LIFE TIME ASSESSMENT OF CLAMP-FORMING MACHINE BOOM DURABILITY

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Summary

The problem of assessment of main carrying elements (belts) of clamp-forming machine boom made of the angle 45×45×5 mm (Steel 3) in the process of diagnostics is considered. The fragment of the belt is modelled by means of a plate, hawing the crack with typical sizes. Analytical relations are given, stresses intensity factors (SIF) K_1 and rates of their change dK_1/da near the apex of a crack are investigated. Six cases of potentially possible crack-like defects initiation are considered, criteria lengths of cracks are determined for them, proceeding from the obtained experimental data.

Keywords: clamp-forming machine, boom carriage, a fatigue crack, durability.

OSZACOWANIE TRWAŁOŚCI KONSTRUKCJI NOŚNEJ PRZENOŚNIKA MASZYNY DO KOPCOWANIA

Streszczenie

Rozpatrzono zagadnienie oszacowania trwałości wykonanych z kątownika 45×45×5 mm (Stal 3) głównych elementów nośnych (pasów) wysięgnika maszyny do kopcowania w trakcie diagnostyki technicznej. Element pasa zmodelowano jako płytkę z pęknięciem o charakterystycznym wymiarze *a*. Przedstawiono wyrażenia analityczne i zbadano wartości współczynników intensywności naprężeń (WIN) K_I i tempo ich zmian dK_I/da przed frontami szczelin. Rozpatrzono sześć przypadków powstania potencjalnie możliwych pęknięć, kryterialne długości których określono na podstawie badań doświadczalnych.

Słowa kluczowe: maszyna do kopcowania, konstrukcja nośna, pęknięcie zmęczeniowe, trwałość.

1. INTRODUCTION

At the present time for many countries of Europe and the world is extremely urgent problem of the reliability and safety of long-term operation of engineering structures [9]. As it is known, the design of structural elements for their functioning in the present conditions of operation loads is performed on the basic of continuum mechanics approach. However, each structural element always possesses certain imperfections. Formed both at the stage of it's manufacture and at the stage of further functioning [9]. Planned operation resource of the equipment is exhausted and in recent years there appear more and more damages of various nature [8]. In this connection, to provide reliable and trouble-free operation of the equipment, quantitative approaches to assessment of the degree of the danger at the detected crack like defects are necessary [3, 4]. Also, methods of express-analysis are needed, these methods, proceeding from the data of nondestructive control or information, regarding the state of the studies surface of the material, will be able to evaluate the particular defects and residual resource of structural element or structure in general.

As a rule, with the increase of production capacity, the impact of various facts on structural elements increases, this leads to undesirable consequences (breakdowns, failures, etc.). Technical diagnostics [8, 9] of technological equipment shows that the amount of so-called unconventional damage in structural elements increases, they are not predicted by normative instructions and documents, they appear as a result of long operation of the equipment on various devalues from operation modes. Such breakages are mainly, of corrosion-mechanical nature and are performed in the first place in the place of increased concentration of strains, caused by the features of the construction or technology of part manufacture technology [12].

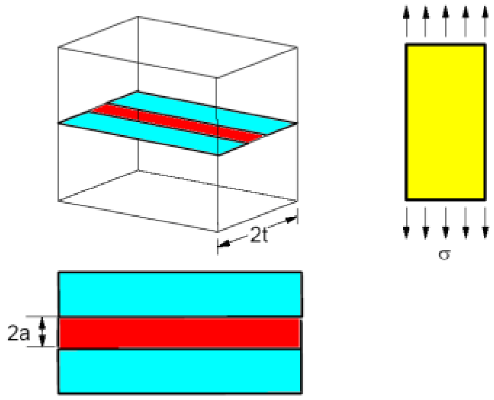
Nowadays, there exist a problem, connected with the existence of various corrosion and corrosion-mechanical defects on the internal surface of structural elements. Along with this, important factor is the monitoring of the existing defects and analysis of further operations of such systems. In spite of rather diverse physical nature of numerous defects origin characteristics feature is localization of physical-mechanical physical-chemical processes of materials fracture. That is why, corrosion-mechanical damaging and fracture of the material can be evaluated on the basis of common methodological approach. Scientific fooling for the analysis of damage is mechanics of materials and constructions failure that studies the regularities of generation and development of irregularities and defects of material structure, such as cracks under cyclic loading [8], along with nondestructive methods of objects monitoring, by means of which the geometry and shape of the existing defects can be modelled.

