Carbon Steels

1. Introduction

To make a number of decisions in the design of cutting tools, machine tool selection, choice of a suitable machining regime, one should be first concerned with the work material and its properties. Among multiple mechanical properties usually listed in reference books, machinability is of prime importance.

Machinability of a material is defined as its ‘suitability’ for cutting. Machinability is a parameter, which in many ways is vague, sometimes qualitative and very often misunderstood. Among endless definitions of this parameter, the following two seem reasonable:

*Machinability definition 1*: Generally refers to the ease with which a metal is cut; greater difficulty to machine means greater forces and lower speeds

*Machinability definition 2*: Relative cutting speed for a given tool life for a particular cutting tool-workpiece combination compared to a standard cut by the same tool; expressed as percent (%) rating; a material that can be cut at a higher speed for the same tool life is said to be more machinable.

As seen, machinability is a rather qualitative material characteristic and thus should be selected for a given special case. For example, a number of criteria for machinability may be considered such as:

- Quality of surface finish
- Dimensional stability of the process
- Cost to remove a given volume of material
- Compare power for equal volume of material removed; ignores tool life
- Ease of chip removal (disposal)

It becomes common practice to specify machinability of materials (in%) based on 100% machinability for AISI 1212 steel, with is a common material with well-known machinability.

In shop practice, tool life is may be more important concern, which ‘ranks’ different tools to be ‘good’ or ‘not good’. Tool life is commonly defined as the
measure of length of time a tool will cut satisfactorily. Tool life depends on tool material; work material; tool geometry; cutting parameters (especially cutting speed). Commonly, tool life is characterized by:

- Wear (flank) limit, e.g., 0.030" for roughing; 0.015" for finishing
- Catastrophic failure: rapid, usually unpredictable, premature failure of tool (excessive plastic deformation; brittle fracture; fatigue fracture; edge chipping)
- Lose dimensional accuracy
- Degradation of surface finish
- Increase in cutting force (power) required

Often, tool life characterizes machinability for a given tool design and tool material.

The major properties of the work material that a tool engineer should be concerned with are as follows:

1. **Yield Strength, Ultimate Strength, and Work Hardening Exponent.** A work material having a low shear and intimate strength as well as the work hardening exponent gives low cutting forces and thus low contact pressure at the tool-chip interface (low tool wear).

2. **Fracture Toughness.** Because metal cutting is purposeful fracture of work material, fracture toughness is the energy, which has to be spent to cut a given volume of a work material. Low fracture toughness, better material in terms of cutting.

3. **Thermal Conductivity.** The cutting process results in heat generation. This heat may stay around the machining zone increasing the temperature of the cutting tool - workpiece contact areas (reducing tool life and imposing residual stress into the machined surface) when the thermal conductivity of the work material is low (stainless steels, Nickel-base high alloys, etc.). Otherwise, this heat is conducted away from the machining zone when the thermal conductivity of the work material is high (cupper, aluminum, medium-carbon steel).
The objective of this instruction is to familiarize the tool design engineers of National Broach and Machine Co. with the designations, properties, and machinability of different groups of work material. It is hoped that these knowledge will help them in their design practice (tool parameters selection) and in the identification of the root cause for tool failure (building of the FRACAS Database).

2. Classification of Work Materials

2.1. Ferrous Alloys

The naming convention for steels can get quite confusing at times. Some are named with a series of letters and numbers; others are named with just numbers. There actually is some degree of order among the chaos.

Two basic methods used in the classification of steels are discussed here. One is a system devised by the American Iron and Steel Institute (AISI) in cooperation with the Society of Automotive Engineers (SAE). This system groups tool steels by their purpose or unique properties. The second method, called the Unified Numbering System (UNS) uses a series of 4 to 5 digits to classify steels according to their primary alloying element, the approximate content of the primary alloying element, and the approximate carbon content in hundredths of one percent.

2.1.1 Carbon steels

Carbon steel, also called plain carbon steel, is a malleable, iron-based metal containing carbon, small amounts of manganese, and other elements that are inherently present. Steels can either be cast to shape or wrought into various mill forms from which finished parts are formed, machined, forged, stamped, or otherwise shaped.
Cast steels are poured to near-final shape in sand molds. The castings are then heat treated to achieve specified properties and machined to required dimensions.

Wrought steel undergoes two operations. First, it is either poured into ingots or strand cast. Then, the metal is reheated and hot rolled into the finished, wrought form. A scaled surface and a decarburized skin characterize hot-rolled steel. Hot-rolled bars may be subsequently finished in a two-part process. First, acid pickling or shot blasting removes scale. Then, cold drawing through a die and re-straightening improves surface properties and strength. Hot-rolled steel may also be cold finished by metal-removal processes such as turning or grinding. Wrought steel can be subsequently heat treated to improve machinability or to adjust mechanical properties.

Carbon steels may be specified by chemical composition, mechanical properties, method of deoxidation, or thermal treatment (and the resulting microstructure).

