Effects of the application of a non-conventional treatment in magnetic field on a steel for industrial gearings

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Abstract. An alloyed steel grade for machine parts construction used in industry have been considered and this material was subjected to a non-conventional treatment. The samples have been tested using an Amsler stand for dry friction tests and the diffractometric analysis completed this study. The plasma treatment plant used was the INI 150 made by the Institute of Radiation Physics and Technology in collaboration with the "Electrotechnics" Enterprise and the Nuclear Apparatus (I.C.E.FIZ.) from Romania and was destined for technological research. The samples considered for tests were type rollers, with 10 mm width, with different diameters to obtain different sliding degrees (ξ), considering different values for the normal load (Q). This paper is a short review of the researches from last years and realizes a synthesis and a correlation of the results to formulate conclusions on the efficiency of the application of non-conventional treatments in magnetic field on special pieces from industry.

1. Introduction
The gearings, as a part of the machine construction used in industry, are subjected to friction. Physical phenomenon known as friction process represents the resistance to motion of two bodies brought into contact. The contact can be formed between the surface layers. If the distance between the surfaces is sufficiently small, the forces between the atoms and molecules bond those surfaces, forming junctions which determine the adhesion level. In the case of the gearings in contact directly the forces are very large and it is important to have superficial layers with characteristics of resistance in accordance with the solicitation of exploitation. That’s why the researchers try to find more opportunities to increase the mechanical properties of the superficial layers.

An important quantity of the aluminum in the structure of the steel increases the thermo-magnetic treatment power and the results are the best. At the same time, the existence of aluminum content in the structure of the steel causes some hardening problems which are countered by the Chromium existence [1, 2].

It was considered an unconventional treatment in magnetic field. The magnetic field applied during the improvement treatment of the steel determines local oscillation through the magnetostriction which provokes local plastic deformations of the steel.

In literature, studies regarding the researches on the influence of the magnetic field applied during the heat treatments on the hardness of the steels for bearings and on the quantity of the residual Austenite (Age7), have been presented. Analyzing the influence of the improvement treatments in magnetic field on the mechanical characteristics of the steel RUL 1 (100 Cr6) and on the wear behavior on tribo-models or on real pieces, resulted the following observations:
a). Through the improvement treatment in magnetic field realized in alternative current (A.C.) the improvement of the mechanical characteristics have been obtained, excepting the resilience (KV/KCU), comparing to the classic improvement treatment of the same steel (without magnetic field).

b). The tests on tribomodels for different thermal treatment variants applied to RUL1 steel have led to the conclusion that the thermo-magnetic treatment applied to this steel increased durability, implicitly, reliability. The influence is higher as it is applied at a lower quenching temperature [1].

For example, at the hardening temperature 810-820˚C – for RUL1 steel- the heating in magnetic field - Alternative Current (A.C.) - with the intensity of \( H=31 \text{Oe} \) conducts to the increasing of the reliability with 22%, the cooling in magnetic field - direct current (D.C.) at the magnetic field intensity \( H=975 \text{Oe} \) conducts to the increasing of the durability with 32%, and the tempering in magnetic field (D.C.) with the magnetic field intensity \( H=1200 \text{Oe} \), conducts to the increasing of the durability with 53%.

From a structural point of view, X-ray diffractometric analyzes showed that residual austenite (\( \text{Arez} \)) content decreased and the degree of tetragonality of Martensite (c/a) decreased too, resulting in more stable homogeneous structures, thus achieving a better behavior in the wear of the bearings [1, 2].

In literature, effects of the thermo-magnetic treatments applied to quick tool steels (Rp5, AISI/SAE M2) have been studied [3]. This steel – reach alloyed – supported a classic thermal treatment (the improvement) and a thermo-magnetic treatment. It were obtained the same conclusions as in the case of the RUL1(100Cr6) steel for bearings: the hardness of the steel have been increased, the residual Austenite quantity decreased and other mechanical characteristics have been improved too.

It was obtained a positive influence of the magnetic field applied during (total or partial) the improvement treatment of the steels.

In the chemical composition of these types of steels, there are both: a large proportion of carbon and the carburizing alloying elements (W, Mo) contents capable to give birth to carbides of the \( \text{M6C} \) type - most important for hardening by dispersing precipitation and for heat stability. Before the hardening treatment, the structure of the steels for tools is a structure similarly with the structure obtained after the globular annealing treatment (as in the case of the steel which will be analysed in this paper).

