SELECTION OF MATERIALS FOR COMPONENTS OF LINEAR STEPPER MOTORS FOR NUCLEAR POWER PLANTS

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Abstract - A description is given of the process of selection of materials, their heat treatment sequences, and possible surface treatments for pawls of linear stepper motors for WWER nuclear power plants. The materials selected for the application were tested as well. The tests included measurement of hardness, impact toughness testing, metallographic characterization and high-temperature wear testing. In surface-treated specimens, the thickness and microstructure of the surface layer were determined.
14Ch17N2 steel proved to be the best candidate, as it showed a superior combination of properties for the application.

Index Terms - Selection of Materials, Mechanical Testing, Microstructure

I. INTRODUCTION

This paper concerns selection of materials for linear stepper motors that meet the specifications for new power units of WWER (water-water power reactor) power plants. The objective was to select a material for a pawl, a critical component with a major impact on the life of the entire device. Pawls are among the most heavily-stressed parts of linear stepper motors. Examinations of various worn parts of drives have revealed that the main cause of their excessive wear was contact fatigue. Attempts were thus made to improve their wear resistance.
The available options include modifying their heat treatment, substitution with another material, and surface treatment. Since the materials should sustain abrasion and pressure, they should possess sufficient strength and hardness. At the same time, they should retain toughness, even in corrosive environments, under high pressures (up to 12 MPa) and at high temperatures of up to 320°C. Five stainless steel grades were identified along with appropriate heat treatments. Surface treatment for enhancing their utility properties was considered as well. All the materials were examined by metallographic techniques and their mechanical properties were tested.

II. SELECTION OF MATERIALS, THEIR HEAT TREATMENT AND SURFACE TREATMENT

A. Selection of materials

Given the nature of the load on pawls and the relative affordability of iron-based materials when compared to other high-temperature materials, such as nickel superalloys, the top candidates are martensitic stainless steels [1]. Four steels of this kind were thus proposed for linear stepper pawls. 95Ch18 steel has a relatively high carbon content (between 0.95 and 1.2 wt. %). Its chromium level is comparable with the other proposed candidates (16 to 18 wt. %). Unlike the other candidate materials, it contains molybdenum. This chemical composition should provide high hardness and wear resistance.
The composition of 20Ch17N2B is similar to that of 14Ch17N2, with the exception of a niobium addition and a higher carbon level.
14Ch17N2 is a medium-carbon steel and promises the best combination of strength and toughness among the candidates.
The 1Ch13N3 grade contains less carbon and chromium than 14Ch17N2.
The 10Ch11N20T3R austenitic stainless steel was selected as an alternative choice to its martensitic counterparts. Austenitic stainless steels are widely used for manufacturing high-temperature components [2]. This steel is titanium-stabilized in order to prevent formation of $Cr_{23}C_6$ carbides [3].

It is expected to possess lower hardness, which is compensated by high toughness and corrosion resistance [4]. When surface-treated, it could offer an attractive alternative to the other candidate materials.

B. Heat treating sequences

Each martensitic stainless steel was oil-quenched and tempered. 95Ch18 and 20Ch17N2B grades were quenched, subjected to deep freezing at -75°C and tempered using two different sequences. Details of the heat treatment cannot be given here, as they are protected as a trade secret of the company ŠKODA JS a.s. The 10Ch11N20T3R grade was tested in as-received condition without additional heat treatment.

C. Surface treatment

The use of surface treatment was motivated by the need for enhanced wear resistance of the surface combined with a strong and tough core. Multiple options had been considered, of which two surface treatment methods were chosen: conventional nitriding and advanced laser surface hardening. Only some of the candidate materials were surface treated. Two samples of the 95Ch18 grade and two samples

of the 14Ch17N2 grade were laser hardened. This was carried out using the Laserline LDF 6000-40 diode laser which features modular flexible optics. The laser beam can thus be adjusted for hardening, welding and cladding applications. The power and the character of laser radiation offered by this equipment are appropriate for the present purpose as well. Thanks to the sensitive output power control and flexible adjustment of the laser beam geometry and energy distribution, parts of various shapes and sizes can be treated.