**Composition:** Wrought steels are most often specified by composition. No single element controls the characteristics of a steel; rather, the combined effects of several elements influence hardness, machinability, corrosion resistance, tensile strength, deoxidation of the solidifying metal, and microstructure of the solidified metal. Effects of carbon, the principal hardening and strengthening element in steel, include increased hardness and strength and decreased weldability and ductility. For plain carbon steels, **about 0.2 to 0.25% C** provides the best machinability. Above and below this level, machinability is generally lower for hot-rolled steels. Standard wrought-steel compositions (for both carbon and alloy steels) are designated by an AISI or SAE four-digit code, the last two digits of which indicate the nominal carbon content. Carbon steels are designated as 10xx, 11xx, 12xx, and 15xx. The initial two digits relate to sulfur (S), phosphorus (P), and manganese (Mn) content:
• 10xx: Plain carbon, nonresulfurized grades (0.050% max S; 0.040% max P; 1.00% max Mn)
• 11xx (1xx): Resulfurized grades (0.33% max S; 0.04% max P; 1.65% max Mn)
• 12xz: Resulfurized and rephosphorized grades (0.35% max S; 0.12% max P; 1.00% max Mn)
• 15xx: Nonresulfurized grades (0.050% max S; 0.040% max P; more than 1.00% Mn).

The letter "L" between the second and third digits indicates a leaded steel; "B" indicates a boron steel. Cast-carbon steels are usually specified by grade, such as A, B, or C. The A-grade (also LCA, WCA, AN, AQ, etc.) contains 0.25% C and 0.70% Mn maximum. B-grade steels contain 0.30% C and 1.00% Mn, and the C-grade steels contain 0.25%C and 1.20% Mn. These carbon and manganese contents are designed to provide good strength, toughness, and weldability. Cast carbon steels are specified to ASTM A27, A216, A352, or A487.

Last two digits indicate the mean of the carbon content range in hundredths of a percent. There are three carbon steel groups:

• Low carbon steels containing from 0.06% to 0.28% C: AISI 1005 to 1026, AISI 1108 to 1119, all AISI 12xx, and AISI 1513 to 1527
• Medium-carbon steels containing from 0.25% to 0.55% C: AISI 1029 to 1053, AISI 1137 to 1151, and AISI 1541 to 1552
• High-carbon steels containing from 0.50% to 1.00% C: AISI 1055 to 1095 and AISI 1561 to 1566.

The 11xx series are usually referred to as free-machining grades, the 12xx series are also free-machining grades, which provide increased chip control.
The 15xx series grades contain from 1.05% to 1.65% Mn for greater hardenability.

Machinability of plane carbon steels depends on their composition and microstructure. There is an approximately linear relationship between the specific power required for machining and the carbon content of the steel. The influence of increasing carbon content of hot-rolled and cold-drawn steels on the power requirement for machining and on the tensile strength is shown in Fig. 1.

![Graph showing specific power and tensile strength as a function of carbon content.](image)

**Fig. 1.** Specific power and tensile strength as a function of carbon content.

Plain carbon steels with carbon content below 0.15% are very soft and adhere strongly to the cutting tool. As a result, it is very difficult to achieve good
surface finish with such steels due to built-up formation on the cutting edge particularly when the depth of cut is small (as in broaching and gear shaving). Here, the selection, proper application, and maintenance of the cutting fluid (coolant) is extremely important.

Machinability of medium carbon steels depends to a large extent on their microstructure. They machine best when they have the coarse pearlite or spheroidised carbide structure. Steels with carbon content in excess of 0.6% machine best in the fully spheroidized condition. As a general rule, tool wear rates increase in a consistent manner as the carbon content of work material is increased beyond 0.35%. Actual machinability of the considered group of steels depends on many metallurgical parameters of a particular steel (grain size, heat treatment, cold work, etc.). For example, steel 1020 may have hardness in the range of 111-255HB and the tensile strength in the range of 55,000 – 129,000 psi (379.34 – 827.64MPa).

In general, surface finish improve with increasing carbon content up to 0.35% , however, the surface finish depends not only on carbon content but also on the cutting operation, the tool geometry and the cutting conditions. Important to remember: When slower cutting processes such as shaping and milling are used, the surface finish is found to be virtually independent on carbon content.

Optional to read:

Microalloying technology has created a new category of steels, positioned both in cost and in performance between carbon steels and the alloy grades. These in-between steels consist of conventional carbon steels to which minute quantities of alloying elements --usually less than 0.5% -- are added in the steelmaking process to improve mechanical properties. Strength and hardness are increased significantly. Any base-grade steel can be microalloyed, but the technique was first used in sheet steel a number of years ago. More recently, microalloying has been applied to bar products to eliminate the need for heat-treating operations after parts are forged. Automotive and truck applications include connecting rods,
blower shafts, stabilizer bars, U-bolts, and universal joints. Other uses are sucker rods for oil wells and anchor bolts for the construction industry.

Mechanical properties: Cast and wrought products are often specified to meet distinct mechanical requirements in structural applications where forming and machining are not extensive. When steels are specified by mechanical properties only, the producer is free to adjust the analysis of the steel (within limits) to obtain the required properties. Properties may vary with cross section and part size. Mechanical tests are usually specified under one of two conditions: mechanical test requirements and no chemical limits on any element, or mechanical test requirements and chemical limits on one or more elements, provided that such requirements are technologically compatible.

Method of deoxidation: Molten steel contains dissolved oxygen -- an important element in the steelmaking reaction. How this oxygen is removed or allowed to escape as the metal solidifies determines some of the properties of the steel. So in many cases, "method of deoxidation" is specified in addition to AISI and SAE chemical compositions.