2. METHODOLOGICAL ASPECTS OF THE RESEARCH

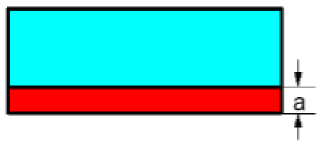
In [2, 11] the analysis aimed at determination of corrosion-cyclic crack resistance of profile steel (Steel 3) of 45×45×5 mm angle of operated clamp-forming machine БУМ-65М2Б3-К type frame has been carried out. However, the results of the research do not give a clear answer regarding further evaluation or durability of this construction element. For such assessment the given paper contains analytical relations for stress intensity factor (SIF) K_1 and their change rate dK_1/da near a size crack tip in the plate used for modelling of the investigation clamp-forming machine (here a – typical size of crack like defect). Six cases of potentially possible crack like defects are considered. Such analytical base serves for assessment the durability of roads with crack like defects by the factor "resistance of construction element to crack growth" [10] that is the characteristic of SIF change rate near the crack tip.

To realize such approach, the extension of the rectangular parallelepiped with such existing crack like defects is considered: through-thickness centred crack; extended surface crack; two extended surface cracks; with semielliptical surface crack; quarter elliptical corner crack; embedded elliptical crack (centred), models of which are shown in Figs. 1–6. The following notations are taken on the figures: σ - normal stress in the direction, perpendicular to the plane of the crack; t - the size of the rectangular parallelepiped in the direction of crack propagation (constant value); in case of central longitudinal crack or edge crack a is a crack length; and if the crack is in the form of an ellipse or its part , then a and c - are the sizes of the ellipse semi axes.

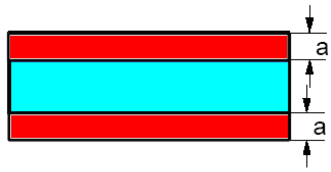
Criterion dimensions of the depth of the crack have been calculated based on experimental studies presented in [2, 11]: 1) the threshold size of crack a_{th}, before reaching which ($a<a_{th}$) no further growth of the size of the crack is observed; 2) the critical size of crack a_{fc}, after reaching which ($a \geq a_{fc}$) spontaneous growth of the size of the crack becomes possible, which leads to fracture of the construction element through brittleness.



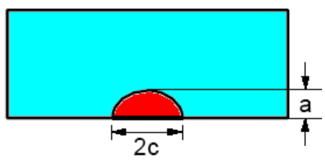
Case I
Fig. 1. Loaded rectangular parallelepiped with through-thickness centred crack: $2t$ –width of the plate; $2a$ – length of the crack; σ – applied efforts



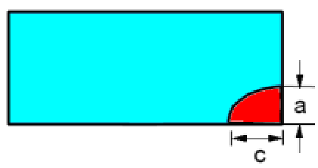
Case II
Fig. 2. Extended surface crack: a – length of the crack



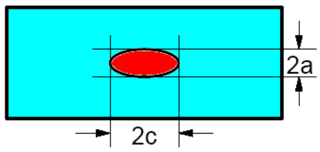
Case III
Fig. 3. Two extended surface cracks: a – length of the crack



Case IV
Fig. 4. Semielliptical surface crack: a – length of the crack; $2c$ – its width



Case V
Fig. 5. Quarterelliptical corner crack: a – length of the crack; c – its width



Case VI

Fig. 6. Embedded elliptical crack (centred): 2*a* – length of the crack; 2*c* – its width

3. ANALYTICAL RELATIONS

Model 1. For determination of the SIF K_1 in case, described in Fig. 1, relation [7] was used

$$K_1 = \frac{1 - 0{,}025\left(\frac{a}{t}\right)^2 + 0{,}06\left(\frac{a}{t}\right)^4}{\sqrt{\cos\left(\frac{\pi a}{2t}\right)}}\sigma\sqrt{\pi a}\,. \quad (1)$$

Model 2. Relations for determination of SIF in the case, presented in Fig. 2, have the form [1]:

$$K_1 = Y\sigma\sqrt{a}\,, \quad (2)$$

where

$$Y = 1{,}99 - 0{,}41\left(\frac{a}{t}\right) + 18{,}7\left(\frac{a}{t}\right)^2 - 38{,}48\left(\frac{a}{t}\right)^3 + $$
$$+ 53{,}85\left(\frac{a}{t}\right)^4 \quad \text{for} \quad \frac{a}{t} \le 0{,}6\,;$$

$$Y = \left[\frac{1}{2}\left(\frac{a}{t}\right)^{-\frac{1}{2}}\left(1 - \frac{a}{t}\right)^{-\frac{3}{2}}\left(1 + 3\left(\frac{a}{t}\right)\right)\right] \quad \text{for} \quad \frac{a}{t} > 0{,}6.$$

