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Deformation Reduction of Bearing Rings by Modification of Heat Treating

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Additional information is available at the end of the chapter

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1. Introduction

Heat treatment of bearing rings implies the risk of deformations caused by internal tension. In order to eliminate internal tension, hardening is followed by tempering. In general, tempering will remove the tension. However, this tempering is not sufficient for the so-called thin-walled rings AX series bearing rings to eliminate the tension. This article discusses how to effectively eliminate occurrence of tensions in thin-walled bearing rings made from 100Cr6 by optimising their heat treatment. Results have been verified by experiments.

Manufacture of roller bearings (figure 1) is a challenging production process. Even though its specific manufacturing operations are widely known and established, some operations in bearing manufacture must be performed within narrow tolerances ranging from only a few micrometres to comply with requirements of tolerance analysis done before the parts are manufactured to ensure that clients receive a quality product that influences safety of plant operation, therefore safety of people. The manufacturing comprises a number of operations needed to produce rings, rolling elements and cages. It includes hammering of forgings at the beginning, turning, heat treatment, cutting, forming, grinding, washing of parts, their description, assembling bearing components and packaging. A number of preventive, intra-operational and final inspections and dimensional, chemical, metallurgic, endurance and other tests are carried out during the manufacturing process [ZVL & ZKL, 1996; ZVL, 2008]. Customers assemble these products in common applications with standard requirements on bearings, but sometimes they have special requirements either for the bearing as a whole, or for any of its parts. In this case it is not sufficient to implement only standard methods and working practices; they have to be modified or optimised. One of such requirements was a request from one of great important American and Deutschland company to produce bearings needed to place a rotor for an axial piston hydroelectric generating set with an inclined plate for one of its tractors. This application has its particulars. It was necessary to

modify the outer ring, inner ring and rolling elements. Mentioned company is considered to be a “Mercedes” in the field of production of tractors, harvesters and similar equipment. The demands on parts are therefore accordingly high. This article will not discuss all the modifications necessary to adjust the technological process of production in order to meet customer’s requirements, although they are all interrelated, influence each other and represent a desired outcome of the targeted modification. We will deal only with the parameter that can be affected by heat treatment of the material in order to avoid unwanted deformations in the material and comply with a stricter requirement on ovality for inner rings.

Papers of authors [Jech, 1983; Panda et al., 2011; Vasilko, 1998] address processes of heat treatment of bearing components with related checks and tests (dimensional, chemical, metrological and endurance tests) and technological aspects of production of bearing rings are discussed in [ZVL & ZKL, 1996; ZVL, 2008].

The goal of the work was to modify the tempering process to eliminate or preclude undesirable deformations of the material and to ensure compliance with the stricter requirements for ovality of inner rings (figure 2).



Figure 1. Tapered roller bearing



Figure 2. Inner ring of Tapered roller bearing

2. Ovality measuring on production plant

Technologically, ovality results from non-symmetrical distribution of internal tensions before hardening and uneven heating and cooling. Ovality is a certain type of circularity deviation.

Since 1950s, devices using very accurate rotational tables or spindles are used in modern industry to measure circularity. The measuring base in this method is the axis of the component to be measured. The measuring device ensures very high accuracy, often better than 0.1 μm . However, it requires time-consuming preparations including centring and alignment of the component, therefore it is intended rather for laboratory measurements. These measuring devices are rarely used in production, also due to their low measuring capacity.

Ovality is checked at the output from the heat treatment line. A special diameter gauge (Figure 3) that included a dial deviation meter was used to measure ovality (table 1). Ovality was measured on three rings so that an ovality deviation was recorded after each rotation by 10°. The following procedure was applied. An bearing ring was inserted into the gauge. The ring was rotated manually in 10° increments. A value was read from the deviation meter after each rotation. If the deviation was higher than 0.2 mm, the ring being measured was discarded. It did not meet quality criteria and could not be passed on for subsequent hard machining.

A high deviation in ovality may indicate uneven heating or cooling during heat treatment. Ovality measurement was made on three inner rings selected randomly from different batches. Ring No. 1 shows acceptable ovality up to 0.2 mm in maximum. Subsequent grinding operations can reduce or remove this deviation from circularity. Ring No. 2 shows ovality over 0.2 mm, so it is not suitable for further machining. It must be discarded. The lowest ovality value can be seen in ring No.3. For ring No. 2, it is necessary to identify the cause of such a significant deviation in cylindricality. The whole batch the ring No. 2 comes from should be checked.