For "killed" steels, elements such as aluminum and silicon may be added to combine chemically with the oxygen, removing most of it from the liquid steel. Killed steels are often specified for hot forging, carburizing, and other processes or applications where maximum uniformity is required. In sheet steel, aging is controlled by killing -- usually with aluminum. Steels intended for use in the as-cast condition are always killed. For this reason, steels for casting are always fully deoxidized. On the other hand, for "rimmed" steels, oxygen (in the form of carbon monoxide) evolves briskly throughout the solidification process. The outer skin of rimmed steels is practically free from carbon and is very ductile. For these reasons, rimmed steels are often specified for cold-forming applications. Rimmed steels are often available in grades with less than 0.25% C and 0.60% Mn.
Segregation -- a nonuniform variation in internal characteristics and composition that results when various alloying elements redistribute themselves during solidification -- may be pronounced in rimmed steels. For this reason, they are usually not specified for hot forging or for applications requiring uniformity.

"Capped" and "semikilled" steels fall between the rimmed and killed steels in behavior, properties, and degree of oxidation and segregation. Capped steels, for example, are suited for certain cold-forming applications because they have a soft, ductile, surface skin, which is thinner than rimmed-steel skin. For other cold-forming applications, such as cold extrusion, killed steels are more suitable.

Microstructure: The microstructure of carbon and alloy steels in the as-rolled or as-cast condition generally consists of ferrite and pearlite. This basic structure can be altered significantly by various heat treatments or by rolling techniques. A spheroidized annealed structure would consist of spheroids of iron and alloy carbides dispersed in a ferrite matrix for low hardness and maximum ductility, as might be required for cold-forming operations. Quenching and tempering provide the optimum combination of mechanical properties and toughness obtainable from steel. Grain size can also be an important aspect of the microstructure. Toughness of fine-grained steels is generally greater than that of coarse-grained steels.

Free-machining steels: Several free-machining carbon steels are available as castings and as hot-rolled or cold-drawn bar stock and plate. Machinability in steels is improved in several ways, including: Addition of elements such as lead (the "leaded" steels such as 12L13 and 12L14), phosphorus and sulfur (the "rephosphorized, resulfurized" steels such as 1211, 1212, or 1213), sulfur (the "resulfurized only" steels such as 1117, 1118, or 1119), and tellurium, selenium, and bismuth (the "super" free-machining steels); cold finishing; educing the level of residual stress (usually by a stress-relieving heat treatment); adjusting microstructure to optimize machinability.
2.1.2 Low-Alloy Steels

Steels that contain specified amounts of alloying elements - other than carbon and the commonly accepted amounts of manganese, copper, silicon, sulfur, and phosphorus - are known as alloy steels. Alloying elements are added to change mechanical or physical properties. A steel is considered to be an alloy when the maximum of the range given for the content of alloying elements exceeds one or more of these limits: 1.65% Mn, 0.60% Si, or 0.60% Cu; or when a definite range or minimum amount of any of the following elements is specified or required within the limits recognized for constructional alloy steels: aluminum, chromium (to 3.99%), cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium or other element added to obtain an alloying effect. Although tool and stainless steels are alloy steels technically, the term 'alloy steel' is reserved for those steels that contain a modest amount of alloying elements and that usually depend on thermal treatment to develop specific properties.

With proper heat treatment, for example, tensile strength of certain alloy steels can be raised from about 55,000 psi (379 MPa) to nearly 300,000 psi (2070 MPa). Subdivisions for most steels in this family include "through-hardenable" and "carburizing" grades (plus several specialty grades such as nitriding steels). Through-hardening grades -which are heat treated by quenching and tempering - are used when maximum hardness and strength must extend deep within a part. Carburizing grades are used where a tough core and relatively shallow, hard surface are needed. After a surface-hardening treatment such as carburizing (or nitriding for nitriding alloys), these steels are suitable for parts that must withstand wear as well as high stresses. Cast steels are generally through hardened, not surface treated.

Carbon content and alloying elements influence the overall characteristics of both types of alloy steels. Maximum attainable surface hardness depends primarily on carbon content. Maximum hardness and strength in small sections
increase as carbon content increases, up to about 0.7%. However, carbon contents greater than 0.3% can increase the possibility of cracking during quenching or welding. Alloying elements primarily influence hardenability. They also influence other mechanical and fabrication properties including toughness and machinability. Lead additions (0.15 to 0.35%) substantially improve machinability of alloy steels by high-speed tool steels. For machining with carbide tools, calcium-treated steels are reported to double or triple tool life in addition to improving surface finish.

Few exact rules exist for selecting through-hardening or surface-hardening grades of alloy steels. In most cases, critical parts are field tested to evaluate their performance. Parts with large sections -- heavy forgings, for example -- are often made from alloy steels that have been vacuum degassed. While in a molten state, these steels are exposed to a vacuum, which removes hydrogen, and, to a lesser degree, oxygen and nitrogen.

Alloy steels are often specified when high strength is needed in moderate-to-large sections. Whether tensile or yield strength is the basis of design, thermally treated alloy steels generally offer high strength-to-weight ratios. For applications requiring maximum ductility, alloys with low sulfur levels (<0.01%) can be supplied by producers using ladle-refining techniques.

In general, wear resistance can be improved by increasing the hardness of an alloy, by specifying an alloy with greater carbon content (without increasing hardness), or by both. The surface of a flame-hardened, medium-carbon steel, for example, is likely to have poorer wear resistance than the carbon-rich case of a carburized steel of equal hardness. Exceptions are nitrided parts, which have better wear resistance than would be expected from the carbon content alone.

