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Research Article

RELIABILITY ANALYSIS OF THE MECHANICAL PROPERTIES OF 30MnB4 HIGH STRENGTH STEEL BOLTS UNDER STATIC LOADING CONDITIONS

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ABSTRACT

The objective of this study is to investigate the mechanical properties of high-strength steel bolts under static loading conditions based on reliability analysis. High-strength steel bolts samples were manufactured by sequential cutting, cold forming, heading and heat treating. All sample bolts were fully threaded hexagon cap M12 bolts, and the material was 30MnB4. During the heat treatment, quenching and tempering processes were applied to the high-strength steel bolts. A standard tensile test was performed on the samples. Stress-strain curves were obtained for the steel bolt samples after different heat treatments. The mechanical properties of the steel bolts, such as yield strength and tensile strength, were determined for the different heat treatments. Reliability analyses of the mechanical properties of the steel bolts under static loading conditions were conducted. The mean values, standard deviations and standard variables of yield strength and tensile strength were calculated. It was concluded that the reliability levels of yield strength and tensile strength (R>99%) satisfied the required yield strength values $R_{P0,2}$ and tensile strength values R_m given in the literature. Furthermore, having high reliability levels production is an advantage for manufacturer both in local and international markets.
Keywords: Reliability analysis, heat treatment, mechanical properties, bolt.

1. INTRODUCTION

The objective of this study is to investigate the mechanical properties of 30MnB4 high-strength steel bolts obtained by different heat treatment processes under static loading conditions based on reliability analysis. Reliability analyses of the mechanical properties of the steel bolts were studied. The mean values, standard deviations and standard variables of yield strength and tensile strength were calculated.

High-strength steel bolts are widely used to assemble machine parts under static or dynamic loading conditions. Therefore, determination of the mechanical properties of steel bolts under static or dynamic conditions is crucial for steel bolt manufacturers to meet the required values, such as yield strength, tensile strength and hardness. The mechanical strength of the material can be improved by the appropriate choice of heat treatment. Additionally, the reliability rates of these values are also crucial for both the manufacturer and customer.

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The reliability of steel bolts is also the most important consideration for meeting the desired quality in various industries such as automotive industry, heavy machine industry and machine tool industry.

The following results for heat treatment have been presented in the literature.

By quenching, the mechanical properties of a high-strength material such as hardness, yield strength and tensile strength are increased. Additionally, tempering reduces the residual stress and hardness after quenching. Furthermore, both the yield strength and tensile strength of the steel bolts increase with decreasing tempering temperature [1].

Thermomechanical processing actually reduces the yield strength even though the tensile strength increases [2].

The type of heat treatment has a significant influence on the strength properties of steel; for example, annealing and normalising produce normal-strength steel, whereas quenching and tempering produce high-strength steel. The ultimate tensile strength and shear strength of steel are of primary importance in evaluating the fire response of bolted connections. These properties vary not only with temperature, but also with the chemical composition and type of heat treatment [3].

The strength of high-strength bolts is generally realised through quenching and tempering, and the microstructures of such products consist of tempered martensite [4].

Over the years, advanced high-strength steels (AHSS) have been intensively investigated to achieve improved strength and adequate toughness. It is well-known that the retention of the austenite phase in the steels after heat treatment may improve the ductility and toughness [5].

The following results for reliability have been presented in the literature.

According to VDI 4000, reliability is the probability that a product does not fail under given functional und environmental conditions during a defined period of time. Reliability includes the failure behaviour of a product and is therefore an important criterion for product evaluation [8, 9].

Statistical analysis can be used to describe and analyse fatigue properties, as well as estimate the probability rate of fatigue failure or product life. Such analysis allows us to evaluate component or product reliability quantitatively and to predict the service performance for a given margin of safety [10].

Traditionally, reliability engineering disciplines are approached based on “empirical” and “testing data analysis.” As a result, reliability engineering methods are often applied after the design decision is made, and they often have minimum impact on upstream decision making [11].

Traditionally, uncertainty parameters include those such as structural dimensions, shapes, and material properties. These parameters are relatively well controlled so that their variability is usually small [12].

2. STUDIES

A flow chart of the experimental study is shown in Figure 1, which includes the bolt manufacturing, heat treatment, tensile testing and reliability calculation steps.

2.1. Material Selection

30MnB4 steel was selected to investigate the effects of heat treatments on the mechanical properties of high-strength steel bolts. The commercial application of boron (B) as an alloying element in steels increase their hardenability [6]. The chemical composition of 30MnB4 steel is shown in Table 1. The selected 30MnB4 contains 0.3% C and is classified as a medium-carbon-steel [13].

Table 1. Chemical composition of the 30MnB4 steel material

C [%]	Si [%]	Mn [%]	Cr [%]	Ni [%]	Al [%]	Cu [%]	Ti [%]	Cu [%]	B [%]
0.317	0.092	1.068	0.203	0.041	0.289	0.056	0.057	0.056	0.004

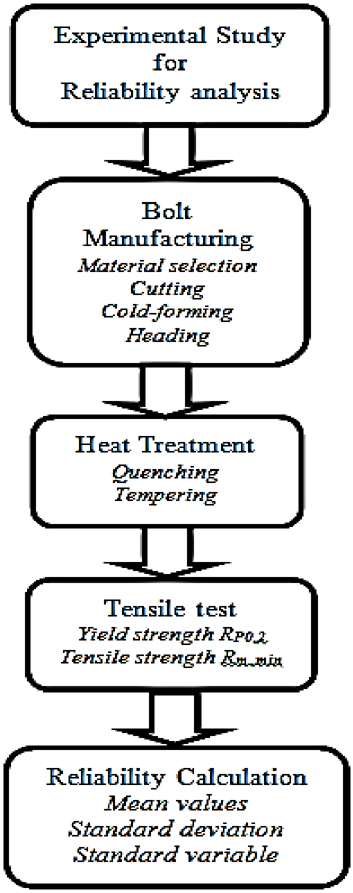

Figure 1. Flow chart of the experimental steps.

