Supervision on the Hardening Process of Roller Bearings by using Eddy Current Testing Methods

Martin Wolfgang SEIDEL[1], Rainer SCHÜßLER[1],
Gerd DOBMANN[2], Winfried MORGNER[3]
[1] imq-Ingenieurbetrieb für Materialprüfung, Qualitätssicherung und Schweißtechnik GmbH, Crimmitschau, Germany
[2] Fraunhofer IzfP Saarbrücken, Germany
[3] MDZWP Magdeburg, Germany

Contact e-mail: m.seidel@imq-gmbh.com

Abstract. The hardening process determines the quality of roller bearings in a crucial way. Therefore this process should be supervised using NDT methods. Eddy- Current Testing (ET) is in general well suited for checking structural changes in hardened steels. However the structure- property- relationships which ET bases on must be taken into account in order to apply these methods in a reliable way.
Therefore dependencies between magnetic permeability μ, and electric resistance ρ and hardening temperature and annealing temperature, respectively were investigated for steel grade 100Cr6. Furthermore relationships between μ and ρ on the one hand and on the other hand carbon content solved on martensite and volume fraction of retained austenite, respectively had been found.
Basing on these relationships conclusions were drawn to the applicability of ET regarding supervision of the hardening process of roller bearing steels.

1. Indroduction

The structure of hardened roller bearings strongly depends on hardening conditions, i.e. the temperature of austenitizing, the quenching process and the annealing temperature. For example: all parts to be hardened in a furnace are to have an austenitizing temperature in a range ± 10 K of the optimal austenitizing temperature to guarantee an amount of retained austenite < 10 % in all hardened parts. In the present state of the art, hardness measurement is commonly used to check the quality of the hardening process. Unfortunately, in the range of optimal austenitizing temperature a difference of Taust ≤ ± 10 K only causes a change of hardness of ± 1 HRC (Fig.1).

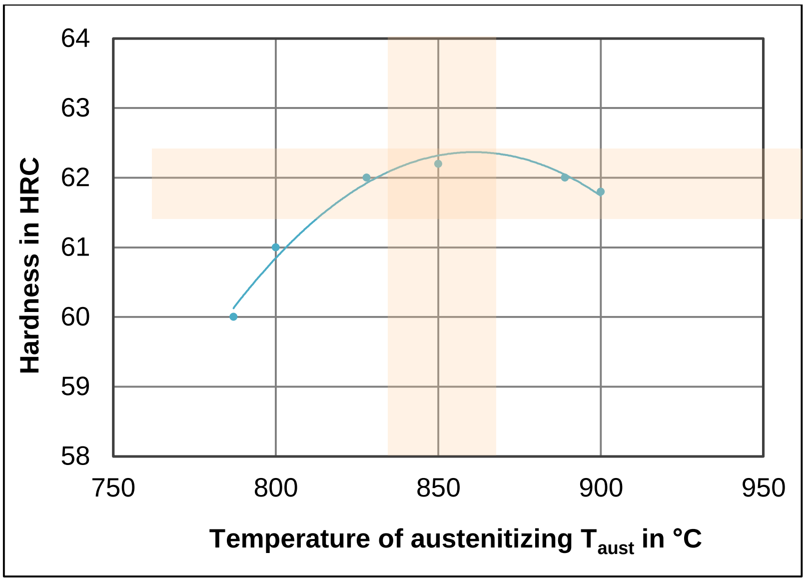


Fig. 1. HRC Hardness of hardened and annealed steel 100Cr6 (SAE 52100) vs. Temperature of austenitizing, red marked: Range of optimal T_{aust}

This is equal to the accuracy of HRC measurement. On these grounds hardness measurement does not allow supervising the hardening process in the way as described above.

