics of $\gamma \rightarrow \alpha$ + carbides transformation, M_s, M_f and the homogeneity range of the γ phase is effected effect on alloying illustrated by figure 2.3.1. and figure 2.3.2. respectively.
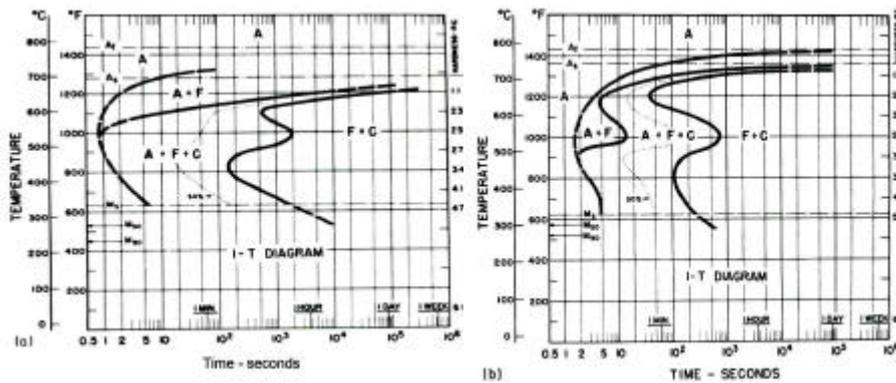

Figure 2.3.1 Influence of alloyingelements of transformation kinetics of austenite. (a) contains 0.4 % C and 1 % Mn (b)in addition 0.9 % Cr. Formation of ferrite and carbides from austenite is retarded.
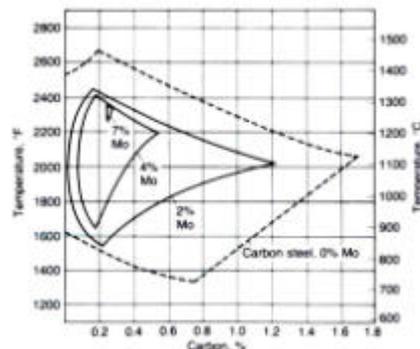
Figure 2.3.2 Effect of the molybdenum content in Fe-C-Mo alloys

3 Principal alloying elements

3.1 Carbon

Carbon is by far the most important alloying element for the hardening properties of all steel types, including tool steels.

As a rule of thumb, hardenable steels should contain at least ~0.2 wt-% carbon dissolved in the iron matrix. At carbon contents up to ~1 wt-% the matrix hardness is continuously increasing and it reaches a maximum of ~65 HRC (plain carbon steels).
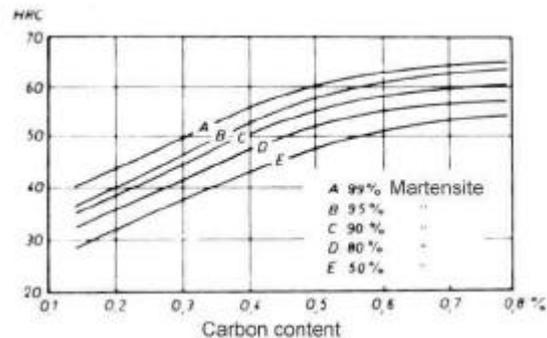
Figure 3.1.1. Hardness as a function of carbon content

On designing tool steels stoichiometric considerations must assure enough carbon to provide matrix hardness and to form desired carbides such as V_8C_7, η-carbide and Cr_7C_3 (~1800- 3000 HV [20]) during heat treatment.

The optimum carbon content is attained when all alloying elements have formed carbides in a hardened and tempered matrix [10], [22].

Carbon itself promotes formation of MC type carbides [17].

3.1.1 Contents of carbon in tempered martensite

Merely considering the Fe-C binary phase diagram, it is seen that ferrite (bcc) as a maximum can contain 0.02 wt-% carbon in solid solution. This corresponds to one carbon atom per ~500 unit cells of ferrite.

However, tempered martensite (which is the matrix constituent of all tool steel types) can be considered as ferrite which is stable with ~0.2 wt-% carbon in solid solution [18], [22]. The reason is that tempered martensite contains a high concentration of lath or plate boundaries originating from the parent martensite where carbon can be localised. In lath type martensite where the dislocation density is relatively high, carbon can additionally be localised at dislocation cores.
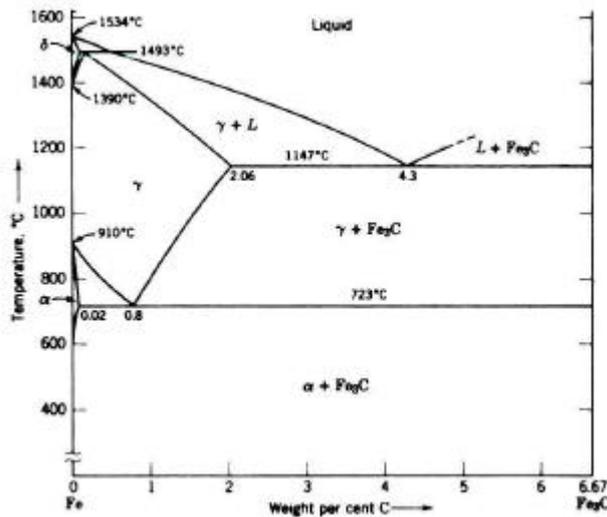
Figure 3.1.1.1 The metastable iron carbon equilibrium phase diagram

3.1.2 Localization of carbon in tempered martensite

The ferrite lattice has two principal locations where carbon can be positioned i.e. tetrahedral- and octahedral interstices; for each unit cell there are six tetrahedral spaces and six octahedral spaces (see figure 3.1.2.1). At both types of interstices, the vacant volume is less than the atomic volume of a carbon atom thus presence of carbon strains the ferrite lattice.

Since the bcc lattice is relatively weak in <100> directions due to relatively few nearest and next nearest neighbours, carbon atoms are preferably positioned in octahedral interstices, despite larger interstices in tetrahedral positions [18].