The other surface treatment process was ordinary gas nitriding [5, 6]. Nitriding in ammonia was applied to one sample of each of the 95Ch18, 1Ch13N3 and 10Ch11N20T3R grades and to two samples of 14Ch17N2 steel, using two different sequences. The basic schedule for all samples was as follows: first stage (temperature: 550°C / time: 10 hours, dissociation rate 30%) + second stage (temperature: 580°C / time: 30 hours, dissociation rate 60-70%). One sample of the 14Ch17N2 grade was subjected to two consecutive basic schedules. The goal was to produce a diffused nitride layer of a greater thickness for better wear resistance.

III. SURFACE HARDNESS TESTING

Rockwell hardness was measured on candidate materials without surface treatment. The highest hardness was found in the 95Ch18 grade.
The lowest hardness was found in sample 6 of the 10Ch11N20T3R austenitic steel. Samples 4 and 5 (14Ch17N2 and 1Ch13N3 grades) exhibited similar hardness levels around 42 HRC. The samples of the 20Ch17N2B steel had a higher hardness: 45 HRC in sample 3 and 47 HRC in sample 7 (Table 1).

Table. 1. HRC hardness readings

Steel	Sample	HRC hardness
95Ch18	Sample 1	57.8
	Sample 2	59.8
20Ch17N2B	Sample 3	45.0
	Sample 7	47.2
14Ch17N2	Sample 4	41.7
1Ch13N3	Sample 5	42.6
10Ch11N20T3R	Sample 6	27.4

IV. IMPACT TOUGHNESS TEST

Charpy impact test was carried out.
The lowest notch toughness was found in 95Ch18 steel. The highest notch toughness values were associated with the 10Ch11N20T3R grade whose microstructure was austenitic. Among the martensitic stainless steels, the highest notch toughness was found in the 14Ch17N2 grade (Table 2).

Table. 2. Impact toughness test values for V-notch [J]

Grade	Sample	Notch toughness [J]
95Ch18	Sample 1	3.5
	Sample 2	4.9
20Ch17N2B	Sample 3	20.7
	Sample 7	9.0
14Ch17N2	Sample 4	63.8
1Ch13N3	Sample 5	32.3
10Ch11N20T3R	Sample 6	127.1

V. EVALUATION OF SURFACE TREATMENT

The microstructures of surface-treated layers were examined and depth profiles of hardness were measured to determine the layer thickness.

A. Laser-hardened samples

The surface hardness of the laser-hardened 95Ch18 grade was slightly less than that of the base material. Hardness then decreased with increasing depth to a minimum of 400 HV1 at 1.5 mm. Further below, it increased again, up to the hardness of the base material (Fig. 1).

The microstructures at the surface and in the base material were similar: a martensitic matrix with abundant coarse primary carbides, sometimes arranged in bands. Laser surface hardening has not dissolved existing large primary carbides. The matrix also contained numerous minute and uniformly-distributed globular secondary carbides. The region of lower hardness had a similar microstructure, in which there were larger and more numerous secondary carbides. Clearly, this region has experienced tempering.

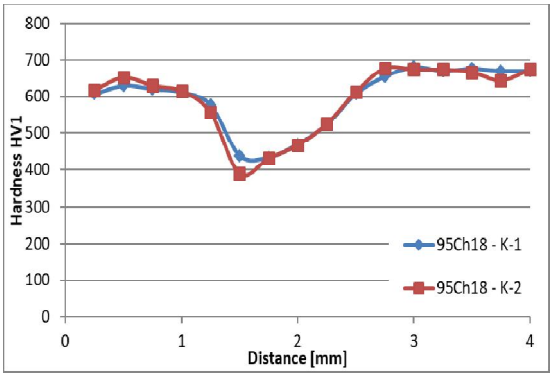


Fig. 1. Hardness profiles through the laser-hardened layer in the 95Ch18 grade

The depth profiles of hardness through the laser-hardened layer in the 14Ch17N2 grade had shapes similar to those found in the 95Ch18 material. The surface hardness was the same as that of the base material. Below the surface, hardness decreased with increasing depth to a minimum just above 300 HV1 at 1.75–2 mm depth. Further below, it increased gradually, up to the level of the base material hardness (Fig. 2).

