Studying the Possibility of the Destruction Control of Machine Parts by Applying Directed Sharp Concentrators

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Abstract: The problem of preventing fatigue failure is highly relevant in all branches of engineering, especially for such structures, the failure of parts in which can lead to accidental effects. But this problem is becoming incredibly important recently due to the need of intensively increasing of the service life and reliability of machines during operation. As a rule, particular attention is paid to the study of the areas in the details with the sharp change in share and size, in which local zones with stress changes exist, leading to the appearance of cracks and, ultimately, to the destruction of these parts. The most extensive research in this area has been performed on various samples. However, the obtained results do not allow to describe the stress state and the stress concentrators with the help of analytical dependencies, especially in the case of sharp cuts and when superposition of stress concentrations, because they do not take into account the scale factor, state of material, etc. In particular, sharp depressions and small cuts (scratches), which do not reduce the strength of the material according to their concentration coefficients, are of special scientific interest, as well as the development of methods for controlling the destruction process. The usage of numerical methods (in particular, the finite element method) significantly expands the possibilities of analysis of stresses in the concentrators of samples and parts. However despite the results achieved, it is considered that it is still difficult to obtain a satisfactory solution for the stress field in the part's concentrator, taking into account local design features. The article examines the stress state and fatigue resistance under bending loading of the on specially developed physical models of a crankshaft produced with different technologies, having a sharp decrease in the radii of fillets. Models with applied sharp concentrators of various geometries were tested. The performed studies allow to conclude that research in this direction is promising, since new knowledge about stress concentrators and their effect on the fatigue strength of full-scale parts can open up new reserves for increasing the fatigue strength of full-scale structures.

Keywords: Stress, Fatigue, Concentrator

1. Introduction

The study of phenomena that occur in stress concentrators, has always received great attention. Thus, Neuber, on the basis of the equations of the linear theory of elasticity, proposed the calculation of stresses at the bottom of a deep groove of a cylindrical rod. It was assumed that the stress concentration depends only on the curvature at the bottom of the groove, and, therefore, the shape of the groove in the rest of it does not significantly affect the stress distribution. The latter made it possible to consider a number of problems on the equilibrium of a body bounded by the surface of a one-sheet hyperboloid of revolution at various positions of the main vector and the main moment of external forces on the end surfaces of a deformed body loaded along a lateral surface [1]. With a strict solution of the problem under consideration, when the radius of rounding at the bottom of the undercut tends to an infinitely small value, the stresses in this place will tend to an infinitely large value. It becomes obvious that the resulting solution is in conflict with the basic assumptions on which it was obtained. Hooke's law loses its force in the field of high stresses. In addition, if the stresses are large, then the deformations are also large, and therefore it is not possible to linearize neither the equilibrium equations, nor the forms equations expressing the deformations through displacements. It should also be noted

that in places of strong sharpening, not only stresses, but also their gradients are infinitely large. Such a change in the stress field can occur within a single crystal grain, and therefore the validity of the assumption of homogeneity and isotropy of the material is violated [2, 3]. As shown by experimental studies, the resultant of normal stresses in the cross section of the concentration zone turns out to be 20-40% less than the external load. This is explained by the impossibility of applying to such zones the notion of independence of the action of normal and tangential stresses [4].

In this regard, it has been suggested that the destruction of a machine part should begin not directly in the areas of concentration of normal stresses, but in the adjacent zones of transition from stress or compression deformations to deplanation shear deformations. However, all these approaches need in extensive experimental confirmation [4].

To partially eliminate the contradictions existing in solutions similar to those proposed by Neuber, a certain dimension was introduced at the bottom of the groove [2]. As a result, the calculated stresses in the concentrators in some cases correspond to the experimental data [6, 7]. The above solutions were obtained by Peterson et al. [8-10] and they are widely used in engineering practice [11, 12].

The growing trends of increasing the reliability of calculations led to a significant increase in requirements for analytical solutions. Thus, it is not always possible to describe the shape of an undercut with hyperbolic or elliptical coordinates [13]. The state of the material, the scale factor, etc. are also not fully taken into account as a rule [14-17]. Therefore, a statistical generalization of the calculated and experimental data on studies of stresses and strains in concentrators of specimens and machine parts seems to be very useful. Sharp depressions and small incisions (scratches), which do not reduce the strength of the material according to their concentration coefficients, can be considered as an exception, which is of particular scientific interest [8, 18].

It is believed that as a machine part is loaded, the notch geometry can change significantly, and in the case of plastic material, fluidity quickly occurs. Such situation makes it difficult to analyze due to the influence of many factors at the same time. Therefore, the stress concentration in this case is estimated by the total effect of the scale factor, the cross-sectional shape and the type of loading on the change in the fatigue limit. However, the patterns of fatigue failure lead to satisfactory results when the radius of rounding of the bottom of the concentrator does not exceed 0.1-0.6 mm, with a greater value for steels with lower strength and non-ferrous metals. A further change in the radius leads to the appearance of other patterns of destruction. Thus, the fatigue limit expressed in maximum normal stresses and the effective stress concentration coefficient do not depend on decrease in the notch radius below the critical, but the theoretical stress concentration coefficient increases accordingly. It should also be noted that the critical radius depends on the grain size, the depth of the notch of the sample, etc. [19].

Despite these difficulties, the obtained dependences of endurance limits of specimens with extremely sharp cuts

indicate the usefulness of studying this effect on real details with actually applied materials and manufacturing techniques, as well as the conditions of their loading.

2. The Study of the Stress State in the Crankshaft's Concentrators Using the Polarization-Optical Method

The usage of numerical methods does not exclude the need for experimental studies of the stress state yet. The study of the stress state with a sharp decrease in the shaft's fillets was studied using the polarization-optical method on specially models made of epoxy resin during hot curing (Figure 1).