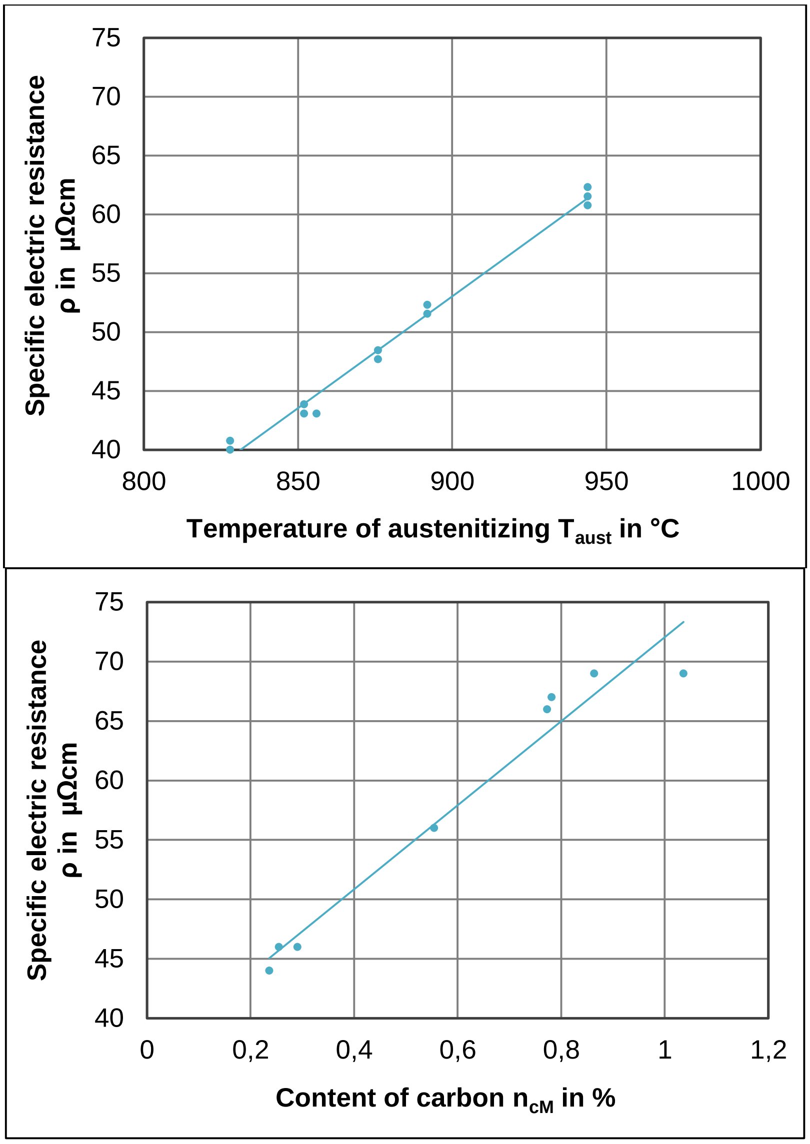
To do this, an NDT method is required which is sufficiently sensitive to small changes of hardening conditions. Principally, eddy current methods (ET) fulfill these terms. However, the crucial question is to find the optimal testing conditions, especially the testing frequencies. Mostly this is done by the trial-and-error-method. A more systematic way consists in analyzing the so-called structure-properties relationships on which ET bases [1,2]. The application of ET for structure testing is based on the dependence of electric resistance and magnetic permeability on the structure.

In section 2 relationships between electrical and magnetic properties of hardened and annealed steel 100Cr6 (SAE 52100) on the one hand and hardening conditions as well as the structure of hardened steel on the other had is presented. In section 3 conclusions are be drawn on the application of ET and compared with experimental results. Section 4 shows results of using ET supervising of the hardening process of roller bearings. The presented results are discussed in more detail in [3].

2. Structure- Property- Relationships

2.1. Austenitizing Temperature

Fig. 2 shows that the dependence of the electric resistance ρ on the austenitizing temperature T_{aust} is nearly linear between 800 ° C and 1000 °C. Increasing the content of carbon dissolved in martensite causes a strong increase of the electric resistance (Fig. 2b).



a)

b)

Fig. 2. Specific electric resistance of hardened 100 Cr6 (SAE 52100)
a) vs. austenitizing temperature b) vs. content of carbon dissolved in martensite

In contrast to resistance, the plot of magnetic permeability vs T_{aust} between 880 °C and 900 °C shows a minimum of µ (Fig. 3). At this temperature, this minimum is caused mainly by the transition of the martensite structure from lathe-shaped martensite to plate-shaped martensite.