2.2. Bolt Manufacturing

To investigate the mechanical properties of high-strength steel bolts based on reliability analysis, bolts were manufactured by cutting, cold forming, heading and heat treating.

The steel bolts were manufactured by cold-forming to increase their strength, toughness and ductility.

The steel bolt samples were manufactured as fully threaded hexagon cap bolts according to DIN 933 [13]. All sample bolts were M12. The prepared steel bolt samples were 40 [mm] in height and then cold forged into cylinders with a final diameter of 12 [mm].

2.3. Heat Treatment

The mechanical strength of the material can be improved through heat treatments. Quenching and tempering processes were applied to the high-strength steel bolts.

2.3.1. Quenching Process

Before the quenching process was carried out, the sample bolts were cleaned at 80±3 [^{o}C] to remove oil. During the quenching process, the steel was heated to 890 [^{o}C] in 1 [h] and cooled at 80±10 [^{o}C] in oil, and then, it was cleaned a second time.

After the quenching process, the obtained structure is a martensite structure. The martensite structure is hard and brittle. Therefore, reducing the hardness with heat treatment is necessary. Furthermore, the transformation from austenite to martensite causes high residual stress in the hardened parts. Therefore, a tempering process is applied on the hardened steel to reduce the residual stress.

2.3.2. Tempering Process

The steel bolt samples were heated to 380 [^{o} C], 430 [^{o} C], 450 [^{o}C], 460 [^{o} C], 490 [^{o} C] and 520 [^{o} C] in 1 [h] in the heat-treatment furnace. The steel bolt samples were then cooled to 25±10 [^{o} C] in boron oil.

The aim of the tempering process is to reduce the residual stress and hardness in the hardened steel. Therefore, the tempering process is applied to reduce the residual stress and hardness after the quenching process.

2.4. Tensile Test

A standard tensile test was performed on the steel bolt samples. The tensile tests were applied using a 40 [t] ALŞA machine at room temperature. Stress-strain curves were obtained for the steel bolt samples subjected to different heat treatments. The standard tensile test was performed on the steel bolts according to EN-ISO 898-1[15]. The fully threaded hexagon cap bolts are shown in Figure 2. The test results are shown in Table 3 and 5.

Figure 2. Fully threaded hexagon cap bolts

Table 2. Dimensions of the sample bolts

Dimensions	Value[mm]
Thickness of the bolt head k	10
Length of the bolt thread l	35
Corner dimension of the bolt head e	24
Diameter of the bolt head s	22
Nominal diameter of the bolt thread d	12
Pitch diameter of the bolt thread d_2	10.863
Minor diameter of the bolt thread d_3	9.853

Table 3. Mechanical properties of the 12.9 10.9 and 8.8 quality steel bolts

Bolt material quality	Yield strength $R_{P,02}$ [N/mm^2]	Relative Frequency h_{rel}	Relative Frequency h_{rel} [%]	Tensile strength R_m [N/mm^2]	Relative Frequency h_{rel}	Relative Frequency h_{rel} [%]
12.9	1220	1/6	0.17%	1272	1/6	0.17%
	1222	1/6	0.17%	1276	1/6	0.17%
	1234	1/6	0.17%	1287	1/6	0.17%
	1240	2/6	0.33%	1289	2/6	0.33%
	1279	1/6	0.17%	1294	1/6	0.17%
10.9	1014	1/6	0.17%	1072	1/6	0.17%
	1020	2/6	0.33%	1075	1/6	0.17%
	1040	1/6	0.17%	1080	1/6	0.17%
	1045	1/6	0.17%	1101	2/6	0.33%
	1052	1/6	0.17%	1114	1/6	0.17%
8.8	967	1/6	0.17%	1018	1/6	0.17%
	974	2/6	0.33%	1024	1/6	0.17%
	984	1/6	0.17%	1027	2/6	0,33%
	996	1/6	0.17%	1030	1/6	0.17%
	1003	1/6	0.17%	1034	1/6	0.17%

2.4.1. Bolt geometry and dimensions

The geometry of fully threaded hexagon steel bolt test samples is shown in Figure 3. The dimensions of a fully threaded hexagon bolt are also given in Table 2.

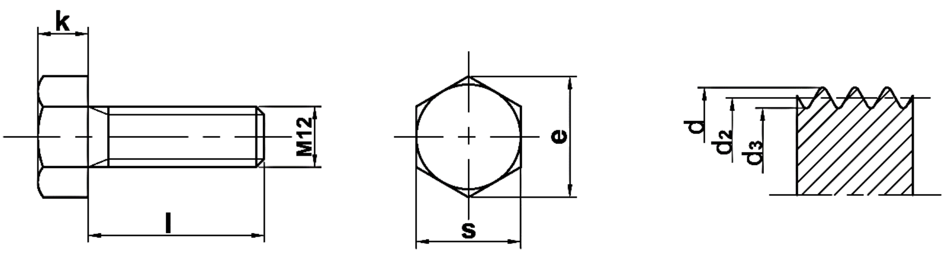

Figure 3. Dimensions of the sample bolts

2.4.2. Cross-section calculation

The cross-section of bolt A_{cs} [mm^2] is calculated as follows:

$$A_{cs} = \frac{\pi d_3^{\ 2}}{4} \tag{1}$$

where d_3 [mm] is minor diameter of the bolt thread is presented in Table 2 and Figure 3.

