Causes of Failure of High-Tensile Stud Bolts Used for Joining Metal Parts of Tower Crane

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Abstract. The causes of the failure of a high-tensile stud 2M48-6gx500 10.9 made from steel grade 30HGSA which led to a temporary inoperability of a tower crane were investigated. The bolts were used to assemble the tower sections and collapsed after 45 days from the moment the crane was commissioned. The cracks in the fracture are identified as fatigue with the characteristic sites of nucleation, sustainable development and static dolomite. To determine the possible causes of stud bolts destruction, metallographic, durometric and mechanical tests were carried out from which it follows that the stud bolt material in its original state corresponded to the delivery conditions. The destruction of the stud bolt appears to have resulted from a combination of several unfavorable factors: uncertainty about the actual tension of the stud bolt due to the lack of information about the magnitude of the twist factor; partial displacement of the centers of the brackets holes and rotation of the stud bolt axis during the sections’ assembly; no tight contact on the support surfaces of the section brackets. All this led to a discrepancy between the actual design of the stud bolt, the appearance of additional forces and the destruction of the stud bolt.

1. Introduction

In the construction of modern large-span and high-rise buildings and structures, tower cranes are widely used, which relate to hoisting mechanisms of increased danger. Tower cranes, in comparison with other types of lifting mechanisms, are most prone to collapse, which is due to their design features [1,2]. One of the traditional ways to improve the reliability of hazardous production facilities, including tower cranes, is to study the reasons for their failure [3]. In this paper, we analyze the possible causes of destruction of a high-strength stud bolt 2M48-6gx500 10.9, which led to temporary inoperability of the tower crane TDK-10.215.

2. Characteristics of the study object

The high-strength stud bolt 2M48-6gx500 of strength class 10.9 is made of steel grade 30HGSA according to the technology providing for its hardening for martensite, the proportion of which in the core of threaded sections should be approximately 90%, followed by tempering in the furnace at a temperature not lower than 425°C [4]. The thread of the stud bolt with a pitch of 5 mm and the plane-cut profile of the cavities according to GOST 24705-81 is formed by the rolling method. Anticorrosive protection of the stud bolt is made in the form of a zinc chromate coating with a thickness of 9 μm.
The stud bolt is used to connect the sections of the tower of the crane TDK-10.215 with a lifting capacity of 10 tons, the maximum reach of the boom is 65 meters and the lifting height is up to 75 meters. In each joint of the sections there are eight stud bolts that are installed in the holes of the brackets and tightened by the design effort.

When examining the metal structures of the TDK-10.215 crane in one of the joints of the tower sections at an altitude of about 47 m, it was found that there was no single stud that collapsed and fell out of the bracket 45 days after the crane was commissioned. To determine the possible causes of the destruction of the stud bolts, metallographic, durometric and mechanical tests were carried out, the results of which are given below.

3. Methods and results of the study

3.1. Fractographic study of fracture
Fractographic studies of the fracture surface were carried out by visual inspection of the fracture of the stud bolt in order to obtain information on the nature of nucleation and the development of a crack. When considering the fracture of the stud bolt (Figure 1), three characteristic areas were identified. The first segment is the zone of nucleation of the first crack that formed in the stretched zone of the stud bolt and is characterized by a relatively flat fracture surface without developed relief. Such a surface is characteristic of a fatigue crack, with the development of which a periodic closure of its shores occurs [5,6].

In our case, the crack developed from the groove of the thread, the geometry of which determines the concentration of stresses, to the center of the cross-section of the stud bolt. When the first crack reached a certain size, the internal stresses were redistributed from the external load, which led to the formation of a second crack on the opposite side of the section-section No. 2 (see Figure 1). This area is characterized by a more developed surface relief with traces of periodic fracture stopping (fatigue grooves). The presence of a sign of the closure of the banks in the first crack and their absence from the second crack suggests that the eccentricity of the acting load [7].

