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COMPARATIVE ANALYSIS OF TWO STEEL GRADES 41CR4 AND P355NL1 FOR WINTER OPERATING CONDITIONS

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One of the main criteria for the quality of steels is the ability to resist brittle fracture. This ability is qualitatively expressed in the value of impact strength and toughness. According to the statistical data at AS "Pasažieru vilciens", at low temperatures, the number of failures of the M-24 bolts for fastening the rubber-cord coupling increases. In this regard, the urgent task is to reduce the number of failures during the winter. The article presents the results of tests of impact strength and toughness, as well as a metallographic analysis of two steel grades 41Cr4 and P355NL1. Also an experiment was carried out, on the basis of which the main conclusions were made on the mechanical properties of two grades of steel 41Cr4 and P355NL1.

Keywords: *steel, impact strength, toughness, metallographic analysis.*

INTRODUCTION

At JSC "Pasažieru vilciens" the main reason for unscheduled repairs of electric multiple unit (EMU) trains motor cars is the failure of the rubber-cord coupling fastening bolts, which are made of 41Cr4 steel. According to the reports on unscheduled repairs (Elektrovilcienu neplāna…) for the period between 2015 and 2022, were 264 cases of failures. According to statistics, the number of failures during the winter (the period from November 15 to March 15) amounted to 119 cases, which is more than 45% of the total number of failures.

Data on the total number of failures of M-24 bolts and failures of bolts in the winter period are presented in Table 1.

Table 1. EMU rubber cord coupling and rubber cord coupling bolt failure

Year	Total number of rubber cord coupling bolt failures, cases	Failures, during the winter period[1], cases	Failures during the winter period, %
2015	25	9	36
2016	29	13	44.8
2017	28	14	50
2018	37	17	45.9
2019	39	18	46.1
2020	38	17	44.7
2021	27	12	44.4
2022	41	19	46.3
∑	264	119	45.07

Note: [1] Winter season November 15 - March 14

According to the data presented in Table 1, it can be concluded that the largest number of failures of rubber cord coupling fastening bolts occurs in the winter period, when the ambient air temperature is low. In low temperature conditions, the metal of the fastening bolts may show a tendency to become brittle and disintegrate as a result of the temperature drop. Fragility decay is the most dangerous form of decay. Its danger is that it occurs without preconditions, for example, without plastic deformation. Crack growth is rapid, and the propagation speed during brittle fracture is approximately equal to the speed of sound in metal. The crack widens and becomes the place of the final disintegration of the bolts (Morozov and Zernin, 1999, Губенко, 2016). The problem of bolt breakage in winter is the most urgent, it requires research into the causes, as well as making proposals to reduce the effect of cold brittleness.

Based on the results of a visual inspection of a large number of broken M-24 bolts for fastening the rubber-cord coupling, it is not possible to unequivocally state the type and nature of the destruction. Various bolt failures are shown on Figure 1.

a **b** **c**

Figure 1. Examples of rubber cord coupling bolt fractures: Sample 1; (**a**) fatigue fracture due to cracking;) Sample 2; (**b**) brittle fracture) Sample 3 (**c**) fatigue fracture due to crack).

Fatigue fracture happens due to the accumulation of progressive defects in the bolt material subjected to alternating stresses and shock loads, leading to microcrack formation, development, crack initiation, and ultimate failure (Hu et. Al., 2021)

The purpose of the study: to conduct tests for impact strength and toughness as well as metallographic analysis and chemical analysis for the presence of harmful impurities. Based on the test results, to propose recommendations for commissioning for real testing of low-carbon steel bolts on a rolling basis for a period of 6 months with regular inspection of the bolts as part of the current preventive maintenance system. Based on the results of six months of testing, consider the possibility of completely replacing the bolts of steel grade 4Cr41 with low-carbon steel P355NL1.

It is likely that the replacement of bolts made of a different steel grade will give an economic effect of more than 5000 euros per year on average.

RESEARCH METHODS

In the RTU laboratory, tests were carried out to determine impact strength and toughness, metallographic and chemical analysis of two steel grades are shown on Figure 2:

1. Steel grade 41Cr4;
2. Steel grade P355NL1.

To investigate the causes of the destruction of bolts, the following tests were carried out in the RTU laboratory:

• impact strength. The tests included at least 50,000 impacts at four different shock loads;
• toughness. The tests were carried out at 3 different temperature ranges +20; 0; -20°C;
• metallographic analysis.

For testing, 10 samples 55 mm long with 10 x 10 mm facets were prepared. The impact strength was tested in the RTU laboratory at an ambient temperature of +4,5 to +6,3 ^{0}C. This temperature regime corresponds to the autumn-winter season of operation.