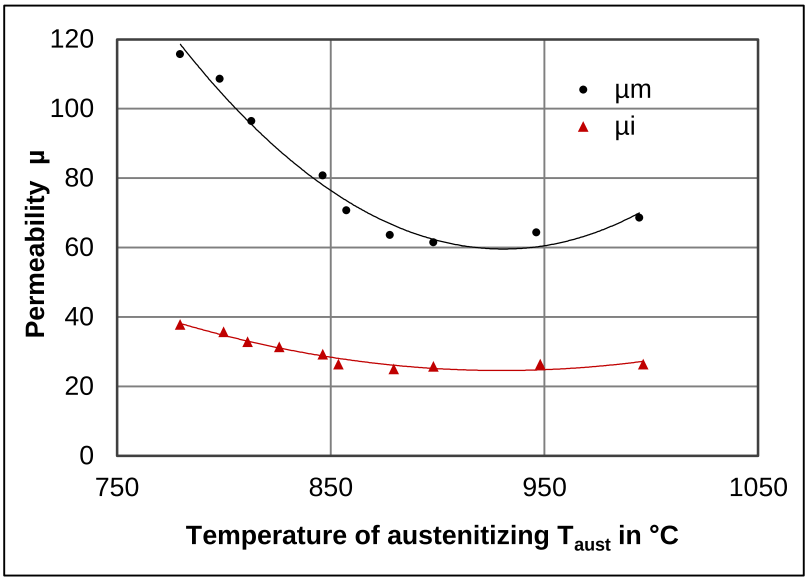


Fig. 3. Initial permeability and maximum permeability of hardened steel 100Cr6 (SAE 52100) vs. autenitizing temperature T_{aust}

2.2. Annealing Temperature T_{ann}

In Fig. 4 electric resistance, coercive force, initial permeability and maximum permeability (related to the value of non-annealed parts) are plotted vs. the annealing temperature.

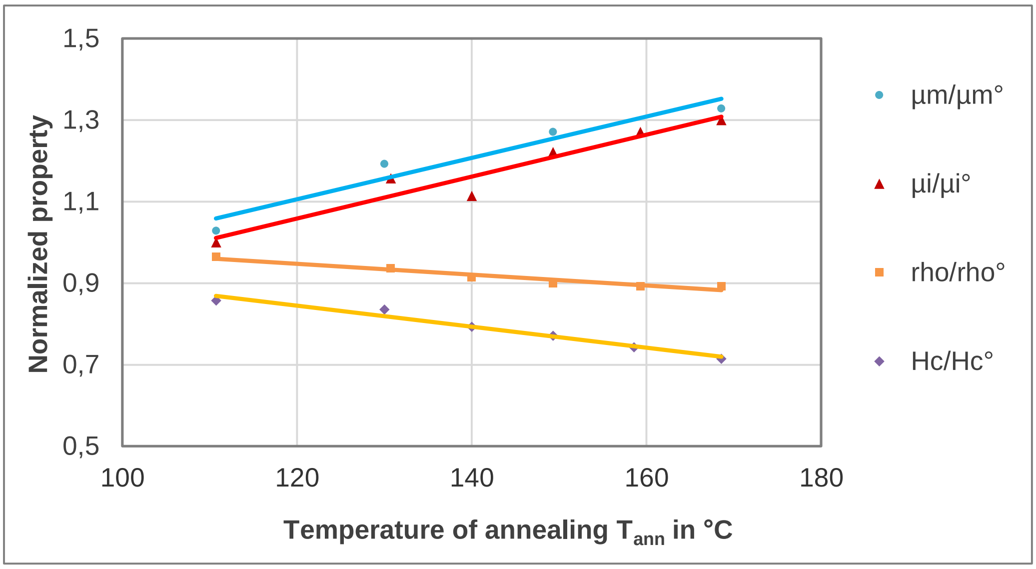


Fig. 4. Specific electric resistance, coercive force and magnetic permeability (related to the values before annealing) of hardened and annealed 100Cr6 (SAE 52100) vs. annealing temperature T_{ann}

Electric resistance and coercive force are decreasing, while the initial permeability as well as the maximum permeability are increasing. In the range of T_{ann} < 180 °C this increase and decrease, respectively, follows a linear function.