| Ring rotation (°) | | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---------------------------------------|------------|------|------|------|------|------|------|------|------|------|------|------|
| Ovality values measured for the rings | Ring no. 1 | 0.02 | 0.04 | 0.09 | 0.13 | 0.16 | 0.17 | 0.17 | 0.18 | 0.19 | 0.2 | 0.19 |
| | Ring No. 2 | 0.21 | 0.2 | 0.19 | 0.18 | 0.17 | 0.16 | 0.13 | 0.09 | 0.04 | 0.03 | 0.03 |
| | Ring No. 3 | 0.09 | 0.05 | 0.02 | 0 | 0.02 | 0.04 | 0.08 | 0.09 | 0.1 | 0.11 | 0.12 |

Table 1. Measured values of ovality

| 110 | 120 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 |
|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 0.18 | 0.17 | 0.17 | 0.16 | 0.13 | 0.09 | 0.04 | 0.02 | 0.03 | 0.04 | 0.09 | 0.13 | 0.16 |
| 0.04 | 0.09 | 0.13 | 0.16 | 0.17 | 0.18 | 0.19 | 0.21 | 0.2 | 0.19 | 0.18 | 0.17 | 0.17 |
| 0.13 | 0.14 | 0.15 | 0.15 | 0.14 | 0.13 | 0.12 | 0.11 | 0.1 | 0.09 | 0.05 | 0.02 | 0.04 |

Table 2. Measured values of ovality - continuation

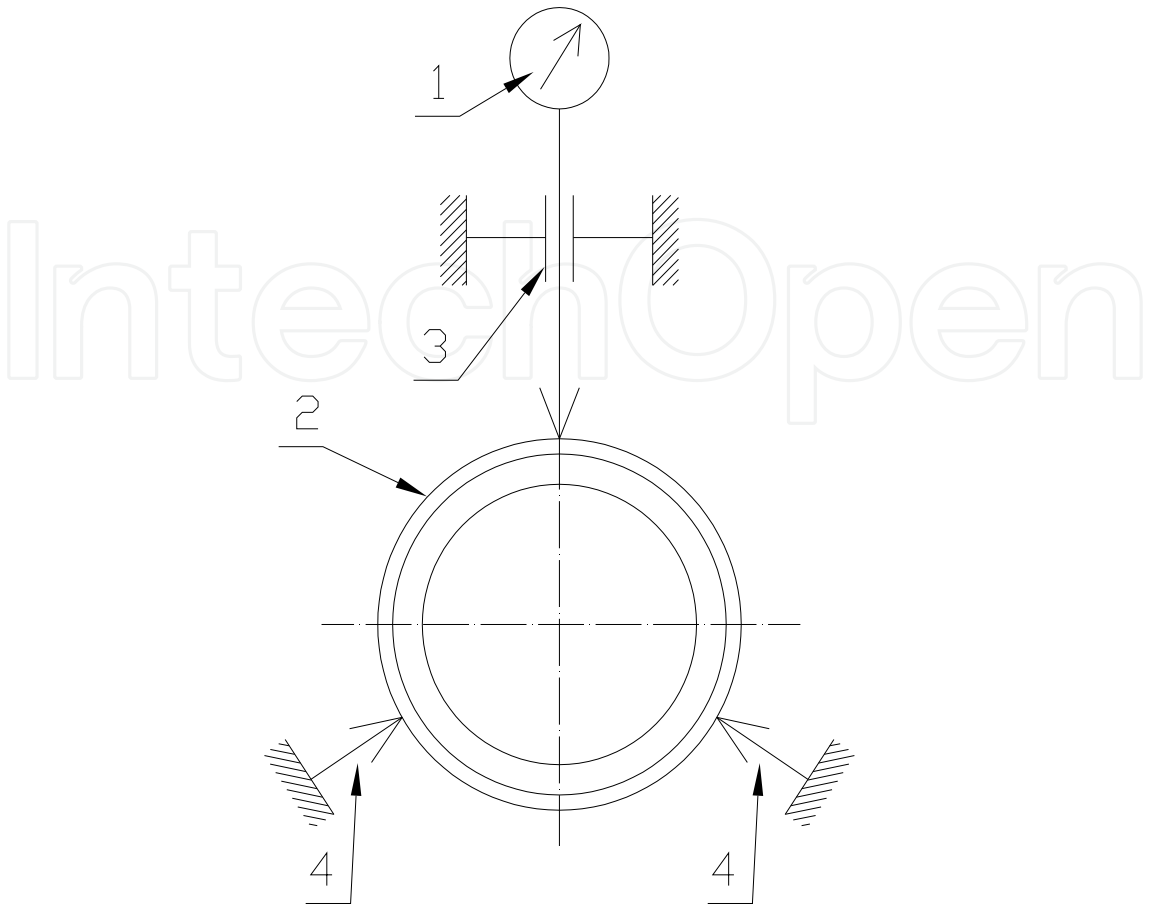


Figure 3. The principle of measuring ovality of outer shape of the outer ring of a roller bearing. 1 - dial deviation meter, 2 - outer ring, 3 - moving measuring contact line, 4 - supporting parts