For any combination of alloy steel and heat treatment, three factors tend to decrease toughness: low service temperature, high loading rates, and stress concentrations or residual stress. The general effects of these three conditions are qualitatively similar, so low-temperature impact tests (to -50°F) are useful for many applications as toughness indicators under various service conditions and temperatures.
Fully hardened-and-tempered, low-carbon (0.10 to 0.30% C) alloy steels have a good combination of strength and toughness, both at room and low temperature. Care must be taken in heat treatment of certain alloy-steel grades, however, because toughness may be decreased substantially by temper brittleness - a form of embrittlement developed by slow cooling through the range of 900 to 600°F, or by holding or tempering in this range. When liquid quenching is impractical (because of the danger of cracking or distortion, or because of cost), various low-carbon nickel or nickel-molybdenum steels in the normalized-and-tempered condition can be used for low-temperature service.

Wrought alloy steels (and carbon steels) are classified by a series of AISI and SAE numbers that designate composition and alloy type. Letters, which are used in addition to the four-digit designations, include the suffix "H," used for steel produced to specific hardenability limits (which allows wider composition ranges for certain alloying elements), and the prefix "E," which indicates a steel made by the basic electric-furnace method.

Low-alloy steels are designated by the AISI four-digit numerical code similar to carbon steels. The first two digits is the code indicate the major alloying component or components:

- 13xx: Manganese steels
- 23xx, 25xx: Nickel steels
- 31xx, 32xx, 33xx, 34xx: Nickel-chromium steels
- 40xx, 44xx: Molybdenum steels
- 41xx: Chromium-molybdenum steels
- 43xx, 47xx, 8xxx, 93xx: Nickel-chromium-molybdenum steels
  94xx, 97xx, 98xx
- 46xx, 48xx: Nickel-molybdenum steels
- 50xx, 51xx, 50xxx, 51xxx: Chromium steels
  51xxx
- 61xx: Chromium-vanadium steels
- 92xx: Silicon-manganese steels
Other specifications, such as those issued by ASTM, specify minimum properties for critical structural, pressure-vessel, and nuclear applications. ASTM specifications classify cast alloy steels by relating the steel to the mechanical properties and intended service condition. Chemical analysis is secondary. There are ASTM specifications for general use such as A27 or A148 when mechanical properties are critical. For low-temperature service, A352 or A757 is recommended when toughness is important. For weldability, A216 is specified when fabrication is critical, and for pressure service, A217 or A389 is recommended when a number of properties are important. Still other ASTM alloy steels are available for special applications. Other specifications such as SAE J435 are used for cast steels in automotive applications. A summary of steel-casting specifications is available from the Steel Founders' Society of America, Des Plaines, Ill.

**UNS Classification.** Under this system, steels are assigned a series of 4-5 numbers. The first number tells us the primary alloying element or elements, with 1 being plain carbon steel containing no significant alloying element. The second number represents the approximate percentage of the primary alloying elements. The final numbers indicate the approximate carbon content of the steel in hundredths of one percent. The following numbers are assigned for:

1 - Plain Carbon (not an alloy steel)
2 - Nickel
3 - Chromium and Nickel
4 - Molybdenum
5 - Chromium
6 - Chromium and Vanadium
7 - Tungsten
8 - Nickel, Chromium and Molybdenum
9 - Silicon and Manganese

Consider a few examples. With 1084 the first digit tells us that this is a plain carbon steel. The second digit shows that there are no alloying elements.
The final two digits show that the steel contains approximately 0.84 percent carbon. Pretty simple. How about 52100? The first digit shows that the primary alloying element is chromium. The second digit means that there is approximately 2 percent chromium (this is rounded off). The last group of numbers shows that the carbon content is roughly 1 percent. One thing that may puzzle you for a while is the second digit. If a steel is classified as 50xx, then is it a chromium steel with no chromium? No. It is a low chromium steel. For example, steel 50100 contains about 0.45 percent chromium. The 0.45 is not enough to round up to 1 percent, so it gets the value of 0. 52100 usually contains about 1.5 percent chromium, so it gets rounded up to a value of 2. A good way to look at the 5xxx types of steel is:

- 50xx = low chromium
- 51xx = medium chromium
- 52xx = high chromium

### 2.1.3 High-Alloy Steels

High-alloy steels are those containing more than 8% of alloying components. Three major groups of high-alloy steels are wrought stainless steels, cast stainless steels, and tools steels.

#### 2.1.3.1 Wrought stainless steels

One of the features that characterize stainless steels is a minimum 10.5% chromium content as the principal alloying element. Four major categories of wrought stainless steel, based on metallurgical structure, are distinguished:

1. Austenitic stainless steels which, in turn, are classified into three groups:
   - The AISI 200 series (alloys of iron-chromium-nickel-manganese).
   - The AISI 300 series (alloys of iron-chromium-nickel).
• Nitrogen-strengthened alloys.

Carbon content is usually low (0.15% or less), and the alloys contain a minimum of 16% chromium with sufficient nickel and manganese to provide an austenitic structure at all temperatures from the cryogenic region to the melting point of the alloy. Nitrogen-strengthened austenitic stainless steels are alloys of chromium-manganese-nitrogen; some grades also contain nickel. Yield strengths of these alloys (annealed) are typically 50% higher than those of the nonnitrogen-bearing grades. They are nonmagnetic and most remain so, even after severe cold working.