The initial structure of the Rp5 steel was formed by a base of Ferrite (F) alloyed with the following elements: W, Mo, Cr, V, at which were added primarily and secondary carburs as: \( \text{M6C}, \text{M23C}, \text{MC}, \text{M3C} \) (M represents the metallic components). In the case of Rp5 steel, Ferrite has a proportion by 71% and the carburs have 28%. Through hardening treatment, 60% from metallic carburs have been dissolved in Austenite (A) in the mass of this steel. Austenite (A) was enriched in Carbon and alloying elements. If the temperature increased suddenly- more than 1230˚C for Rp5 steel grade, the Austenite was enriched in Carbon until \( 0.5\% \), but the hardening temperature have been limited by the increasing of the Austenite boundery [2, 3].

In the presence of the magnetic field, the ferromagnetic germs of martensite generate pressures on the surrounding austenite by magnetostriction. There is an acceleration of the martensitic transformation velocity. If continues to increase the ferromagnetic domains, the magnetostriction effects increase. The internal forces generates limits of separation between Austenite (A) and Martensite (M), permitting the evolution of the transformation \( \text{A} \rightarrow \text{M} \), until a specific label, resulting a smaller content of Austenite (A) [2, 4].

Therefore, the action of the magnetic field increases the number of martensitic germs in the same volume, resulting a finer martensite than in the classical thermal treatment conditions.

Because of the magnetostrictive internal forces, the diffusion conditions of the atoms of Carbon inside the elementar cells have been created. Results, the tetragonality grade of Martensite decreases. Also, the fragility of the steel decreases [1-4].

A higher quantity of Martensite was obtained during the tempering of a 13Cr6Ni2Mo supermartensitic stainless steel (X2CrNiMoV13-5-2) using magnetic field [5]. It can be observed that each phase of heat treatment in the magnetic field influences the durability in a different way: hardening treatment in the magnetic field leads to an increase in durability by 49% compared to classical treatment. The high tempering treatment with cooling in magnetic field determines an increasing of the durability by 40%, comparing to the classic treatment.
On the other hand, if Aluminum and Chromium contents increase in the structure of the steel the residual austenite quantity decreases more rapidly. The Martensite quantity and implicit, the hardness of the steel increase significantly, more than in the case of the steels with approx. the same content of Carbon but with lower quantity of Aluminum. As a consequence, the magnetic field intensity, the content of the Carbon and the content of the Aluminum from the steels have an important influence. Because of these aspects, the tendency of breaking decreases and the probability of the fragile breakage no longer exists [2, 6].

Magnetostriction determines local oscillations and results local plastic deformations [2-5].

The variation of the number of germens of Martensite depends by the content of the Carbon and by the intensity of the magnetic field applied during the heat treatments [2].

In table 1 were presented these values variations.

| Germens number (M) | 0.03%C | 0.4%C | 0.6%C | 0.8%C | 1%C | 1.6%C |
|--------------------|---------|-------|-------|-------|-----|-------|
| H = 0.8 MA/m       | 1.11    | 1.34  | 1.18  | 1.18  | 1.20| 1.35  |
| H = 1.6 MA/m       | 1.23    | 1.30  | 1.34  | 1.39  | 1.44| 1.81  |
| H = 4MA/m          | 1.68    | 1.90  | 2.06  | 2.26  | 2.46| 4.35  |

2. Experimental procedure

For the experimental procedure, the samples have been realized as rollers from a steel grade for the improvement treatment, with the following chemical composition principal content: Fe 72.89%, 0.38 % C, 1.02% Al, 1.38 % Cr, 0.17 % Mo, 0.50 % Mn, 0.25 % Si, 0.26 % Ni, 0.02 % P, 0.02 % S. The existence of the Molybdenum content in the composition of the steel decreases the stiffening phenomenon.

The first stage from the complex program of treatments consisted of thermo-magnetic treatments. The treatment t1 represents a hardening treatment (at 920 °C) followed by a high tempering (at 620°C), being a classic improvement treatment.