| | | | | | | | | | | | | |
|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 240 | 250 | 260 | 270 | 280 | 290 | 300 | 310 | 320 | 330 | 340 | 350 | 360 |
| 0.17 | 0.17 | 0.18 | 0.19 | 0.2 | 0.19 | 0.18 | 0.17 | 0.17 | 0.16 | 0.13 | 0.09 | 0.05 |
| 0.16 | 0.13 | 0.09 | 0.05 | 0.02 | 0.04 | 0.09 | 0.13 | 0.16 | 0.18 | 0.19 | 0.2 | 0.21 |
| 0.08 | 0.1 | 0.1 | 0.11 | 0.12 | 0.13 | 0.14 | 0.15 | 0.15 | 0.14 | 0.13 | 0.12 | 0.1 |

Table 3. Measured values of ovality - continuation

3. Customer’s requirements

In principle, the customer required a bearing that would withstand higher axial loads without any major run-in and with reduced ring ovality due to the placement of the rotor in an axial piston hydroelectric generating set. Table 4 shows a comparison of basic modified parameters between the standard design (Standard) and the design required by the customer (Special). As mentioned before, this paper will discuss only the issue of reducing ovality in the inner ring. Finding a solution for such task is even more difficult because the bearing is a thin-walled bearing (AX series) that is much more sensitive to material deformations and ring ovality compared to other bearings with a more favourable ratio of ring thickness and width.

| Bearing part and parameter | 32010AX Standard | 32010AX Special |
|--|---------------------|--------------------|
| Inner ring | | |
| - Raceway run-out to the hole [mm] | 0,007 | 0,005 |
| - Support face run-out to the main face [mm] | 0,007 | 0,005 |
| - Raceway roughness [μm] | 0,20 | 0,15 |
| - Support face roughness [μm] | 0,20 | 0,07 |
| - Waviness [μm] | 0,35 | 0,25 |
| - Ovality [mm] | 0,006 | 0,003 |

Table 4. Comparison of basic parameters of 32010AX bearings between “Standard” and “Special” designs

4. Experimental section

Material deformations and ring ovality are caused by internal tension generated during machining and heat treatment operations. To process a bearing ring by turning, it has to be fixed at three points. The fixing is done pneumatically. A deformation may occur due to poor fixing, or due to a failure to follow technological conditions, when more material is removed. When rings are grinded after heat treatment, similar undesired deformations occur, if technological conditions are not followed. Major deformations occur even during the heat treatment itself, i.e. when the rings are hardened, due to uneven heating and cooling. Deformation that appeared after heat treatment are then reproduced at subsequent grinding, worsening this effect even more.

The customer accepted only 0.003 mm of stricter ovality for the outer ring after grinding, compared to the standard prescribed value of 0.006 mm (see Table 4), which tightens the requirements by 50%. To achieve this final ovality of rings after grinding, then the ovality of rings after hardening can be no more than 0.1 mm, which is also a stricter value compared to the standard requirement of 0.2 mm.

Ovality is defined as the difference in diameters measured in one plane perpendicular to each other. This means that, for example, the maximum diameter D_{\max} is measured first – i.e. the maximum value is found when the ring is turned, then the ring is rotated by 90° and the second, minimum diameter D_{\min} is measured. The outer shape of the ring should be close to a circle, but in fact, the outer ring is elliptical in shape. Our aim is to keep this ovality as small as possible.

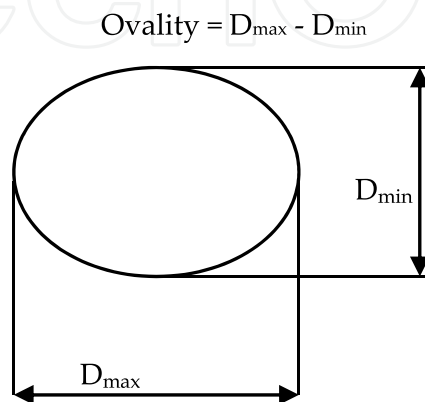


Figure 4. Definition of ovality

4.1. Hardening and tempering of bearing components

Steel 100Cr6 with the following chemical composition (values in % by weight)² was used to manufacture bearing rings and rolling elements: C=0.9-1.1; Mn = 0.3-0.5; Si = 0.15-0.35; Cr = 1.3-1.65; P=max 0.027; S=max 0.03; Ni=max 0.3; Cu=max 0.25; Ni+Cu=max 0.5. Desired mechanical properties of roller bearings are obtained by hardening and tempering their components at low temperature. The required hardness of bearing components is achieved by hardening and tempering is used to reduce internal tension and fragility of the hardened bearing steel.