Like carbon, nitrogen increases the strength of a steel. But unlike carbon, nitrogen does not combine significantly with chromium in a stainless steel. This combination, which forms chromium carbide, reduces the strength and corrosion resistance of an alloy. Until recently, metallurgists had difficulty adding controlled amounts of nitrogen to an alloy. The development of the argon-oxygen decarburization (AOD) method has made possible strength levels formerly unattainable in conventional annealed stainless alloys. Austenitic stainless steels are generally used where corrosion resistance and toughness are primary requirements. Typical applications include shafts, pumps, fasteners, and piping in seawater and equipment for processing chemicals, food, and dairy products.

2. Ferritic stainless steels. Ferritic wrought alloys (the AISI 400 series) contain from 10.5 to 27% chromium. In addition, the use of argon-oxygen decarburization and vacuum-induction melting has produced several new ferritic grades including 18Cr-2Mo, 26Cr-1Mo, 29Cr-4Mo, and 29Cr-4Mo-2Ni. Low in carbon content, but generally higher in chromium than the martensitic grades, these steels cannot be hardened by heat treating and are only moderately hardened by cold working. Ferritic stainless steels are magnetic and retain their basic microstructure up to the melting point if sufficient Cr and Mo are
present. In the annealed condition, strength of these grades is approximately 50% higher than that of carbon steels.

Ferritic stainless steels are typically used where moderate corrosion resistance is required and where toughness is not a major need. They are also used where chloride stress-corrosion cracking may be a problem because they have high resistance to this type of corrosion failure. In heavy sections, achieving sufficient toughness is difficult with the higher-alloyed ferritic grades. Typical applications include automotive trim and exhaust systems and heat-transfer equipment for the chemical and petrochemical industries.

3. Martensitic stainless steels. Martensitic steels are also in the AISI 400 series. These wrought, higher-carbon steels contain from 11.5 to 18% chromium and may have small quantities of additional alloying elements. They are magnetic, can be hardened by heat treatment, and have high strength and moderate toughness in the hardened-and-tempered condition. Forming should be done in the annealed condition. Martensitic stainless steels are less resistant to corrosion than the austenitic or ferritic grades. Two types of martensitic steels - 416 and 420F - have been developed specifically for good machinability.

Martensitic stainless steels are used where strength and/or hardness are of primary concern and where the environment is relatively mild from a corrosive standpoint. These alloys are typically used for bearings, molds, cutlery, medical instruments, aircraft structural parts, and turbine components. Type 420 is used increasingly for molds for plastics and for industrial components requiring hardness and corrosion resistance.

4. Precipitation-hardening stainless steels develop very high strength through a low-temperature heat treatment that does not significantly
distort precision parts. Compositions of most precipitation-hardening stainless steels are balanced to produce hardening by an aging treatment that precipitates hard, intermetallic compounds and simultaneously tempers the martensite. The beginning microstructure of PH alloys is austenite or martensite. The austenitic alloys must be thermally treated to transform austenite to martensite before precipitation hardening can be accomplished.

These alloys are used where high strength, moderate corrosion resistance, and good fabricability are required. Typical applications include shafting, high-pressure pumps, aircraft components, high-temper springs, and fasteners.

2.1.3.2 Cast stainless steels

Cast stainless steels usually have corresponding wrought grades that have similar compositions and properties. However, there are small but important differences in composition between cast and wrought grades. Stainless-steel castings should be specified by the designations established by the ACI (Alloy Casting Institute), and not by the designation of similar wrought alloys.

Service temperature provides the basis for a distinction between heat-resistant and corrosion-resistant cast grades. The C series of ACI grades designates the corrosion-resistant steels are divided into three groups:

- Chromium steels (11.5-30.0% Cr and 1-4% Ni).
- Chromium-nickel steels (10.5-30% Cr and 3.5-22.0% Ni)
- Nickel-chromium steels (22.0-34.0% Ni and 18.0-22.0% Cr)

Heat-resistant steels (H-series) are used for structural applications at service temperatures between 1,200 and 2,200°F. Carbon and nickel contents of the H-series alloys are considerably higher than those of the C series. H-series steels are not immune to corrosion, but they corrode slowly - even when exposed to fuel-combustion products or atmospheres prepared for carburizing and nitriding. C-series grades are used in valve, pumps, and fittings. H-series grades are used
for furnace parts and turbine components. Galling and wear are failure modes that require special attention with stainless steels because these materials serve in many harsh environments. They often operate, for example, at high temperatures, in food-contact applications, and where access is limited. Such restrictions prevent the use of lubricants, leading to metal-to-metal contact – a condition that promotes galling and accelerated wear.

In a sliding-wear situation, a galling failure mode occurs first, followed by dimensional loss due to wear, which is, in turn, usually followed by corrosion. Galling is a severe form of adhesive wear that shows up as torn areas of the metal surface. Galling can be minimized by decreasing contact stresses or by the use of protective surface layers such as lubricants (where acceptable), weld overlays, platings, and nitrided or carburized surface treatments.

2.1.3.3 Tool steels

The same properties that qualify tool steels for tools and dies are also used for other parts that require resistance to wear, stability during heat treatment, strength at high temperatures, or toughness. Tool steels are increasingly being used for mechanical parts to reduce size or weight, or to resist wear or high-temperature shock.