Model 3. Relation (2) was used for SIF calculation for described in Fig. 3, however here [7]:

$$Y = \frac{1{,}122 - 0{,}561\left(\frac{a}{t}\right) - 0{,}015\left(\frac{a}{t}\right)^2 + 0{,}091\left(\frac{a}{t}\right)^3}{\sqrt{1 - \frac{a}{t}}}\,.$$

Model 4. Calculation formulas for SIF (Fig. 4) have the form [5]

$$K_{1a} = \sigma F\sqrt{\pi a}\,, \quad (3)$$

where

$$F = \frac{M_1 + M_2\left(\frac{a}{t}\right)^2 + M_3\left(\frac{a}{t}\right)^4}{\sqrt{Q}}F_w\,;$$

$$F_w = \sqrt{\frac{1}{\cos\left(\frac{\pi c}{2W}\sqrt{\frac{a}{t}}\right)}}\,; \quad Q = 1 + 1{,}464\left(\frac{a}{c}\right)^{1{,}65}\,;$$

$$M_1 = 1{,}13 - 0{,}09\left(\frac{a}{c}\right); \quad M_2 = -0{,}54 + \frac{0{,}89}{0{,}2 + \frac{a}{c}}\,;$$

$$M_3 = 0{,}5 - \frac{1}{0{,}65 + \frac{a}{c}} + 14\left(1 - \frac{a}{c}\right)^{24}\,.$$

Model 5. Calculation formulas for SIF (Fig. 5) have the form [5]:

$$K_{1a} = K_\varphi \quad (\varphi = \pi/2); \quad (4)$$

where

$$K_\varphi = \sigma F\sqrt{\frac{\pi a}{Q}}\,;$$

$$F = \left[M_1 + M_2\left(\frac{a}{t}\right)^2 + M_3\left(\frac{a}{t}\right)^4\right]g_1 g_2 f_\varphi\,;$$

$$Q = 1 + 1{,}464\left(\frac{a}{c}\right)^{1{,}65}\,; \quad M_1 = 1{,}08 - 0{,}03\frac{a}{c}\,;$$

$$M_2 = -0{,}44 + \frac{1{,}06}{0{,}3 + \frac{a}{c}}\,;$$

$$M_3 = -0{,}5 + 0{,}25\frac{a}{c} + 14{,}8\left(1 - \frac{a}{c}\right)^{15}\,;$$

$$g_1 = 1 + \left[0{,}08 + 0{,}4\left(\frac{a}{t}\right)^2\right](1 - \sin\varphi)^3\,;$$

$$g_2 = 1 + \left[0{,}08 + 0{,}15\left(\frac{a}{t}\right)^2\right](1 - \cos\varphi)^3\,;$$

$$f_\varphi = \left[\left(\frac{a}{c}\right)^2\cos^2\varphi + \sin^2\varphi\right]^{\frac{1}{4}}\,.$$

Model 6. SIF for the scheme, presented in Fig. 6, was calculated by the formula [5]

$$K_{1a} = FF_w\sigma\sqrt{\pi a}\,, \quad (5)$$

where

$$F = \frac{M_1 + M_2\left(\frac{a}{t}\right)^2 + M_3\left(\frac{a}{t}\right)^4}{\sqrt{Q}}\,;$$

$$F_w = \sqrt{\frac{1}{\cos\left(\frac{\pi c}{2W}\sqrt{\frac{a}{t}}\right)}}\,; \quad Q = 1 + 1{,}464\left(\frac{a}{c}\right)^{1{,}65}\,;$$

$$M_1 = 1\,; \quad M_2 = \frac{0{,}05}{0{,}11 + \left(\frac{a}{c}\right)^{\frac{3}{2}}}\,; \quad M_3 = \frac{0{,}29}{0{,}23 + \left(\frac{a}{c}\right)^{\frac{3}{2}}}\,.$$

It should noted that in Fig. 4, 5 and 6, where the crack is set by various ellipse like figures, by changing the relation of ellipse axes of crack like defect of different geometry.

