CHAPTER 3

VALVE STEEL MATERIAL AND THERMAL PROCESSING

This chapter discusses the materials used for making internal combustion engine inlet and exhaust valves. The general heat treatments followed for the valve steel materials are also discussed below in detail. The cryogenic treatment (SCT and DCT) performed in the present investigation is also discussed in this chapter.

3.1 SELECTION OF MATERIAL

There are essentially two basic types of steel used to make engine valves. One is "martensitic" steel and the other is "austenitic" steel. The difference is in the microstructure of the steel and how the various ingredients in the alloy interact when the molten steel is cast and cooled. As a rule, martensitic steels are magnetic while austenitic steels are non-magnetic. Steel alloys with a martensitic grain structure typically have a high hardness at room temperature (35 to 55 HRC) after tempering, which improves their strength and wear resistance. These characteristics make this type of steel a good choice for applications such as engine valves. But as the temperature goes up, martensitic steel loses its hardness and strength. Above 773 K (500 ^{o}C) or so, low carbon alloy martensitic steel loses too much hardness and strength to hold up well. For this reason, low carbon alloy martensitic steel is only used for intake valves, not exhaust valves. Intake valves are cooled by the incoming air/fuel mixture and typically run around 673 K to 773 K

(400^{o}C to 500^{o}C), while exhaust valves are constantly blasted by hot exhaust gases and usually operate at 923 K to 1073 K (650^{o}C to 800°C) or higher. Materials that may be used for these valve applications include carbon steel alloys, stainless steels, high-strength nickel-chromium-iron alloys and titanium.

The key difference between intake and exhaust valves is the temperature at which they operate. The exhaust valve is a component for controlling the burning gas flow through a continuous opening and closing. Inlet valves run cooler and are washed with fuel vapours, which tend to rinse away lubrication on the valve stem. So for intake valves, wear resistance may be more important than high temperature strength or corrosion resistance, if the engine will be involved in any kind of endurance racing. Exhaust valves, on the other hand, run much hotter than intake valves and must withstand the corrosive effects of hot exhaust gases. Steels used for manufacturing exhaust valves of internal combustion engines must have high strength and corrosion resistance against combustion products at high temperatures. These are the two most important requirements for exhaust valve steels.

Though austenitic stainless steel can handle high temperatures very well, the steel is softer than martensitic steel at lower temperatures and cannot be hardened by heat-treating. To improve wear resistance, a hardened wafer tip may be welded to the tip of the valve stem, or, in some applications an austenitic stainless valve head may be welded to a martensitic stem to create a two-piece valve that has a long wearing stem and heat resistant head. The only disadvantage with a two-piece valve is that it does not cool as well as a one-piece valve. The junction where the two different steels are welded together forms a barrier that slows heat transfer up the stem. Consequently, a premium valve material is absolutely essential for the exhaust side - especially in turbocharged and supercharged engines and those that inject nitrous oxide to boost power. The materials that are used for making engine valves are 23-8N, 21-2N, 21-4N, En 51, En 52, En 24 & 21-12N. Among these materials, En 52 is commonly used for making inlet valves and the 21-4N for making exhaust valves. 21-4N steel meets the "EV8" Society of Automotive Engineers specification for exhaust valves.

3.2 THERMAL TREATMENT OF En 52 AND 21-4N VALVE STEELS

Heat treatment involves varying the mechanical properties of a material by strategically exposing the product to a heating or cooling process. Heat treatments can have many objectives including increased strength and ductility, lower residual stress, or improved toughness of the material, all of which are done with the primary goal in mind of enhancing the performance and maximizing the service life of the product. All basic heat-treating processes for steel involve the transformation or decomposition of austenite.

The working performance of the valve steel is critically related to its heat treatment. All steels are alloys of iron and carbon, while other alloying elements are added to confer particular properties. Steels can be softened or hardened and have their properties altered by heat treatment. The principal uses of heat treatment are to make further processing operations easier or possible. The first step in the heat treatment of steel is to heat the raw material to a temperature above the austenitizing temperature in order to form austenite and then cooled rapidly. Hardening and tempering develop the appropriate bulk and surface properties. The manipulation of the response to heat treatment is a prime reason for adding alloying elements to steels. The conventional heat treatment cycle varies depending on the material. Martensitic stainless steels normally are hardened by being heated to the austenitizing range of 925 to 1065 ^{o}C and then cooled in air or oil (ASM Handbook 2001). Soaking times employed for sections 13 mm thick and under in the hardening of martensitic stainless steels is 30 to 60 min and for each additional inch of thickness 30 min has proved adequate. Martensitic stainless steels can be quenched in either oil or air. Although oil quench is preferred, air cooling may be required for large or complex sections to prevent distortion or quench crack. Austenitic valve alloys are most often solution treated and aged. The thermal treatment processes for the En 52 and 21-4N valve steels are shown in Figure 3.1.