The resulting mechanical properties are then determined primarily by the microstructural state, distribution of internal tensions before hardening, uniformity of heating to austenitizing temperature, austenitizing conditions and cooling down from the austenitizing temperature.

The method of heating affects resultant oxidation and surface decarburization. Local overheating and imperfect soaking must be avoided during heating, because they lead to cracks formed during cooling. Austenitizing conditions, i.e. austenitizing temperature and dwell at the austenitizing temperature, affect quality of hardened bearing components. Dwell time selected depends on the shape and material of the component, its heating method and baseline microstructure. The dwell at the austenitizing temperature has a lower effect than the temperature value.

The outcomes of hardening depend also on the speed of heat dissipation. For bearing steel, the cooling rate must be very high for a temperature range of approximately 650 °C and below. The cooling efficiency of different environments depends mainly on thermal conductivity, specific heat, evaporating heat, viscosity of the hardening environment and amount of dissolved gases. The cooling process in water is very fast and is used to harden bearing balls. Different ingredients are added into quenching water; some of which increase the cooling capacity and some of them slow it down.

Due to the lower cooling rate, thus a smaller temperature gradient between the surface and core of the component being hardened, it is more convenient to cool bearing components in mineral oils rather than in water. The most suitable medium for a common hardening environment in terms of cooling rate is J4 bearing oil that can achieve the maximum cooling rate of 65 °C/s at surface temperature of 550 °C. Cooling in an AS140 salt solution (a mixture of KNO₃ NaNO₃) is used to equalise the temperature at 150 °C between the surface and core of the component. After this cooling, the component continues to cool down in oil or is finally cooled down in water. Increased cooling rate causes higher susceptibility of the hardened component to develop cracks, resulting from the higher temperature difference between the surface and the core of the hardened component, creating internal tensions.

Hardening and tempering of rings is one of the most important operations in production of roller bearings and it should ensure dimensional stability in addition to the required hardness of 60 to 63 HRC. Dimensional stability is necessary for subsequent technological operations needed to achieve the correct geometry of a finished bearing and stability of these dimensions in long-term operation. When bearing steels are hardened, martensite or a structure with a specific volume different than the original martensite is formed.

Internal tensions occur because various structures develop in various volumes and at different stages in terms of time and temperature due to the temperature gradient. Tensions arising from differences in temperature between the component surface and its core are referred to as thermal tensions. Structural tensions originate from the difference in specific volumes of the initial austenite and martensite formed or in other stages.

Temperature tensions can be affected by reducing or extending the process of heating, especially by preheating. Structural tensions depend on chemical composition of steel and course of the heat treatment.

Dimensional changes in chrome bearing steel increase with a higher hardening temperature. Tempering will reduce the increase in volume, and the reduction is higher with a higher hardening temperature.

In bearing rings, hardening and tempering influence their ovality. Ovality is related with volume changes only a little. It originates from the technology, resulting from an uneven distribution of internal tensions before hardening and uneven heating and cooling.

Cooling rate in the hardening process has an impact on volume change in components. The higher is the rate the higher is the deformation and the higher is also the difference in length between the states after hardening and tempering. The dimensional changes (Fig. 5) that occur after heat treatment are caused by the lack of stability of the microstructure of hardened and tempered bearing steel in the given operating conditions [Vasilko, 1998]. This is the result of permanent changes in instable structural stages of martensite and residual austenite. Therefore, stabilization of dimensions in hardened and tempered bearing components depends on the degree of super saturation of a solid solution - martensite and the residual austenite content, i.e. on the microstructure as well as on operating conditions, temperature, time and tensions.