In the research corresponding dimensions less dependences for the considered cases form and location on the basis of the given analytical relations and constructed:

$$(\sqrt{t}/\sigma)\cdot(dK_{\rm I}/da)=F(a/t), \qquad (6)$$

That is why, in further study of the result of research, we will introduce variable parameter (a/t) that characterizes the effective size of the defect.

It should be noted that characteristic feature of this dependences is that certain value of the parameter (a/t), is always observed on them, starting from this value sharp increase of stress intensity coefficient $K_{\rm I}$ change rate takes place. This value $(a/t)^*$ was considered as characteristic one for assessment of the strength and reliability of structural elements with crack like defects.

RESULTS AND THEIR DISCUSSION

For determination of the characteristic values of the crack length in the studies of structural elements experimental base given in [2, 11] and analytical relation, described by Paris power dependence [6], was used

$$da/dN = C\cdot(\Delta K)^n, \qquad (7)$$

where C and n – constant characterizing system "material-environment". Such constants, along with limiting values of SIF are presented in Table 1 for various systems "material-environment" (coefficient of skewness cycle is marked as R).

Values ΔK_{th} and ΔK_{fc} given in the Table 1 were the base for determination of the characteristic values a_{th} and a_{fc} correspondingly. Along with these values obtained on the base of experimental data processing, values of a^* were calculated using the technique [10] that corresponds to characteristics value $(a/t)^*$ determined on the base of relation (6). During the study of processes of growth crack like defects in load carrying elements of arrows of clamp-forming machine took into account the fact that the spread of cracks in the direction perpendicular to the medial surface of the walls of angle most affects on the structural strength. Therefore, all future calculations are shown just for this case.

Assessments of the durability of the investigated element of the construction with potentially possible crack like defects of various forms and geometry is performed on the base of the relation [8], that provides the attainment conditions of spontaneous fracture of the structural elements, i.e.

$$N_{fc}=\int_{a_{th}}^{a_{fc}}\frac{da}{F(\Delta K_{\rm I})} \qquad (8)$$

where N_{fc} – number of load cycles prior to fracture of structural elements; $F(\Delta K_{\rm I})$ – known function of SIF $\Delta K_{\rm I}$.

Besides, for investigated situations, the period (the number of load cycles) N^*, is calculated during this period crack like defects achieves characteristic size a^* starting from which the rate of SIF $K_{\rm I}$ change rapidly increase. The value N^* calculated by the formula, along to (8):

$$N^*=\int_{a_{th}}^{a^*}\frac{da}{F(\Delta K_{\rm I})}. \qquad (9)$$

It should be mentioned, that the value of a^* depends only on the geometry of structural element and method of its loading. As well as on the form and location of crack like defect and a_{fc} – on the same factors, and on the material and conditions of its testing. that is why, during investigation of specific structural elements, made of the given material and which ah are in the set operation conditions (i.e., for the specific system "material – environment") values of a^* parameter may be formally less or greater than the critical size of the defect a_{fc}.

To results of calculation of durability for the material of clamp-forming machine frame angle 45×45×5 mm are given in Table 2.

Table 1. Constants of "material - environment" and the criterion values of SIF

System "material-environment"	Constants of system "material-environment"		ΔK_{th}	ΔK_{fc}
	C	n		
Exploited				
Air R = 0.1	2.50E-13	3.87	4.703	28.026
Air R = 0.6	1.28E-11	2.76	2.106	25.729
Corrosion environment R = 0.6	1.42E-10	1.88	0.830	32.714
Air R = 0.75	1.99E-13	4.85	3.605	14.979
Corrosion environment R = 0.75	4.71E-11	3.14	1.271	11.470

Table 2. Data for calculating of the durability of clamp-forming machine frame angle 45×45×5 mm