Whilst the magnetic permeability increases by 30 % at T_{ann} = 180 °C, the decrease of electric resistance is much smaller.

Results of ρ, H_c and µ beyond 180 C were not reported for 100Cr6/SAE 52100. But steel 36CrNiMo4/SAE 4340 shows the same linear behaviour of H_c as 100Cr6 at annealing temperatures below 200 °C. Beyond 200 °C the Coercive force drops dramatically to a minimum of 450 °C[4]. For 100Cr6 it needs further experimental work to verify the behavior of ρ, H_c and µ in this range of annealing temperatures.

3. Conclusions for the application of Eddy-Current Testing

The structure-property relationships discussed above allow drawing conclusions on the application of eddy current testing.

First it can be stated that a definite relation between the ET signal and the austenitizing temperature can be expected only at higher testing frequencies. This is due to the fact that at higher frequencies the electric resistance acts more strongly to the ET signal than the magnetic permeability. At lower frequencies the magnetic permeability dominates, and therefore a definite relation exists only below $T_{aust} < 880$ °C. Fig. 5 shows ET signals of hardened roller bearing rings plotted vs. T_{aust}.

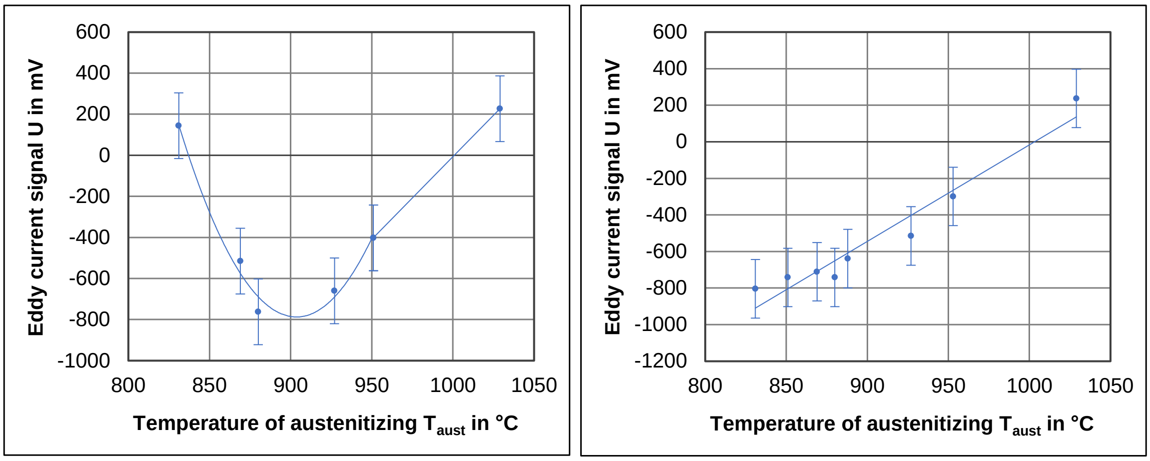


Fig. 5 Eddy-current signal of hardened rolling bearing rings vs. austenitizing temperature T_{aust}; left: testing frequency f = 1000 Hz; right: testing frequency f = 1 Hz

As expected, at a testing frequency of 10 Hz the curve shows a minimum at $T_{aust} \approx$ 880 °C, whilst at a testing frequency of 1000 Hz exists a linear function within the whole range of applied T_{aust} . This means that low testing frequencies may be applied only if it can be assured that the austenitizing temperature is $T_{aust} < 880$ °C. Otherwise higher testing frequencies must be applied.