Tool steels are metallurgically "clean," high-alloy steels that are melted in relatively small heats in electric furnaces and produced with careful attention to homogeneity. They can be further refined by argon/oxygen decarburization (AOD), vacuum methods, or electroslag refining (ESR). As a result, tool steels are often specified for critical high-strength or wear-resistant applications. Because of their high alloy content, tool steels must be rolled or forged with care to produce satisfactory bar products.

To develop their best properties, tool steels are always heat treated. Because the parts may distort during heat treatment, precision parts should be semifinished, heat treated, then finished. Severe distortion is most likely to occur
during liquid quenching, so an alloy should be selected that provides the needed mechanical properties with the least severe quench.

Tool steels are classified into several broad groups, some of which are further divided into subgroups according to alloy composition, hardenability, or mechanical similarities. Common classification of Tool Steels is as follows:

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description or Notable Properties</th>
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<tbody>
<tr>
<td>W</td>
<td>Water hardening</td>
</tr>
<tr>
<td>S</td>
<td>Shock resisting</td>
</tr>
<tr>
<td>O</td>
<td>Oil hardening</td>
</tr>
<tr>
<td>A</td>
<td>Air hardening</td>
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<tr>
<td>D</td>
<td>Die steel, air hardening, high chromium</td>
</tr>
<tr>
<td>H</td>
<td>Hot work, chromium, tungsten, and/or molybdenum</td>
</tr>
<tr>
<td>T</td>
<td>Tungsten alloy, high speed steel</td>
</tr>
<tr>
<td>M</td>
<td>Molybdenum alloy, high speed steel</td>
</tr>
<tr>
<td>L</td>
<td>Low alloy, special purpose</td>
</tr>
<tr>
<td>F</td>
<td>Carbon-tungsten, special purpose</td>
</tr>
<tr>
<td>P</td>
<td>Mild steels, low carbon and other types</td>
</tr>
</tbody>
</table>

Water-hardening, or carbon, tool steels, designated Type W by AISI, rely solely on carbon content for their useful properties. These steels are available as shallow, medium, or deep hardening, so the specific alloy selected depends on part cross-section and required surface and core hardresses.

Shock-resisting tool steels (Type S) are strong and tough, but they are not as wear resistant as many other tool steels. These steels resist sudden and repeated loadings. Applications include pneumatic tooling parts, chisels, punches, shear blades, bolts, and springs subjected to moderate heat in service.

Cold-work tool steels, which include oil and air-hardening Types O, A, and D, are often more costly but can be quenched less drastically than water-hardening types. Type O steels are oil hardening; Type A and D steels are air
hardening (the least severe quench), and are best suited for applications such as machine ways, brick mold liners, and fuel-injector nozzles. The air-hardening types are specified for thin parts or parts with severe changes in cross-section - parts that are prone to crack or distort during hardening. Hardened parts from these steels have a high surface hardness; however, these steels should not be specified for service at elevated temperatures.

Hot-work steels (Type H) serve well at elevated temperatures. The tungsten and molybdenum high-alloy hot-work steels are heat and abrasion resistant even at 600 to 1,000°F. But although these alloys do not soften at these high temperatures, they should be preheated before and cooled slowly after service to avoid cracking. The chromium grades of hot-work steels are less expensive than the tungsten and molybdenum grades. One of the chromium grades H11, is used extensively for aircraft parts such as primary airframe structures, cargo-support lugs, catapult hooks, and elevon hinges. Grade H13, which is similar to H11 is usually more readily available from suppliers.

High-speed tool steels - Types T (tungsten alloy) and M (molybdenum alloy) – make good cutting tools because they resist softening and maintain a sharp cutting edge at high service temperatures. This characteristic is sometimes called "red hardness." These deep-hardening alloys are used for steady, high-load conditions rather than shock loads. Typical applications are pump vanes and parts for heavy-duty strapping machinery.

Other grades, called special-purpose tool steels, include low-cost, Type L, low-alloy steels, often specified for machine parts when wear resistance combined with toughness is important. Carbon-tungsten alloys (Type F) are shallow hardening and wear resistant, but are not suited for high temperatures or for shock service.

Type P mold steels are designed specifically for plastic-molding and zinc die-casting dies. These steels are seldom used for nontooling components.

2.1.4 Conclusion notes on steels
2.1.4.1 Other steels that may not be subject of the above-discussed classification

Many steel mills have formulated their own special-purpose tool-steel alloy. Such alloys may not match a specific AISI designation and must be specified by trade name. Special-purpose tool steels may be superior to the standard grades when used as intended, but they should be specified only after careful evaluation of mechanical properties, heat-treat behavior, and availability in comparison with the standard grades. As an example, we can consider so-called fatigue-proof steel, which is essentially high-carbon steel with relatively high sulfur content, or stress-proof steel, which is high-carbon steel having high silicon and sulfur content. Although both of them have elevated hardness and good machinability, they lose their nice properties on heating when heating temperature exceeds 600°F.

2.1.4.2 Proper specification of the work material in the FRACAS system

The above-discussed classification is to give you initial ideas about the work material classification. It can be considered as the preparation stage to reveal the real work material properties because the same work material can exhibit considerable different properties depending on its heat, chemical, mechanical or other treatment. Therefore, after establishing to what particular group the work material in question belongs to, it is strongly recommended to use a WEB site: http://www.matweb.com/, which can be used only after a particular group is properly established. Using this site, one should be able to find particular mechanical properties of a given work material and its machinability (as compared against steel 1212 as the reference material). This machinability data along with proper material designation should be inserted in a FRACAS form.