Carbon atoms are randomly distributed in the non-stressed lattice (primarily at octahedral positions). If however, an external stress is applied the distribution is affected. An applied tensile stress parallel to the [100] direction promotes the uptake of carbon at the positions in figure 3.1.2.1 d) in order to reduce the total strain energy in the system [13].

(a)   b)   (c)   (d)
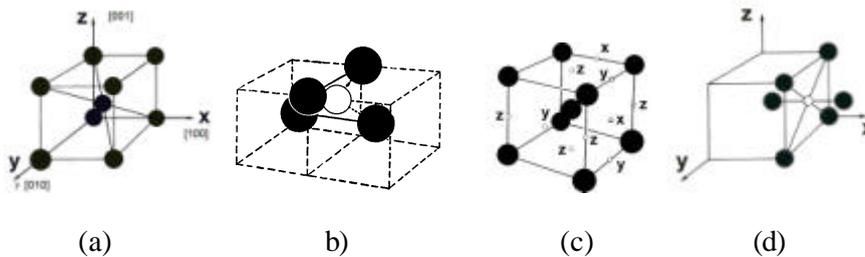
Figure 3.1.2.1. Positions of carbon atoms in the ferrite bcc lattice. (a) the bcc unit cell. (b) a carbon atom positioned in a tetragonal interstice. (c) x, y, z is octahedral interstices. (d) preferred site when applying an external tensile stress in the x-direction.

The reduction in total strain energy for carbon atoms positioned in the strained octahedral sites can be understood in terms of the two closest neighbours i.e. the "a/2-neighbours" are dragged further apart, thus making more space, and thus a carbon atom fits in better.

3.2 Chromium

In tool steels chromium will form carbides of the types $Cr_{23}C_6$ and some Cr_7C_3 during annealing depending on the chromium content. These carbides dissolve during austenitisation at temperatures exceeding ~900 °C and are totally dissolved at ~1100 °C. [10]

Although consequently the M_s- and M_f temperatures are lowered, the addition of chromium is found to increase the hardenability (e.g. on lowering of M_s and M_f vs. impeding nucleation and growth of pearlite and bainite, the latter effect is the stronger).

Chromium improves the cutting performance due to formation of wear resistant carbides, and improvement of the tempering resistance [22], [10].

3.3 Tungsten and molybdenum

Tungsten and molybdenum exhibit similar effects, and on atomic level they are more or less interchangeable: 1 wt-% Mo equals 1,6-2 wt-% W (same atom-%). An important difference is that the molybdenum steel types (e.g. molybdenum high-speed steels) have a significant greater tendency towards decarburization than tungsten steel types at the same W_{eq}, making heat treatment of these (molybdenum containing) steels more difficult [20].

Both W and Mo lower the solidus temperature (The effect is more pronounced for Mo - see figure 2.3.2). Likewise addition of either W or Mo narrows the domaine where austenite is stable (Mo to a greater extent -see figure 2.3.1).

The secondary hardening- and cutting performance of tool steels is enhanced proportional with W_{eq}.

W encourages the formation of M_6C type carbides [17] (M is either W, Fe and Mo or a combination) commonly denoted as $(Fe,Mo,W)_6C$ or η-carbide. These carbides dissolve in the austenite matrix at temperatures ranging from ~1150 °C to the solidus temperature, in practice they do not dissolve completely.
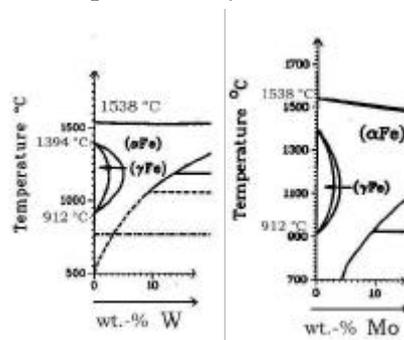
Figure 3.3.1 Eguilibrium diagrams for Fe_Mo and Fe-W respectively. Note that the division is not the same on the temperature scale.

On heat treating most tool steel types the austenitisation temperature is kept well below 1150 °C.

When an austenitisation temperature in that range is required, the holding time is usually only a few minutes. Hence, the W and/or Mo containing carbides present in the as delivered condition will not dissolve during conventional heat treatments. The fraction of Mo and W bounded as carbides tights up carbon, improves the hardenabillity by raising M_s and M_f. The fraction of W and Mo in solid solution lowers M_s and M_f, but may benefit by slowing down pearlite and bainite nucleation and growth.

Molybdenum promotes formation of M_2C type carbides [17]. These carbides become unstable at elevated temperatures, and at ~750 °C they transforms to M_6C type carbides by reaction with Fe. [6], [17].

Addition of both elements results in grain refinement [22]

3.4 Vanadium

Originally vanadium was used as a scavenger to remove slag, impurities, and to reduce nitrogen dissolved in the matrix and to act as de-oxidant during the production of the steel [19].

Soon it was found that vanadium formed very hard and thermally stable MC type carbides usually2 as isolated particles. These carbides improve the resistance against abrasive wear and provide very good cutting performance [17], [10], [22].

Vanadium carbides are very limited soluble in the matrix, hence addition of vanadium will not delay the rate of diffusional decomposition of austenite but raises the M_s- and M_f temperature by binding carbon (forming carbides), thereby improving the hardenability. Besides adding of vanadium results in grain refinement of the matrix [22].

3.5 Manganese

Manganese is present in most commercial steels. It increases the depth of hardening and increases the σ_Y/σ_{UTS} ratio. Manganese containing steels can be hardened in oil, even though manganese augments the retained austenite content [22], [6], [26]

3.6 Cobalt

Cobalt is the only alloying element in HSSs, which can appreciably increase the thermal stability up to ~650 °C and secondary hardness up to 67- 70 HRC [6], but it reduces the toughness and wear resistance [10].

Addition of cobalt causes the solidus temperature to rise. During austenitisation of cobalt containing steels it is therefore possible to dissolve a larger fraction of the carbides and thereby enhance the hardenability. The high austenisation temperature results in a relatively large amount of retained austenite after quenching, but this effect is somewhat compensated by a lower stability of austenite owing to cobalt. [10], [19].

