Investigation of causes of XCMG QY25K lorry-mounted crane accident

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Abstract. The article conducted a study of the causes of the accident of the XCMG QY25K lorry-mounted crane. Visual inspection of the emergency boom (boom in a critical condition) was carried out with the analysis of the state of the material in the broken section. The microstructure of steel in the crack zone was investigated. Chemical analysis of steel with a determination of the mass fraction of chemical elements was performed. Studies of the strength and hardness of material samples were carried out. Theoretically, the maximum tensile and compressive stresses in the section of the failed boom are determined. Comprehensive analysis of the obtained theoretical and experimental research results made it possible to establish the true cause of the accident of the lorry-mounted crane.

1 Introduction

During loading operations, when a slab weighing 3 tons was removed from the ground, an accident occurred in the lorry-mounted crane XCMG QY25K [1]. The extended telescopic boom was destroyed due to the crack through its cross-section. The two fallen sections turned out to be hanged (vertically) on the boom cables. The process of failure was short-time framed; the crack occupied (propagated through) almost the entire section.

Article (regarding the fact of the accident) involved clarifying the circumstances of the incident. A visual inspection of the lorry-mounted crane (in a critical condition) at the construction site was carried out and the necessary preliminary measurements were made, fragments of the metal boom were selected for further examination. The chemical composition of the boom material and its mechanical properties were studied. Fractographic investigation of the failure site, calculation of the stress state of the boom material was also carried out. A conclusion was drawn up on the causes of the accident.

Laboratory studies to determine the chemical composition of material samples were carried out by the test center of OJSC «Brestgazoapparat». Laboratory tests of steel samples for tension and studies of material hardness were carried out at the testing center of the Institution of education «Brest State Technical University».

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2 Visual inspection

The air of the vehicle-mounted crane after the boom failure is shown in Fig. 1, a, b, the broken section of the boom on both sides of the rupture is shown in Fig. 1, c.

Fig. 1. View of vehicle-mounted crane and boom after failure

An important structural feature of the boom is the presence of a strapping plate on its body (in the zone immediately adjacent to the crack and subjected to tension during crane operation). The strapping plate is welded along the entire contour; the welded seam is processed by a cut at an angle of about 45° to the surface. The thickness of the strapping plate is the same as the thickness of the boom, the length along the boom is about a meter, the width is 270 mm, the end sections are made narrow a width (160 mm), and the end line of the strapping plate is perpendicular to the axis of the boom.

The position of boom breaking cross-section fully corresponds to a position of edge-flange weld on a strap.

A characteristic feature of the broken cross-section is the presence in a section (in its stretched zone along the entire length of the weld) - the failure surface, which lies in the plane of the section (perpendicular to the axis of the boom). This directly characterizes the fracture region as brittle and due to tensile stresses. At one of its ends, there is a crack up to 15–20 mm long, running along the contour of the weld seam.

Almost the rest of the fracture of the broken section surface is oriented at an angle of about 45° to the plane of section, which indicates the yielding (plastic) nature of failure of the principal material of boom by shear (Fig. 2, a – c). Along the contour of the section, there are pronounced shear lips with a thickness of about 0,5 mm. The appearance of the yielding region was the result of the continued loading of the section after the occurrence of a brittle failure crack (after reaching the critical length of the crack). Thus, these circumstances already indicate the negative role of the transverse welded seam on the ends of the strapping plate.

As a result of cleaning the surface of a boom, an initial brown crack with a corrosion residue and old polymerized oil became visible, occupying about 40–50 mm at the edge of the welded seam. At the edge of the welded seam, the crack acquired a continuation along the side of the strapping plate (Fig. 2, d, e). On this section of the crack (on the side of the

strapping plate), irregularities are protruding (projecting) from the plane of the crack, some of which has a bright (vibrant) shade, and part is matte. On the opposite surface, the crack is seen as continuous, having a brown color.

Fig. 2. Boom section in the failure zone

The origin of the protrusions is associated with the presence in these places of the initial characteristic spots of failure. The places of failure (which, due to friction at local contacts of opposite points of adjacent surfaces that occurred at the time of application and removal of the live load) gradually became smoother. Bright sections appeared at the time of complete failure of the section. It can be seen that the initial crack developed deep from the side of the outer surface of the boom since «fresh» shear lips with a thickness of about 0,5–0,8 mm are visible from the inner side. To the right of this zone, there is an irregular «fresh» surface of failure, along which there was a crack movement during a rapid rupture of the boom. A characteristic point in the structure of this zone is the presence of irregularities on the side of the weld seam, which in this area has penetrated more deeply into the body of the boom. In general, the nature of irregularities indicates the spread of the crack to the right of the original defects.