Experience shows that most of tool life and machining quality problems have their origin in the work material. Trying to cut cost of machining and/or enhance part performance, the
automotive industry is in a continuous search for different heat treatments and chemical compositions of work materials. In many cases, these changes are not indicated on part prints. Therefore, in any investigation of tool failure, the first suspect should always be the work material. Obtaining data on its real chemical composition, heat treatment procedure, and actual mechanical properties should be of prime concern.

Example of a report on the work material in a failure report:

I. Initial failure report has specified that a customer uses AISI 1035 steel as the work material.

II. Conducting the FRACAS study, one should, using the above-discussed classification, find out that this is a medium-carbon steel.

III. Opening WEB site: [http://www.matweb.com/](http://www.matweb.com/) click on “Ferrous Metals” and check the option “Medium Carbon Steel” and then click “Find”.

IV. As seen, AISI 1035 Steel can be found in #39, 48, 52-65. To get particular material properties, the further analysis is needed. First of all, one needs to know the method of the steel production. Assume that he/she can get it from customer and it is a cold-drawn steel. Furthermore, OD diameter is also needed. One should request this information from the customer. Assuming that this diameter is 70 mm (2.76 in). After obtaining these data, one should select # 57 that matches the data. By clicking on the selected steel, one will get a table. From this table, the following data should be reported: Tensile Strength, Ultimate; Tensile Strength, Yield; Hardness (Brinell); Elongation, %;

V. In some practical cases, only steel type is available and it is difficult to obtain any further information to conduct the analysis. In this case, the actual hardness of the work material should be
measured using any available in the customer shop method. The Using a conversion table, the obtained results should be converted into Brinell hardness. For example, if KNOOP Hardness in the considered case has been measured and the result is HK 170, then using conversion formula (Isakov, E., Mechanical Properties of Work Materials, Hanser Gardner Publ. Cincinnati, 2000, page 54 – book is available in NB&M Co)

\[ HB = 0.901 \cdot NK - 4.6, \]

one can calculate that the steel has HB 149. Using the table on Page 83 of the same book, one can find out that the Tensile Strength is 75,000 psi. These two results should be reported in the FRACAS form.

Optional to read:

2.1.4.3 HSLA steel

Those steel alloys known as high-strength low-alloy (HSLA) steels provide increased strength-to-weight ratios over conventional low-carbon steels for only a modest price premium. Because HSLA alloys are stronger, they can be used in thinner sections, making them particularly attractive for transportation-equipment components where weight reduction is important. HSLA steels are available in all standard wrought forms -- sheet, strip, plate, structural shapes, bar-size shapes, and special shapes.

Typically, HSLA steels are low-carbon steels with up to 1.5% manganese, strengthened by small additions of elements, such as columbium, copper, vanadium or titanium and sometimes by special rolling and cooling techniques. Improved-formability HSLA steels contain additions such as zirconium, calcium, or rare-earth elements for sulfide-inclusion shape control.
Grades known as "improved-formability" HSLA steels (sheet-steel grades designated ASTM A715, and plates designated ASTM A656) have yield strengths up to 80,000 psi, yet cost only about 24% more than a typical 34,000-psi plain-carbon steel. Because these alloys must compete with other structural metals such as AISI 1010 steel and aluminum, they must be as inexpensive as possible. However, formulating and rolling a steel that meets this cost requirement is not easy, and the finished product presents a number of trade-offs. For example, the increase in strength from 35,000 to 80,000 psi may be accompanied by a 30 to 40% loss in ductility.

Improved-formability HSLA steels were developed primarily for the automotive industry to replace low-carbon steel parts with thinner cross-section parts for reduced weight without sacrificing strength and dent resistance. Typical passenger-car applications include door-intrusion beams, chassis members, reinforcing and mounting brackets, steering and suspension parts, bumpers, and wheels. Trucks, construction equipment, off-highway vehicles, mining equipment, and other heavy-duty vehicles use HSLA sheets or plates for chassis components, buckets, grader blades, and structural members outside the body. For these applications, sheets or light-gage plates are specified. Structural forms (alloys from the family of 45,000 to 50,000-psi minimum yield strength HSLA steels) are specified in applications such as offshore oil and gas rigs, single-pole power-transmission towers, railroad cars, and ship construction. In equipment such as power cranes, cement mixers, farm machinery, trucks, trailers, and power-transmission towers, HSLA bar, with minimum yield strengths ranging from 50,000 to 70,000 psi is used.

Forming, drilling, sawing, and other machining operations on HSLA steels usually require 25 to 30% more power than do structural carbon steels. Most HSLA alloys have directionally sensitive properties. For some grades, formability and impact strength vary significantly depending on whether the material is tested longitudinally or transversely to the rolled direction. For example, bends parallel
to the longitudinal direction are more apt to cause cracking around the outside, tension-bearing surface of the bend. This effect is more pronounced in thick sheets. This directional characteristic is substantially reduced in HSLA steels that have been treated for sulfide shape control.

2.1.4.4 Steels for strength

Developed primarily for high-strength applications, these steels are usually heat-treated alloys that provide strengths at least equal to those of as-rolled steel. Heat-treated constructional alloy steels and the ultrahigh-strength steels are used in applications where high strength can be converted to a weight-saving advantage over other steels.