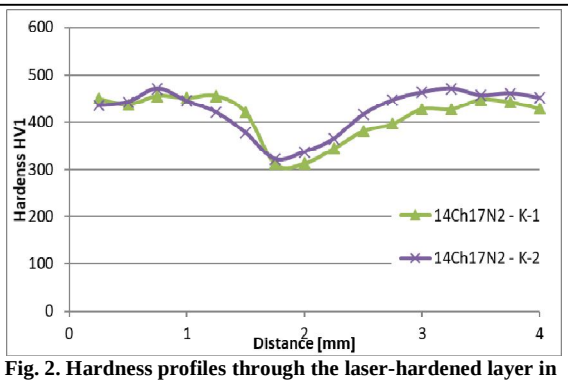


Fig. 2. Hardness profiles through the laser-hardened layer in the 14Ch17N2 grade

Sample 4 contained a martensitic matrix with δ-ferrite and uniformly-distributed small secondary carbides. Their concentration was higher in the softer region (Fig. 3).

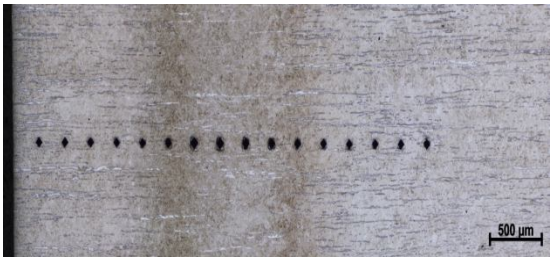


Fig. 3. Indentations in laser-hardened surface in 14Ch17N2 – K-1

B. Nitrided samples

In nitrided layers, hardness and thickness were determined and the highest hardness level was sought. The layer thickness is defined as the distance between the surface and a "hardness limit" line, where the "hardness limit " for nitrided layers equals the core hardness + 50 HV. The materials possessed different core hardnesses, hence their nitrided layer thicknesses varied, despite similar hardness profiles.

In the 95Ch18 grade, hardness was close to 900 HV0.3 at the surface but it decreased toward the interior. The thickness of the nitrided layer was more than 0.3 mm.

In 14Ch17N2, the nitrided layer thickness was 0.25 mm and the surface hardness reached 775 HV0.3. The other sample of this grade, which had been nitrided twice using the same sequence, had a thicker nitrided layer, 0.45 mm, but showed a lower surface hardness: 708 HV0.3.

In the 1Ch13N3 grade, the surface hardness was close to 750 HV0.3. The thickness of this nitrided layer was more than 0.4 mm.

The nitrided layer in 10Ch11N20T3R contained cracks (Fig. 4). As a consequence, very low hardness was found near the surface. With increasing depth, the values rose to just below 1000 HV0.3 and then plunged again to the level of base material hardness. The nitrided layer thickness was thus a mere 0.1 mm (Fig. 5). The likely reason was the differences in the behaviour of this austenitic steel to the martensitic stainless steels. Therefore, the quality of the nitrided layer in the 10Ch11N20T3R grade was poor.

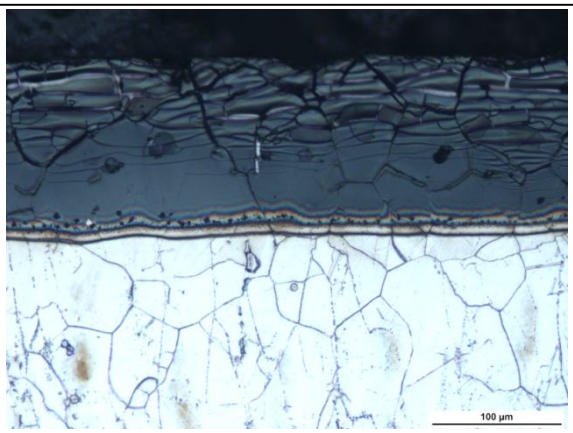


Fig. 4. Nitrided layer in 10Ch11N20T3R steel

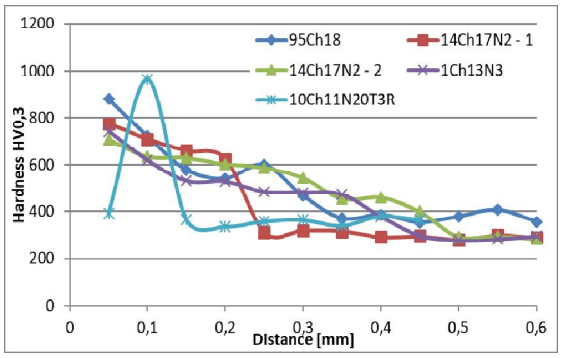


Fig. 5. Hardness profiles in nitrided layers

VI. TESTS OF NITRIDED 14CH17N2 STEEL

During nitriding, the material is exposed to high temperatures for 30 hours. This was the reason for exploring the impact of the process on its mechanical properties. Together with the samples, a larger workpiece was processed in order to provide material for notch toughness testing specimens, for measuring HRC hardness and for microstructure characterization.