At higher frequencies than 1000 Hz the ET signal characterizes the content of carbon dissolved in martensite. Due to the fact that retained austenite does not act significantly to electric resistance as well as to magnetic permeability, it is not possible to supervise the amount of retained austenite in a direct way. Only in case of a defined relation between martensite structure and the content of retained austenite the ET signal also represents the content of retained austenite.

4. Application of Eddy-Current Testing

In this section two application examples are to be discussed.

The first example concerns the supervising of a new hardening furnace. The furnace must guarantee that the temperature at each place on the conveyor belt is in the range $\Delta T_{aust} \leq \pm 7$ K. To check whether this condition is fulfilled, rings are marked and placed a several positions inside the furnace. The testing results of the quenched parts are shown in Fig. 6.

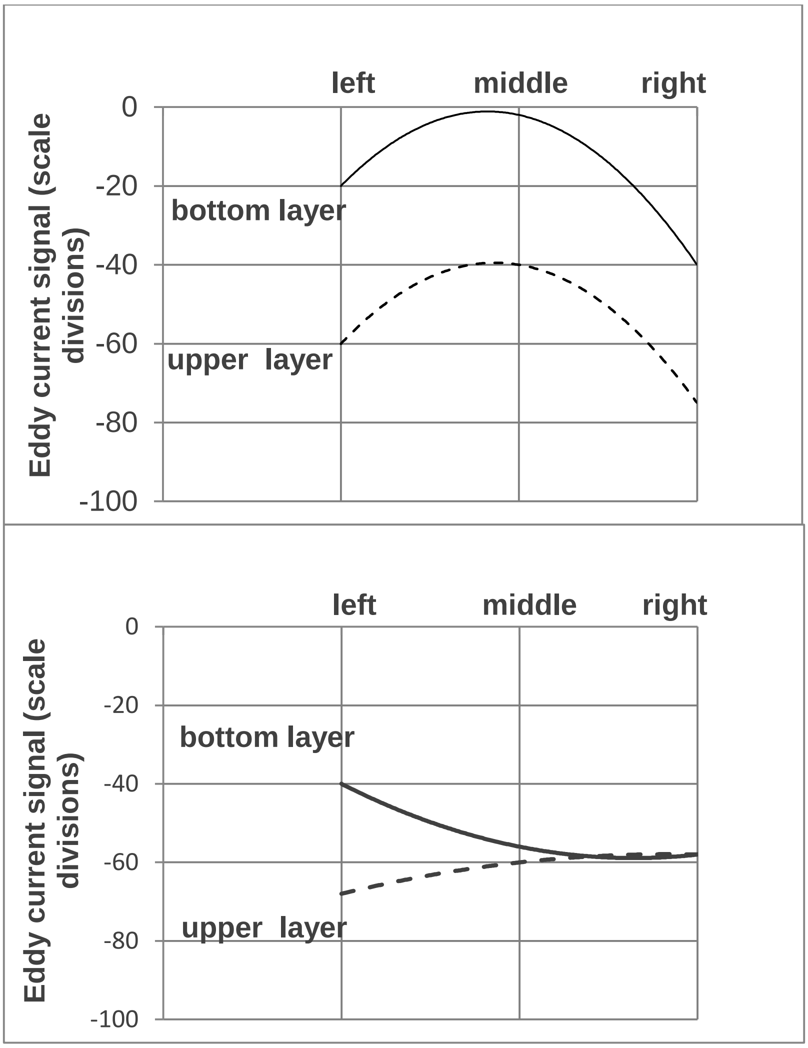


Fig. 6 Eddy-current signal of hardened rolling bearing parts austenitized at different positions in a furnace above: initial state of the furnace down: after reconstruction

In the initial state the ET signals of the rings differ significantly: The lowest signals were measured at rings placed on the right side of the conveyor belt in the upper layer. The rings placed in the middle of the belt in the bottom layer had the highest signals. This corresponds with the results of hardness measurements between 66 HRC and 63 HRC. In the initial state the furnace does not fulfill the requirement of ΔTaust $\leq \pm$ 7 K. The furnace had to be reconstructed. After that, the ET signals as well as hardness were in the expected range.

