

# THE EFFECT OF QUENCHING CONDITIONS ON THE HARDNESS OF N690 STEEL

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Quenching is a commonly used method of heat treatment of steels with the objective of achieving the desired properties, most often increasing of hardness. To achieve the desired properties, it is important to correctly set the technological and process parameters, especially the correct quenching temperature, time endurance, the cooling rate and the quenching medium selection. The influence of the selected quenching conditions on the steel hardness modification is monitored in the submitted contribution. The hardness modification dependent on the variable quenching conditions is monitored during the heat treatment of N690 steel. The monitored parameters are the time endurance at the quenching temperature and the use of various quenching media. The time endurance at the quenching temperature was chosen to be 0 min., 10 min., and 17 min. The quenching media selected were water, Mogul TK 22 oil, and compressed air cooling. The results achieved show that the highest average hardness values were reached by N690 steel samples cooled in oil with an endurance time of 10 min.

## KEYWORDS

N690 steel, heat treatment, quenching, quenching conditions, Rockwell hardness test

## 1 INTRODUCTION

Various types of advanced material have come to the foreground in the development of many industries, but steel is still one of the most widely used materials due to its relatively low cost, use in many technical applications, and good mechanical properties that can be improved by heat treatment [Nunes 2018].

Stainless steels are particularly popular among the steels. Due to their resistance to corrosive degradation caused by the environment, stainless steels have found applications in various fields such as the marine industry, the chemical and petroleum industries, the food industry, and nuclear energy [Boucherit 2021, Zhang 2022].

One of the stainless steels used frequently is BÖHLER N690, that is a martensitic chromium corrosion-resistant steel with a high carbon content with the addition of cobalt, molybdenum and vanadium. In general, martensitic stainless steels (MSS) are characterized by a good combination of high strength and ductility [Ciger 2021]. Since casted MSS consists mainly of massive ferrite and granular carbide dispersed in a ferrite matrix, its wear and fatigue resistance cannot meet certain requirements. Heat treatment is often used to extend the service life of MSS and to improve surface hardness and other mechanical properties. After quenching, the structure of MSS consists of martensite, ferrite and small amount of carbide. It is the martensite in the steel that improves the wear resistance and surface strength of the steel [Agarwal 2024, Zhang 2019]. As mentioned above, mechanical properties can be improved by effective heat treatment. Quenching before tempering is a key technique to improve the mechanical properties of steels, where the final structure is significantly affected by the quenching conditions during the heat treatment [Zhang 2018, Wang 2023].

Quenching is commonly used heat treatment process used to control the mechanical properties of the steel. In short, quenching consists of raising the temperature of the steel above a certain critical temperature, called the austenitizing temperature, maintaining it at this temperature for a specified period of time, and then rapidly cooling it in a suitable medium to room temperature. The resulting microstructures formed by quenching (ferrite, pearlite, bainite, and martensite) depend on the cooling rate and the characteristics of the steel, which are commonly expressed in the continuous cooling transformation (CCT) diagram [Silva 2004, Podaril 2019]. The purpose of quenching is to increase the hardness of the steel by creating an imbalanced structure. High hardness can be achieved by creating a martensitic structure. In some specific cases, we try to achieve a bainitic structure during quenching. In real hardening processes, a martensitic structure is usually achieved on the surface of the body, creating mixture of martensite, bainite, and other types of microstructures in the core of the body [Almula 2023, Amosun 2023, Podaril 2019].

The main parameters of the quenching process are therefore the austenitization temperature and time and the cooling rate. The grain size is a function of the austenitization temperature and time. A coarse austenite grain size can promote quenching and increase the proportion of retained austenite. On the other hand, a finer austenite grain size, obtained at lower austenitization temperatures, results in finer martensite units, which provide higher strength and toughness. The most common quenching media are mineral oils, water and water solutions and salts. The severity of the quenching fluid depends on its ability to mediate the heat transfer at the hot metal interface during quenching. Its selection depends on the hardenability of the alloy and the cooling rate required to achieve the desired microstructure [Adasooriya 2021, Park 2020, Nunes 2018].