3.7 Silicon

Alloying with silicon raises the solubility of carbon in the matrix and hence the as-quenched hardness. It has virtually no influence on the carbide distribution [6], but it promotes the formation of M_6C type carbides [17].

During steel production up to 0.2 wt-% silicon is added, primarily to react with oxygen e.g. silicon act as a de-oxidiser. If more than 0.2 wt-% silicon is added, it serves to improve the deep hardening properties. Additions up to ~1 wt-% provides hardness and improves temper-stability but reduces the ductility. At high concentration, silicon causes embrittlement [22], [10], [6].

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2 Pippels have found precipitation of needle formed secondary VC carbides in a M2 HSS.

In general silicon improves resistance against softening of martensite, and displaces tempered martensite embrittlement to higher temperatures [1].

3.8 Nickel

Addition of nickel increases the strength of the steel by entering into solid solution in ferrite (see section 4. 2.). It is used in low alloy steels to increase toughness and hardenability. Presence of nickel reduces lattice distortion and cracking during quenching [26].

4 Alloying element carbides

4.1 Formation

As mentioned in section 2. 3. the carbide forming elements are substitutionally dissolved in the iron lattice (ferrite or austenite).

Generally, these elements cause local distortion of the host lattice because their atomic radii are different from that of iron (see appendix 2, table B). The total strain is minimised if these atoms diffuse to locations resulting in less total lattice distortion e.g. dislocation cores or grain boundaries. Hence, there is a driving force for diffusion of alloying elements to these sites [18].
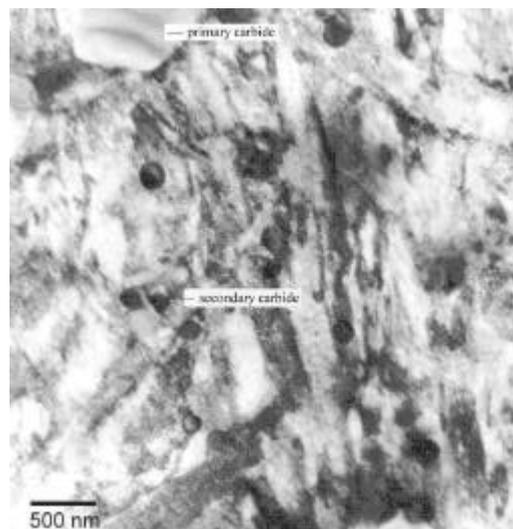
Figure 4.1.1. Bright field micrograph of an AISI M3:2 type high-speed steel in quenched and tempered condition. Different sized carbides are present in a matrix of tempered lath martensite.

Diffusion of substitutionally dissolved elements is temperature dependent.

Even in alloys, that contain a relatively large amount of strong carbide forming elements, no experimental evidence has bean found, that alloying element carbides or clusters of the type X-C are formed below ~300 °C [13].

At temperatures above ~500 °C (lower than typical tempering temperatures for tool steels) the diffusion of alloying elements becomes significant, and they will start to develop carbides [24].

Alloy-carbide grows at the expense of cementite (Fe$_3$C→alloy-carbide), either by *in situ* transformation (nucleation at cementite/ferrite interfaces followed by growth) or, following dissolution of cementite, by separate nucleation and growth in energetically favourable locations as described above [18].

The effect of precipitation of alloy-carbides is evident, especially in high-speed steels, where precipitation of fine and ultra-fine alloy-carbides at ~550 °C is responsible for the secondary hardening effect giving these steels red hardness [23].

4.2 Strengthening by carbides

Carbides contribute to strengthening of tool steels in two different ways.
1. Since especially the alloy-carbides are significant harder than the matrix, carbides provide resistance against abrasive wear.
2. They contribute to the high yield strength of especially some tool steels by impeding the mobility of matrix dislocations.

Ad. 1. Relatively large carbides (ranging from 1-6 µm and up to 25 µm in powder metallurgically and conventionally processed tool steels respectively) embedded in the matrix provides resistance against abrassive wear, especially if they are homogeneously distributed. [15]

Ad. 2. Precipitated (alloying element) carbides provide enhanced yield strength by hindering of dislocation movement.

Precipitates/carbides intersect matrix-slip-planes in a random fashion during growth. When a dislocation gliding in its matrix-slip-plane meets a precipitate, it is forced to either cut through or around it, and it will choose the route offering lowest resistance. Figure 4.2.1. shows how a dislocation typically is effected by obstacles. By definition, obstacles are considered *strong* or *weak* depending on whether the angle a dislocation bends in its vicinity is large or small, respectively. An obstacle effecting the entire dislocation line to approximately the same extent is termed *diffuse*, if not it is *termed localised*.
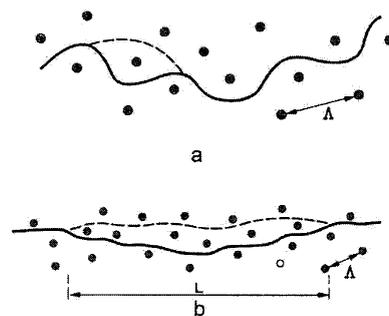
*Figure 4.2.1. A dislocation moving from the position of the full to the dashed line. The obstacles of mean spacing **L** exerts diffuse forces. The obstacles forces is strong in (a) and weak in (b).*

Dislocations from the matrix cannot move through incoherent precipitates such as primary carbides but must bow around it. Often a dislocation passes precipitates according to the *Orowan mechanism* illustrated in figure 4.2.2.. The dislocation loops formed around the precipitates decreases the effective spacing between the precipitates thereby increasing the so-called *Orowan stress* which is inversely proportional to the distance between the precipitates [11]. Accordingly, the force that the precipitates exert on the next dislocation that wants to pass is increased.
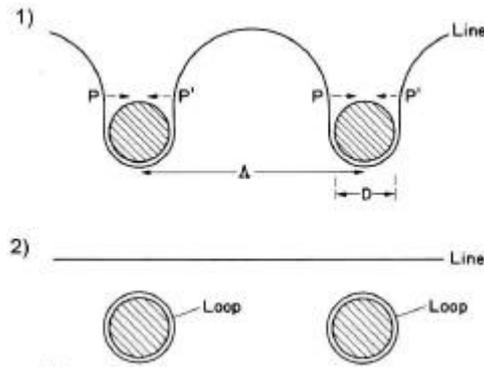
Figure 4.2.2. Illustration of the two principal steps in the Orowan mechanism.