2.4.3. Stress and elongation calculation

Stress σ is defined as load per unit area or unit load and for the tensile specimen it is calculated as follows [7]:

$$\sigma = \frac{P}{A_{cs}} \tag{2}$$

Where P [N] is the applied load at any instant and A_{cs} is the original cross-section area of the specimen. The stress is assumed to be uniformly distributed across the cross-section [7].

Elongation or strain ε is the change in length per unit length and is calculated as follows [7]:

$$\varepsilon = \frac{l - l_0}{l_0} \tag{3}$$

Where l_0 is the original gage length and l is the gage length at any load P. The elongation is dimensionless.

2.4.4. Stress-elongation (σ-ε) curves

The stress-elongation curve *(σ-ε)* for 30MnB4 high-strength bolt material without heat treatment is shown in Figure 4. The yield strength $R_{P,02}$ is 708.3 [N/mm^2] and tensile strength R_m is 758.6 [N/mm^2], while elongation ε is 21.6%.

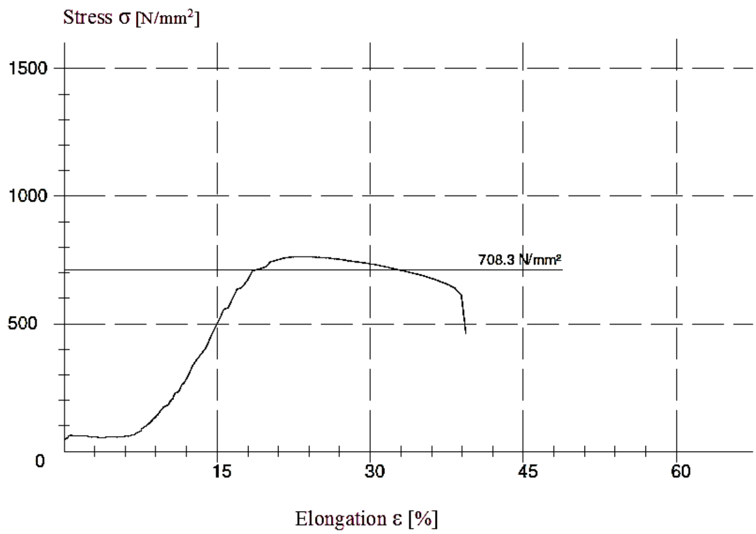

Figure 4. Stress-elongation *(σ-ε)* curve for 30MnB4 material without heat treatment.

The stress-elongation *(σ-ε)* curve for quenched 30MnB4 high-strength bolt material is shown in Figure 5. The yield strength $R_{P,02}$ is 1488.3 [N/mm^2] and tensile strength R_m is 1509.4 [N/mm^2], while elongation ε is 28 %.

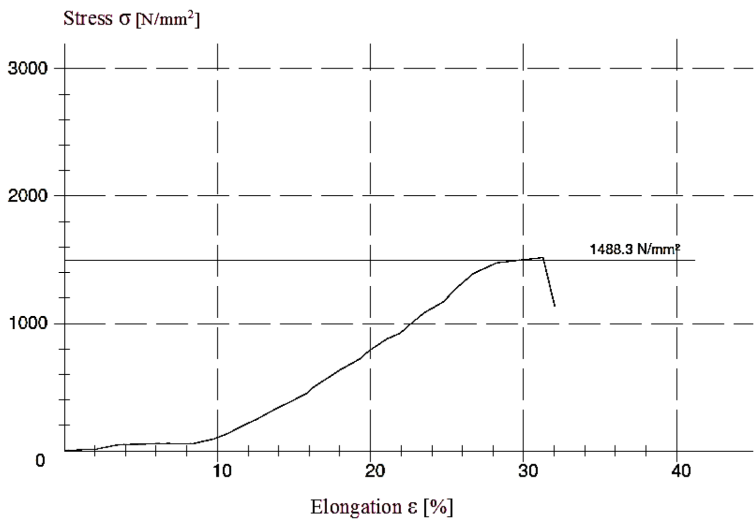

Figure 5. Stress-elongation *(σ-ε)* curve for quenched 30MnB4 material.

The stress-elongation *(σ-ε)* curve for high-strength bolt material tempered at 520 [C] is shown in Figure 6. The yield strength $R_{P,02}$ is 886.1 [N/mm^2] and tensile strength R_m is 940 [N/mm^2], while elongation ε is 24.9%.