Figure 2. Samples for research

During the tests, the samples were subjected to 50 thousand impacts with different impact loads: 0.208 kg; 0.638 kg; 0.751 kg; 0.751 kg; 1.375 kg; 2.007 kg. shown in Figure 3.

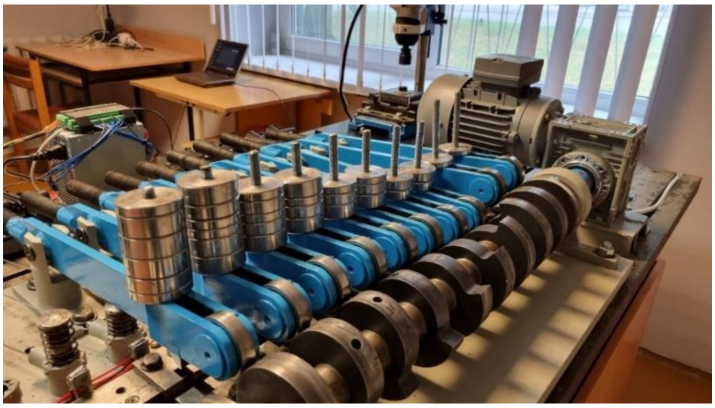


Figure 3. Test bench

The test bench is driven by a 3-phase asynchronous motor and, through a reduction gearbox, rotates the cam shaft from which, using a translational movement, the lever is raised to a height of 10 mm. As a result, a shock load occurs on the samples to be studied. To increase the magnitude of the shock load on the lever, it is possible to install an additional weight. The tests were carried out in an unheated room at an ambient temperature of +4,5 ^{0}C -+6,3 ^{0}C, temperature was mesured with a thermometer having an accuracy class of ±0,1^{0}C.

When testing for impact strength, the test results were processed by the computer program "Metal Fatgue Testop". As a result of the tests, no destruction of the samples was stated. The results of the impact strength are shown on Figure. 4.

Figure 4. Impact test data

RESEARCH RESULTS AND DISCUSSION

Based on the test results, it was stated that all samples passed the impact strength test.
After the impact strength test, the bolts were subjected to toughnesstests. The purpose of the study is to compare the toughnessparameters at three different temperature conditions -20°C; 0°C; +20°C. Sample cooling -20°C; 0 C was carried out in a refrigeration unit by direct cooling to the required temperature -20°C; 0° C The cooling temperature was measured using a thermometer with an accuracy class of ±0.1°C.Test data are presented in Table 2.

Table 2. Toughness impact test data

Simple Nr.	Sample steel grade	Toughness parameter J/cm^2		
		–20^{o}C	0°C	+20^{o}C
1	4Cr41	26.2	46.4	68.3
2	4Cr41	25.6	43.8	66.1
3	4Cr41	26.9	48.7	67.9
4	P355NL1	32.2	54.3	65.1
5	P335NL1	32.9	55.1	66.2
6	P335NL1	31.6	54.5	69.4

During the research process, harmful impurities of phosphorus and sulphur were found in bolt samples made from 4Cr41 steel. The percentage of phosphorus (P) is:

- in sample No. 1 – 0.125%;
- in sample No. 2 – 0.0650%,

• in sample No. 3 – 0.0813%.

In all three 4Cr41 steel samples, the phosphorus content significantly exceeds the norms set by the EN 10083-3:2007-01 standard, according to which it should be less than 0.025%.

For samples produced from steel P335NL1, the harmful impurities are composed:

• for sample No. 4 – 0.0242%;

• for sample No. 5 – 0.0166%;

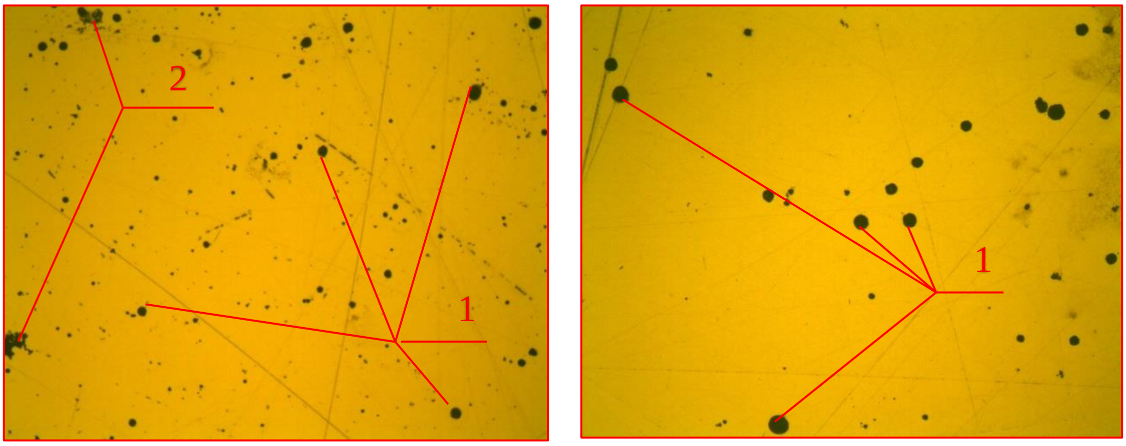
• for sample No. 6 – 0.0169%.