Eddy current testing may also be applied to carry out a statistical process control (SPC) of the hardening process. Fig. 7 shows the results of SPC.

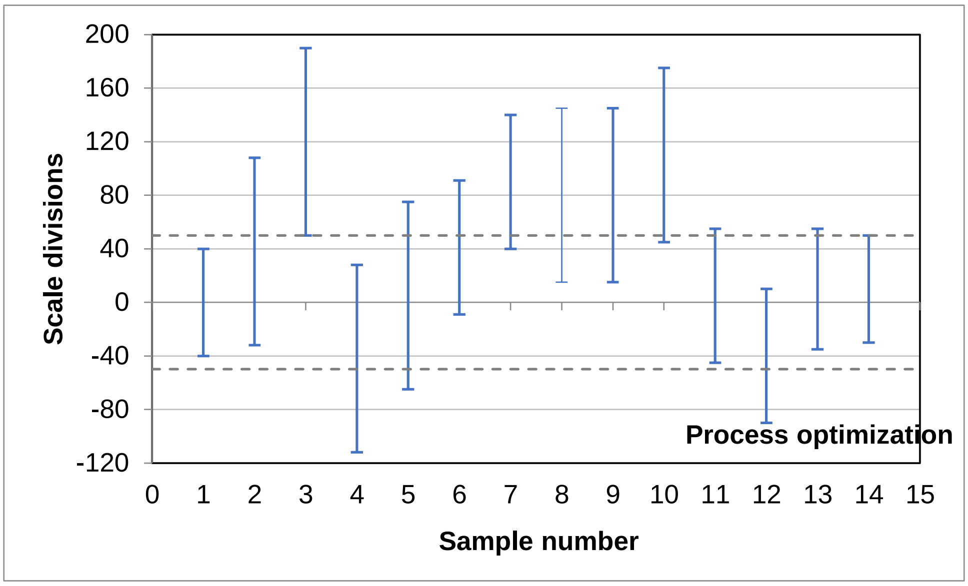


Fig.7. Statistical process control of the hardening process of roller bearing parts by eddy-current methods

The random samples of approximately 10 or 15 quenched parts were tested and signals were automatically plotted in an SPC scheme. At the beginning the hardening process was rather unstable: the signals of the samples increased beyond the upper threshold. Then the hardening conditions, i.e. temperature and the speed of the conveyor belt, were changed. The next 7 samples showed the same behaviour. Yet, after the next optimization of the process the signals turned out to stay between the upper and lower thresholds. .

5. Summary

The hardening process is to be supervised by applying material testing methods in order to guarantee a uniform high quality of all hardened parts. Hardness testing methods are suited to that purpose only in a limited way because of the fact that in the range of the optimal austenitizing temperature there is only a small change in hardness.

In contrast, the changing of austenitizing conditions acts on the electric and magnetic properties of hardened steels much more strongly. Eddy current testing methods base on dependencies between structure and electromagnetic properties. Therefore eddy current methods are basically well suited to supervise the hardening process.

The analysis of relations between austenitizing conditions and structure on the hand and magnetic permeability and electric resistance on the other hand allow drawing conclusions on the applicability of ET regarding the supervision of the hardening process of roller bearing steels.

For example, in case of hardened steel grade 100Cr6 (SAE 52100) it was shown that at lower testing frequencies the supervising of the austenitizing temperature is possible only if ensured that the austenitizing temperature does not rise beyond 880 ^{0}C. Otherwise, higher testing frequencies must be applied. In that case the testing signal shows a strong correlation to the content of carbon dissolved in martensite. Due to the fact that retained austenite does not act significantly on electric resistance as well on magnetic permeability, it will not be possible to supervise the amount of retained austenite in direct way.

The hardening process in conveyor furnaces can be supervised in a very effective way. One example to show this concerns the supervising of a hardening furnace before and after reconstruction. Another one shows how to apply eddy current testing for statistical process control.

6. References

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