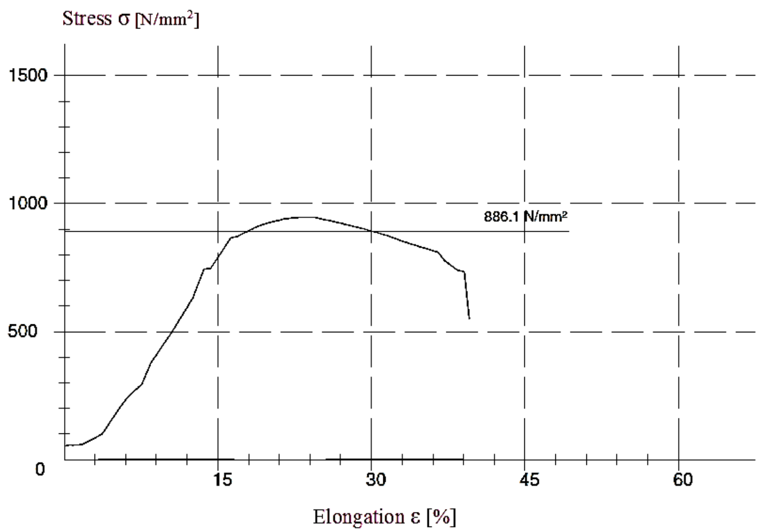

Figure 6. Stress-elongation *(σ-ε)* curve for 30MnB4 material tempered at 520 [C].

The stress-elongation *(σ-ε)* curve for 30MnB4 high-strength bolt material tempered at 490 [C] is shown in Figure 7. The yield strength $R_{P,02}$ is 965 [N/mm^2] and tensile strength R_m is 1027 [N/mm^2], while elongation ε is 23%.

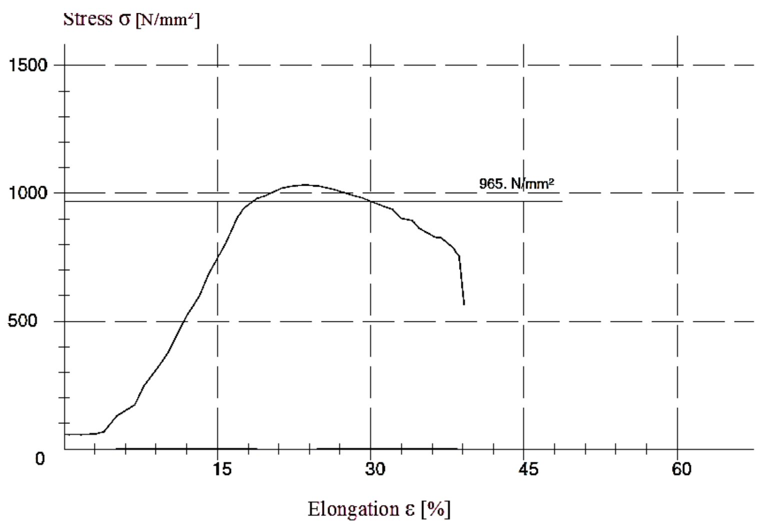

Figure 7. Stress-elongation *(σ-ε)* curve for 30MnB4 material tempered at 490 [C].

The stress-elongation *(σ-ε)* curve for 30MnB4 high-strength bolt material tempered at 450 [C] is shown in Figure 8. The yield strength $R_{P,02}$ is 1004.4 [N/mm^2] and tensile strength R_m is 1068.7 [N/mm^2], while elongation ε is 23.1%.

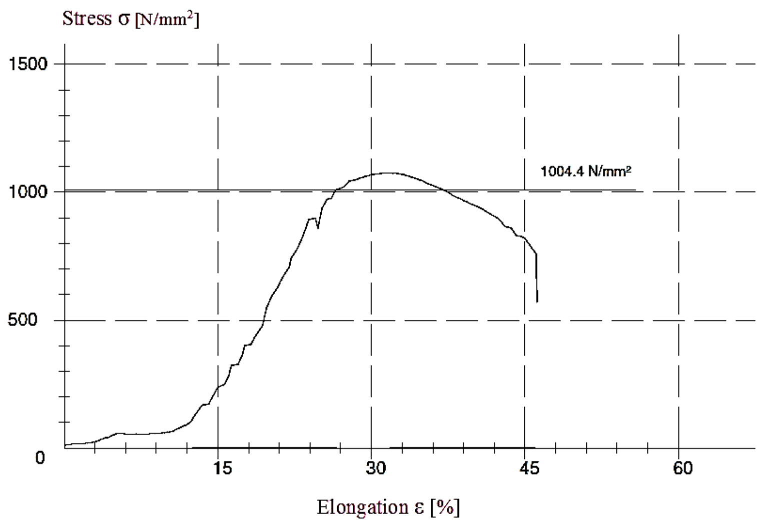

Figure 8. Stress-elongation *(σ-ε)* curve for 30MnB4 material tempered at 450 [C].

The stress-elongation *(σ-ε)* curve for 30MnB4 high-strength bolt material tempered at 430 [C] is shown in Figure 9. The yield strength $R_{P,02}$ is 1018.3 [N/mm^2] and tensile strength R_m is 1080.4 [N/mm^2], while elongation ε is 23.1%.

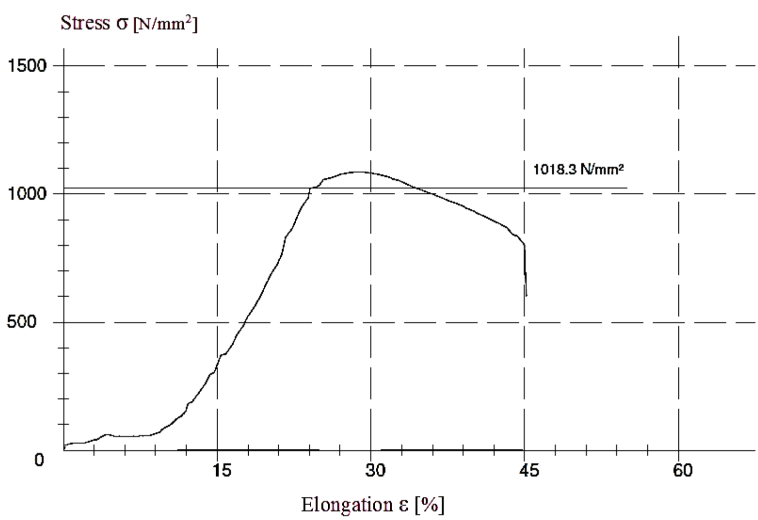

Figure 9. Stress-elongation *(σ-ε)* curve for 30MnB4 material tempered at 430 [C].