For all samples, the phosphorus content is within the normal limit of the standard, which should be less than 0.025% (EN 10028:3).

• Phosphorus (P) reduces metal plasticity, forms Fe_3P compound with iron. The crystals of this compound are very brittle, as a result of which the steel acquires high brittleness in a cold state - cold embrittlement (Kobayashi, et. al., 2012). It also leads to a decrease in impact resistance, especially at low temperatures. As phosphorus enters the crystal lattice, the size of the crystal lattice of the metal atom increases, as a result of which the interatomic bonds weaken, which in turn leads to the formation of microcracks in the area of non-metallic inclusions and further leads to the disintegration of the bolts (Bhadeshia & Honeycombe, 2017; EN 10083-3:2007-0; Batdorf and Chang, 1979).

• Sulphur (S) does not dissolve iron, so any amount of it in combination with iron forms iron sulphide FeS, which appears as inclusions. The presence of sulphur in steel negatively affects plasticity, toughness, increases steel wear, reduces fatigue strength and reduces corrosion resistance. The FeS compound makes the steel brittle at high temperatures, which causes red brittleness (Bhadeshia & Honeycombe, 2017; EN 10083-3:2007-0; Batdorf and Chang, 1979).

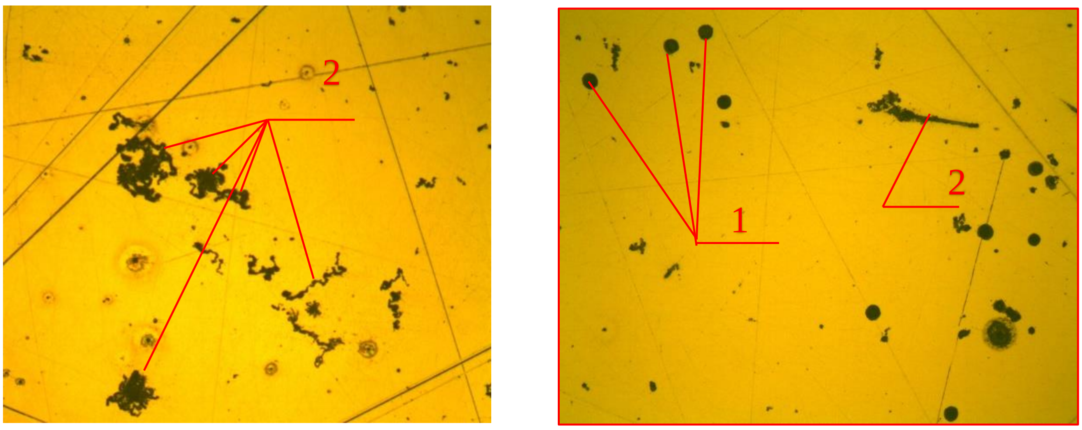
Metallographic analysis of samples of steel grades P355NL1; 4Cr41 after testing for impact strength and thoughness are shown on Figure5 and Figure 6. The studies were carried out at magnification (x50; 200).



a b

Figure 5. Microstructure of steel P355NL1: (**a**) Microstructure fragments (x50); (**b**) Microstructure fragments (x200)

1 – Defects in the form of non-metallic inclusions;2 – Microcracks along grain boundaries



a b

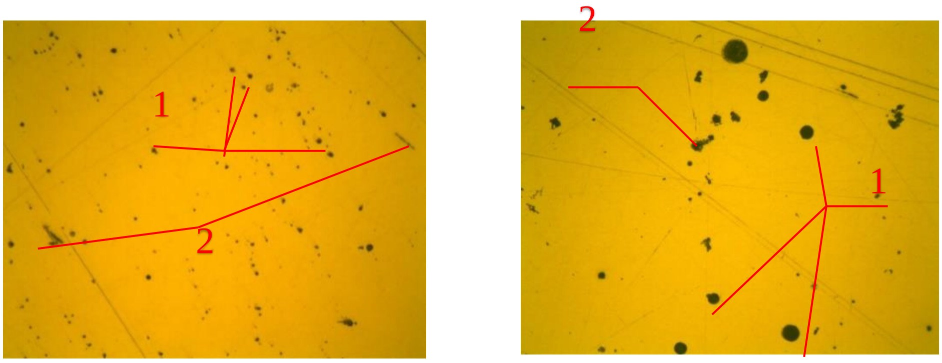
Figure.6. Microstructure of steel 41Cr4: (**a**) Microstructure fragments (x50); (**b**) Microstructure fragments (x200)
1 – Defects in the form of non-metallic inclusions;2 – Microcracks along grain boundaries

According to the test results in P355NL1 steel, a smaller amount of defect formation, as well as the absence of microcracks, was stated.

