STUDY OF WEAR RESISTANCE OF METAL ALLOY 100Cr6 AS A RESULT OF VARIOUS HEAT TREATMENT MODES

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ABSTRACT

This study investigates the abrasive wear resistance of 100Cr6 (AISI 52100) bearing steel under three distinct heat treatment conditions: spheroidising annealing (as-delivered), normalising at 880°C, and oil quenching from 840°C followed by low-temperature tempering at 160°C. Cylindrical specimens were subjected to abrasive wear testing using a silicon carbide disc (P80 grit) under a constant load of 450 g over test durations of 25 and 60 min. Wear resistance was evaluated by the mass loss method, and microstructural characterisation was performed by optical metallography at 800x magnification. The results demonstrate that the as-delivered condition, characterised by a ferritic matrix with globular carbides and a hardness of 10 HRC, exhibits the highest mass loss and lowest wear resistance (E = 7417 m g $^{-1}$). Normalising produces a ferrite-pearlite matrix with a hardness of 18 HRC and improves wear resistance approximately four-fold (E = 29499 m g $^{-1}$). The quenched and tempered condition yields a tempered martensite matrix with finely dispersed carbides (< 0.5 μm) and a hardness of 61, 63 HRC, achieving the highest wear resistance (E = 67568 m g $^{-1}$) - approximately nine times greater than the as-delivered state. The findings confirm that optimised heat treatment is decisive in maximising the tribological performance of 100Cr6 steel for bearing applications.

Keywords: steel, microstructure, hardness, metallographic, heat treatment, wear resistance.

INTRODUCTION

Abrasive wear represents one of the most prevalent and economically significant surface degradation mechanisms encountered in mechanical components operating under conditions of friction and contact loading. The progressive material removal caused by hard asperities or abrasive particles sliding against a softer surface led to dimensional inaccuracy, reduced service life, and ultimately premature component failure. Consequently, the development and characterization of wear-resistant steels have remained a subject of sustained scientific interest in the field of tribology and materials engineering.

Among the high-carbon chromium bearing steels, 100Cr6 (DIN EN 1.3505, equivalent to AISI 52100) occupies a prominent position due to its exceptional combination of hardness, contact fatigue strength, and abrasive wear resistance. Following appropriate quenching and tempering heat treatment, this steel exhibits high and uniform hardness, good wear resistance, and high contact fatigue strength [1]. Its chemical composition, comprising 0.95, 1.10 wt.% and 1.35, 1.65 wt.% Cr, enables austenitization at 830, 870°C followed by tempering in the range of 150, 300°C, yielding surface hardness values of up to 65 HRC [2]. The microstructure of 100Cr6 steel is a critical determinant of its tribological performance. Polat et al. demonstrated that pearlitic, bainitic, and martensitic matrices can be obtained depending on the quenching medium, with the martensitic matrix providing the highest wear resistance as evidenced by minimum mass loss, while both abrasive and adhesive wear mechanisms were identified on the worn surfaces [3]. These findings are further corroborated by Erişir et al., who established that the initial microstructural condition directly governs carbide size distribution in the final martensitic matrix, and that finer carbides - achieved through optimized heat treatment routes - yield superior hardness and outstanding resistance against wear [4]. With respect to abrasive wear mechanisms specifically, untreated specimens exhibit conventional ploughing, microcutting, and spalling as dominant material removal modes, whereas cryogenic treatment applied after quenching promotes the dispersive precipitation of nanocarbides within the martensitic matrix, which plays a significant role in improving both mechanical properties and wear resistance [5].

From a practical standpoint, 100Cr6 is primarily intended for small and medium-sized bearing components subjected to rolling contact and high-cycle fatigue loading, although it is also extensively employed for other machine elements requiring high tensile strength and hardness [6]. Its most widespread industrial applications include rolling element bearings, woodworking tools, lathe spindle centres, reamers, dies, and components for grinding hard and highly abrasive materials [2, 7]. In demanding environmental conditions such as nearshore and offshore installations, bearings are exposed to elevated salinity which, in combination with moisture, gives rise to highly corrosive NaCl environments, imposing additional requirements on the surface integrity of the material [7].

