15th Scientific/Research Symposium with International Participation
„METALLIC AND NONMETALLIC MATERIALS“ B&H, 24th and 25th April 2025

ISOTHERMAL QUENCHING STEEL 100Cr6

Almaida Gigović-Gekić, Diana Ćubela, Hasan Avdušinović, Amer Karić
University of Zenica, Faculty of Engineering and Natural Sciences
Travnička cesta 1, Zenica
Bosnia and Herzegovina

Branka Muminović
Institute “Kemal Kapetanović”
Travnička cesta 7, Zenica
Bosnia and Herzegovina

Keywords: bearing steel, 100Cr6 steel, isothermal quenching, microstructure, hardness,

ABSTRACT

Steels for rolling bearings are important in the world production of special steels. They are used for the production of rolling bodies and rings. Since these are very responsible parts in machine construction, high-quality standards are required for these steels. The service life of rolling bearings, in addition to working conditions also depends on the properties of the steel used for their production and the production technology. Heat treatment is one of the phases in the production of the bearing and has a significant influence on the final properties of the bearing. This paper presents the results of testing the influence of isothermal quenching at two different temperatures and for different holding times on a microstructure and hardness of steel 100Cr6. Isothermal quenching is often used in practice to avoid tempering after quenching.

1. INTRODUCTION

Steels for rolling bearings have high and uniform hardness, resistance to wear and fatigue, high strength and toughness, corrosion (pitting) resistance and good workability. Requirements for the uniformity of the chemical composition of this steel, the content and arrangement of non-metallic inclusions and the distribution of carbides are very strict, and this is one of the most demanding types of steel in terms of production. The stated requirements must be fulfilled with the appropriate choice of chemical composition, metallurgical production process, plastic deformation process, heat treatment, grinding and fine finishing. Rolling bearings have been produced for decades and over time the types of steel used for production have become established, so today use of high hardness and low inclusion content clean steel for fatigue and wear resistance, use of carburised grade surface hardened steel for improved fatigue, wear and pitting resistance and use of stainless grade steel for resistance against severe environmental factors [1,2]. The Bearing Steel Market was worth approximately USD 5.9 billion in 2022 and is projected to expand at a CAGR exceeding 3.2% from 2023 to 2032. The high carbon chromium bearing steel segment held a significant share, valued at USD 2.857 billion in 2022. This type of steel, including SAE 52100 (and its equivalents 100Cr6 and EN-31), is extensively utilized across the automotive, aerospace, industrial machinery, and power generation industries [3]. The term hardened steel is usually used for a medium or high carbon steel which is quenched and tempered. A carbon content of about 1% satisfies the need to achieve high hardness as well as an even distribution of carbides, thanks to which resistance to mechanical wear is achieved. The chromium content of 0.5 to 1.5 % gives these steels good hardenability up to the critical section of 30 mm. To ensure better hardenability (larger cross-section), steels are additionally alloyed with manganese, silicon and molybdenum. In addition to hardenability, with an increase in the content of chromium, and especially molybdenum, the toughness in the hardened state also improves. Molybdenum also reduces sensitivity to overheating. The quenching temperature typically ranges from 830 to 870°C. This is usually followed by cooling in oil, although it can also be done in water for simpler shapes. The tempering temperature is in the area of incomplete dissolution of carbides, and such carbides are harder than martensite and do not affect the reduction of hardness, even increasing the resistance to mechanical wear. In addition to cooling in water and oil, a salt bath heated from 220 to 250 ˚C can be used as a means of cooling, after which a bainitic microstructure is obtained, with a hardness of about 59 HRC [4]. After the hardening process, the steel attains very high hardness and strength but remains brittle and lacks resistance to dynamic loads. In order to reduce brittleness, hardness and strength, and increase toughness and resistance to dynamic loads, the material is tempered. Tempering is done in the interval from 160 to 500 ºC, depending on the desired hardness, followed by air cooling. The hardness achieved after hardening and tempering is about 64 HRC [2,4].