It should be noted that other features than carbides (or rather precipitates) impede movement of dislocations, e.g. substitutionally dissolved atoms and grain boundaries.

4.3 Carbides as crack initiation sites

Carbides are beneficial in tool steels because they provide strength and wear resistance, however they are also likely to act as crack initiation sites.

When in use, a tool experiences different levels of elevated temperature, highest at the tool tip/outermost surface.

The thermal expansion coefficients and Young modules of carbides are different from those of the matrix. Therefore, matrix/carbide interfaces seems likely to be crack initiation sites, especially if they are in- or semi coherent with the matrix. It is commonly stated, that no coherency exists between the matrix and the primary carbides. This is ascribed to the large difference in lattice parameter between ferrite and typically "tool steel carbides" (e.g. lattice parameter, a(Fe,bcc) = 2.8664 Å, a(V_8C_7) = 8.33409 Å, a(η-carbide) = 11,1094 Å).

However, habit planes exist where these carbides and ferrite can be fully coherent (e.g. d =), and in recent HREM investigations on type M2 HSS heat treated for industrial purposes by Pippels and co-workers it is concluded that the carbides (primary and secondary) are fully coherent with the ferritic matrix.
Investigations of wrought T42 HSS showed that MC-type carbides sometimes crack during heat treatment or at applied loads (tensile as well as compressive), and that all observed cracks initiated in or in the vicinity of MC-type carbides [7].

In excess of ~20 vol.-% carbides are present in the hardened and tempered condition of highly alloyed tool steel types, thus providing several crack initiation sites. If cracks initiates in several carbides or at several carbide/matrix interfaces, crack growth by coalescence may become critical.

5 Classification of tool steels

Tool steels are classified according to at least three different systems:
1. Composition
2. Hardness
3. Properties
(Alternatively tool steels could be classified according to application.)

Classified after composition tool steels can be subdivided into three major groups. 1) Hyper eutectoid- (often denoted ledeburetic-) and eutectoid steels with a hardness of 60- 65 HRC or above, 2) ledeburitic steels with a hardness of 45- 55 HRC and 3) high-alloy low carbon steels with a hardness of 40- 60 HRC [6].

However, since tool steels of various compositions can exhibit similar behaviour, this classification system is of academic interest only. Classification after hardness is not sufficient for proper selection.

According to the classification system developed by the American Iron and Steel Institute (AISI), tool steels can be subdivided in seven different groups, based on prominent characteristics such as alloying elements, heat treatment and application. These groups are high-speed-, cold-work-, hot-work-, shock-resisting-, mould- special-purpose- and water-hardening steels (see appendix 1). In this survey only the AISI classification system is considered.

5.1 Water-hardening steels

Water-hardening steels are denoted group W steels. They are essentially plain carbon and low alloyed steels.

Carbon is the principal alloying element, but small additions of chromium and vanadium are often added for grain refinement, improved resistance against wear and (to a less extend) improved hardenability. (Group W steels can only be hardened to few millimetres below the surface).

These tools have low resistance towards softening at elevated temperatures. They are used for applications with limited dynamic load and at low speed such as lath tools, woodworking- and engraving tools. [23], [5], [6].

5.2 Low-alloy special purpose steels

Low-alloy special-purpose steels are denoted group L steels. Their principal alloying elements are chromium and vanadium. Besides these elements, they contain 0.50- 1.10 wt-% carbon and small amounts of nickel and molybdenum.

L2 type steels are shallow hardening. Quenched in oil, hardness of 57 HRC in sections of 13 mm can be achieved.

Quenching of type L6 steels in oil results in a surface and near surface hardness of 64 HRC, retaining a hardness of above 60 HRC in sections of 750 mm [5].

They are used for punches, dies and drills [19].

5.3 Mould steels

Mould steels or group P steels, contains chromium and nickel as principal alloying elements and have a low carbon content (0.1 -0.3 wt.-%). Types P4 and P6 can achieve full hardness by cooling in air [5].

As stated by the name, the main application of these steels are as moulds, which are subjected to heavy pressure, relatively low temperatures (~200 °C) and abrasive wear from the moulding powders e.g. plastics, ceramics or metals. These steels have a hard surface and a tough bulk [23], [19].

Group P steels exhibit low- and limited- resistance to softening at elevated temperatures [5].

5.4 Shock-resistant steels

The group of shock-resistant steels has the prefix S. The principal alloying elements of this group are carbon, manganese, silicon, chromium, tungsten and molybdenum (vanadium is commonly also included). The carbon content is medium ~0.50 wt-%. The (relatively) high silicon addition is unique for this group of steels, and is responsible for reduced sensitivity to fracture in some tempered microstructures.

The hardenability and the depth to which these steels can be hardened varies. Some types are quenched in water (S2) and others in oil (S1, S5, S6). Type S2 steels are shallow hardening whereas type S7 steels deep harden.

Steels from this group exhibit high strength, moderate wear resistance and a remarkably high toughness. They are able to resist repetitive high impact loads (they are hard and tough at the same time), and are primarily used for applications such as hammering and punching [5], [23], [22], [19].

5.5 Hot-work steels

Hot work steels exhibit very good thermal resistance against softening, at the (elevated) working temperature or during heat treatment [19].

All hot-work steels are described by the prefix H in the AISI nomenclature, and contain typically a relatively low carbon content of 0.30- 0.40 wt-% carbon. Type H steels are divided into three groups according to the principal alloying element providing red hardness. Some of the highly alloyed Group H steels resemble HSSs but have a lower carbon content as well as a lower alloying element content [3].