The present investigation is aimed at a systematic examination of the abrasive wear resistance of 100Cr6 steel as a function of heat treatment parameters and tribological loading conditions, with the objective of extending current knowledge of its behaviour under contact conditions representative of practical engineering applications.

EXPERIMENTAL

The experimental investigations were conducted using 100Cr6 bearing steel supplied in the form of cylindrical rods. The chemical composition, as certified by the material certificate of conformity, was as follows: C - 1.05 wt.%, Mn - 0.40 wt.%, Si - 0.35 wt.%, Cr - 1.55 wt.%, P - 0.027 wt.%, and S - 0.020 wt.%. A total of nine specimens as shown in Fig. 1 with circular cross-sections of Φ10 mm and lengths ranging from 45 to 60 mm were prepared for the experimental program. Microstructural characterization was performed using a metallographic microscope IM-05 MET with digital metallographic analysis system. Bulk hardness measurements were carried out using a combined Brinell-Rockwell hardness tester.

To investigate the influence of microstructural condition on the abrasive wear behaviour of the steel, the prepared specimens were subjected to a series of heat treatment procedures. The applied heat treatment regimens are summarized in Table 1.

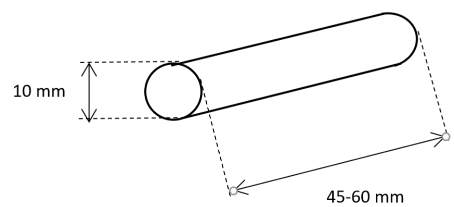

Table 1. Heat treatment regimens applied to 100Cr6 steel specimens.

Fig. 1. Shape and size of samples subjected to heat treatment and wear resistance testing.

Heat treatment type	Temperature, °C Cooling medium	Isothermal hold time, min	Condition type
Spheroidizing annealing (as-delivered condition)	-	-	Condition A
Normalizing	880 / Air	40	Condition B
Quenching	840 / Oil	30	Condition C
Tempering	160 / Air	60	Condition C

The applied heat treatment procedures are considered standard practice for this class of tool and bearing steel. Quenching followed by low-temperature tempering was employed to achieve maximum surface hardness, while normalizing was applied to improve machinability and to facilitate smooth surface finish during subsequent turning operations.

Wear resistance was evaluated for specimens with shape as shown in Fig.1 tested with a machine schematically shown in Fig. 2. Abrasive wear resistance testing was performed according to the abrasive disc method, based on the general principles outlined in ASTM G65, utilizing a silicon carbide abrasive disc with P80 grit size. Abrasive wear testing was carried out on a custom-built device, using a silicon carbide abrasive disc. The machine could change the speed, the applied load and the type of wear conditions during its operation [8]. The apparatus may be classified among tribological testing machines that allow variation of friction and contact conditions, enabling the reproduction or controlled simulation of wear processes arising in service. Wear resistance parameters are determined by the weight method using an analytical balance accurate to 0.0001 g. The experimental conditions for wear resistance tests are shown in Table 2.

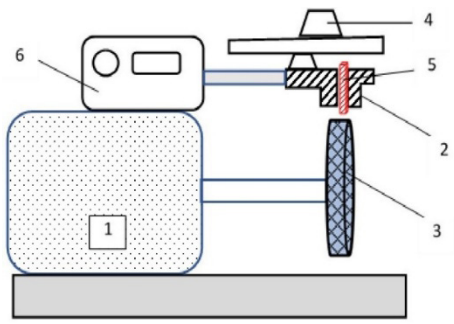

Fig. 2. A scheme of laboratory abrasive wear test machine: 1 - electric drive unit with speed control; 2 - jaws for fixing the test specimens; 3 - abrasive disc with grits P 80; 4 - shiftable weight; 5 - tested specimen; 6 - control panel.

Table 2. Experimental conditions for wear resistance test.