The aim of the tests conducted in this study is to determine whether the isothermal hardening process, compared to conventional hardening and tempering, can produce a material suitable for the production of rolling bearings. A good combination of high hardness, impact strength and plasticity can be achieved through the use of the isothermal quenching. The isothermal quenching is based on austenitization followed by rapid cooling to bainitic transformation temperature and remaining at this temperature for the time needed to complete the bainite conversion and final cooling to ambient temperature [5]. The bainite microstructure in 100Cr6 bearing steel can be classified into upper and lower bainite in terms of carbide precipitation. The lower bainite, in which bainite carbide is formed inside bainite ferrite, is the expected microstructure in isothermal quenching due to its high hardness and toughness [6]. Numerous studies have focused on the isothermal quenching process and improving strength and toughness of bainitic 100Cr6 bearing steel. Through choosing isothermal quenching temperature and extending holding time properly, Krishna et al. [7] have found that the impact toughness has been improved remarkably due to obtaining more lower bainitic microstructure in the matrix. Moreover, it is found that optimizing the martensite-bainite (M/B) duplex microstructure can improve the impact toughness without sacrificing strength [6]. In this way, there would be no need for the tempering process, which would save energy and time, and consequently money.

2. EXPERIMENTAL PART

Material tested in this work was the steel 100Cr6 with a chemical composition given in Table 1 and mechanical properties in Table 2.

Table 1. Chemical composition of 100Cr6 steel [8,9,10]

	Chemical composition [wt. %]							
	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Mo**
ASTMA295	0.98/ 1.10	0.15/ 0.35	0.25/ 0.45	max. 0.025	max. 0.025	1.30/ 1.60	max. 0.25	max. 0.10
ISO 683-17	0.93/ 1.05	0.15/ 0.35	0.25/ 0.45	0.025	0.015	1.35/ 1.60	-	max. 0.10
Sample	0.95	0.35	0.43	0.007	0.016	1.60	0.22	0.03

Table 2. Mechanical properties of 100Cr6 steel in soft annealing state [8]

Tensile testing	Yield strength [N/mm^2]	441
	Tensile strength [N/mm^2]	714
	Elongation after fracture [%]	25
	Reduction of area [%]	63
Absorbed energy	KV 150 [J]	6.1
Hardness	HB 2.5/187.5	206

From Table 1, it can be seen that the chemical composition of the steel complies with ASTM 295 and ISO 683-17 standards. Table 2 presents average values the mechanical properties obtained through tensile, impact, and hardness testing, although the mentioned standards prescribe only the hardness value. The achieved hardness value for the annealed condition meets the standard requirement, which is a maximum of 207 HB [9,10] for both standards.

An isothermal hardening heat treatment was performed on two series of 100Cr6 steel samples with dimension Ø20 x 15 mm in the soft annealed state. The quenching temperature of 860°C and soaking time of 10 minutes were the same for both series. However, the first series of sample isothermal quenched at 400°C for different time: 10 seconds (sample 1), 100 seconds (sample 2), and 1000 seconds (sample 3), after which they were air-cooled. The second series of samples was isothermally quenched at 250°C for different time: 100 seconds (sample 1.1), 1000 seconds (sample 1.2), and 7200 seconds (sample 1.3), after which they were air-cooled. The samples were heated in a chamber furnace without a protective atmosphere.

The microstructural analysis was carried out using an Olympus optical microscope with maximum magnification of 1000x and hardness testing was performed in accordance with the standards BAS EN ISO 6506-1:2015 [11] and BAS EN ISO 6508-1:2017 [12].

The determination of the presence and quantity of magnetic phases in steel (pearlite, bainite, martensite) as well as non-magnetic phases (retained austenite/carbides) was performed using the Feritscope MP30E device, manufactured by Helmut Fischer GmbH (Figure 1).