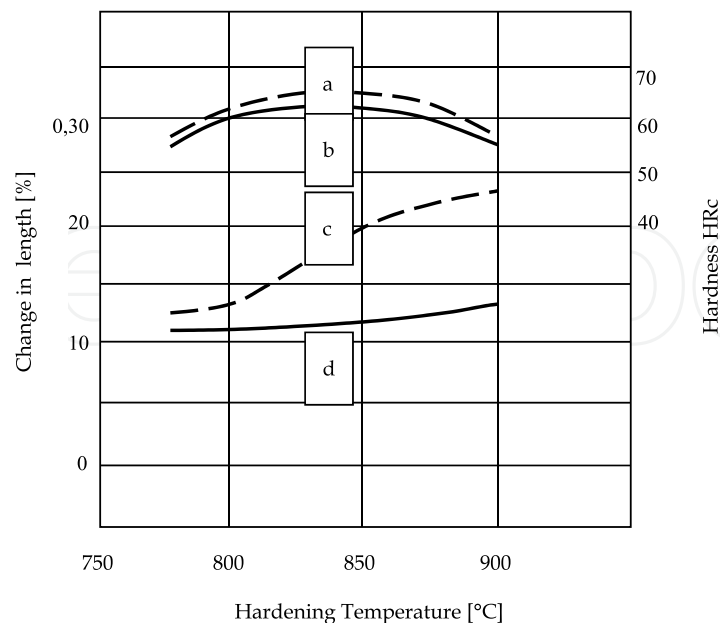


Figure 5. Effect of hardening temperature on change in length and hardness after hardening and tempering [8]: a – hardness after hardening; b – hardness after hardening and tempering 150°C; c – change in length after hardening; d - change in length after hardening and tempering 150°C

With this heat treatment, we try to get a fine martensitic structure of components, as shown in Fig. 6 - microstructure of 100Cr6 steel; properly tempered; martensite and fine, evenly distributed carbides.

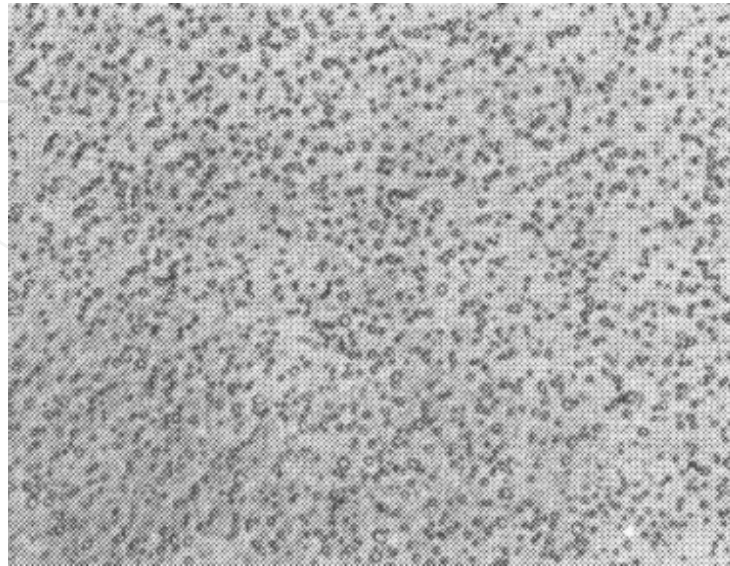


Figure 6. Microstructure of 100Cr6 bearing steel formed by martensite and fine carbides

To harden and temper bearing components, furnace equipment is used that can increase the level and quality of heat treatment and improve work productivity (Fig. 7) [Vasilko, 1998]. The company, where optimisation was implemented, uses a renovated hardening line, later fitted with computer control, and tempering is done on PP017/50 device (Fig. 8) [ZVL, 2008]. Furnace equipment can be operated also by the computer system, making easier the process of controlling and inspecting the heat treatment. Records on various parameters, such as temperature and time, are kept, making it possible to get back to them even after a longer period of time (Table 5) [ZVL, 2008].