Experimental conditions	Wear resistance parameters
Abrasive emery disc	Grain size P 80
Load on the workpiece F, g	F = 450 g
Test time t, min	t = 25 min, t = 60 min
Distance travelled S, m	S = 3000 m, S = 7200 m

RESULTS AND DISCUSSION

In the case of friction and wear, the so-called processing of the surface conformity occurs. Running-in is a process of gradual change in the contact between two surfaces as a result of a transition in the initial roughness in magnitude and direction and mutual adhesion of two working surfaces until a stable roughness and a constant wear value are achieved. Usually, during running-in, the wear intensity decreases. Simultaneously with the change in roughness, processes occur on the surfaces associated with a change in the mechanical parameters of the parts, mainly because of surface cold treatment. In order to unify the experiments, the running-in time in this work was chosen to be 5 minutes. Data on the mass wear of the samples of the studied material after different heat treatment regimens are shown in Table 3 and Fig. 3. The results show significant wear in the as-delivered condition, i.e.: the mass loss after 25 min of abrasive

Table 3. Parameters for mass wear conducted at different intervals on a grinding machine with an abrasive.

Mass wear	Δm = ms - mf, g						
	Running-in period	5 min	10 min	15 min	20 min	25 min	60 min
Upon delivery condition	0.1102	0.1756	0.2247	0.2945	0.3407	0.4045	0.7275
Normalization at 880°C/40 min	0.0383	0.0596	0.0713	0.0789	0.094	0.1017	0.1434
After quenching at 840°C and tempering at 160°C	0.0111	0.0128	0.0197	0.0241	0.0266	0.0283	0.0444

where: m_s - the mass of the specimen before abrasive treatment, m_f - the mass of the specimen after abrasive treatment

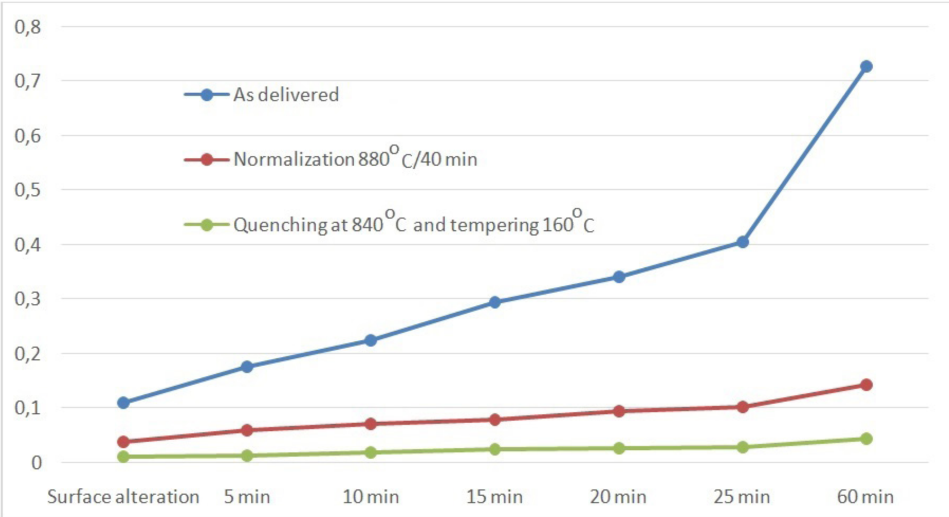

Fig. 3. Mass loss of specimens during wearing after different heat treatment.

wear is 0.4045 g, and after 60 min it is 0.7275 g. The samples subjected to normalization at a temperature of 880°C and isothermal holding for 40 min demonstrate significant resistance to mass wear with a hardness of 18 HRC throughout the duration of the experiments. These results are consistent with expectations and confirmed by the data in Table 3. The mass loss after 25 min of abrasive wear is only 0.1017 g, and after 60 min - 0.1434 g.

In Fig. 3, the abrasive wear resistance of the sample without heat treatment (i.e. in the as-delivered condition) shows a trend of the highest mass wear during the test. These high wear values are due to a microstructure consisting of a soft ferrite matrix and evenly distributed iron and chromium carbides in it (Fig. 5).