The stress-elongation *(σ-ε)* curve for 30MnB4 high-strength bolt material tempered at 380 [C] is shown in Figure 10. The yield strength $R_{P,02}$ is 1210.2 [N/mm^2] and tensile strength R_m is 1289.6 [N/mm^2], while elongation ε is 27.5%.

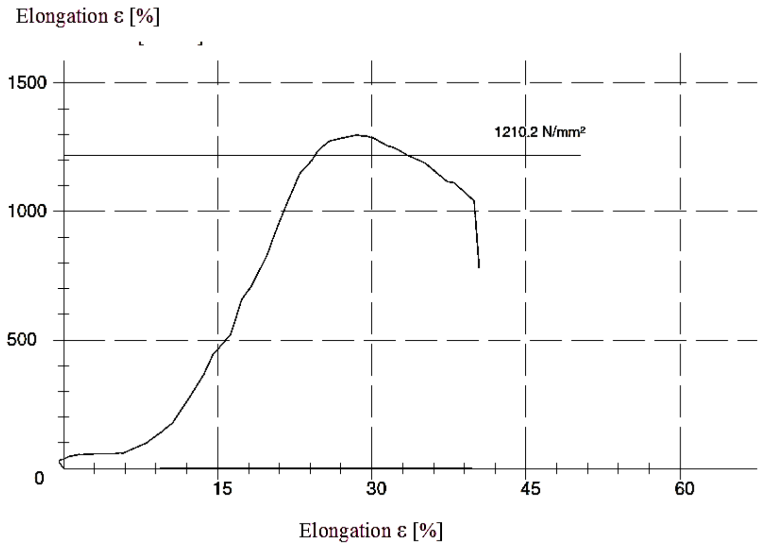

Figure 10. Stress-elongation curve for 30MnB4 material tempered at 380 [C].

2.4.3. Microstructure

The failure surface of the sample bolts is observed by using a Nikon ECLIPSE MA-100, KAMERAM model X-ray microscope at 500 times magnification.

The microstructures of high-strength 30MnB4 steel bolts without the heat treatment process is pearlite, as shown in Figure 11. Pearlite microstructure is obtained by slow cooling of austenite microstructure as follows:

Pearlite=Austenite + Slow cooling (4)

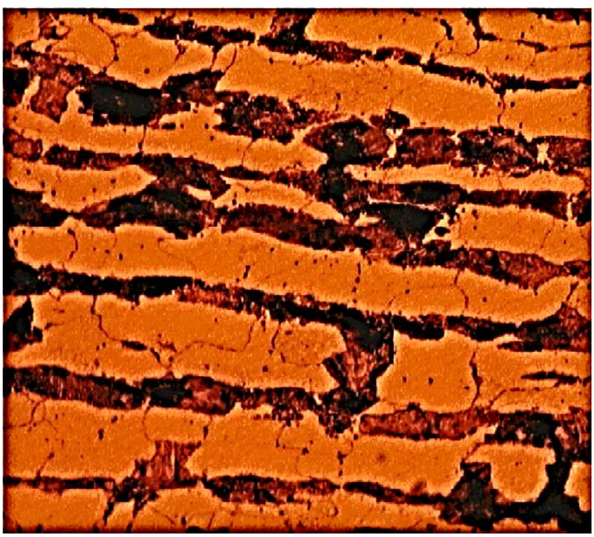

Figure 11. Microstructure of the high-strength steel bolts without heat treatment.

The microstructures of high-strength 30MnB4 steel bolts after the quenching process is martensite, as shown in Figure 12. Martensite microstructure is obtained by rapid quenching of austenite microstructure as follows:

Martensite=Austenite + Rapid quenching (5)

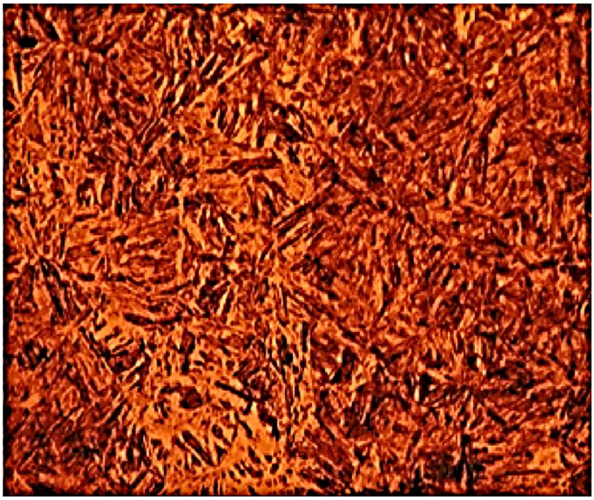

Figure 12. Microstructure of the high-strength steel bolts after the quenching process at 890 [^{0}C].