![Figure 1. Surfaces of kink stud bolts 2M48-6gx500 10.9: a - left side of the fracture surface; b - right side of the fracture surface.](image)

With the growth of both cracks, the cross-section of the stud bolt was weakened to a critical size, at which the acting stresses from the external load reached the ultimate strength of the material. At stresses equal to the ultimate strength of the material, the proportion of the remaining cross section occurred according to the mechanism of quasi-shattering failure-section No. 3 (see Fig. 1), which is characterized by a coarser fracture surface.

3.2. Measuring the thread pitch
The thread pitch of the stud bolt was determined in two sections according to the distance between the tops of the thread profile. One of the sites was in close proximity to the site of destruction (site 1), and
the second - in an unloaded section of the stud bolt (section 2), which was behind the nut. The results of measurements of the maximum deviations in the thread pitch are given in Table. 1.

From the analysis of the results of measurements it follows that at the point of destruction of the stud bolt, the distance between the thread tips is 5.6 mm, which is 12% higher than the normative value. Moving away from the place of destruction, the distance between the thread tips decreases and is 5.3 mm. On the unloaded portion of the stud bolt, the distance between the thread tips is 5.0 mm, which corresponds to the requirements of GOST 24705-81.

The presence of an increased distance between the thread tips on the destroyed section of the stud bolt and its absence on the unloaded section indicates the development of plastic deformations on the threaded portion of the stud bolt.

### Table 1. Results of measurements of the stud bolt thread pitch.

| Section №1 | Number of the peak | 1-2 | 2-3 | 3-4 | 4-5 | 5-6 | 6-7 | 7-8 | 10-11 |
|------------|-------------------|-----|-----|-----|-----|-----|-----|-----|-------|
| Distance between peaks, mm | 5.6 | 5.5 | 5.3 | 5.4 | 5.3 | 5.3 | 5.3 | 5.3 |

| Section №2 | Number of the peak | 1-2 | 2-3 | 3-4 | – | – | – | – | – |
|------------|-------------------|-----|-----|-----|---|---|---|---|---|
| Distance between peaks, mm | 5.0 | 5.0 | 5.0 | – | – | – | – | – |

### 3.3. Tensile tests

Tensile tests were carried out according to GOST 1497-84 on samples of type III with a diameter of 6 mm cut from the smooth part of the stud bolt. The sampling points were located at a distance of at least 100 mm from the point of destruction of the stud bolt in diametrically opposite sections of its cross section, which are closest to the outer surface of the stud bolt.

From the obtained results it follows that the average values of the strength and plasticity characteristics of the stud bolt material do not contradict the requirements of GOST R 52643-2006 (Tables 2, 3), while the conditional yield strength of steel has a spread. In particular, the conditional yield strength of the first sample was lower by 12.1% than the normative value, and the second one - by 12.3% higher. This variation can be explained by the fact that the tests were carried out on samples cut from the torn portion of the stud bolt from various sections of its cross section.

### Table 2. Requirements for the mechanical properties of the stud bolt strength class 10.9 in accordance with GOST R 52643-2006.

| Mechanical properties | \(\sigma_{0.2}, \text{N/mm}^2\) | \(\sigma_{b}, \text{N/mm}^2\) | \(\delta_s, \%\) | \(\psi, \%\) | KCU, J/cm² | HRC |
|-----------------------|-----------------------------|-----------------------------|----------------|-------------|--------------|-------|
| no less | 940 | 1040 | 9 | 35 | 49 | 32-39 |

### Table 3. Results of tensile tests of samples from a damaged stud bolt.

| № | Mechanical properties | \(\sigma_{0.2}, \text{N/mm}^2\) | \(\sigma_{b}, \text{N/mm}^2\) | \(\delta_s, \%\) | \(\psi, \%\) |
|---|-----------------------|-----------------------------|-----------------------------|----------------|-------------|
| 1 | \(\sigma_{0.2}\), N/mm² | 826 | 1011 | 15.7 | 49.0 |
| 2 | \(\sigma_{0.2}\), N/mm² | 1056 | 1118 |  –* |  –* |

* Destruction of the sample occurred outside its calculated length.
To confirm the strength class of the broken stud bolt from the same batch of products, treated tensile samples [4] with a diameter of 36 mm were made. From the test results follows (Table 4), that in the state of delivery the damaged stud bolt corresponded to the strength class 10.9 in accordance with GOST 52643-2006.