The treatment t2 represents a complete martensitic hardening treatment in weak alternative magnetic field (with cooling in water) and high tempering treatment (with cooling in water, in strong magnetic field - Alternative Current (A.C.). In this case, the sample was introduced in the centre of the electrical coil located in the walls of a cylindrical oven. All treatment have been made completely in magnetic field (A.C.) and the results obtained through the treatment t2 have been presented in figure 1.

In figure 1 was presented the effect of the intensity of magnetic field (H) on the hardness of the steel (HB) in the case of a complete martensitic hardening process in weak alternative magnetic field (with cooling in water) followed by a high tempering treatment with cooling in water, in a strong magnetic field - Alternative Current (A.C.).

It must be mentioned that all these treatments have been made completely in magnetic field (A.C.).
Treatment t4 represents a thermo-magnetic treatment corresponding to magnetic field- Direct Current (D.C.) applied just during the cooling in water.

The second stage of the treatments presumes the existence of the ionic nitriding treatment (plasma nitriding) applied at 530 °C. This treatment was applied after the improvement treatments, a classic one (T1) or in magnetic field: Alternative Current (T3) and Direct Current (T4) treatments. T2 = t2 and plasma nitriding. The temperature of the thermo-chemical treatment was considered at 530 °C, being specific for this kind of the improvement steel [7 - 9]. In case of a low temperature (100 °C – 510 °C), plasma nitriding produces the expanded austenite (the S-phase) with good behavior at friction process. The phase γ (Fe₃N) appears at higher temperatures than 500 °C and reduce the thickness of the S-phase.

In this paper it was considered an improvement steel grade alloyed with Aluminum and Chromium and the treatments temperatures have been chosen for this case [6].

The increasing of the depth of the superficial layers in the case of unconventional treatment applied has been reported in accordance with the depth of the superficial layer for the same steel which suffered a classic improvement treatment before a thermo-chemical treatment.

The wear tests have been made on Amsler machine, type roller on roller, with different diameters to obtain different sliding degrees (for example, for ξ = 20%, the outer diameter of the conducting roller had 43.9 mm and the second roller had 40 mm. Rolls width was 10 mm. The wear moment Mf = 40 daN·cm, the normal load (Q) was 150 daN, the friction coefficient (μ) was 0.121, the lenght of friction zone of the rollers (Lf) was 74.606 m. Figure 2 presents the scheme of the wear tests.

3. Results and Discussion

After each hour of wear tests, during three hours, for each sample, the calculations have been made depending on diffractometric analysis. The results [2] presented in Table 2 have been obtained.

![Figure 2](image)

**Figure 2.** Rolling-sliding configuration: “+” represents tensile stresses; “-” represents compressive stresses, in the case of the wear tests

| Code samples | ~% I₉Fe₃N | ~% B₂Fe₃N | ~% I₀Fe₃N | ~% B₂Fe₄N | ~c/a B₂₁₁ | ~c₁ B₂₁₁ | Δ0 | t [h] | Q [daN] | ξ [%] |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|----|------|--------|------|
| 322(T1)      | 4         | 4         | 20        | 1.81      | 2.526     | -         | 0  | -    | 150    | 20   |
| 322(T1)      | 6         | 4.40      | 26        | 2.40      | 2.526     | -         | 1  | 150  | 20     |
| 322(T1)      | 4         | 4         | 20        | 1.81      | 2.260     | -         | 2  | 150  | 20     |
| 322(T1)      | 20        | 5         | 26        | 3.33      | 2.260     | -0.10     | 3  | 150  | 20     |
| CA1(T3)      | 16        | 1.50      | 16        | 3.00      | 1.750     | -0.10     | 0  | -    | -      |
| CA1(T3)      | 15        | 2         | 17        | 2.98      | 1.750     | -         | 1  | 150  | 20     |
| CA1(T3)      | 18        | 4         | 18        | 3         | 2         | -         | 2  | 150  | 20     |
| CA1(T3)      | 18        | 4         | 18        | 2.70      | 2.160     | -0.15     | 3  | 150  | 20     |
| CA0(T4)      | 10        | 3.20      | 12        | 3         | -         | -         | 0  | -    | -      |
| CA0(T4)      | 6         | 2.94      | 10        | 3.20      | -         | -         | 1  | 150  | 20     |
| CA0(T4)      | 5         | 3         | 8         | 2.70      | -         | -         | 2  | 150  | 20     |
| CA0(T4)      | 5         | 3         | 8         | 2.70      | -         | -         | 3  | 150  | 20     |
The contact geometry of the friction couple (roller on roller), the technological parameters (surface quality, thermo-chemical treatment) and the exploitation conditions (for example, the thermal solicitation) are the factors which influence this kind of wear process [6, 7, 8].