The submitted contribution is devoted to the assessment of the selected quenching process parameters influence on the hardness modification of BÖHLER N690 steel. The manufacturer of this steel states that after proper quenching, BÖHLER N690 steel should reach a hardness of 59-61 HRC. The manufacturer specifies a quenching temperature of 1030 - 1050 °C, but the quenching conditions are not specified. Therefore, taking into account the above-mentioned factors affecting the resulting hardness of quenched samples, the time endurance at the austenitizing temperature and the type of quenching medium were selected as the assessed parameters affecting the modification in HRC hardness. Water, Mogul TK 22

quenching oil and compressed air were used as the quenching medium.

The endurance time of the samples at the austenitizing temperature was chosen to be 0 min., 10 min. and 15 min., while the time endurance of 0 min means that samples were placed in the hardening furnace even during the furnace ramp-up to the hardening temperature and after reaching it, the samples were quenched in the hardening medium. After conducting experiments, it was demonstrated that in order to achieve compliance in the achieved HRC hardness with the values stated by the manufacturer, it is advantageous to use oil as a quenching medium, with the highest HRC hardness values achieved by samples left at the austenitizing temperature for 10 min.

## 2 DESCRIPTION OF EXPERIMENTAL PROCEDURE

Samples made of BÖHLER N690 steel were subjected to the quenching process. Samples with dimensions of 10 mm x 20 mm x 5 mm (l x w x h) were prepared from steel blanks. The chemical composition of BÖHLER N690 steel is given in Tab. 1.

**Table 1.** Chemical composition of BÖHLER N690 steel

Element	Concentration, wt. %
C	1.08
Mn	0.4
Si	0.4
Cr	17.3
Mo	1.1
V	0.1
Co	1.5

The producer of BÖHLER N690 steel states that with proper hardening, this steel should reach a hardness of 59-61 HRC. The manufacturer prescribes a hardening temperature in the range of 1030-1050 °C. No further specifications of hardening conditions are given. Since the manufacturer does not state the endurance time at the hardening temperature, 18 samples were produced for experiment, divided into 3 groups of 6 samples each.

The first group was hardened in water, the second in Mogul TK 22 hardening oil, and the third was cooled with compressed air. These three groups were divided into 3 series of 2 samples each. Each series of samples had a different endurance time at the hardening temperature. The first series was hardened as soon as it reached the quenching temperature, while the samples from this group were placed in the quenching furnace even during its rise to the quenching temperature.

**Table 2.** Quenching conditions overview for individual samples

Quenching medium	Time endurance		
	1. Series 0 min.	2. Series 10 min.	3. Series 15 min.
Water	Sample 1	Sample 3	Sample 5
	Sample 2	Sample 4	Sample 6
Oil Mogul TK 22	Sample 7	Sample 9	Sample 11
	Sample 8	Sample 10	Sample 12
Pressurized air	Sample 13	Sample 15	Sample 17
	Sample 14	Sample 16	Sample 18

The samples of the second series were quenched after 10 minutes of endurance time at the quenching temperature and the last series of samples were quenched after 15 minutes of

endurance time at the quenching temperature. The quenching temperature, or austenitization temperature, was selected and maintained at 1050 °C. The distribution and designation of the individual samples is given in Tab. 2.

Quenching of N690 steel samples was performed in an electric hardening furnace, where the samples in the first series were placed first and then heating was started to the final temperature of 1050 °C. After reaching the temperature, the first 6 samples from the first series were taken first and quenched. When the furnace was opened, the temperature dropped by approximately 100 °C. The second series of samples was quenched only after the quenching temperature was reached again and 10 minutes had elapsed. The third series was quenched in the same way with 15 minutes time endurance at the quenching temperature. A schematic representation of the furnace heating time diagram and the time endurance of the samples at the austenitizing temperature is shown in Fig. 1.