On both sides of the weld seam and the strapping plate, the failure surface is a «fresh», uniform uninterrupted structure, located at an angle of about 45° to the plane of the failure section. Along the contour of the surface, very narrow shear lips are visible. Failure is yield shear-like except for the central zone along the lateral vertical sides of the boom surface, where the plane of failure coincides with the plane of section.

In some places along the contour of the crack, elongated protrusions in the form of thin wedges with a base of about 5 mm are visible. They also indicate the ductility of the boom material.

The appearance of a small longitudinal crack in the corner of the weld seam occurred at the time of the boom break after the propagation (run) of the principal crack (a subsequent study showed that the break is «fresh»).

3 Study the microstructure of the material

The structure of the material in the crack zone on the polished sections (micro slices) was investigated. The study showed the presence of both old through cracks at the border of the principal and surface micro cracks. Surface cracks are oriented mainly along the boom axis. This indicates their origin as a result of the occurrence of shrinkage stresses during the

cooling of the weld seam in the thermally activated zone of the material (Fig. 3), and not from the effects of stresses that arose during the operation of the crane.

Fig. 3. Microstructure of steel

In addition, there is a significant increase (enlargement) of the material directly at the failure boundary (in the seam area) compared to the structure of the base material (Fig. 4). This is also due to the peculiarity of welding processes.

Fig. 4. Microstructure of steel at the crack boundary

4 Chemical analysis of the material

For chemical analysis of crane boom material composition (and its comparison with that specified in engineering documentations «the high-quality structural S960Q hot-rolled steel having the minimum yielding limit $\sigma_T = 960$ MPa after Q&T according to EN10027-1 [2]») samples of material were selected. Samples were taken from sections of sheets located at a distance of 35–40 cm from the transverse weld seam, as well as from a section of material directly adjacent to the crack.

However, the data obtained from the material located in the weld seam area show an increased content of some elements (hydrogen, sulfur, titanium). The saturation of the material with these elements contributes to its embrittlement. Sulfur, being a harmful chemical impurity, reduces fatigue resistance and corrosion resistance, and at high temperature, for example, during welding, increases brittleness. Studies also showed an excess of titanium by 2 times the maximum normalized value that increases the strength of steel.

Thus, the composition of the steel can be attributed to low-alloyed (high strength steel) steel. In terms of its chemical composition, steel is close to low-alloyed steel of increased strength 09G2, GOST 19281-2014 [3], the chemical composition of which is given in Table 2.

Table 1. Comparison of the chemical composition of steel S960Q (as per EN 10025-6: 2004) and samples taken from the boom.

	Mass fraction of chemical elements, %														
	C	Si	Mn	P	S	Cr	Mo	Ni	V	Nb	Ti	Cu	N	Zr	Fe
As per EN 10025-	<0,2	<0,8	<1,7	<0,025	<0,015	<1,5	<0,7	<0,2	<0,12	<0,06	<0,05	<0,5	<0,015	<0,15	the rest
For samples	0,07	0,226	1,69	0,011	0,002	0,025	0,005	0,012	0,023	0,044	0,100	0,015	-	-	-
Compliance	corresponds	corresponds	corresponds	Corresponds	corresponds	corresponds	corresponds	corresponds	corresponds	corresponds	doesn't correspond	corresponds	doesn't correspond	doesn't correspond	doesn't correspond

Table 2. Chemical composition of steel 09G2 (as per GOST 19281-2014).

C	Si	Mn	Ni	S	P	Cr	V	N	Cu	As
up to 0,12	0,17-0,37	1,4 – 1,8	up to 0,3	up to 0,035	up to 0,03	up to 0,3	up to 0,12	up to 0,008	up to 0,3	up to 0,08

Equivalent carbon content calculated by actual chemical composition classifies the steel as limited to arc weldability, i.e. needing to perform certain technological measures during welding. This confirms (the likelihood) of a latent initial crack that was found in a fractographic investigation.

$$C_3=C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15=0,364 \qquad (1)$$

5 Study of mechanical properties of a material

The study of actual mechanical properties was carried out by testing material samples for tension and hardness. To determine the tensile stress-strain diagram of the boom material, samples were cut in the form of strips 120 mm long, 20 mm wide. Three sections of the crane boom adjacent to the failure section were cut out - from the strapping plate, from the sheet of the upper plane of the boom (on its detached part), and the sheet of the side part of the body (above the longitudinal weld seam). Samples were cut from crane boom sections located at a distance of 30-40 mm from the failure section. Sample sizes are selected following the requirements of GOST 1497-84 [4]. Determination of force-displacement relationships was carried out on a tensile machine IR-5145-500-11 in the BSTU test center. Three samples of strapping plate material and two of the other sections were tested because of the high stability of the results (Fig. 5).