The microstructures of high-strength 30MnB4 steel bolts after the tempering process is tempered martensite, as shown in Figure 13. Tempered microstructure is obtained by reheating of martensite microstructure as follows:

Tempered martensite =Martensite + Reheat (6)

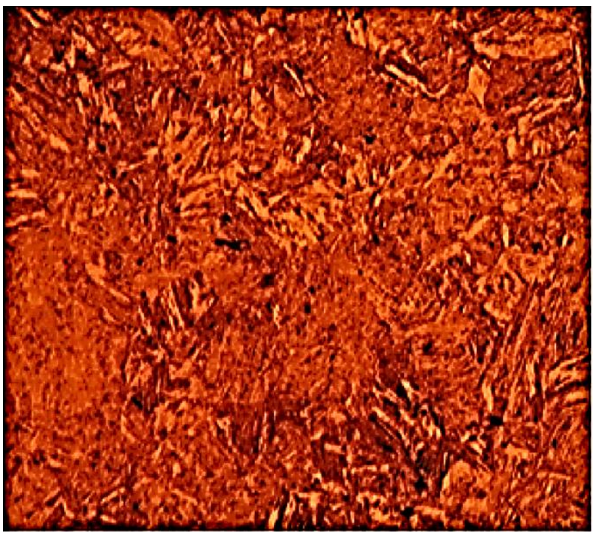

Figure 13. Microstructure of the high-strength steel bolts after the tempering process at 380 [^{0}C].

2.5. Failure Analysis

A standard tensile test was repeated six times on the steel bolt samples for reliability analysis. The standard test results are presented in Table 3 and 5.

The histogram of the failure probability of the yield strength of the 12.9 quality steel bolts is presented in Figure 14. The yield strength of 12.9 quality steel bolts varies between 1220 [N/mm^2] and 1279 [N/mm^2] during the tensile test.

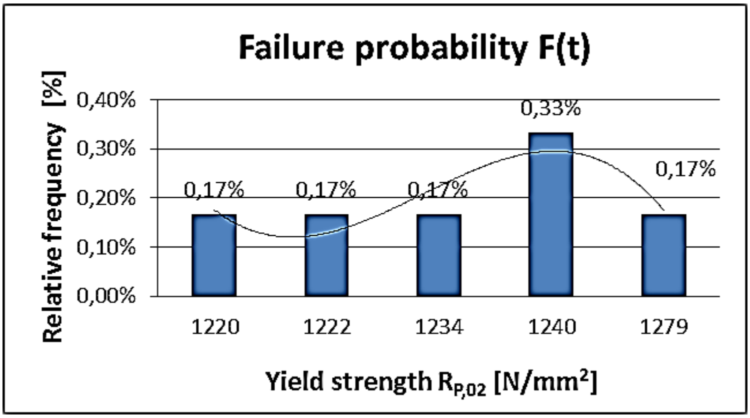

Figure 14. Failure probability of the yield strength of the 12.9 quality steel bolts.

The histogram of the failure probability of the tensile strength of the 12.9 quality steel bolts is presented in Figure 15. The tensile strength of 12.9 quality steel bolts varies between 1272 [N/mm^2] and 1294 [N/mm^2] during the tensile test.

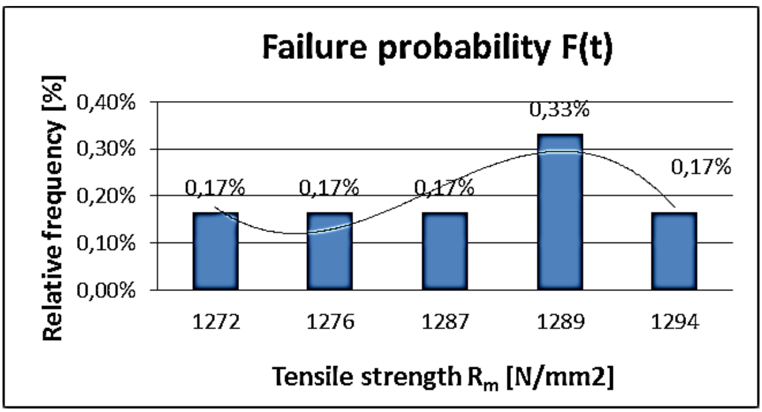

Figure 15. Failure probability of the tensile strength of the 12.9 quality steel bolts.

The histogram of the failure probability of the yield strength of the 10.9 quality steel bolts is presented in Figure16. The yield strength of the 10.9 quality steel bolts varies between 1014 [N/mm^2] and 1052 [N/mm^2] during the tensile test.

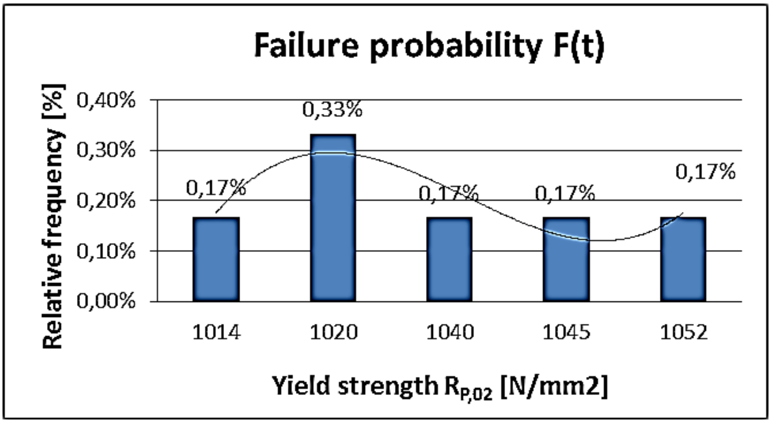

Figure 16. Failure probability of the yield strength of the 10.9 quality steel bolts.