**Figure 1.** Temperature and sample heating curve diagram

The hardness measurement was performed using a Vilson 574 hardness tester with automatic evaluation of hardness values. The hardness was evaluated in accordance with ISO 6408-1, Rockwell hardness test using the HRC method. The indenter consists of a diamond cone with a 120° apex angle and a tip radius of 0.2 mm, which is preloaded with a force of 98.07 N for 3 seconds, at which the tip of the cone reaches the initial measurement position. Subsequently, the test sample is loaded with main force of 1.471 kN. The time endurance at the main loading force is 4 seconds.

At the end of the test, the indenter returns to the preload position and an automatic evaluation of the obtained indentation depth of the indenter is performed. Before the hardness test itself, all samples were cleaned with a wire brush and then the surfaces intended for measurement were grounded to remove oxidation layers and other impurities. Grinding was performed using a belt grinder using an A100 grit sanding belt. On each sample, the hardness was verified in three places by three indentations. The first indentation is placed directly in the axis of symmetry of the rectangle and the other two are placed at least 4 mm from the edge.

## 3 RESULTS AND DISCUSSION

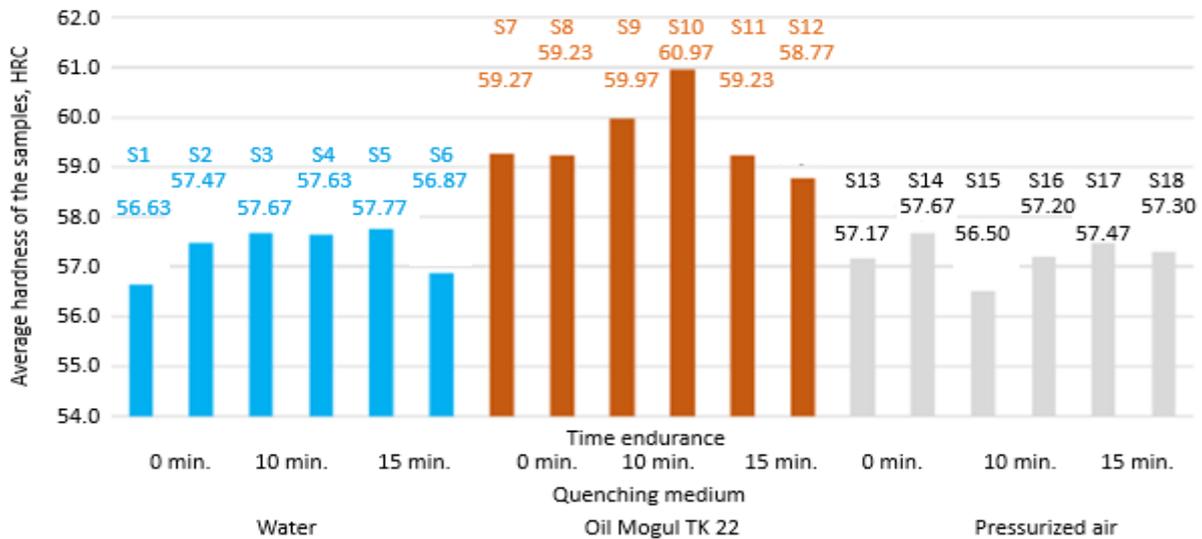
### 3.1 Hardness measurement of BÖHLER N690 steel quenched samples

When measuring the HRC hardness of individual samples quenched under variable quenching conditions, the hardness values shown in Tab. 3 were obtained.

For better visualization of the HRC hardness values comparison of samples quenched under variable quenching conditions, a graph comparing the average hardness of samples quenched under variable quenching condition was constructed, shown in Fig. 2.