Phases from superficial layer versus the wear tests duration corresponding to the non-conventional treatment in magnetic field – Direct Current T4, have been presented in figure 3.

In figures 4 and 5, the evolution of phases Fe3N and Fe4N from superficial nitride layer and the degree of tetragonality of Martensite (c/a) have been presented, for case of classical treatment without the magnetic field influence (T1) and respectively, for non-conventional treatment in magnetic field – Alternative Current (T3).

The hardness of Martensite (M) leads to high mechanical strength and low plasticity which are the result of the complexity of its structure, a solid solution supersaturated with interstitial carbon and tetragonal network formed by processes of sliding. It’s important to study the degree of the tetragonality of Martensite which influences the hardness of the superficial layers.
Figures 6 and 7 present the evolution of the internal tensions of second order depending on the duration of the wear tests, in both cases: in classical treatment regime T1 and in the case of the non-conventional treatment T3. The internal tensions of the phases determine a lower resistance of the Fe₃N phase during the cyclical fatigue. This fact was determined by mechanical oscillations created by the magnetic field (Alternative Current) through the permanently changes of the field lines directions, because of the magnetostriction existence. The magnetostriction - caused by the magnetic field - changes the re-crystallization conditions and the speed of germination. In this situation, the hardness of the superficial nitrided layers increased. The degree of tetragonality of Martensite (c/a) was higher in the case of γ'-Fe₄N (see figure 5).

After plasma (ion) nitriding, the nitrided superficial layer had a higher depth in the case of applying the magnetic field. Figure 8 present the evolution of the micro-hardness values in superficial layer, depending by the treatment, following the thickness of the white layer [6].

The following notes have been used:

HVₐ = micro-hardness in the case of the treatment T3;
HVₐ = micro-hardness in the case of the treatment T4.

It can be observed an improvement of the mechanical properties, for example the micro-hardness of the superficial layer increased in the case of the non-conventional treatment (T3) because of the distribution of the γ'-Fe₄N phase, especially in the case of the increasing of the normal load (Q) and for the increasing of the sliding degrees (ξ). The structural and magnetic properties of epitaxial γ'-Fe₄N iron nitrides films have been investigated by Costa – Krämer J L, Borsa D M, and others, in [14] and they explain why this phase is so important. According with [7, 10], the magnetization properties described are so far consistent with a single phase of epitaxial film, having a cubic structure and a positive anisotropy constant, i.e., the [100] directions are easy magnetization axes. All the magnetic characteristics presented so far are then dictated by the value of the anisotropy constant. This value can be estimated from the hysteresis loops obtained applying the field along a hard magnetization axis, if the value of the saturation magnetization is known [6, 8, 10-13].
Figures 9 and 10 presents the evolution of the microhardness values after the treatments T1 and T3 respectively T1 and T2 depending on the thickness of the nitried layer (GT1) obtained through plasma (ion) nitriding, before the wear tests.

4. Conclusions

After the first stage of the treatment the hardness of the steel increased with 38% in the case of the non-conventional treatments (alternative current-magnetic field) because the Martensite amount increased, comparing to classic treatment case. The micro-hardness of the superficial layer of steel increased with approx. 20 - 30% in the case of plasma nitriding applied after thermo-magnetic treatment, depending on the treatment regime applied, comparing to the classic treatment applied on the witness samples.

From the diffractometric point of view, the samples present changes regarding the content of Fe$_3$N and Fe$_4$N phases in the thermo-chemically treated superficial layer, during the wear process, considering the non-conventional thermo-magnetic treatment applied as a basic treatment, before plasma nitriding and comparing to classic treatment. This situation implies changes in structure and implies the increasing of the hardness of the material, including in superficial layers thermo-chemical treated after thermo-magnetic treatments. For example, Fe$_4$N amount increasing implies a higher micro-hardness in superficial layers of the steel and a higher mechanical resistance at friction wear tests. Magnetic field influences positively the amount of Fe$_3$N and mechanical properties of the steel.

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