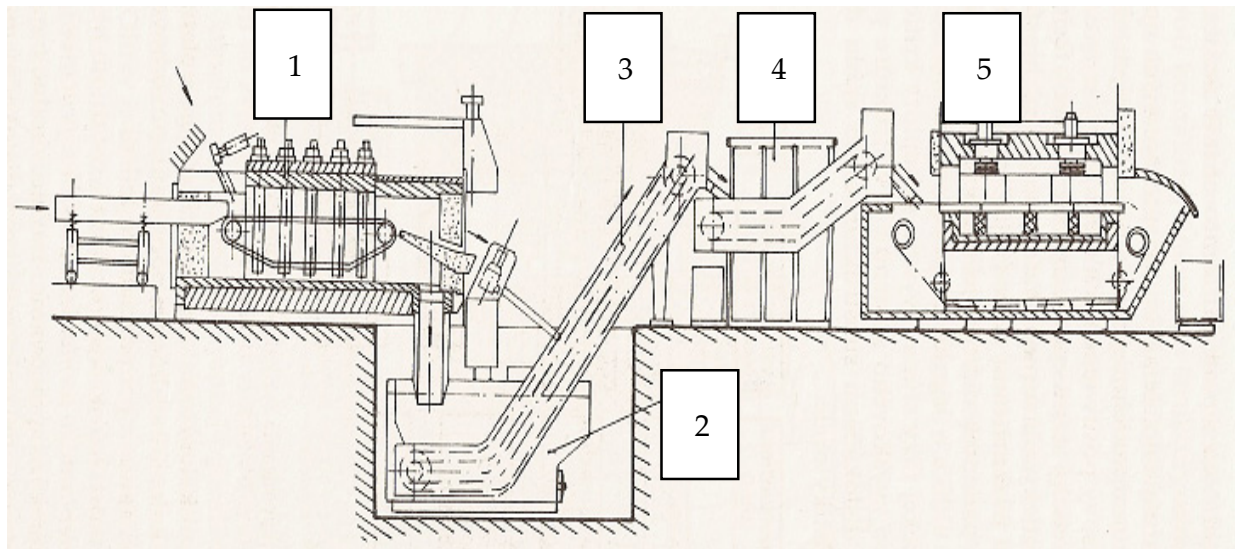


Figure 7. Diagram of furnace equipment for hardening and tempering bearing components (1 - hardening furnace, 2 - hardening tank, 3 - carrier, 4 - washing machine, 5 - tempering furnace).