5.5.1 Chromium hot-work steels

These steels have compositions described by the H10 to H19 standards. They are relatively low alloyed with contents of chromium of ~3- 5 wt-%. The principal alloying elements are carbon, chromium, tungsten and in certain cases vanadium.

The low alloy content promotes toughness at the relatively low normal working hardness of ~40- 55 HRC. Equation 1 in section 3. 1. shows that these steels have relatively high M_s- and M_f temperatures, and they may be air hardened to full working hardness for sections up to 300 mm in thickness [5], [22].

Chromium hot-work steels are the most widely used for forging and die casting applications [19].

5.5.2 Tungsten hot-work steels

These steels are called type H steels. The AISI types H21 to H26 have qualitatively and quantitatively almost the same principal alloying elements as the HSSs, but contain less carbon. Compared to HSSs tungsten hot-work steels exhibit higher toughness, but otherwise similar characteristics as HSSs. In fact, type H26 is merely a low carbon version of T15 (see app. 1).

The rather high alloying contents of type H steels provides enhanced thermal stability at elevated temperatures and makes them more prone to brittleness at the normal work hardness of 40- 55 HRC relative to chromium hot-work steels.

Among the hot-work steels, H types are the hardest.

Though it is possible to air-harden these steels, they are commonly hardened in oil or salt baths as to prevent scaling. [5], [19], [23]

Examples of applications are extrusion dies for brass and bronze and hot punches [19].

5.5.3 Molybdenum hot-work steels

At present only two Mo-type hot work steels are in use, H42 and H43 [5].

The principal alloying elements are carbon, molybdenum, chromium and vanadium.

Analogous to group M and T steels (HSSs), the molybdenum- and tungsten hot-work steels show similar properties for the same value of W_{eq}.

Relative to tungsten hot-work steels, the costs resulting from necessary precautions during heat treatment exceed the savings due to lower initial costs. Consequently tungsten hot-work steels are most widely applied [5], [22].

5.6 Cold-work steels

Cold-work steels are not designed to resist softening (see section XXX, HSS) at elevated temperatures, and are therefore restricted to applications at temperatures below ~200- 260 °C. [5]

They are divided into three groups: A (air-hardening steels), D (high-carbon, high-chromium steels) and O (oil-hardening steels) [5]. The principal alloying elements differ for the three groups, but in general the total alloying contents are too small to provide high temperature resistant steels [6].

Even components of fairly large dimensions made of cold work steels do not change shape upon quenching. In general, these steels are safe to harden and they are classified as *non-deforming* [23].

5.6.1 Group A steels

Steels from group A contain sufficient amounts of alloying elements to achieve full hardness on air-cooling, and a hardness level at 59- 60 HRC can be obtained in sections of 100- 120 mm [6]. Group A steels have a (very) high degree of shape stability upon quenching, and the carbide distribution is virtually homogeneous.

The principal alloying elements are carbon, molybdenum, chromium and manganese. Sometimes group A steels are subdivided in chromium- and manganese rich types. Intercomparison shows that chromium types have improved resistance against softening at elevated temperatures, whereas manganese types can be hardened at temperatures ~110 °C lower [22].

The stability with respect to dimensional changes makes group A steels suitable for high precision tools.

5.6.2 Group D steels

The principal alloying elements in group D steels are carbon and chromium – present in 1.5- 2.35 wt-% and 12 wt-% respectively. The high chromium content provides high red hardness.

Large fractions of carbides are present (especially) in the higher carbon containing types, which provide excellent resistance against wear.

Compared to group A, group D steels are more susceptible to distortion, edge brittleness and may suffer from cracking during hardening.

Group D steels are applied as long-run dies for blanking, forming and deep drawing.[5], [22]

5.6.3 Group O steels

Group O steels are essentially high-carbon steels with a relatively low content of principal alloying elements. Consequently, the hardenability of steels from group O is worse than for group A steels (see section 3. 2.). Group O steels can be through-hardened upon quenching in oil.

Because of the low contents of alloying elements, only carbon (iron carbides) provides hardness and wear resistance. Consequently, the wear resistance is not as good as for group A and group D steels.

Combined with their relatively low initial costs, steels from this group are widely used for short run applications such as blanking and forming dies, gauges, collets, etc.

5.7 High-speed steels (HSSs)

By definition a HSS provides high hardness to enable high speed cutting of materials. Consequently these steels are primarily used as all kinds of cutting tools, but some grades are also suitable for cold work applications.

The steels often contain ~ 20 wt-% alloying elements. The principal alloying elements are molybdenum and/or tungsten, chromium, vanadium, cobalt and carbon.

HSSs are divided into two groups, M (molybdenum) or T (tungsten) depending on whether the atomic percent of molybdenum or tungsten is highest.

Two HSSs containing the same total molar fractions of alloying elements but with the difference that one contains tungsten and the other molybdenum are equal in performance. Likewise, they are similar in (many) other respects including hardenability. Consequently the total content of molybdenum and/or tungsten is often described by the so-called *tungsten equivalent*, W_{eq} - in wt-%.

W_{eq} varies from ~17- 20 wt-% (see appendix 1). Some group M steels contain as much as 10 wt-% tungsten, whereas group T steels only contain up to 1 wt-% molybdenum. (Steels from both groups always contain at least 1 wt-% vanadium.)

The atomic mass of tungsten is about twice that of molybdenum, therefore only half the amount of molybdenum in wt.-% is required to achieve the same atom ratio. For economical reasons, 95 % of HSSs produced in USA in 1995 belong to group M.

HSSs can be hardened to 65- 70 HRC, and they have very high wear resistance. The high hardness of these steel types combined with red hardness (that is, the capability to resist softening at temperatures high enough to cause steel to emit light in the red part of the visible spectrum) explains why HSSs mainly find their application as cutting tools.

Red hardness is ascribed to precipitation of fine secondary alloying element carbides, which are coherent with the matrix. [5], [10] [19].

5.7.1 Group M vs. group T steels

Despite the many similarities, there are differences between steels of group M and group T. Some important differences are outlined below.

Group M steels has slightly higher toughness than group T steels at the same hardness value.