**Table 3.** HRC hardness values of individual samples

Quenching medium	Time endurance	Sample No.	Hardness 1. indent, HRC	Hardness 2. indent, HRC	Hardness 3. indent, HRC	Average, HRC
Water	0 min.	Sample 1	57.3	56.4	56.2	56.63
		Sample 2	57.0	57.9	57.5	57.47
	10 min.	Sample 3	58.0	57.2	57.8	57.67
		Sample 4	57.6	57.4	57.9	57.63
	15 min.	Sample 5	58.0	57.9	57.4	57.77
		Sample 6	56.2	56.8	57.6	56.87
Oil Mogul TK 22	0min	Sample 7	58.1	59.6	60.1	59.27
		Sample 8	58.8	59.3	59.6	59.23
	10 min.	Sample 9	59.8	60.1	60.1	59.97
		Sample 10	60.6	59.8	62.5	60.97
	15 min.	Sample 11	58.6	58.9	60.2	59.23
		Sample 12	59.1	58.0	59.2	58.77
Pressurized air	0 min.	Sample 13	56.2	57.9	57.4	57.17
		Sample 14	57.6	57.2	58.2	57.67
	10 min.	Sample 15	56.6	57.0	55.9	56.50
		Sample 16	57.5	57.2	56.9	57.20
	15 min.	Sample 17	58.4	57.1	56.9	57.47
		Sample 18	57.3	57.8	56.8	57.30
Initial without processing		Referential	16.2	15.6	17.4	16.40



**Figure 2.** Comparison of average hardness values of individual samples

As emerges from Tab. 2, certain differences in the hardness of samples are evident, especially depending on the quenching environment. Although the differences are relatively small, the lowest hardness values were measured for samples quenched with compressed air, because the cooling rate was probably not sufficient. Another interesting point is the relatively low, almost comparable hardness of samples quenched in water, which of these three quenching media removes heat from quenched material the fastest. The cause of such low hardness during quenching in water may be the formation of a steam cushion, which will not allow sufficient heat dissipation from the steel. For further experiments, it would certainly be more appropriate to use a water shower, which prevents the formation of steam

cushions. Samples quenched in Mogul TK 22 quenching oil achieved a relatively high average hardness of 58.7-60.9 HRC, which is quite satisfactory considering that these measured hardness values practically coincide with the hardness range specified by the manufacturer.

### 3.2 Assessment of selected samples microstructure

The objective of performing metallographic tests (microstructure of samples) is to compare the structure of the starting material and the quenched one. 18 samples were subjected to heat treatment and hardness evaluation. For the assessment and comparison of the internal structure, a sample labeled Sample 10 (S10) was selected, which achieved the highest average hardness of 60.97 HRC, and a reference

sample, without heat treatment, with an average hardness of 16.40 HRC. It can be predicted that if the quenched sample Sample 10 achieved a hardness of around 60 HRC, it is likely to be a martensitic structure with austenitic matrix. After metallographic preparation of the samples, the samples were etched in Nital etchant with a concentration of 5% for 45 s [Gulyaev 2022]. Metallographic assessment was performed on an Olympus GX51 microscope at 100x magnification. Microstructure of the reference sample, i.e., unheated, is presented in Fig. 3.