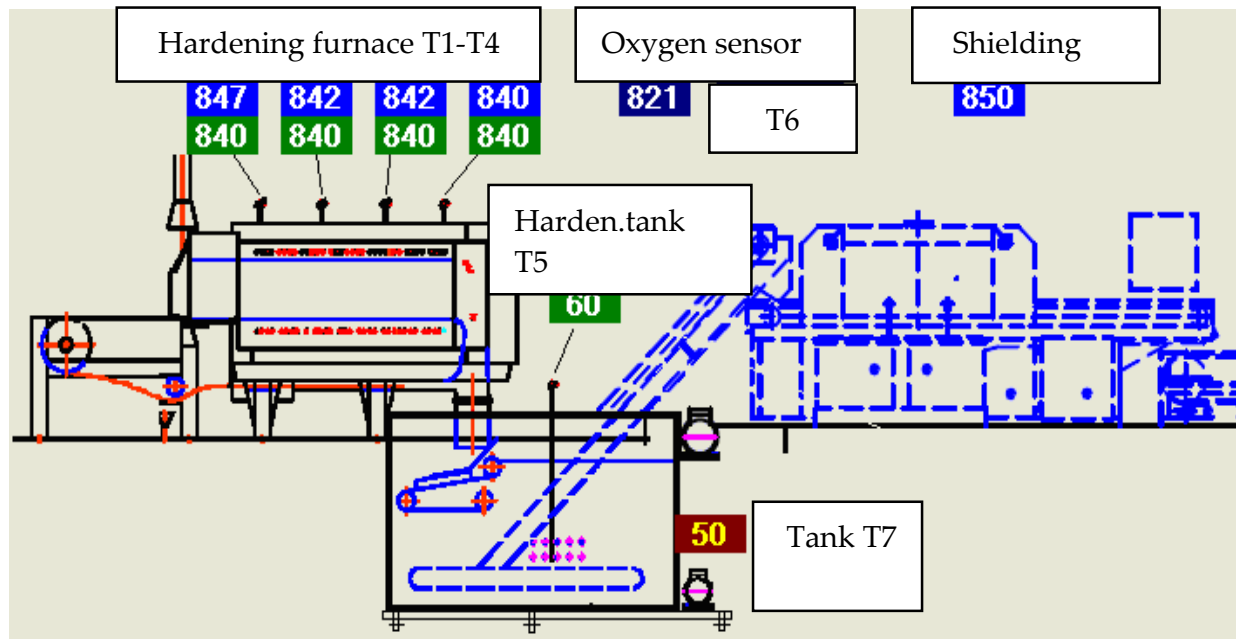


Figure 8. Diagram of the computer-controlled hardening line

| Temperature – hardening furnace [°C] | | | | Temperature - hardening tank [°C] | Temperature–exhaust gas oxygen sen. [°C] | Tempera- ture - tank [°C] | Time [hour:min] |
|--|-----|-----|-----|--------------------------------------|---|---------------------------------|--------------------|
| T1 | T2 | T3 | T4 | T5 | T6 | T7 | t |
| 842 | 842 | 842 | 844 | 57 | 822 | 50 | 9:49 |
| 834 | 842 | 843 | 845 | 57 | 822 | 50 | 9:50 |
| 832 | 842 | 843 | 845 | 57 | 822 | 50 | 9:51 |
| 832 | 841 | 843 | 844 | 57 | 822 | 50 | 9:52 |
| 835 | 841 | 842 | 842 | 57 | 822 | 50 | 9:53 |
| 838 | 841 | 842 | 840 | 57 | 821 | 50 | 9:54 |
| 841 | 841 | 841 | 839 | 57 | 822 | 50 | 9:55 |
| 843 | 841 | 840 | 840 | 57 | 821 | 50 | 9:56 |
| 842 | 841 | 840 | 842 | 57 | 821 | 50 | 9:57 |
| 838 | 841 | 841 | 844 | 57 | 821 | 50 | 9:58 |
| 836 | 841 | 843 | 844 | 57 | 821 | 50 | 9:59 |
| 836 | 841 | 843 | 844 | 57 | 821 | 50 | 10:00 |
| 838 | 841 | 843 | 842 | 57 | 821 | 50 | 10:01 |
| 841 | 841 | 843 | 841 | 57 | 821 | 50 | 10:02 |
| 843 | 841 | 842 | 839 | 57 | 821 | 50 | 10:03 |
| 841 | 841 | 841 | 839 | 57 | 821 | 50 | 10:04 |
| 838 | 841 | 841 | 842 | 57 | 820 | 50 | 10:05 |
| 836 | 841 | 840 | 844 | 57 | 820 | 50 | 10:06 |
| 837 | 841 | 840 | 844 | 57 | 820 | 50 | 10:07 |
| 839 | 841 | 842 | 843 | 57 | 821 | 50 | 10:08 |
| 842 | 841 | 843 | 842 | 57 | 820 | 50 | 10:09 |

Table 5. Sample output from the computer-controlled hardening line with measuring data

4.2. Heat treatment of standard bearing rings

For standard bearings, the rings are hardened and tempered in accordance with the conditions specified in Table 6. Heat treatment is followed by grinding and super finishing of functional areas. The value of ovality of hardened and tempered rings achieved after this processing is 0.2 mm.

| Description of actions | Hardening | Tempering |
|------------------------|-------------------------|--------------------|
| Device Name | hardening furnace Ø 100 | furnace PP017 / 50 |
| Zone temperature [°C] | 840 ± 5 | 170 ± 5 |
| Oil temperature [°C] | 50 – 80 | – |
| Method of placement | 1 row | freely |
| Variator | 3 – 5 | – |
| Heating time [min] | 60 – 80 | 155 ± 5 |
| Output [pcs/hour] | 1 080 | 1 080 |

Table 6. Heat Treatment Technological Procedure

Hardness tests are done on selected pieces after hardening and tempering. The required hardness after hardening is 63.5 to 65.5 HRc. The required hardness after tempering is 60 to 63 HRc. After tempering, the bearing rings are inspected for ovality and microstructure.

When bearing material is being heat treated, oxidation occurs at common heating. To prevent oxidation of the surface, the heat treatment is done in a controlled atmosphere consisting of nitrogen.

4.3. Optimised heat treatment and grinding mode

The heat treatment method (Table 6) followed by grinding as described in 4.2 is not sufficient to achieve the required ovality of 0.1 mm needed by the customer for the special bearings. It was necessary to develop, technologically master and verify a different, additional method of heat treatment and subsequent grinding of the rings, which would guarantee lower internal tensions, deformations and ovality values, whereas the required hardness of the rings should remain unchanged. Tempering is known to be used to eliminate internal tensions. This had been already done after hardening (see Section 4.2, Table 6), but resultant values of ovality were inadequate. It is also known that hardness of tempered parts decreases when tempering is done as described in Table 6, so any further tempering using this process was not possible.

Considering these facts and drawing from our experience, a procedure was suggested to ensure lower levels of ovality from 0.2 to 0.1 mm:

1. Heat treatment (hardening and tempering) as in 4.2, Table 6
2. Pre-grinding of functional surfaces in bearing rings, but not to reach the final value; only with a partial use of the total allowances for grinding – rough grinding
3. Re-tempering of the rings using the 155 °C/65' process, i.e. under different technological conditions than in 4.2. The technological conditions – see Table 7.
4. Fine grinding of functional surfaces of the rings

| Description of action | Tempering |
|-----------------------|------------|
| Device Name | PP017 / 50 |
| Zone temperature [°C] | 155 ± 5 |
| Method of placement | freely |
| Heating time [min] | 65 ± 5 |
| Output [pcs/hour] | 1 080 |

Table 7. Technological procedure of additional tempering

Table 5 shows that two parameters have been modified for additional tempering. The first one is the tempering temperature, which is now lower, i.e. 155±5 °C. This is a substantial change that will ensure lower internal tensions and ovality reduced by 50% against the standard design. The second one is the heating time, which is 65±5 minutes. It is a sufficient time. However, if a longer time was preserved, the effect would be the same without any risk of lower hardness values. Tempering, referred to as “artificial ageing” is followed by hardness tests on selected pieces. The required hardness after tempering remains constant of 60 to 63 HRc.

Ovality on finished rings was measured using the Talyrond 73 device, see Figure 9. The measuring device ensures very high accuracy, better than 0.1 µm.