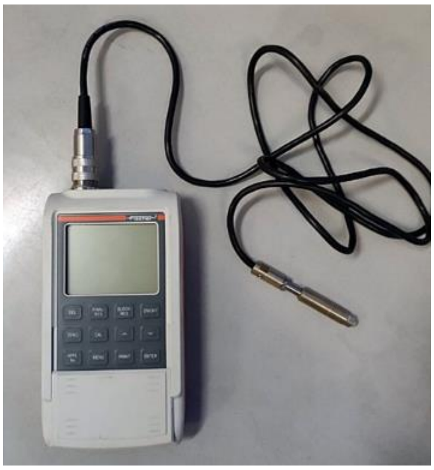


Figure 1. Feritscope MP30E device, manufactured by Helmut Fischer GmbH

3. RESULTA AND ANALYSIS

3.1. Microstructure analysis

The microstructure was examined on samples that were metallographically prepared by grinding, polishing, and etching in a 2 and 5% Nital solution. The results of the microstructural analysis are shown in Figures 2 - 4. A microstructure sample in the soft annealed state is shown in Figure 2. The microstructure consists of ferrite with spheroidized carbides.

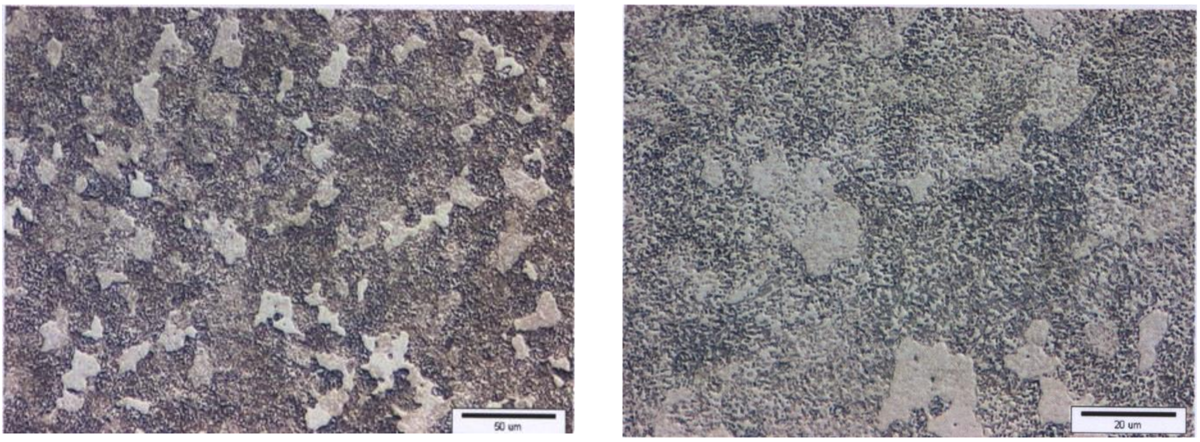
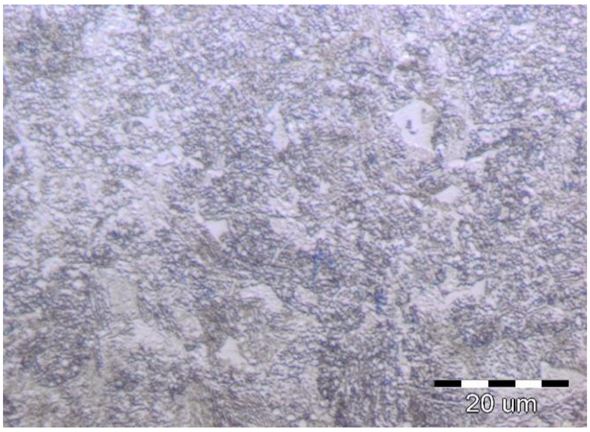
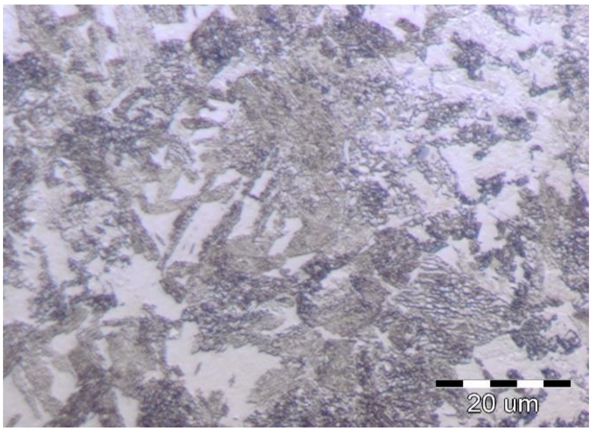