After the additional heat treatment, the samples demonstrate relatively uniform wear throughout the process and, accordingly, the wear values after quenching are lower by almost 4 - 5 times. This difference is visible even with the naked eye on the wear treated surface of the samples Fig. 4. It is reflected in Fig. 3 after abrasive testing, and in Fig. 4 in the text the samples are shown in a way that allows them to be directly compared.

The hypereutectoid chromium bearing steel 100Cr6 has a nominal composition of approximately 1.05 wt.% C and 1.5 wt.% Cr [9, 10]. Owing to its elevated carbon and chromium contents, the alloy forms substantial quantities of secondary carbides of the M_3C (cementite) and M_7C_3/$M_{23}C_6$ types [11, 12], which govern hardness, wear resistance, and rolling contact fatigue life of

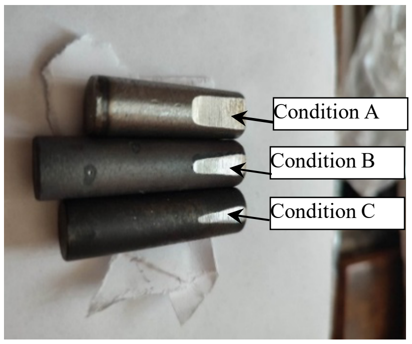

Fig. 4. Abrasive wear resistance on a sample from 100Cr6 (EN:1.3505) steel.

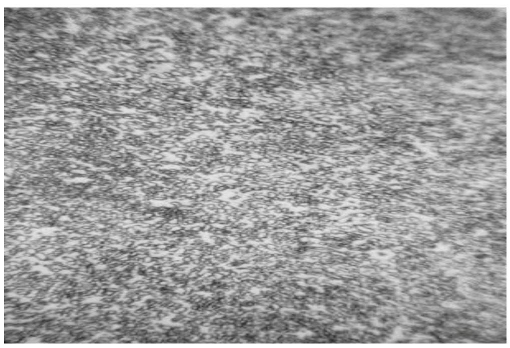

Fig. 5. Optical micrograph of 100Cr6 steel after spheroidising annealing (Condition A), 800x. Ferritic matrix with uniformly distributed globular cementite carbides. Nital etch.

bearing elements [13]. The structural and phase state of the carbide population is highly sensitive to the applied heat treatment [14, 15]. Proper characterization of the carbide phase is therefore a prerequisite for optimizing the manufacturing process and ensuring the required in-service properties of precision bearing components. The present study provides a systematic comparison of the carbide morphology across three industrially relevant thermal conditions, supported by optical micrographs obtained at 800x magnification.

Specimens were prepared from hot-rolled bar stock of steel 100Cr6 conforming to DIN EN ISO 683-17 [10]. Metallographic preparation comprised grinding on successive SiC abrasive papers to P1000 grit, followed by diamond polishing to 1 µm and final polishing with colloidal alumina (Al_2O_3, 0.05 µm) to a mirror finish. Microstructural relief was revealed by chemical etching with 3 % Nital solution. Observation was performed using a reflected-light optical metallographic microscope at a magnification of 800x in bright-field mode.

Microstructural description of Condition A - Spheroidising annealing (As-delivered state).

The micrograph (Fig. 5) reveals a uniform ferritic matrix with equiaxed grains, within which globular (spheroidised) carbide particles are homogeneously distributed. The carbides exhibit a rounded, near-spherical morphology. Isolated coarser carbide globules with diameters estimated at 1 - 2 µm are observed alongside a larger population of finer particles (< 1 µm). No lamellar pearlite is detected.

The globular carbides observed represent periodized cementite (Fe_3C) [11, 16], formed during prolonged sub - Ac_1 annealing through the coalescence and spheroidization of lamellar cementite lamellae and secondary carbides [14]. The carbide volume fraction in the as-delivered condition is approximately 8, 12 vol.%, consistent with published data for this steel grade [13]. The homogeneous distribution of carbide globules ensures optimal machinability and provides the recommended starting microstructure prior to hardening.