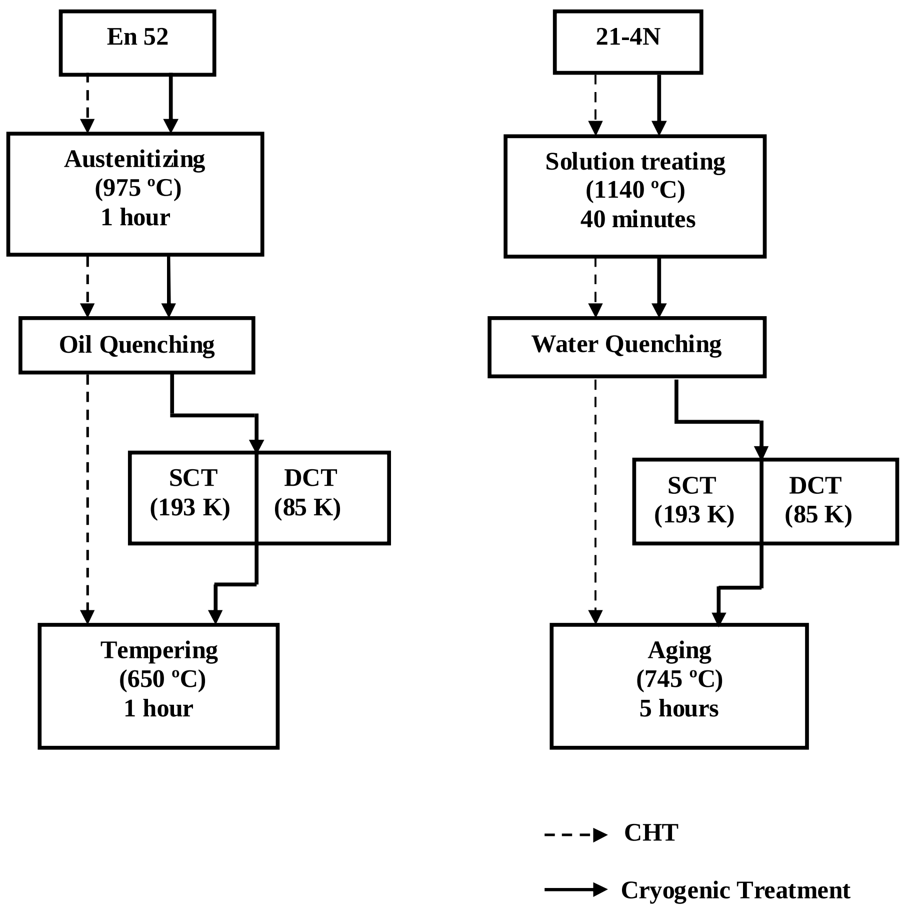

Figure 3.1 Thermal treatment processes for the En 52 and 21-4N valve steels

Yushu Wang (2007) mentioned that typical austenitic valve alloys such as 21-4N, 21-2N, or 23-8N are solution treated at approximately 1050-1200 °C for 30-90 minutes until carbides and nitrides are dissolved in solution. Then they are quenched into cold water to acquire a hardness of 22-35 HRC. Subsequently, age hardening for these alloys is performed above 700-850 ^{o}C for 1-16 hours. The heat treatment for the En 52 and 21-4N valve steels is conducted based on the valve alloy heat treatment discussed by Yushu Wang (2007) and Alok Nayar (2007). The machined specimens are grouped into three and are subjected to three different treatment processes as explained below. The former treatment of valve steel consisted of hardening/ solutionizing and tempering/aging, whereas, in the latter, an additional intermediate step of cryogenic treatment has been incorporated.

3.2.1 Regular Heat Treatment Process

For the En 52 valve steel the heat treatment procedure consists of austenitizing followed by oil quench (quench-hardening) and then tempering. In the quench-hardening process of the En 52 valve steel, the specimens are heated to 1248 K (975 ºC), soaked for 1 hour and then quenched in oil. This rapid cooling from the austenitizing temperature causes the transformation of austenite, which is soft and ductile, into martensite, which is very hard and brittle. This also suppresses the conversion of austenite into ferrite and cementite. Hence, the structure of hardened steel consists mainly of tetragonal martensite and some amount of retained austenite that depends on the chemical composition of steel. This transformation is diffusion-less and time-independent, and there is no change in the chemical composition. The hardening of steel depends entirely on the formation of martensite. It increases the compressive strength and wear resistance of steels, but by itself leaves the steel very brittle. So, after quench hardening, the samples are immediately subjected to tempering. This is the process of reheating the hardened steel to 923 K (650 ºC) (Alok Nayar 2007) and holding it for 1 hour and then cooling it in air to impart toughness. Tempering is carried out to reduce brittleness even by sacrificing some hardness and tensile strength, to relieve internal stresses, and to increase toughness and ductility.