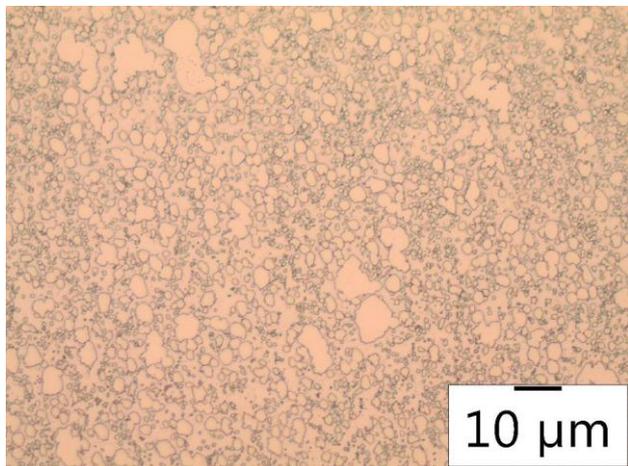


Figure 3. Microscopic structure of the reference sample /x100/

The cross-sectional area shows an annealed structure, where retained austenite (darkly outlined features) is present in the martensitic matrix, with irregularly larger grains of retained austenite present in some places [Turtelli 2006]. The very dark particles are complex chromium carbides M<sub>23</sub>C<sub>6</sub> (M<sub>7</sub>C<sub>3</sub>), which occur preferentially in the underlying martensitic matrix. Microstructure of the heat-treated Sample 10 (S10) is presented in Fig. 4.

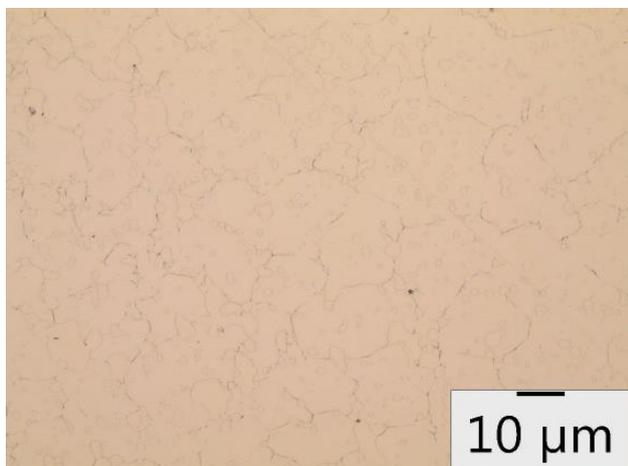


Figure 4. Microscopic structure of Sample 10 /x100/

In the cross-section, a cloudy structure and complex chromium carbides (M<sub>23</sub>C<sub>6</sub> or M<sub>7</sub>C<sub>3</sub>) are visible. They reveal the former boundaries of large austenitic grains, occasionally dark bands containing numerous (concentrated) carbides are visible. At the boundaries of the earlier austenitic grains. Isolated coarse carbides are visible, mainly complex chromium carbides M<sub>23</sub>C<sub>6</sub>. The larger number of carbides is small due to the low carbon content of 1.08 wt. %. Residual austenite of variable size is visible in the martensitic matrix and at the boundaries of the original austenitic grains.

## 4 CONCLUSIONS

The contribution deals with the influence of selected quenching conditions on the resulting hardness of samples made of BÖHLER N690 steel. The quenching temperature was maintained at 1050 °C. At this temperature, the selected samples were left for a time endurance of 0 min., 10 min. and 15 min. Water, Mogul TK 22 quenching oil and compressed air were used as the quenching medium. Based on the results obtained from the experiments performed, it can be stated that the highest HRC hardness was achieved is samples that were quenched in oil with the endurance time at the quenching temperature for 10 min.

Despite the achieved results and the setting of the quenching process for BÖHLER N690 steel in laboratory conditions, it must be stated that the steel manufacturer does not recommend a specific type of quenching oil and the Mogul TK 22 quenching oil was used in the experiment. In this direction, the authors want to continue research and experiment with quenching oils of different characteristics when quenching steels.

It is also necessary to clarify the fact that water-quenched samples achieve lower hardness than oil-quenched samples, while water, due to its higher thermal conductivity, should remove heat from the quenched samples more intensively than oil. However, this phenomenon could have occurred because steam cushions surrounded the samples during water quenching and thus heat was not removed quickly. To optimize this type of heat treatment, it would therefore be appropriate to use a water shower, which prevents the formation of steam cushions during the quenching of components. Research will continue in this direction as well.

The presented results will serve as a platform for further research in the field of heat treatment and enhancement of the performance and quality properties of martensitic stainless steels. Subsequently, they expand the knowledge base in the field of heat treatment of metals, which is part of technically oriented subjects taught at all levels of education.

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