These tests showed that nitriding had led to a notable decrease in both elongation and notch toughness (Tables 3 and 4).

14Ch17N2 steel contained a martensitic matrix with δ-ferrite prior to nitriding. In addition, some uniformly-distributed minute secondary carbides were present in its microstructure. After nitriding, its microstructure was the same but the numbers of larger carbides were much higher.

Table. 3. HRC hardness readings

Steel	Sample	HRC hardness
14Ch17N2 – heat-treated	Sample 4	41.7
14Ch17N2 – nitrided	---	29.3

Table. 4. Impact toughness test values

Steel	Sample	Notch toughness [J]
14Ch17N2 – heat-treated	Sample 4	63.8
14Ch17N2 – nitrided	---	28.2

VII. WEAR TESTING

The purpose of wear testing was to compare the wear resistance levels among the materials. The pin-on-disc method was employed. This test consists in forcing a ball indenter into the surface of a rotating flat specimen. The indenter is loaded by a prescribed force (exerted by a weight) and attached to a rigid arm. Strain gauges fitted to the arm recorded the resulting friction force. The wear rate of the material is found by examining the wear track created by the indenter in the surface. The measured parameters include the actual amount of wear (material loss) and the impression (deformation) in the test specimen. This simple method allows friction and wear to be studied using contact between two surfaces of virtually any materials, either dry or lubricated. The amount of wear of the specimen is found by measuring the cross section of the wear track produced by the indenter, using the contact contour measuring machine SURTRONIC 25 and subsequent calculation. The tests were performed at 300°C, using a ball indenter load of 10 N and 10000 cycles. The wear rates in samples 1 and 2 (95Ch18 grade) was the lowest among all the samples. Relatively favourable values were found in sample 6 (14Ch17N2B grade). The wear rates in the other samples were approximately equal (Fig. 6).

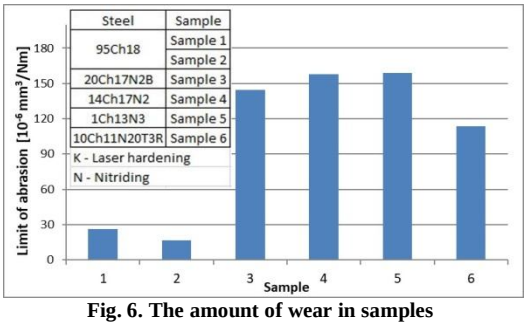


Fig. 6. The amount of wear in samples

Samples after laser surface hardening, i.e. those of 95Ch18 and 14Ch17N2 grades, showed poorer wear resistance than before the hardening process.

By contrast, nitriding has led to a notable improvement in wear resistance in 14Ch17N2 and 1Ch13N3 grades, and even in 14Ch11N20T3R steel.

In the 95Ch18 grade, nitriding caused a slight decrease in wear resistance (Fig. 7).

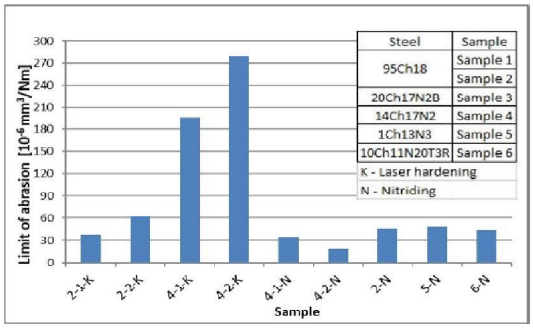


Fig. 7. Wear rates in surface-treated samples

VIII. METALLOGRAPHIC ANALYSIS

The microstructure of the 95Ch18 grade (samples 1 and 2) consisted of martensite. It was homogeneous and that the prior austenite grain size was small. This martensitic matrix contained an abundance of coarse primary carbides, some of which were arranged in bands. The matrix also contained numerous minute and uniformly-distributed globular secondary carbides (Fig. 8).