Figure 2. Microstructure sample in a soft annealed state, Nital 2%

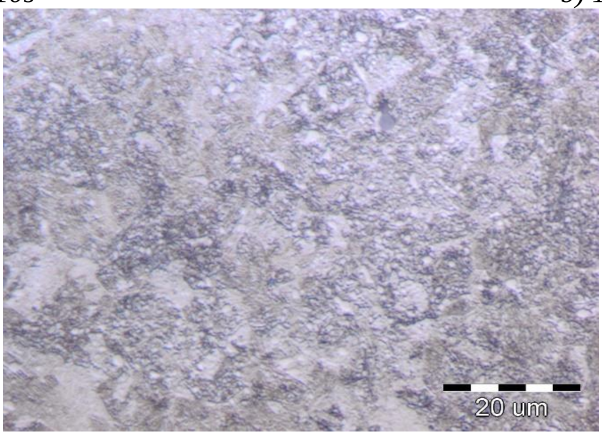
Figure 3 illustrates the results of the microstructural analysis for samples that were isothermally quenched at 400°C. The analysis revealed that the microstructure primarily consists of a ferrite/pearlite structure with unevenly distributed carbides. Pearlite is present in both lamellar and spheroidized forms. No carbides were observed on the ferrite grains. With longer holding times, bainite also appears in the microstructure. After a holding time of 100 seconds, the presence of rod-like pearlite was observed.



a) 10s



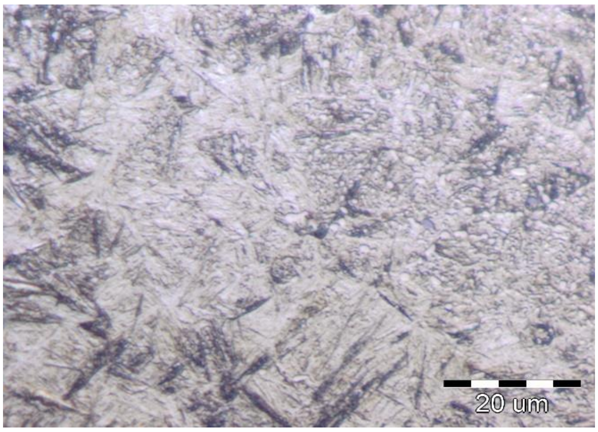
b) 100s



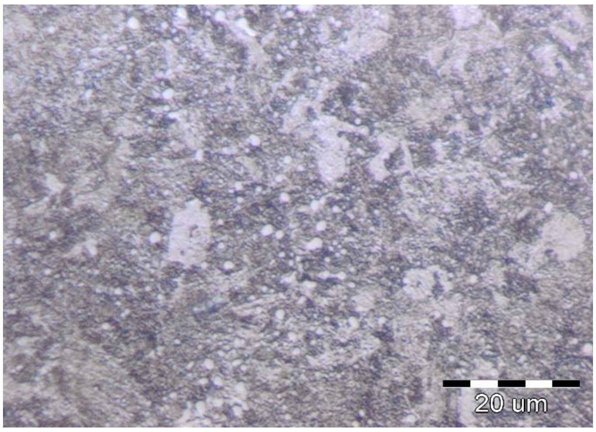
c) 1000s

Figure 3. Microstructure 100Cr6 steel after isothermal quenching at 400 °C for a) 10s, b) 100s and c)1000s, Nital 5%

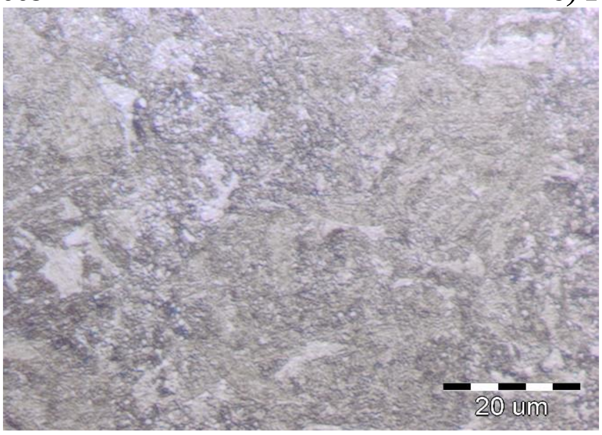
Figure 4 presents the microstructure of samples that were isothermally quenched at 250°C for 100 s, 1000 s, and 7200 s, followed by air cooling.