Table 4. Results of tensile tests of samples from a batch of unbroken stud bolts.

| №  | Mechanical properties |       |       |       |
|----|-----------------------|-------|-------|-------|
|    | σ₀,₂, N/mm²           | σₖ, N/mm² | δ₅, % | ψ, %  |
| 1  | 982                   | 1087   | 11,1  | 43,9  |
| 2  | 970                   | 1079   | 13,4  | 45,7  |

3.4. Impact bending tests
An assessment of the propensity of the steel to brittle fracture was carried out on samples of type 1 (KCU) and 11 (KCV) according to GOST 9454-78, samples for which were cut according to a scheme similar to tensile tests. It follows from the test results (Table 5) that, at a temperature of 200°C, the impact strength on samples of the KCU type is 54 J/cm² and meets the requirements of GOST R 52643-2006. When transitioning from KCU samples to KCV samples, which correspond more closely to the transition radii in the corners of the flattened thread profile, the impact strength of steel has decreased by an average of 30%, which indicates an increased risk of brittle fracture, especially at a negative temperature. The flat-cut profile of the thread cavities is characterized by small radiiuses of curvature and a high concentration of stresses [8,9], which can lead to the formation of a crack.

Table 5. Impact bending test results.

| №  | Impact strength, J/cm² | KCU²₀  | KCV²₀  |       |
|----|------------------------|--------|--------|-------|
|    |                        | Single | Average| Single | Average|
| 1  | 55                     | 55     | 38     | 38    |
| 2  | 54                     | 54     | 37     | 37    |
| 3  | 53                     | 53     | 39     | 39    |

As an example, Figure 2 shows photos of thin sections of threaded profile thread studs 2M48-6gx500 10.9, from which it follows that cracks are generated at the points of conjugation of the vertex surfaces and cavities of the thread profile.

From this it follows that in order to improve the performance of high-strength stud bolts operated under extreme conditions, it is advisable to use threads with a rounded profile of depressions, the geometry of which creates a lower stress concentration in the minimum section of the stud bolt.

Figure 2. The flat-cut thread profile of the stud bolt 2M48-6gx500 10.9 before (a) and after (b) the failure in the acceptance test.
3.5. Determination of hardness
The hardness of the samples was measured using a Rockwell hardness tester TR5014 on transverse templates cut from two sections: an unloaded portion of the stud and a portion in close proximity to the point of failure.

The results of the measurements showed that at a distance of at least 14-16 mm from the surface of the stud bolt, the hardness is 39 HRC, and in the center 32 HRC for the unloaded section. For a region close to the point of failure, the corresponding hardness values are 37 and 34 HRC.

Thus, it can be stated that the hardness of steel throughout the section, meets the requirements of GOST 52643-2006, shown to the studs of strength class 10.9.

3.6. Metallographic studies
Investigation of the microstructure of the stud bolt samples was carried out on an optical metallographic microscope Axio Observer D1.m. Samples were cut along the axis of the stud bolt from the unloaded and broken sections of the thread. To study the microstructure of the steel, the etching of the sections was carried out in a solution of nital. After etching the samples, a layer of decarburized metal with a ferrite structure was found on the outer surface of the thread of the stud bolt. Measurement of the thickness of the decarburized layer, carried out by means of the Thixomet Pro hardware and software complex, showed that the layer thickness in both samples is about 60 μm. At individual vertices of the teeth there is no decarburized layer, which indicates a violation of the geometry of the thread profile during the operation of the stud bolt.