Group M steels have a maximum obtainable hardness of ~ 70 HRC, which is achieved in the higher-carbon and cobolt-containing steels M41, M42, M43, M44 and M47. However, only few industrial applications require this maximum hardness. Most commonly, heat treatment of group M steels is adjusted to provide a hardness of ~ 66- 68 HRC. Optimum red hardness is achieved for steels from this group.

Group M steels readily decarburize during heat treatment and are in general more sensitive to the hardening conditions than group T steels, consequently group M steels are austenitizised at lower temperatures than group T steels.

The hardenabillity of steels from group T steels are better than that of steels from group M.

All steels from group T can be hardened to at least 64.5 HRC and the maximum obtainable hardness is 67 HRC, which is achieved from types with high carbon contents and hard carbides e.g. T15 [5].

Appendix 1 - Variation limits in composition of each tool steel group.

Designation					Composition, %					
AISI	UNS	C	Mn	Si	Cr	Ni	Mo	W	V	Co
Molybdenum high-speed steels										
M1	T11301	0.78-0.88	0.15-0.40	0.20-0.50	3.50-4.00	0.30 max	8.20-9.20	1.40-2.10	1.00-1.35	...
M2	T11302	0.78-0.88; 0.95-1.05	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.50-5.50	5.50-6.75	1.75-2.20	...
M3, class 1	T11313	1.00-1.10	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.75-6.50	5.00-6.75	2.25-2.75	...
M3, class 2	T11323	1.15-1.25	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.75-6.50	5.00-6.75	2.75-3.75	...
M4	T11304	1.25-1.40	0.15-0.40	0.20-0.45	3.75-4.75	0.30 max	4.25-5.50	5.25-6.50	3.75-4.50	...
M7	T11307	0.97-1.05	0.15-0.40	0.20-0.55	3.50-4.00	0.30 max	8.20-9.20	1.40-2.10	1.75-2.25	...
M10	T11310	0.84-0.94; 0.95-1.05	0.10-0.40	0.20-0.45	3.75-4.50	0.30 max	7.75-8.50	...	1.80-2.20	...
M30	T11330	0.75-0.85	0.15-0.40	0.20-0.45	3.50-4.25	0.30 max	7.75-9.00	1.30-2.30	1.00-1.40	4.50-5.50
M33	T11333	0.85-0.92	0.15-0.40	0.15-0.50	3.50-4.00	0.30 max	9.00-10.00	1.30-2.10	1.00-1.35	7.75-8.75
M34	T11334	0.85-0.92	0.15-0.40	0.20-0.45	3.50-4.00	0.30 max	7.75-9.20	1.40-2.10	1.90-2.30	7.75-8.75
M35	T11335	0.82-0.88	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.50-5.50	5.50-6.75	1.75-2.20	4.50-5.50
M36	T11336	0.80-0.90	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.50-5.50	5.50-6.50	1.75-2.25	7.75-8.75
M41	T11341	1.05-1.15	0.20-0.60	0.15-0.50	3.75-4.50	0.30 max	3.25-4.25	6.25-7.00	1.75-2.25	4.75-5.75
M42	T11342	1.05-1.15	0.15-0.40	0.15-0.65	3.50-4.25	0.30 max	9.00-10.00	1.15-1.85	0.95-1.35	7.75-8.75
M43	T11343	1.15-1.25	0.20-0.40	0.15-0.65	3.50-4.25	0.30 max	7.50-8.50	2.25-3.00	1.50-1.75	7.75-8.75
M44	T11344	1.10-1.20	0.20-0.40	0.30-0.55	4.00-4.75	0.30 max	6.00-7.00	5.00-5.75	1.85-2.20	11.00-12.25
M46	T11346	1.22-1.30	0.20-0.40	0.40-0.65	3.70-4.20	0.30 max	8.00-8.50	1.90-2.20	3.00-3.30	7.80-8.80
M47	T11347	1.05-1.15	0.15-0.40	0.20-0.45	3.50-4.00	0.30 max	9.25-10.00	1.30-1.80	1.15-1.35	4.75-5.25
M48	T11348	1.42-1.52	0.15-0.40	0.15-0.40	3.50-4.00	0.30 max	4.75-5.50	9.50-10.50	2.75-3.25	8.00-10.00
M62	T11362	1.25-1.35	0.15-0.40	0.15-0.40	3.50-4.00	0.30 max	10.00-11.00	5.75-6.50	1.80-2.10	—
Tungsten high-speed steels										
T1	T12001	0.65-0.80	0.10-0.40	0.20-0.40	3.75-4.50	0.30 max	...	17.25-18.75	0.90-1.30	—
T2	T12002	0.80-0.90	0.20-0.40	0.20-0.40	3.75-4.50	0.30 max	1.0 max	17.50-19.00	1.80-2.40	...
T4	T12004	0.70-0.80	0.10-0.40	0.20-0.40	3.75-4.50	0.30 max	0.40-1.00	17.50-19.00	0.80-1.20	4.25-5.75
T5	T12005	0.75-0.85	0.20-0.40	0.20-0.40	3.75-5.00	0.30 max	0.50-1.25	17.50-19.00	1.80-2.40	7.00-9.50
T6	T12006	0.75-0.85	0.20-0.40	0.20-0.40	4.00-4.75	0.30 max	0.40-1.00	18.50-21.00	1.50-2.10	11.00-13.00
T8	T12008	0.75-0.85	0.20-0.40	0.20-0.40	3.75-4.50	0.30 max	0.40-1.00	13.25-14.75	1.80-2.40	4.25-5.75
T15	T12015	1.50-1.60	0.15-0.40	0.15-0.40	3.75-5.00	0.30 max	1.00 max	11.75-13.00	4.50-5.25	4.75-5.25
Intermediate high-speed steels										
M50	T11350	0.78-0.88	0.15-0.45	0.20-0.60	3.75-4.50	0.30 max	3.90-4.75	...	0.80-1.25	...
M52	T11352	0.85-0.95	0.15-0.45	0.20-0.60	3.50-4.30	0.30 max	4.00-4.90	0.75-1.50	1.65-2.25	...
Chromium hot-work steels										
H10	T20810	0.35-0.45	0.25-0.70	0.80-1.20	3.00-3.75	0.30 max	2.00-3.00	...	0.25-0.75	...
H11	T20811	0.33-0.43	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	1.10-1.60	...	0.30-0.60	...
H12	T20812	0.30-0.40	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	1.25-1.75	1.00-1.70	0.50 max	...
H13	T20813	0.32-0.45	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	1.10-1.75	...	0.80-1.20	...
H14	T20814	0.35-0.45	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	...	4.00-5.25	...	...
H19	T20819	0.32-0.45	0.20-0.50	0.20-0.50	4.00-4.75	0.30 max	0.30-0.55	3.75-4.50	1.75-2.30	4.00-4.50
Tungsten hot-work steels										
H21	T20821	0.26-0.36	0.15-0.40	0.15-0.50	3.00-3.75	0.30 max	—	8.50-10.00	0.30-0.60	...
H22	T20822	0.30-0.40	0.15-0.40	0.15-0.40	1.75-3.75	0.30 max	—	10.00-11.75	0.25-0.50	...
H23	T20823	0.25-0.35	0.15-0.40	0.15-0.40	11.00-12.75	...	...	...	...	...