The histogram of the failure probability of the tensile strength of the 10.9 quality steel bolts is presented in Figure 17. The tensile strength of the 10.9 quality steel bolts varies between 1072 [N/mm^2] and 1114 [N/mm^2] during the tensile test.

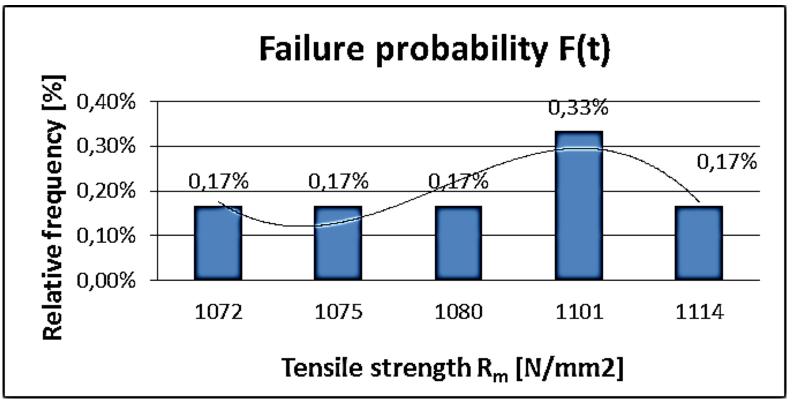

Figure 17. Failure probability of the tensile strength of the 10.9 quality steel bolts.

The histogram of the failure probability of the yield strength of the 8.8 quality steel bolts is presented in Figure 18. The yield strength of the 8.8 quality steel bolts varies between 967 [N/mm^2] and 1003 [N/mm^2] during the tensile test.

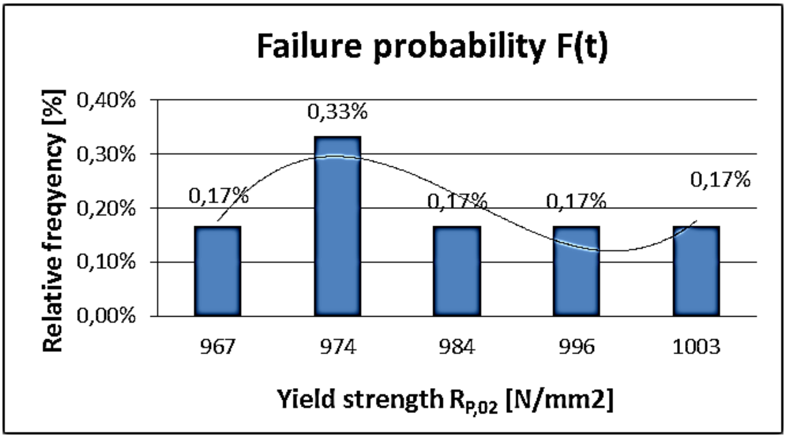

Figure 18. Failure probability of the yield strength of the 8.8 quality steel bolts.

The histogram of the failure probability of the tensile strength of the 8.8 quality steel bolts is presented in Figure 19. The tensile strength of the 8.8 quality steel bolts varies between 1018 [N/mm^2] and 1034 [N/mm^2] during the tensile test.

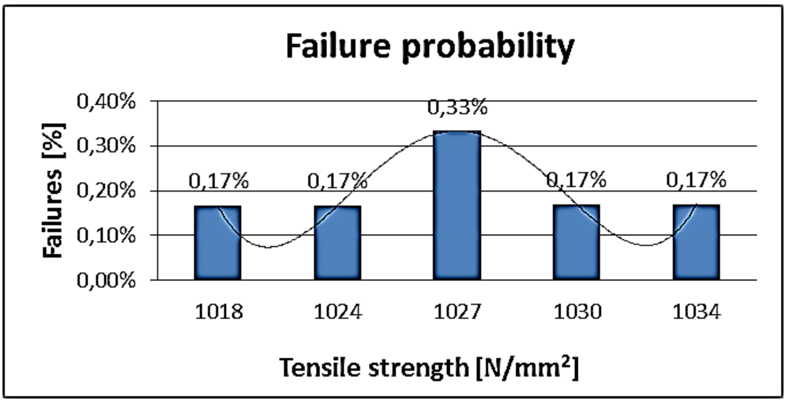

Figure 19. Failure probability of the tensile strength of the 8.8 quality steel bolts.

2.6. Reliability Analysis

The term reliability is part of our daily language especially when speaking about functionality of a product. A very reliable product is a product that fulfils its function at all times and under all operating conditions. According to consumer interviewed on significance of product attributes, reliability ranks in first place as the most significant attribute. To achieve a high customer's satisfaction, reliability must be examined during the product development cycle from viewpoint of the customer, who treats reliability as a major topic [8].