Fig. 8. Microstructure of 95Ch18 steel, 100×

20Ch17N2B steel contained a martensitic matrix with a small amount of banded δ-ferrite. Heat treatment caused some δ-ferrite grains to decompose. In some locations, the matrix therefore contained clusters of coarse chromium carbides. Large amounts of small secondary carbides were also found in the martensitic matrix.

14Ch17N2 steel contained a martensitic matrix with a small amount of banded δ-ferrite as well. The grains of δ-ferrite were delineated with carbides. In addition, some uniformly-distributed minute secondary carbides were present in the microstructure (Fig. 9).



Fig. 9. Microstructure of 14Ch17N2 steel, 100×

The microstructure of 1Ch13N3 consisted of martensite. No coarse primary carbides or delta ferrite particles were found in the martensitic matrix. Some uniformly-distributed minute globular secondary carbides were present.

The microstructure of 10Ch11N20T3R consisted of martensite. It was homogeneous and fine-grained (Fig. 10).

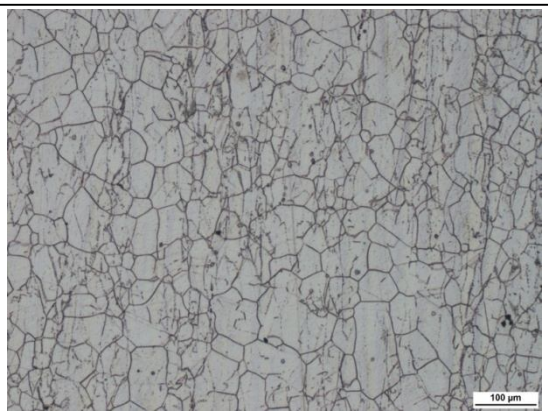


Fig. 10. Microstructure of 10Ch11N20T3R steel, 100×

DISCUSSION OF RESULTS

The following materials and their heat treatment sequences were put to test: 95Ch18, 20Ch17N2B, 14Ch17N2, 1Ch13N3 and 10Ch11N20T3R.

Several surface treatment options had been considered, of which two were chosen: conventional nitriding and advanced laser surface hardening.

The highest hardness was found in the 95Ch18 grade. The lowest hardness was found in sample 6 of the 10Ch11N20T3R austenitic steel. 14Ch17N2 and 1Ch13N3 grades exhibited similar hardness levels around 42 HRC. The hardness of the 20Ch17N2B grade was higher: 45 HRC and 47 HRC in samples 3 and 7, respectively. The 10Ch11N20T3R grade, whose microstructure was austenitic, had lower hardness than the martensitic steels: 27.4 HRC.

Notch toughness decreased with increasing hardness in the samples. In 14Ch17NB, the KV_2 notch toughness was 63.8 J. In 20Ch17N2B, it was one third of the value in 14Ch17NB, i.e. 20.7 J. In 1Ch13N3 it was half that of 14Ch17NB: 32.3 J. A very low toughness of 9 J was found in sample 7 (20Ch17N2B grade tempered at 350°C). In 95Ch18, the value even dropped below 5 J. Only the 10Ch11N20T3R grade showed a higher toughness level, 127 J. In laser-hardened 95Ch18 and 14Ch17N2 grades, the depth profiles of hardness appeared similar. The surface and core hardness were approximately equal. This means that laser hardening failed to increase the surface hardness. Martensitic steels had been heat treated to high hardness. The additional surface hardening has not increased the hardness level. Below the surface, the thermal exposure even led to tempering of martensite and to lower hardness than at the core. Laser surface hardening thus failed to meet its intended purpose.

In samples of martensitic steels, the nitrided layer was intact. Its thickness was between 0.3 and 0.4 mm. In sample 4-2-N, which was nitrided twice, the layer thickness was in excess of 0.45 mm. By contrast, the layer in sample 6 (10Ch11N20T3R grade) was cracked. Its thickness was around 0.1 mm. The comparison of tests performed on the 14Ch17N2 grade prior to and after nitriding suggested that the process had reduced both elongation and notch toughness. Hence, nitriding had a clear adverse impact on mechanical properties of 14Ch17N2 steel.