Designation					Composition(s), %					
AISI	UNS	C	Mn	Si	Cr	Ni	Mo	W	V	Co
Oil-hardening cold-work steels										
O1	T31501	0.85-1.00	1.00-1.40	0.50 max	0.40-0.60	0.30 max	...	0.40-0.60	0.30 max	...
O2	T31502	0.85-0.95	1.40-1.80	0.50 max	0.50 max	0.30 max	0.30 max	...	0.30 max	...
O6	T31506	1.25-1.55(c)	0.30-1.10	0.55-1.50	0.30 max	0.30 max	0.20-0.30	...	...	...
O7	T31507	1.10-1.30	1.00 max	0.60 max	0.35-0.85	0.30 max	0.30 max	1.00-2.00	0.40 max	...
Shock-resisting steels										
S1	T41901	0.40-0.55	0.10-0.40	0.15-1.20	1.00-1.80	0.30 max	0.50 max	1.50-3.00	0.15-0.30	...
S2	T41902	0.40-0.55	0.30-0.50	0.90-1.20	...	0.30 max	0.30-0.60	...	0.50 max	...
S5	T41905	0.50-0.65	0.60-1.00	1.75-2.25	0.50 max	...	0.20-1.35	...	0.35 max	...
S6	T41906	0.40-0.50	1.20-1.50	2.00-2.50	1.20-1.50	...	0.30-0.50	...	0.20-0.40	...
S7	T41907	0.45-0.55	0.20-0.90	0.20-1.00	3.00-3.50	...	1.30-1.80	...	0.20-0.30(d)	...
Low-alloy special-purpose tool steels										
L2	T61202	0.45-1.00(b)	0.10-0.90	0.50 max	0.70-1.20	...	0.25 max	...	0.10-0.30	...
L6	T61206	0.65-0.75	0.25-0.80	0.50 max	0.60-1.20	1.25-2.00	0.50 max	...	0.20-0.30(d)	...
Low-carbon mold steels										
P2	T51602	0.10 max	0.10-0.40	0.10-0.40	0.75-1.25	0.00-0.50	0.15-0.40	...	...	...
P3	T51603	0.10 max	0.20-0.60	0.40 max	0.40-0.75	1.00-1.50	...	...	...	...
P4	T51604	0.12 max	0.20-0.60	0.10-0.40	4.00-5.25	...	0.40-1.00	...	...	...
P5	T51605	0.10 max	0.20-0.60	0.40 max	2.00-2.50	0.35 max	...	...	...	...
P6	T51606	0.05-0.15	0.35-0.70	0.10-0.40	1.25-1.75	3.25-3.75	...	...	...	...
P20	T51620	0.28-0.40	0.60-1.00	0.20-0.80	1.40-2.00	...	0.30-0.55	...	...	...
P21	T51621	0.18-0.22	0.20-0.40	0.20-0.40	0.50 max	3.90-4.25	...	...	0.15-0.25	1.05-1.25Al
Water-hardening tool steels										
W1	T72301	0.70-1.50(e)	0.10-0.40	0.10-0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	...
W2	T72302	0.85-1.50(e)	0.10-0.40	0.10-0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.15-0.35	...
W5	T72305	1.05-1.15	0.10-0.40	0.10-0.40	0.40-0.60	0.20 max	0.10 max	0.15 max	0.10 max	...

(a) All steels except group W contain 0.25 max Cu, 0.03 max P, and 0.03 max S; group W steels contain 0.20 max Cu, 0.025 max P, and 0.025 max S. Where specified, sulfur may be increased to 0.06 to 0.15% to improve machinability of group A, D, H, M, and T steels. (b) Available in several carbon ranges. (c) Contains free graphite in the microstructure. (d) Optional. (e) Specified carbon ranges are designated by suffix numbers.

Appendix 1 - continued.