Austenitic valve steel (21-4N) is an iron-based austenitic precipitation-hardened stainless steel. So it is solution-treated and quenched in water; this is followed by precipitation hardening. Solution-heated processes are usually used in metals that have an affinity for carbon; they include iron, aluminium, titanium, niobium, molybdenum and even nitrogen, as well as a number of others. In this process, the materials are heated to the austenizing temperature and held for a short period while those compounds dissolve, and then the samples are quenched in water. In solutionizing, the valve steel samples are heated to 1413 K (1140 ºC) and held for 40 minutes followed by a water quench. After solution-heating the samples are subjected to the aging process. It is the process of reheating the solution-heated valve steel to 1018 K (745 ºC) and soaking it for 5 hours followed by cooling it in air. In the aging process the alloying elements diffuse through the microstructure and form inter metallic particles. These inter metallic particles will nucleate and fall out of the solution and act as a reinforcing phase, thereby increasing the strength of the alloy.

3.2.2 Cryogenic Treatment Process

The cryogenic treatment is performed as an add-on process over the normal heat treatment process of the valve steels to enhance its properties. Cryogenic treatment is an extension of the conventional heat treatment to achieve 100% martensite. This treatment alters the material microstructure that enhances its strength and wear resistance. Cryogenic treatment is the process of cooling a material to extremely low temperatures to generate enhanced mechanical and physical properties. There are two types of cryogenic treatment, called “shallow cryogenic treatment”, treated at temperatures around 193 K (−80 ^{o}C), and “deep cryogenic treatment”, treated at temperature closer to the liquid nitrogen temperature. For maximum benefits cryogenic treatment should be introduced between the hardening and tempering processes (Vimal et al 2008).

3.2.2.1 Shallow Cryogenic Treatment

After hardening the En 52 valve steel samples in the conventional process, the samples are directly placed in the mechanical freezer at 193K (–80 ^{o}C), and soaked for an hour. The samples are removed from the freezer and allowed to reach ambient temperature. They are then tempered at 923 K (650 ^{o}C) for an hour. For the 21-4N valve steel the solutionized samples are kept in the mechanical freezer at 193K (–80 ^{o}C) and soaked for an hour, and then removed and aged at 1018 K (745 ^{o}C) for 5 hours (Alok Nayar 2007).

3.2.2.2 Deep Cryogenic Treatment

In order to achieve deep cold temperatures, materials cannot be directly kept in the freezer at 85 K similar to that of shallow cryogenic treatment, because the temperature difference is very high and fast cooling will lead to quench cracks. In the present investigation the En 52 valve steel material which has undergone the conventional hardening and the solutionized 21-4N valve steel are slowly cooled from room temperature to 85K at a rate of 1 K/min, soaked at 85 K for 24 hours, and finally heated back to the room temperature at a rate of 0.6 K/min. This controlled process is achieved using the computerized control A.C.I. CP-200vi (Massachusetts, U.S.A) cryogenic treatment processor.

3.2.2.3 Cryogenic treatment processor

The processor is a well-insulated chamber with liquid nitrogen as the working fluid. Figure 3.2 shows the image of the cryogenic treatment processor. The cryogenic processor consists of a treatment chamber, which is connected to a liquid nitrogen tank (MVE DURA-CYL 160MP) through a vacuum insulated hose. The temperature sensors inside the chamber sense the temperature and accordingly the PID temperature controller operates the solenoid valve to regulate the liquid nitrogen flow. The liquid nitrogen passes through the spiral heat exchanger and enters the pipe leading to the bottom of the chamber as nitrogen gas. The blower at the top of the chamber sucks the gas coming out at the bottom and makes it circulate effectively inside the chamber and reduces the chamber temperature.

Figure 3.2 Cryogenic treatment processor

The programmable temperature controller of the cryogenic processor is used to set the deep cryogenic treatment parameters, which in turn, controls the solenoid valve and the heater in the chamber to achieve process parameters like soaking time, temperature and cooling rate. Through the data acquisition system, the deep cryogenic treatment processes are recorded and stored. The En 52 samples taken out from the processor are tempered at 923 K (650 ^{o}C) for an hour and the 21-4N are aged at 1018 K (745 ^{o}C) for 5 hours.