High-yield-strength, quenched-and-tempered constructional alloy steels are usually heat treated at the mill to develop their properties so they require no further heat treatment by the fabricator. Although these heat-treated alloy steels are available in all conventional product forms, they are most common in plate products. Some grades are also available as abrasion-resistant (AR) modifications. In these conditions, high hardness is the desired property, with some toughness being sacrificed. Over 20 types of these proprietary high-strength alloy steels are produced. Some have been developed to combine improved welding characteristics along with high strength. Most have good impact properties in addition to high strength. An example of the high-yield-strength grades in this class is HY-80/100, which is used for naval vessels. This material combines high strength and toughness with weldability.

Ultrahigh-strength steels start with grade 4340 and are modifications of this alloy. When these steels are used for aerospace components, they are usually produced by the vacuum-arc-remelt (VAR) process. Steels commonly considered to be in the ultrahigh-strength category have yield strengths greater than 180,000 psi. They are classified into several broad categories based on chemical composition or metallurgical-hardening mechanisms.
Medium-carbon alloy steels are generally modifications of grade 4330 or 4340 (usually with increased molybdenum, silicon, and/or vanadium). These grades provide excellent hardenability in thick sections.

Modified tool steels of the 5% Cr, 1% Mo, 1% V hot-work die-steel variety (H11 modified, H13) provide the next step in increased hardenability and greater strength. Most steels in this group are air hardened in moderate to large sections and, therefore, are not likely to distort or quench crack. Structural uses of these steels are not as widespread as they once were, mainly because of the development of other steels costing about the same but offering greater fracture toughness.

Maraging steels contain 18% nickel, along with appreciable amounts of molybdenum, cobalt, and titanium, and almost no carbon. These alloys can be strengthened significantly by a precipitation reaction at a relatively low temperature. They can be formed and machined in the solution-annealed condition but not without difficulty. Weldability is excellent. They can be heat treated to 250 to 300-ksi yield strength with a simple 900°F aging treatment. Fracture toughness of the maraging steels is considerably higher than that of the conventional high-strength steels.

Maraging steels are used in a variety of high-performance applications, and most extensively in aircraft and tooling components. The 9% Ni, 4% Co alloys were designed to provide high strength and toughness at room temperature as well as at moderately elevated temperatures – to about 800°F. Weldability and fracture toughness are good, but the alloys are susceptible to hydrogen embrittlement. These steels are used in airframes, gears, and large aircraft parts.

Iron-based superalloys. Iron, nickel, and cobalt-based alloys used primarily for high-temperature applications are known as superalloys. The iron-based grades, which are less expensive than cobalt or nickel-based grades, are of three types: alloys that can be strengthened by a martensitic type of transformation, alloys that are austenitic and are strengthened by a sequence of hot and cold working (usually, forging at 2,000 to 2,100°F followed by finishing at 1,200 to 1,600°F), and austenitic alloys strengthened by precipitation hardening.
Some metallurgists consider the last group only as superalloys, the others being categorized as high-temperature, high-strength alloys. In general, the martensitic types are used at temperatures below 1,000°F; the austenitic types, above 1,000°F.

The AISI 600 series of superalloys consists of six subclasses of iron-based alloys:
601 through 604: Martensitic low-alloy steels.
610 through 613: Martensitic secondary hardening steels.
614 through 619: Martensitic chromium steels.
630 through 635: Semiaustenitic and martensitic precipitation-hardening stainless steels.
650 through 653: Austenitic steels strengthened by hot/cold work.
660 through 665: Austenitic superalloys; all grades except alloy 661 are strengthened by second-phase precipitation.

Iron-based superalloys are characterized by high temperature as well as room-temperature strength and resistance to creep, oxidation, corrosion, and wear. Wear resistance increases with carbon content. Maximum wear resistance is obtained in alloys 611, 612, and 613, which are used in high-temperature aircraft bearings and machinery parts subjected to sliding contact. Oxidation resistance increases with chromium content.

The martensitic chromium steels, particularly alloy 616, are used for steam-turbine blades. The superalloys are available in all conventional mill forms -- billet, bar, sheet, and forgings -- and special shapes are available for most alloys. In general, austenitic alloys are more difficult to machine than martensitic types, which machine best in the annealed condition. Austenitic alloys are usually "gummy" in the solution-treated condition and machine best after being partially aged or fully hardened.

Crack sensitivity makes most of the martensitic steels difficult to weld by conventional methods. These alloys should be annealed or tempered prior to welding; even then, preheating and postheating are recommended. Welding
drastically lowers the mechanical properties of alloys that depend on hot/cold work for strength.

All of the martensitic low-alloy steels machine satisfactorily and are readily fabricated by hot working and cold working. The martensitic secondary-hardening and chromium alloys are all hot worked by preheating and hot forging. Austenitic alloys are more difficult to forge than the martensitic grades.

2.2. Cast Irons

Cast irons are specified as common and special cast irons.

The basic property of standard work materials may be found using the following URL:
ISO 4948-1:1982
Steels -- Classification -- Part 1: Classification of steels into unalloyed and alloy steels based on chemical Composition
ASM Handbook, Volume 1, Properties and Selection: Irons, Steels, and High-Performance Alloys

Relevant professional/standardization organizations

Society of Automotive Engineers (SAE)
American Iron & Steel Institute (AISI)
American Society for Testing & Materials (ASTM)
American Society for Metals (ASM)
U.S. Government (Mil & Federal) Specifications