For reliability analysis, the mean values, standard deviations and standard variables of the yield strength and tensile strength were calculated and presented in Table 4 and 5

Table 4. Reliability analysis parameters of yield strength

Quality class of bolts	**Tempering temperature [^{0}C]**	**Yield strength $R_{p0,2}$ [N/mm^2]**	**Mean values σ_m [N/mm^2]**	**Standard deviations S_σ [N/mm^2]**	**Standard variables z_σ [-]**	**Reliability R [%]**
12.9	380	1100	1239	21.34	-6.51	> 99
10.9	430	940	1032	15.77	-5.83	> 99
8.8	460	640	983	14.05	-24.41	> 99

Table 5. Reliability analysis parameters of tensile strength

Quality class of bolts	**Tempering temperature [^{0}C]**	**Tensile strength R_m [N/mm^2]**	**Mean values σ_m [N/mm^2]**	**Standard deviations S_σ [N/mm^2]**	**Standard variables z_σ [-]**	**Reliability R [%]**
12.9	380	1220	1284	7.82	-8.18	> 99
10.9	430	1040	1090	17.12	-2.92	> 99
8.8	460	800	1027	6.13	-37.03	> 99

2.6.1. Failure Probability Function

The failure probability function is given as follows in Reference [8,9].

$$f(\sigma) = \frac{1}{S_\sigma \sqrt{2.\pi}} \exp\left[-\frac{(\sigma - \sigma_m)^2}{2.S_\sigma^2} \right] \tag{7}$$

2.6.2. Mean Values

The mean values of the stresses σ_m [N/mm^2] are calculated as follows [8, 9]:

$$\sigma_m = \frac{1}{n} \sum_{i=1}^{n} \sigma_i \,, \tag{8}$$

where n is the test quantity and σ_i [N/mm^2] is the measured stress for each test.

2.6.3. Standard Deviations

The standard deviations of the stresses S_σ [N/mm^2] are calculated as follows [8, 9]:

$$S_\sigma = \left[\frac{1}{n-1} \sum_{i=1}^{n} (\sigma_i - \sigma_m)^2 \right]^{1/2} \tag{9}$$

where σ_i [N/mm^2] is the measured stress for each test and σ_m [N/mm^2] is the mean values of the stresses.

2.6.4. Standard Variables

The standard variables of the stresses are calculated as follows [8, 9]:

$$z_\sigma = \frac{\sigma_i - \sigma_m}{S_\sigma} \tag{10}$$

where σ_i [N/mm^2] is the yield strength ($R_{P0,2}$) or tensile strength (R_m) of the material which is given in the literature.

3. RESULTS AND DISCUSSIONS

Reliability analysis parameters of the yield strength of high-strength 30MnB4 steel bolts are presented in Table 4, for the 12.9, 10.9 and 8.8 quality steel bolts, where the mechanical properties are given respectively in Tables 3 and 4. The mean values of the yield strength σ_m are bigger than the required yield strength of steel bolts such as 12.9, 10.9 and 8.8 quality bolts. Additionally, the reliability levels of the yield strength satisfy the required yield strength values $R_{P0,2}$ which are given in the literature.

Reliability analysis parameters of the tensile strength of high-strength 30MnB4 steel bolts are presented in Table 5, for the 12.9, 10.9 and 8.8 quality steel bolts, where the mechanical properties are given respectively in Tables 3 and 5. The mean values of the tensile strength σ_m are bigger than the required tensile strength of steel bolts such as 12.9, 10.9 and 8.8 quality bolts. Additionally, the reliability levels of the tensile strength satisfy the required tensile strength values Rm which are given in the literature.

4. CONCLUSIONS

The objective of this study is to investigate the mechanical properties of high-strength steel bolts under static loading conditions based on reliability analysis. All sample bolts were M12, and the material was 30MnB4. Heat treatment, quenching and tempering processes were applied to the high-strength steel bolts. A standard tensile test was performed on the samples. Stress-strain curves were obtained for the steel bolt samples after different heat treatments. The mean values, standard deviations and standard variables of yield strength and tensile strength were calculated. The following conclusions are drawn from our results:

i. By heat treating at different temperatures, it is possible to obtain high-strength steel bolts with different properties.

ii. By quenching, the mechanical properties of the high-strength material such as yield strength and tensile strength are increased; in contrast, elongation is reduced because of the martensite structure.

iii. By tempering, the mechanical properties of the high-strength material increase with decreasing tempering temperature because of the tempered-martensite structure.

iv. Furthermore, the residual stress and hardness after quenching are reduced by the tempering process.

v. By tempering at different temperatures, it is possible obtain different physical properties of high-strength bolt materials, such as 12.9, 10.9 and 8.8.

vi. By tempering at 380 [^{0}C], 12.9 quality bolt material was obtained. Reliability levels of the 12.9 quality bolt material for the yield strength $R_{P0,2}$ and tensile strength R_m (R>99%) satisfy the required values which are given in the literature.

vii. By tempering at 430 [°C], 10.9 quality bolt material was obtained. Reliability levels of the 10.9 quality bolt material for the yield strength $R_{P0,2}$ and tensile strength R_m (R>99%) satisfy the required values which are given in the literature.

viii. By tempering at 460 [°C], 8.8 quality bolt material was obtained. Reliability levels of the 8.8 quality bolt material for the yield strength $R_{P0,2}$ and tensile strength R_m (R>99%) satisfy the required values which are given in the literature.

ix. Although it is possibly to estimate that the reliability of all bolts is near 99% since all tensile test stresses are over the required strength values, reliability analysis is necessary to estimate the product reliability for each manufacturing stage.

The reliability levels of mechanical properties of bolt steel satisfy bolt costumer requirements. It is possible to decrease material stock-cost by manufacturing different bolt quality with same material by applying different heat treatment and different temperature.

Furthermore, having high reliability levels production is an advantage for manufacturer both in local and international markets. The authors recommend that the reliability levels of the bolt should be included in the bolt manufacturer's product catalog as mandatory information by trade regulations thus, protecting the customer rights of the bolt.

In the future study, fatigue strength of bolts steel materials will be investigated based on reliability analysis.

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