5. Result and discussion

Hardening and tempering has an impact on ovality in rings. The dimensional changes that occur after heat treatment are caused by the lack of stability of the microstructure of hardened and tempered bearing steel in the given operating conditions [Vasilko, 1998]. The aim of the heat treatment was to obtain a fine martensitic structure of components. A microstructure composed mainly from martensite is formed by hardening components made from bearing steel. The martensitic microstructure usually contains a low percentage of residual austenite in terms of volume. Rate of heating adjusted to the hardening temperature, or inclusion of pre-heating, can affect the value and distribution of thermal tension in the bearing ring being heated. Structural tensions that arise during heat treatment by hardening and tempering are determined by the chemical concept of the steel used and heat treatment process parameters. Dimensional changes that occur during the tempering process may be a consequence of ϵ -carbide precipitation, decomposition of residual austenite, cementite precipitation, dislocation substructures welded together and re-distribution of residual tensions after mechanical processing [Perez et al., 2009].

To ensure production requirements on special bearings for this customer (see Table 4) it was necessary to optimise both the dimensional parameters and the heat treatment method and subsequent machining in order to reduce internal tensions. Modified heat treatment mode and subsequent fine grinding made it possible to fulfil the requirement of lower ovality from 0.006 to 0.003 mm. The useful value of the bearings improved, too, with these modifications in heat treatment and adjusted dimensional parameters:

- reduced friction and tear and wear
- lower noise of the equipment when these bearings are used
- lower operating temperature even when running the equipment in
- minimum run-in time
- possibility to set initial stretch more reliably
- running smooth even in the first hours of operation
- slight increase in dynamic load (due to optimised shape of ring and tapered roll raceways)



Figure 9. Measuring ovality using the Talyrond 73 measuring device

Extract from a chemical composition protocol - chemical analysis of 100Cr6 used is shown in Table 8. The material corresponds to the prescribed values.

| Tested element | Prescribed values | Measured values |
|----------------|-------------------|-----------------|
| C | 0,9 – 1,1 | 1,02 |
| Mn | 0,3 – 0,5 | 0,35 |
| Si | 0,15 – 0,35 | 0,28 |
| Cr | 1,3 – 1,65 | 1,51 |
| P | max. 0,027 | 0,01 |
| S | max. 0,03 | 0,014 |
| Ni | max. 0,30 | 0,06 |
| Cu | max. 0,25 | 0,09 |
| Ni+Cu | max. 0,5 | 0,15 |

Table 8. Chemical composition of 100Cr6 bearing material in % by weight

Extract from a metallographic analysis protocol under DIN 17230, DIN 50602, SEP 1520, and corporate standard is shown in Table 9. The material corresponds to the prescribed values.

| Tested property | Max. prescribed values | Measured values |
|------------------------------|------------------------|-----------------|
| HRC hardness | 60 – 63 | 62 |
| Post-grinding heating | none parts | none parts |
| Microstructure | 3 – 6 | 5 |
| Carbide mesh | 5,3 | 5,2 |
| Carbide streakiness - closed | 6,2 | 6,0 |
| Carbide streakiness - free | 7,3 | 7,1 |
| Sulphides – SS | 1,3 | 1,2 |
| Oxides – OA | 3,3 | 3,1 |
| Oxides – OS | 6,2 | 6,0 |
| Oxides – OG | 8,3 | 8,1 |

Table 9. Metallographic analysis of 100Cr6 bearing material used

When a verification series was manufactured, the bearings were tested for endurance using a ZT1 testing station. There are 20 bearings tested simultaneously; up to the fifth discarded bearing; 90% of the bearings must withstand 1 million revolutions. Basic dynamic load rating prescribed in the catalogue is assessed. The attained value was 201% compared to the catalogue.

6. Conclusion

The herein described method of achieving lower internal tensions with effect on reduced deformations and ring ovality made it possible to attain ovality of finished rings of 0.003 mm compared to the standard requirements on ovality of 0.006 mm. This result was achieved with a satisfactory assessment of chemical, metrological and metallographic analysis with a further effect on improved endurance of bearings. This manufacturing method has been tested several times since then and the desired effect was confirmed. Subsequently, this procedure has been applied also to other types of the so-called thin-walled bearings for others customers, in particular from the automotive industry, who demanded stricter ovality values. The possibility to use this technology has been confirmed in all cases.

Note: Compliance with and check of prescribed processing condition are essential for heat treatment. An appropriate way how to improve checks during the heat treatment is to use a computer-controlled hardening line. Obviously, this incurs higher input costs. According to information from the company where this optimised method of heat treatment was implemented, the system started to be used for a typical hardening line and the benefit in terms of quality exceeded their expectations.

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