a) 100s



b) 1000s



c) 7200s

Figure 4. Microstructure 100Cr6 steel after isothermal quenching at 250 °C for a) 100s, b) 1000s and c)7200s, Nital 5%

During isothermal annealing at 250°C for 100 seconds, a bainitic/martensitic microstructure forms, characterized by distinct thin bainitic needles. With longer holding times, the proportion of bainite in the microstructure increases, and in the sample held in the bath for 1000 seconds, the presence of pearlite can also be observed. Carbides are present in all samples, distributed unevenly.

3.2. Analysis of Non-Magnetic Phase Presence

The analysis of the non-magnetic phase aimed to determine the proportion of carbides and retained austenite in the microstructure, as these phases can influence the mechanical properties of the steel, particularly its hardness. For this investigation, the Feritscope MP30E device was used. The device operates based on the magnetic induction method. The magnetic field generated by the coil interacts with the magnetic parts of the sample. Changes in the magnetic field induce a voltage proportional to the ferrite content in a second coil. This voltage is then evaluated [13]. The magnetic test is based on the fact that austenite is non-magnetic, whereas delta ferrite is magnetic. This method is non-destructive, fast, and can be used both in laboratories and on-site in production. Standard ISO 13520:2023 [14] defines, among other methods, the procedure for determining ferrite content using the magnetic response method. Before testing, the instrument probe and the measured surface must be cleaned and dried to remove scale, grease, fibers, or dirt that could affect measurement accuracy. If impurities are present, the connection between the probe and the test surface may be disrupted due to the small contact area. During testing, it is essential to ensure full contact between the probe and the test material. Since the non-magnetic phase is not homogeneously distributed within the matrix, multiple measurements must be performed on the same sample. The measurement results are presented in Tables 3.

Table 3. Analysis of Non-Magnetic Phase Presence

Sample	Heat treatment (IQ-isothermal quenching)	Magnetic phase, [%]						
		1	**2**	**3**	**4**	**5**	**Average percent of magnetic phase, [%]**	**Non-magnetic phase, [%]**
1	860 °C/10 min + IQ (400 °C/10s)	79.3	82.7	83.9	83.7	83.4	82.6	17.4
2	860 °C/10 min + IQ (400 °C/100s)	75.7	75.2	75.6	75.9	77.1	75.9	**24.1**
3	860 °C/10 min + IQ (400 °C/1000s)	81.3	82.0	84.2	82.2	85.5	83.04	16.96
1.1	860 °C/10 min + IQ (250 °C/100 s)	68.6	71.7	69.3	71.5	71.9	70.6	**29.4**
1.2	860 °C/10 min + IQ (250 °C/1000 s)	87.3	86.9	86.0	87.5	87.3	87	13.00
1.3	860 °C/10 min + IQ (250 °C/7200 s)	85.0	82.4	87.7	86.8	87.8	85.94	14.06

According to the results in the table, it can be seen that sample 1.1 has the highest average value of the non-magnetic phase, while sample 1.2 has the lowest value of the non-magnetic phase. However, as in the previous case, there is no significant deviation in the lower values of the non-magnetic phase.

3.3. Hardness analysis

The hardness was tested on samples prepared for metallographic examination, specifically on the ground and polished surface. In accordance with the standard, five measurements were taken for each sample, and the average value was calculated. The results are presented in Table 4.