Designation		Composition, %								
AISI	UNS	C	Mn	Si	Cr	Ni	Mo	W	V	Cu
Oil-hardening cold-work steels										
O1	T31501	0.85-1.00	1.00-1.40	0.50 max	0.40-0.60	0.30 max	...	0.40-0.60	0.30 max	...
O2	T31502	0.85-0.95	1.40-1.80	0.50 max	0.50 max	0.30 max	0.30 max	...	0.30 max	...
O6	T31506	1.25-1.55(c)	0.30-1.10	0.55-1.50	0.30 max	0.30 max	0.20-0.30	...	...	...
O7	T31507	1.10-1.30	1.00 max	0.60 max	0.35-0.85	0.30 max	0.30 max	1.00-2.00	0.40 max	...
Shock-resisting steels										
S1	T41901	0.40-0.55	0.10-0.40	0.15-1.20	1.00-1.80	0.30 max	0.50 max	1.50-3.00	0.15-0.30	...
S2	T41902	0.40-0.55	0.30-0.50	0.90-1.20	...	0.30 max	0.30-0.60	...	0.50 max	...
S5	T41905	0.50-0.65	0.60-1.00	1.75-2.25	0.50 max	...	0.20-1.35	...	0.35 max	...
S6	T41906	0.40-0.50	1.20-1.50	2.00-2.50	1.20-1.50	...	0.30-0.50	...	0.20-0.40	...
S7	T41907	0.45-0.55	0.20-0.90	0.20-1.00	3.00-3.50	...	1.30-1.80	...	0.20-0.30(d)	...
Low-alloy special-purpose tool steels										
L2	T61202	0.45-1.00(b)	0.10-0.90	0.50 max	0.70-1.20	...	0.25 max	...	0.10-0.30	...
L6	T61206	0.65-0.75	0.25-0.80	0.50 max	0.60-1.20	1.25-2.00	0.50 max	...	0.20-0.30(d)	...
Low-carbon mold steels										
P2	T51602	0.10 max	0.10-0.40	0.10-0.40	0.75-1.25	0.10-0.50	0.15-0.40	...	...	...
P3	T51603	0.10 max	0.20-0.60	0.40 max	0.40-0.75	1.00-1.50	...	...	...	...
P4	T51604	0.12 max	0.20-0.60	0.10-0.40	4.00-5.25	...	0.40-1.00	...	...	...
P5	T51605	0.10 max	0.30-0.60	0.40 max	2.00-2.50	0.35 max	...	...	...	...
P6	T51606	0.05-0.15	0.35-0.70	0.10-0.40	1.25-1.75	3.25-3.75	...	...	...	...
P20	T51620	0.28-0.40	0.60-1.00	0.20-0.80	1.40-2.00	...	0.30-0.55	...	...	...
P21	T51621	0.18-0.22	0.20-0.40	0.20-0.40	0.50 max	3.90-4.25	...	...	0.15-0.25	1.05-1.25Al
Water-hardening tool steels										
W1	T72301	0.70-1.50(e)	0.10-0.40	0.10-0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	...
W2	T72302	0.85-1.50(e)	0.10-0.40	0.10-0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.15-0.35	...
W5	T72305	1.05-1.15	0.10-0.40	0.10-0.40	0.40-0.60	0.20 max	0.10 max	0.15 max	0.10 max	...

(a) All steels except group W contain 0.25 max Cu, 0.03 max P, and 0.03 max S; group W steels contain 0.20 max Cu, 0.025 max P, and 0.025 max S. Where specified, sulfur may be increased to 0.06 to 0.15 to improve machinability of group A, D, H, M, and T steels. (b) Available in several carbon ranges. (c) Contains free graphite in the microstructure. (d) Optional. (e) Specified carbon ranges are designated by suffix numbers.

Appendix 2 - Table A Classification and description of tool steels; Table B Physical data for the principal alloying elements used in tool steels.

Table A Classification and description of tool steels.

AISI classification	Division into groups by AISI standards	Important group characteristic	Principal alloying elements	Examples of applications
High speed steels	Group M, Mo-rich	High hardness for high speed cutting	C, Mo, W, V, Cr	Cutting tools of all sorts.
	Group T, W-rich	of materials, red hardness.	C, W, V, Cr, Co	
Cold-work steels	Group A, air hardening	Deep hardening in air (up to 100 mm)	C, Mn, Cr, Mo	Punches, forming-, coining dies.
	Group D, high-C high-Cr	High wear resistance at normal temp.	C, Cr, (Mo)	Long run dies for blanking.
	Group O, oil hardening	High wear resistance at normal temp.	Varies	Dies for punches and blanking
Hot-work steels	Group H, Cr-hot-work steels	Deep hardening, high toughness	C, Cr, W, (V)	Dies for extrusion of Al and Mg.
	Group H, W-hot-work steels	Improved thermal stabilty relative to the Cr-	C, W, V, Cr, Co	Extrusion dies for brass, Ni al-
	Group H, Mo-hot-work steels	Hot-work steels, properties similar to HSSs.	C, Mo, W, V, Cr, Co	loys and steel.
Shock-resisting steels	Group S	High shock loading resistance	Mn, Si, Cr, W, Mo	Chissels, hammers, punches.
Mold steels	Group P	Low softening resistance at elevated temp.	Cr, Ni	Molds, critical-finish molds.
Spec.-purpose steels	Group L	Low alloyed steels. Group W- exhibits im-	Cr, V, Ni, Mo	Various
Water-hardened steel	Group W	proved toughness relative to group L steels.	C	Woodworking-, coining tools.

Table 1 Physical data for the principal alloying elements used in tool steels.

Principal alloyimg element	Fe	C	Mo	W	Cr	V	Si	Co	Mn	Ni
Lattice parameters [Å]	2,8665 (bcc)	a = 2,4612	3,147	3,1652	2,8848	3,024	5,4306	a = 2,5071 (hcp)	8,913 (sc <727°C)	3,5240
	3,6467 (fcc)	c = 6,709						c = 4,0686 (hcp)	6,315 (sc <1100 °C)	
	2,9315 (bcc)							3,5447	3,86 (fcc <1138°C)	
Atomic radius [pm]	126	77	139	139	128	134	117	125	127	124
Phase-stabiliser			α	α	α	α	α	γ	γ	γ

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Abstract (max. 2000 characters)

On designing a tool steel, its composition and heat treatment parameters are chosen to provide a hardened and tempered martensitic matrix in which carbides are evenly distributed. In this condition the matrix has an optimum combination of hardness and toughness, the primary carbides provide resistance against abrasive wear and secondary carbides (if any) increase the resistance against plastic deformation.

Tool steels are alloyed with carbide forming elements (Typically: vanadium, tungsten, molybdenum and chromium) furthermore some steel types contains cobalt. Addition of alloying elements serves primarily two purpose (i) to improve the hardenabillity and (ii) to provide harder and thermally more stable carbides than cementite.

Assuming proper heat treatment, the properties of a tool steel depends on the which alloying elements are added and their respective concentrations.

Descriptors INIS/EDB