All samples tested were broken into sections perpendicular to the direction of the tensile load to form (shape) a neck. The rupture plane is perpendicular to the sample surface (without slope). By the thickness of the samples in their structure, three sections can be distinguished - the middle and two peripheral (Fig. 6), which indicates a significant cold hardening (strain hardening) of the surface layers of the boom sheet material (sheeting) [5].

Characteristic tensile stress-strain diagrams of a specimen are shown in Fig. 7, the results of experimental studies are given in Table 3.

Fig. 5. Tensile testing of material samples

Fig. 6. Sections of the samples after testing

Table 3. Results of samples strength tests.

Sample number	Sampling location	Geometric dimensions of samples, mm		Strength characteristics, MPa	
		H	B	σ_y	σ_{str}
1	Strapping plate	5	19,95	732,8	804,7
2		5	19,95	737,8	809,8
3		4,15	20,10	739,3	811,6
4	Basis	4,15	20,10	703,7	755,9
5		4,10	20,05	712,8	766,0
6	Side part	4,10	20,00	725,6	779,5
7		4,10	20,00	725,6	778,7

Fig. 7. Specimen tensile stress-strain diagrams

Based on sample tests, it is possible to conclude that the material is sufficiently high in ductility ($\delta \approx 25\%$). However, the main circumstance manifested during the tests lies in significantly lower levels of yield limits and short-term strength of the material of all samples compared to the standard properties of steel S960Q (instead of [2] data established by the standard: $\sigma_y \geq 960$ MPa and $\sigma_{str} = 980\text{--}1150$ MPa, while tests show values: $\sigma_y \approx 703\text{--}739$ MPa, $\sigma_{str} \approx 755\text{--}810$ MPa).

Moreover, there was some difference between the characteristics of the material of the boom body and the strapping plate: about 15 MPa in yield limit and 25 MPa in ultimate strength (higher values belong to the strapping plate).

The boom material was tested for hardness using an ultrasonic hardness measuring instrument TKM-459 in accordance with GOST 9012-59 [6]. For hardness tests, material sections were selected at a distance of 30–60 mm from the crack and in sections (in the weld seam area) immediately adjacent to the crack. The test results are shown in Table 4.

Table 4. Brinell Hardness Measurement Results.

№	Hardness, HB			
	The principal material (upper zone)	The principal material (side)	The principal material (under the strapping plate)	Strapping plate material
1	179	164	175	236
2	202	193	186	208
3	191	218	168	239
4	166	211	186	194
5	182	204	178	241
6	175	200	171	193
7	173	155	195	214
8	189	172	199	189
Mean	182,13	189,63	182,25	214,25

The measurement results show that the hardness of the strapping plate and the base boom material are different, which corresponds to the results of the tensile tests of the samples.

6 Stresses in the rupture section

During the inspection of the boom (in emergency condition) at the construction site, the geometric dimensions of the failure section were indicated. Based on the obtained data, a

scheme is plotted (Fig. 8, a), using which the area A , the moment of inertia J_z , and the section modulus of the section W_z are determined. They were: $A = 65,2 \text{ cm}^2$, $J_z = 30430 \text{ cm}^4$ and $W_{z1} = 1232 \text{ cm}^3$ (for the stretched section zone), and $W_{z2} = 1021 \text{ cm}^3$ (for the compressed zone). The thickness of the sheet material accepted in the calculations is 4 mm. A Diagram of boom loading is given in Fig. 8, b (G – boom weight, P – the weight of the load, L – length of loaded section).

Fig. 8. Design section diagram (a) and design model of crane boom loading

The design stresses in the stretching zone are approximately $\sigma_s \approx 195 \text{ MPa}$, in the compression zone – $\sigma_c \approx 250 \text{ MPa}$. The weakening of the section due to the presence of initial cracks leads to a slight increase in tensile stresses to about the value of $\sigma_s \approx 210 \text{ MPa}$.

The stresses values obtained concerning the yield stresses are not high (even if take into account the possible dynamic nature of loading when the load takes off from the ground). On the other hand, the stresses obtained do not take into account the stress concentration (which always occurs at the crack tops and depends on the nature of the loading, the structure of the material, the length, and the shape of the crack). At the same time, fractography of the failure zone indicates the repeated cases of increasing yield limit at the crack boundary. This led to the accumulation of large residual deformations. It also created conditions for the exertion (manifestation) of low-cycle fatigue of the material and a reduction of durability.

7 Conclusion

The stress at the section of failure (in case of no defects) could not exceed the permissible level, which indicates that there was no violation of the crane operating conditions (at the time of the accident).

The failure of the boom of the XCMG QY25K lorry-mounted crane occurred due to the gradual development of the initial material defects that arose during the manufactory welding process when an additional plate onto the boom section of the crane was welded. This caused the failure of the boom when the crack (corresponding to the load in the accident) achieved a critical length.

References

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