Microstructural description of condition B - Normalizing from 880°C

The micrograph (Fig. 6) shows a ferrite-pearlite matrix resulting from the austenitisation at 880°C - within the two-phase (Ac_1 - Acm) field - followed by air cooling. The pearlite colonies display a characteristic is fine lamellar morphology. Small bright carbide particles, attributable to undissolved or re-precipitated carbides, are visible within the matrix.

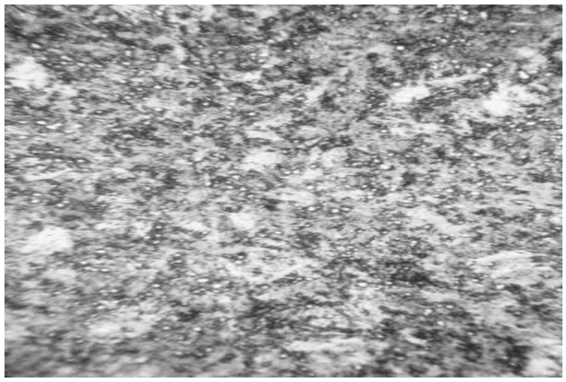

Fig. 6. Optical micrograph of 100Cr6 steel after normalizing from 880°C (Condition B), 800x. Ferrite–pearlite matrix with residual globular carbides. Nital etch.

At the normalizing temperature of 880°C the solubility of carbon in austenite is approximately 5, 6 wt.% [9, 17], implying that a significant fraction of the initial globular cementite remains undissolved. The bright particles observed in the matrix represent residual secondary cementite [11, 17]. Their volume fraction is reduced relative to the as-delivered condition owing to partial dissolution, and their morphology retains residual globularity. The pearlitic constituent contains finely lamellar cementite confined within the pearlite colonies [14]. The normalized microstructure yields higher hardness and lower ductility compared with the annealed state but is considered unfavourable as a final condition for bearing components due to the heterogeneous carbon distribution.

Microstructural description of condition C - Quenching from 840°C and tempering at 160°C.

The micrograph on Fig. 7 reveals the characteristic microstructure of tempered martensite, displaying acicular martensitic plates within a dark-grey matrix. Bright, finely dispersed carbide particles, considerably smaller than those observed in Conditions A and B, are uniformly distributed throughout the matrix. No preferential carbide enrichment along martensitic packet boundaries is detected.

The bright carbides observed in the quenched-and-tempered condition are of dual origin: (1) undissolved primary and secondary carbides [11, 13], incompletely dissolved during austenitisation at 840°C (< Acm), retaining a spherical or sub-globular morphology; and (2) carbides precipitated during tempering [12, 18], at 160°C metastable ε-carbides ($Fe_{2.4}C$) or transitional η-carbides may precipitate from the supersaturated martensite [4], contributing to precipitation hardening. The low tempering temperature is insufficient to induce carbide coarsening, so the particles remain finely dispersed (< 0.5 μm) [19], providing an optimum combination of high hardness (61, 63 HRC) and contact fatigue resistance - the target properties for bearing applications. In table 4 a comparative phase assessment was done.

The corresponding values of wear resistance and wear rate are summarized in Table 5 and Fig. 8.

The wear intensity in the as-delivered condition is V = 13.48.10^{-5} g m^{-1} and E = 7417 m g^{-1}, respectively. The wear

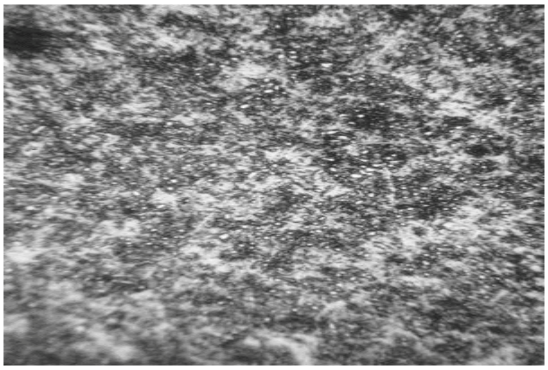

Fig. 7. Optical micrograph of 100Cr6 steel after quenching from 840°C and tempering at 160°C (Condition C), 800x. Tempered martensite matrix with finely dispersed carbides. Nital etch.