Table 4. Results of hardness

Sample	Heat treatment	Hardness HV 10					Average hardness HV 10
		1	**2**	**3**	**4**	**5**	
1	860 °C/10 min + IQ (400 °C/10s)	383	383	366	366	370	374
2	860 °C/10 min + IQ (400 °C/100s)	441	464	454	464	441	**453**
3	860 °C/10 min + IQ (400 °C/1000s)	401	421	413	409	409	411
1.1	860 °C/10 min + IQ (250 °C/100 s)	724	792	803	792	772	**777**
1.2	860 °C/10 min + IQ (250 °C/1000 s)	454	441	429	441	464	446
1.3	860 °C/10 min + IQ (250 °C/7200 s)	488	503	498	488	514	498

Based on the hardness results presented in Table 3, it can be observed that the highest hardness is achieved by sample 1.1, which was isothermally quenched at 250°C and held at that temperature for 100 seconds. This is the only sample that meets the hardness requirements for the production of rolling bearings, while the other samples do not [4]. Additionally, the results indicate that samples with a higher proportion of the non-magnetic phase also exhibit greater hardness. Since, under these heat treatment conditions, the non-magnetic phase may consist of retained austenite and/or carbides, it is assumed that carbides were registered as the non-magnetic phase due to their contribution to increased hardness.

4. CONCLUSIONS

The aim of the experiments conducted in this study was to determine whether the isothermal quenching process, compared to conventional quenching and tempering, could produce material suitable for the production of rolling bearings. The following conclusions can be drawn from the obtained results:

- The microstructure of the steel quenched at 400°C and air-cooled is predominantly ferrite/pearlite with unevenly distributed carbides. Hardness values, depending on the holding time, range from 374 to 453 HV. The highest hardness is found in the sample held at this temperature for 100 seconds, which has the highest percentage (24.1%) of the non-magnetic phase.
- The microstructure of the steel quenched at 250°C and air-cooled exhibits a bainitic/martensitic structure. The sample held for the shortest time (100s) at the isothermal quenching temperature has the highest proportion of the non-magnetic phase (29.4%) and the highest hardness (777 HV).

Based on the literature requirements [4], which state that the hardness of samples after quenching and tempering to a bainitic microstructure should be around 59 HRC, it can be concluded that isothermal quenching at 250°C, with a 100s holding time and air cooling, will provide satisfactory properties.

REFERENCES

[1] Mandal S.K., Steel Metallurgy Properties, Specification and Application, McGraw-Hill Education, New Delhi, 2015

[2] Pavlović P., Materijal čelik, SKTH/Kemija u industriji, Zagreb, 1990

[3] https://www.gminsights.com/industry-analysis/bearing-steel-market. Accessed 2025 Feb 14.

[4] https://steelnavigator.ovako.com/steel-grades/100cr6/. Accessed 2025 Feb 14.

[5] https://www.secowarwick.com/wp-content/uploads/2017/09/MM_2017_09_Modern-heat-treatment-of-ferrous.pdf. Accessed 2025 Feb 20.

[6] Li Y., Jiang Z., Wang P., Li D., Effect of austenitizing temperature on isothermal quenching microstructure and mechanical properties of 52100 bearing steel, Materials Science and Engineering: A, Volume 892, 2024.

[7] Krishna P. V., Srikant R. R., Iqbal M., Sriram N., Effect of Austempering and Martempering on the Properties of AISI 52100 Steel, Hindawi Publishing Corporation ISRN Tribology Volume 2013, Article ID 515484, http://dx.doi.org/10.5402/2013/515484

[8] Gigović A., Prilog izučavanju uticaja nemetalnih uključaka na kvalitet čelika 100Cr6 proizvedenog u vakuumskoj i otvorenoj indukcionoj elektro peći, magistarski rad, Univerzitet u Zenici, Fakultet za metalurgiju i materijale, Zenica, 2007.

[9] Standard ASTMA295- Standard Specification for High-Carbon Anti-Friction Bearing Steel

[10] Standard ISO 683-17- Heat-treated steels, alloy steels and free-cutting steels — Part 17: Ball and roller bearing steels

[11] Standard BAS EN ISO 6506-1:2015

[12] Standard BAS EN ISO 6508-1:2017

[13] https://helmut-fischer.gr/files/items/4/BROC_FMP30_FERITSCOPE_902-039_en.pdf Accessed 2024 Jun 19.

[14] Standard ISO 13520:2023, Determination of ferrite content in austenitic stainless steel castings