To clarify the thickness of the fully and partially decarburized layer, the hardness was measured on a FM-800 microhardnesser, the results of which are shown in Figure 3.

A generalization of structural studies of the decarburized layer and microhardness measurements allows us to conclude that the depth of the complete decarburization zone is of the order of 15 μm, the depth of the partially decarburized zone reaches 60 μm.

The microstructure of both samples is uniform in cross-section of the stud bolt and consists of troostosorbite release (Figure 4). In the outer layers, the troostite component predominates. In the center, the amount of troostite does not exceed 50%, the rest - sorbitol leaves. Also in the structure there are sections of pre-eutectoid ferrite (less than 3%).

Despite compliance with the requirements of GOST R 52643-2006 by type of structure, the toughness on KCV20 samples for this stud bolt was not high. Taking into account that tower cranes are operated in the range from 40 to -40°C, this structure, in our opinion, will not be able to provide the required fracture toughness. According to modern concepts, the increase in the viscosity of steel can be achieved either by retaining austenite in the structure [10] or by retaining a certain amount of lower bainite in the structure [11, 12]. Of these options, the second method is most preferable for the steel under consideration - by isothermal quenching. However, it is doubtful to achieve the requirements of GOST R 52643-2006 in this treatment for strength indicators. Therefore, the use of 10.9 new grades of strength classes, such as 30X2NMFA, 20X2NMTRB, etc., should be considered.
for the manufacture of stud bolts [13,14], with higher fracture toughness values in the climatic temperature range.

![Figure 4. Microstructure of the thread site near the point of failure, x1000: a - base of the thread tooth; b - center of the stud bolt cross-section.](image)

4. Conclusion

Based on the studies, the following conclusions were drawn:

1. According to the parameters of mechanical properties (strength, hardness, toughness and plasticity), the stud bolt material does not have any gross deviations from the requirements of GOST R 52643-2006 and generally corresponds to the strength class 10.9.

2. The microstructure of the stud bolt is uniform in cross-section and length and consists of troostosorbite tempering. The depth of complete decarburization on the surface of the thread is 15 μm, which meets the requirements of GOST R 52643-2006.

3. The cracks found in the fracture are identified as fatigue with characteristic sites of nucleation and sustainable development [5,6,7]. The presence of a sign of periodic closure of the banks at the first crack and their absence in the second crack suggests that the load is eccentric.

4. The possibility of destruction of the stud bolt affects the lack of information about the actual value of the twist factor. Observing the requirements of GOST R 52643-2006 for this parameter, but without having the test results, it is possible both to draw and not to reach it for design effort [15,16]. In the worst case this discrepancy can reach 45%.

5. For the given (design) tension of the stud bolt, equal to 865 kN, the stresses in it are 588 N/mm², which is well below the minimum conditional yield point and time resistance, which were determined during mechanical testing of the samples (see Table 2, 3). From this it follows that when creating the design tension force, the stud bolt should not have collapsed.

7. The destruction of the stud bolt, apparently, was the result of a combination of several unfavorable factors, which include:

   a) uncertainty about the actual tension of the stud bolt due to the lack of information about the magnitude of the twisting factor;

   b) partial displacement of the centers of the holes of the brackets and the rotation of the stud bolt axis during assembly of the sections;

   c) absence of a tight contact on the support surfaces of the brackets of the sections. The presence of a gap in the joint or its opening during operation is extremely undesirable, since in this case the external load is completely transmitted to the stud bolt, which leads to the appearance of additional stresses in it [7,17,18].

The presence of these factors led to a mismatch between the actual design of the stud bolt, the appearance of additional internal force factors (in particular, the bending moment) and the achievement of the limiting state [19,20]. This unfavorable event was more likely to occur with respect to the last, within the joint, stud bolt, which is the closing link in assembling sections.
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