It was proposed to manufacture an experimental batch of bolts from P355NL1 steel to test their performance on rolling stock as fastening of a rubber-cord coupling.

Testing of the bolts was carried out on a one of series ER2T EMU motor car Nr. 7118-bogies. To fasten the rubber-coded coupling, bolts made of steel gradeP355NL1 were used on the first wheelset, and bolts made of steel grade 4 Cr41 were installed on the other wheelset according to the specification (Electric train periodical…, 1997).

According to the results of the work of the investigated bolts for the period of time from 15.10.2022. to 15.04.2023. their destruction was not ascertained. The car mileage for this interval was 84354 km. At the expiration of the declared service life, the bolts were subjected to a metallographic analysis for the presence of defects in the microstructure. The results of the metallographic analysis of the microstructure after 6 months of operation of the bolts on the rolling stock are shown on Figure. 7 and Figure 8. The studies were carried out at magnification (x50; x200).



a b

Figure.7. Microstructure of steel P355NL(**a**) Microstructure fragments (x50), (**b**) Microstructure fragments (x200)
1 – Defects in the form of non-metallic inclusions;2 – Microcracks along grain boundaries

Metallographic analysis revealed a large number of non-metallic impurities in all samples. In-service failure of M24 bolts can often start from initial defects of metallurgical origin caused by non-metallic impurities. These initial defects during the life of the bolt (mileage ran) increase in number and size, which can later lead to breakage.

Non-metallic impurities play a decisive role in the appearance of microcracks (Taylor et. al., 2021), which in turn can lead to the appearance of macrocracks and, consequently, the disintegration of bolts. Any factor that favors the initiation of cracks and their development in the vicinity of non-metallic impurities presents a major hazard that can cause slow or rapid fracture of bolts. (Губенко, 2016; Bhadeshia & Honeycombe, 2017).

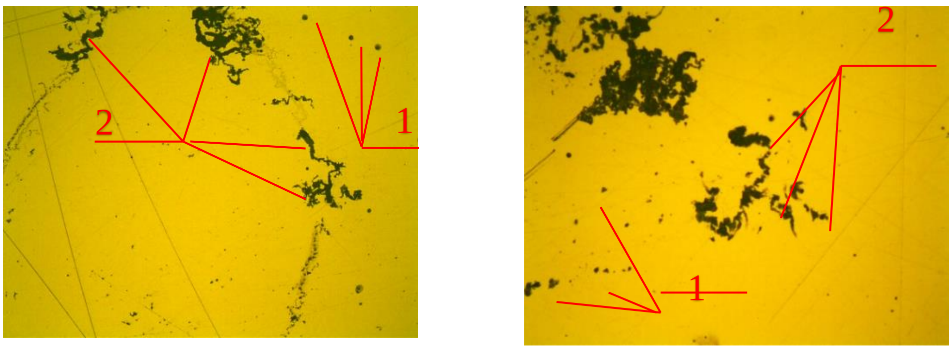


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Figure 8. Microstructure of steel 41Cr4: (**a**) Microstructure fragments (x50); (**b**) Microstructure fragments (x200)
1 – Defects in the form of non-metallic inclusions; 2 – Microcracks along grain boundaries

The appearance and development of microcracks and cracks significantly affects the reliability of bolts, which later leads to their destruction. According to the results of metallographic analysis, it was stated in steel 41Cr4 that there were more defects in the microstructure. Based on the results of metallographic analysis of grade P355NL steel presented in Fig. 7, the presence of the formation of non-metallic inclusions along the grain boundaries was stated. When carrying out a metallographic analysis of the grade 41Cr4 steel presented in Fig. 8, it was found that at the same mileage of the 41Cr4 sample, a larger number of defects formed along the grain boundaries was found in the microstructure. They merge and form microcracks as a result of the impact load.

CONCLUSIONS

1. According to the results of experiments, it was stated that P335NL1 steel has the best toughness. Exceeding toughness of steel 41Cr4 at temperatures of 0 and -20ºC ranged from 4 to 7 J/cm^2, which in percentage terms amounted to more than 18%.

2. The results of the metallographic analysis after 6 months of operation of the bolts showed that the P335NL steel grade had fewer defects than the 41Cr4 steel grade.

3. Based on the results of chemical analysis, it was stated that 41Cr4 steel contains more phosphorus, which does not comply with the parameters of EN 10083-3:2007-01.

4. According to JSC ”Pasažieru vilciens” P335NL steel also has a lower cost factor (the cost is 25% less compared to 41Cr4 steel.

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