The microstructure of 14Ch17N2 steel consisted of a martensitic matrix with δ-ferrite and uniformly-distributed small secondary carbides. After nitriding, the microstructure of 14Ch17N2 contained a martensitic matrix with δ-ferrite as well but the number of larger carbides was appreciably greater.

The purpose of wear testing was to compare the wear resistance levels among the materials. The pin-on-disc method was conducted at a temperature of 300°C. The wear rates in samples of 95Ch18 upon both treatments were much lower than in the other materials. In samples 3, 4, 5 and 6, the wear rates were roughly equal. In this group, the best result was found in sample 6 (10Ch11N20T3R steel). Unfortunately, laser surface hardening failed to improve wear resistance. In fact, this property deteriorated in all specimens. As grain refinement was not achieved in the laser-hardened layer, the desired increase in hardness and wear resistance failed to materialize. The surface hardness remained unchanged or even decreased. Laser surface hardening therefore failed to contribute to improvement in wear resistance. Nitriding of 95Ch18 has not led to better wear resistance. Instead, the resistance decreased slightly. By contrast, nitriding improved this property in samples 4, 5 and 6. The largest increase in wear resistance was found in sample 4-2-N (14Ch17N2 steel), which was nitrided twice and therefore possessed a thicker nitrided layer and exhibited uniformly decreasing hardness with increasing depth. An improvement in wear resistance was also found in the 10Ch11N20T3R grade, in which the layer was thin and discontinuous.

Metallographic analysis of the samples revealed that the microstructure was martensitic. The microstructures in samples 1 and 2 (95Ch18) were very similar. Their martensitic matrices contained abundant coarse primary carbides, which were sometimes arranged in bands. The matrix also contained numerous minute and uniformly-distributed globular secondary carbides. Sample 3 (20Ch17N2B steel) had a martensitic matrix with a small amount of banded δ-ferrite. Heat treatment caused most δ-ferrite grains to decompose. In some locations, the matrix therefore contained clusters of coarse chromium carbides. δ-ferrite particle were only preserved in rare locations. They were delineated by clusters of coarse chromium carbides. Large amounts of small secondary carbides, sometimes along prior austenite grain boundaries, were also found in the martensitic matrix. The microstructure of specimen 4 (14Ch17NB) was similar to that of material 3: martensitic matrix with δ-ferrite. In steel 4, however, the content of δ-ferrite was much higher, although its particles were arranged in bands as well. The grains of δ-ferrite were delineated with carbides. In addition, some uniformly-distributed minute secondary

carbides were present in the microstructure. The microstructure of sample 5 (1Ch13N3) consisted of martensite. Unlike in the previous materials, no coarse primary carbides or delta ferrite particles were found in the martensitic matrix. Some uniformly-distributed minute globular secondary carbides were present. In contrast to all previous samples, the microstructure of sample 6 (10Ch11N20T3R) consisted of austenite. It was homogeneous and fine-grained. Sample 7 (the 20Ch17N2B grade tempered at 350°C) had a martensitic matrix. δ-ferrite was not found in this sample. Large amounts of small secondary carbides were also found in the matrix. Particles of a carbide precipitated preferentially in large numbers along prior austenite grain boundaries, causing embrittlement and poor notch toughness.

CONCLUSION

The analyses conducted in this study lead to a conclusion that the optimum variant is the 14Ch17N2 material, either in an untreated or nitrided condition. 14Ch17N2 offers very good wear resistance and a very good toughness of 63.8 J in untreated condition. Although the value drops to 28.2 J after nitriding, this value is still comparable to or higher than in the other untreated martensitic steels. Nevertheless, the core hardness declines after nitriding. Should the nitrided layer fail, the material would suffer severe wear. Good wear resistance after nitriding and high notch toughness was found in 10Ch11N20T3R as well. However, as 10Ch11N20T3R has low hardness which is expected to decrease further after nitriding, and upon considering the nature of the load acting on the pawls, the 14Ch17N2 grade appears to be the most promising candidate. On the basis of the analyses herein, the 14Ch17N2 grade was chosen as the material for making heavy-duty pawls in linear stepper motors operating in WWER nuclear power plants.

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