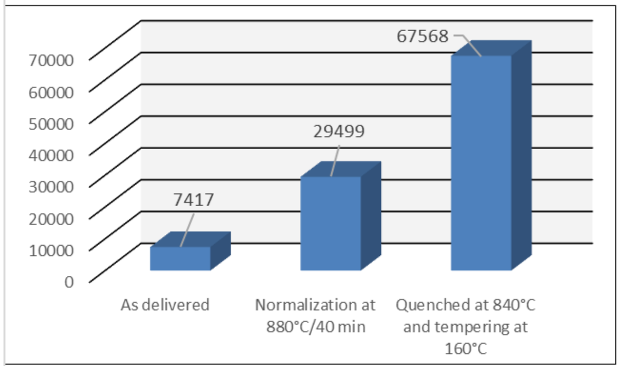

Fig. 8. Abrasive wear resistance of samples after heat treatment at different processing.

Table 5. Durability for wear resistance and wear intensity of heat-treated steel 100Cr6.

Steel 100Cr6	Wear intensity, V = Δm/S, g m^{-1}	Wear resistance E = 1/V, m g^{-1}
Upon delivery condition	0.00013483	7417
Normalization at 880°C/40 min	0.00003390	29499
After quenching at 840°C and tempering at 160°C	0.00001480	67568

Table 4. Comparative assessment of the presenting phases in heat treated samples.

Parameter	Condition A (Annealed)	Condition B (Normalized)	Condition C (Quenched and tempered)
Matrix constitution	Ferrite	Ferrite + Pearlite	Tempered martensite
Carbide morphology	Globular	Globular + lamellar (within pearlite)	Fine dispersed (globular)
Carbide size	0.5 - 2 μm	0.3 - 1.5 μm	< 0.5 μm
Distribution	Uniform	Uniform, partial coalescence	Uniform, dispersed
Carbide vol. fraction (approx.)	~ 10 - 12 %	~ 6 - 8 %	~ 6 - 10 %
Hardness	10 HRC	18 HRC	61 - 63 HRC

intensity after normalization of the samples at 880 °C and a holding time of 40 minutes is V = 3.39.10^{-5} g m^{-1} and E = 2 9499 m g^{-1}. The samples quenched from 840°C in oil and subjected to low-temperature tempering at 160°C have V = 1.48.10^{-5} g m^{-1} and wear resistance E = 67568 m g^{-1}.

CONCLUSIONS

After analysing the results obtained between the initial state of the material and the effect of heat treatment under different regimes, clear conclusions about the wear resistance of 100Cr6 steel should be drawn.

The delivery state of the material is defined after heat treatment (spheroidizing annealing) performed at the manufacturing plant, which is the starting point for comparing the data.

Normalizing from 880°C results in partial carbide dissolution and the formation of a ferrite–pearlite matrix with residual globular carbides, a condition unfavourable for final bearing components due to heterogeneous carbon distribution and insufficient hardness potential. A hardness of 18 HRC was achieved.

Oil quenching from 840°C followed by low-temperature tempering at 160°C generates the target microstructure of tempered martensite with finely dispersed carbides (< 0.5 µm), yielding the required hardness of 61 HRC and rolling contact fatigue resistance for bearing applications.

The wear intensity in delivery state is V = 13.48.10^{-5} g m^{-1} and E = 7417 m g^{-1}, and after normalization at 880°C for 40 min the intensity is V = 3.39.10^{-5} g m^{-1} and E = 29499 m g^{-1}. After quenching at 840°C with cooling in oil and subsequent low-temperature annealing at 160°C, the wear intensity is V = 1.48.10^{-5} g m^{-1}, and the wear resistance is E = 67568 m g^{-1}.

A four-fold increase in abrasive wear resistance was achieved after normalization at 880°C. After quenching with tempering at 160°C the abrasive wear resistance is about nine times higher than in delivery state condition of materials.

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