Model	System "material - environment"	a_{th}, mm	a*, mm	a_{fc}, mm	N*, load cycles	N_{fc}, load cycles
1	Air R = 0.1	1.880	1.78798	4.790	3.21963E+9	3.38333E+9
	Air R = 0.6	0.440		4.760	2.82305E+9	2.86926E+9
	Corrosion environment R = 0.6	0.070		4.840	1.43501E+9	1.47147E+9
	Air R = 0.75	1.220		4.360	2.57181E+9	2.59100E+9
	Corrosion environment R = 0.75	0.160		4.010	1.13219E+9	1.13549E+9
2	Air R = 0.1	0.340	1.92487	2.360	2.13364E+9	2.14310E+9
	Air R = 0.6	0.070		2.260	1.19300E+9	1.19798E+9
	Corrosion environment R = 0.6	0.010		2.540	6.12409E+8	6.22859E+8
	Air R = 0.75	0.200		1.560	1.24230E+9	1.24026E+9
	Corrosion environment R = 0.75	0.020		1.210	4.70958E+8	4.67498E+8
3	Air R = 0.1	0.355	2.43187	2.340	2.78527E+9	2.78529E+9
	Air R = 0.6	0.070		2.310	1.32656E+9	1.32661E+9
	Corrosion environment R = 0.6	0.010		2.380	6.75687E+8	6.75888E+8
	Air R = 0.75	0.205		1.945	1.40588E+9	1.40581E+9
	Corrosion environment R = 0.75	0.025		1.590	4.25079E+8	4.24997E+8
4 (a/c=0.,15)	Air R = 0.1	0.370	1.67381	2.900	2.69699E+9	2.72121E+9
	Air R = 0.6	0.070		2.790	1.39655E+9	1.40455E+9
	Corrosion environment R = 0.6	0.010		3.070	6.80365E+8	6.87156E+8
	Air R = 0.75	0.220		1.990	1.41521E+9	1.41772E+9
	Corrosion environment R = 0.75	0.020		1.540	5.38525E+8	5.37327E+8
5 (a/c=0.1)	Air R = 0.1	0.330	2.18112	2.900	2.55968E+9	2.58262E+9
	Air R = 0.6	0.060		2.760	1.32074E+9	1.33582E+9
	Corrosion environment R = 0.6	0.010		3.140	6.31235E+8	6.56420E+8
	Air R = 0.75	0.200		1.870	1.25190E+9	1.25295E+9
	Corrosion environment R = 0.75	0.020		1.420	4.53023E+8	4.53771E+8
5 (a/c=0.4)	Air R = 0.1	0.440	1.89196	4.790	3.16376E+9	3.40914E+9
	Air R = 0.6	0.080		4.440	1.65990E+9	1.75638E+9
	Corrosion environment R = 0.6	0.010		4.990	8.17629E+8	9.16876E+8
	Air R = 0.75	0.260		2.660	1.64067E+9	1.66308E+9
	Corrosion environment R = 0.75	0.030		1.950	5.36172E+8	5.44873E+8
6 (a/c=0.1)	Air R = 0.1	0.445	1.78779	3.960	7.24979E+9	7.25430E+9
	Air R = 0.6	0.090		3.880	2.27052E+9	2.27290E+9
	Corrosion environment R = 0.6	0.010		4.090	8.91654E+8	8.96233E+8
	Air R = 0.75	0.270		3.230	4.78990E+9	4.78888E+9
	Corrosion environment R = 0.75	0.030		2.780	8.63784E+8	8.61696E+8
6 (a/c=0.4)	Air R = 0.1	0.580	1.97500	4.990	9.50509E+9	9.58667E+9
	Air R = 0.6	0.115		4.990	2.95614E+9	2.98480E+9
	Corrosion environment R = 0.6	0.015		4.990	1.12263E+9	1.14845E+9
	Air R = 0.75	0.345		4.620	6.28671E+9	6.29350E+9
	Corrosion environment R = 0.75	0.040		3.920	1.08600E+9	1.08585E+9

From the results, obtained in the table, its seen that corrosion environment greaten influences the durability of the investigated structural element and such trend is observed for all the considered cases as well as for all modeled crack like defects.

It should be noted that for engineering recommendations its necessary to select from the given values of N^* and N_{fc} the least value that will be criterial value for assessment of considered structural element durability.

CONCLUSIONS

On the basis of experimental research criterial value of SIF for the steel 3, used for manufacturing of clamp-forming machine frame angle 45×45×5 mm is determined. Applying analytical relations for SIF characteristics value of crack like defects length, that may take place in the considered frame construction are calculated. Practical calculations for assessment of the given object durability are designed with modelled crack like defects of various form and geometry on the base of load cycles number.

On the other hand it was determined that each case of «material-environment» system and each type of crack like defects requires separate study, since the impact on durability of structural element of any parameter and increase of cracks is felt. Also, given results give the opportunity to carry out the express-analysis of residual resource of engineering construction that works as in the atmosphere and in aggressive environments.

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