Previously, we have discussed the steel chemistries of various alloy compositions and their basic relationships with temperature and carbon content to form the desirable crystalline structures for the mechanical properties needed in the finished product. However, the job is not yet complete without cooling the heated steel.

Grain size is largely dependent upon the steel making practice and is an important factor in governing the mechanical properties of the steel. A fine austenite grain size will generally improve toughness, ductility and fatigue strength but may reduce hardenability.

Why Controlled Quenching & Tempering is Important

by Guy Avellon

Under slow or moderate cooling rates, carbon atoms are able to diffuse out of an austenitic structure to become b.c.c. (body-centered-cubic). With a further increase in cooling rate, insufficient time is allowed for the carbon to diffuse out of solution but cannot become a b.c.c form while the carbon is trapped in solution. The resultant structure is martensite, which is a form of iron in which some carbon is trapped in a body-centered-tetragonal structure. This highly distorted lattice structure is the prime reason for the high hardness of martensite.

The goal of hardening any steel is to produce a fine grain, fully martensitic microstructure, as it is much harder than austenite. Martensite is formed upon cooling. Martensite is formed only from austenite and almost instantaneously at relatively low temperatures. The maximum hardness obtainable from a steel in the martensitic condition is a function of the carbon content only. The minimum cooling rate (ºF or ºC per second) that will avoid the formation of any softer products of transformation is known as the critical cooling rate.

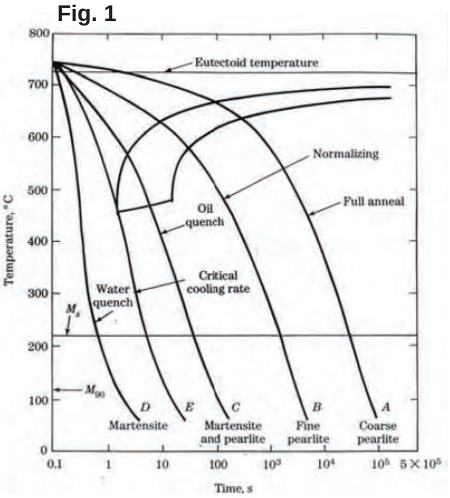
The critical cooling rate is determined by the chemical composition of the steel, the Jominy test and the austenitic grain size. These factors influence how fast steel must be cooled in order to form only martensite. How the steel cools will determine its properties.

Before heating and quenching any steel, a Jominy test must be performed to determine its hardenability. This is where heat lot numbers are important, as each heat lot will have different alloys and/or different chemical content per-centages that will affect the end results. The end-quench hardenability test, or the Jominy test will determine the hardenability of the steel heat lot. After heat treating and quenching per standard methods for that product, hardness readings are taken at 1/16" intervals from the quenched end at a depth of 0.015". Each location on the test piece represents a certain cooling rate. For each steel and alloy, there is a cooling guide called a 'Time-Temperature-Transformation' graph, or TTT for short. It is also known as an Isothermal Transformation Diagram. This is illustrated below, Fig. 1. The bottom axis of the graph is the logarithmic time in seconds. It becomes apparent that the cooling rate must be very fast once the steel cools to 1333ºF (723ºC) to go from austenite to martensite. Misjudge the time and the structure becomes something else. The cooling path chosen determines the structure and properties of the steel.

The combination of heat treating and quenching refines the structure of the steel to enhance its physical characteristics. During the quench, the cap screw's temperature may be brought from above the upper transformation temperature to 600ºF (316ºC) in 2 seconds.

The SAE J429 and several ASTM product standards specify oil quenching on special alloys, such as; A354 BD and SAE Grade 8 cap screws, as well as A449 cap screws ¼" through ¾" diameters. The SAE J429 permits water quench on grades 5 and 5.2. Larger diameter A449 fasteners may be quenched in water. The choice of the quenching liquid is determined by the amount of heat which must be dissipated, a function of the cap screw's cross-sectional area of diameter, and the steel to be quenched.

Fig. 1



Oil quenchants have been the preferred medium for controlled and rapid cooling rates.

However, other quench media have been used and proven effective; such as molten salt, soluble oil-water mixture, polymer solutions, water brine and caustic soda solutions. To achieve specific results, it is desirable to obtain the greatest quench severity that can be used without subjecting the steel to cracking, distortion or excessive stresses that cannot be overcome by subsequent tempering. Due to the high heat of the steel, the quenching media must be controlled to provide optimum results on a continual basis.

After quenching, the tensile strength and hardness of the cap screw often exceeds optimum levels. The SAE J429 specifies a microstructure of approximately 90% martensite prior to tempering. The ‘as quenched’ hardnesses are also taken to confirm core hardness. Since the hardnesses are high enough to produce a brittle material, the cap screws must be ‘softened’ from an additional heat-treating process called tempering.

Tempering

Tempering is required to relieve the internal stresses that are built up during the initial heat treat hardening process. Tempering is similar to the annealing process carried out on the raw steel wire prior to bolt-making procedures. The formation of martensitic steel is extremely hard and very brittle, which also leaves high residual stresses in the steel. Therefore, hardening is almost always followed by tempering or drawing, which consists of heating the steel to some temperature below the lower critical temperature.

Tempering takes the super hardened martensitic structure and makes the cap screw less brittle, more ductile and improves its toughness by transforming the martensite partially into ferrite and cementite. This treatment also increases the steel’s shock resistance, and lowers the tensile strength to desirable levels. It is this combination of heat treating, quenching and tempering that imparts a cap screw with its final physical specifications of hardness, proof load, yield strength and tensile strength. Steel that has a fully martensitic structure before tempering will produce the highest yield strength, the highest ductility, the highest fatigue strength and the greatest toughness.

Some high strength specialty bolts begin life with a steel differing in composition from standard ASTM, ISO or SAE recommended chemical compositions. The basic difference is during the tempering process. Unless enhanced alloys are used and special care is taken with the heat-treating process, cap screws with higher than standard specification tensile strength and hardness are also more brittle. Regardless of the steel choice, it is the heat treatment that determines the fastener’s final characteristics with a 90-100% martensitic structure.

The hardness of tempered martensite allows it to be very suitable for tool steels, since the resistance to abrasion and deformation is important in such applications. It is a common component in machine parts and forging dies. Tempered steels containing silicon are used to make springs and other parts that can be twisted without permanent deformation. By the addition of varying amounts of chromium, manganese and nickel to martensitic steels, very strong and corrosion resistant stainless steel products are produced in the 400 series; surgical instruments, cutlery, ball bearings, valves, pumps and heat exchangers.

Heating, cooling and tempering is a critical art form.