It is known that the polarization-optical method is based on a proportional change in the refractive indices of light of an optically sensitive material in the process of its loading. The method allows to obtain the parameters of the stress state over sections and to conduct measurements in areas of strong stress concentration. This method has a particularly high accuracy in the study of concentrators in plane-elastic models (the error of the method is ~ 5%).

Production of models, stabilization of material properties, direct measurement with the analysis of data was performed by known methods. The models were loaded on a special device by a bend.

Isochrome paintings were obtained in monochromatic sodium light, isoclines - in white light. To improve the accuracy of the model was loaded gradually.
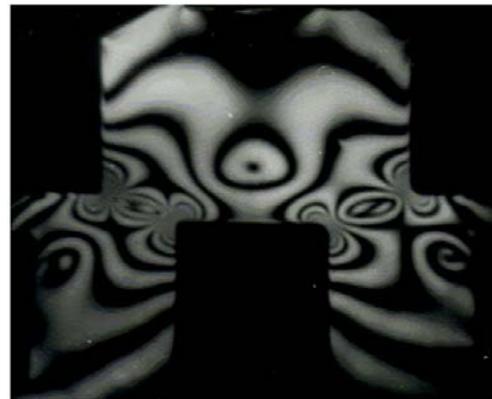
Figure 1. *Isochrome distribution obtained on polarization-optical models under the action of bending.*

3. Development of Physical Crankshaft's Crank Model

Ensuring the strength of structural elements is still determined mainly by field tests. It is considered very useful to obtain the dependences of fatigue strength not only on the characteristics of the applied force cycle, material, shape, and technology of the part, but also from factors that take into account its interaction with adjacent structures. However, such studies are very costly, and in some cases simply impossible. Therefore, scientific research is often limited to

the results of testing parts in bench loading conditions. Consequently, the development and implementation of original solutions cause considerable difficulties. These issues are to a certain extent solved by modeling.

To study the fatigue resistance of the crankshaft full-scale design, a model of its crank has been developed (see Figure 2).

The model is made of the corresponding steel. The working section includes partially made main and crank necks, the axes of which are displaced relative to each other by the radius of the crank R, as well as the fillets r of the neck transition to the cheek. The cross-sectional dimensions of the plate section between the protrusions are selected similar to the cross-sectional dimensions of the crankshaft cheeks. With an appropriate choice of the size of the stresses in dangerous sections of the model and the crankshaft can be the same in magnitude and distribution pattern.

Figure 2. Model of a crankshaft's crank.

In this case, the maximum tension value occurs in the neck overlap area. Other design may lead to an unjustified increase in the weight of the models or to an existing change in the distribution of stresses in the fillets.

4. Analysis of the Results Obtained

4.1. Study of the Stress-Strain State in Models with Concentrators having a Small Radius of Curvature

To ensure the necessary reliability of crankshafts, the transition areas of the necks to the cheek are usually sought to perform using increased radii or describe them with several radii, with special curved lines. Then these places are ground, polished or subjected to other types of processing and hardening. The latter is achieved both by increasing the mechanical characteristics of the material, combining these characteristics with the induction of residual compressive stresses, and by creating conditions for the deceleration of developing cracks or driving them into the region of low stresses.

The studies were based on the established fact that the fatigue strength no longer depends on its sharpness for all stress concentrators with radii r $<$r$_{crit}$ [19].

The experiment was conducted using the polarization-optical method. Models of epoxy resin, one of the fillets of which has been made in the form of a sharp transition at an angle of 90° with a radius of 0.18 mm, and the second - with a radius of 4.0 mm (Figure 1), were loaded with a bend. As shown by direct measurements, the isochromes in the small-radius fillets "pressed" to the edge of the model due to the significant stretching of the isochrome, forming the core in the overlap (Figure 3).

Bench tests of the fatigue resistance of crankshaft crank models with different fillets radii were performed. As a result, it was confirmed that the position established in engineering practice that, with a decrease in the radius of the fillets, the stresses in the crankshaft concentrators increase. However, when making a transition with the fillets radii of 0.1... 0.2 mm under loading, the nature of the destruction of the model is changing (the fatigue failure did not begin with the fillet, but from the end faces similar to a plate (see - Figure 4).

The radii of fillets less than critical one, more dependent on cheek width.

In this case, the endurance limit of models, having the fillets radii less than the critical one, is more dependent on cheek width.
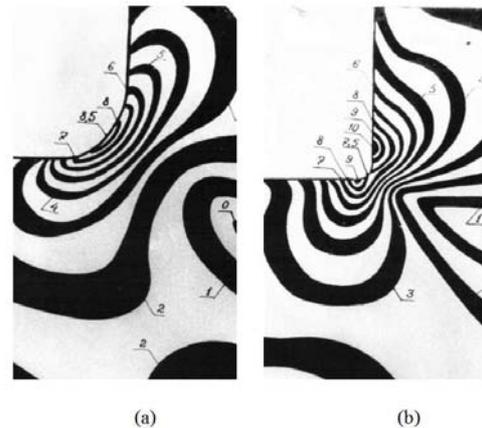

Figure 3. Isochromes distribution in crankshaft models under bending action: (a) with a fillet radius r = 4.0 mm; (b) with a fillet radius r = 0.18 mm.

At the same time it is necessary to agree with the opinion existing in the literature that when assessing the performance of a structure, reducing the radii of concentrators requires a more complete account of the state and quality of materials, the scale factor, etc.

4.2. Influence of Technology for Manufacturing Crankshaft Models

Evaluation was carried out on the change in fatigue resistance of full-size crank models. Models were obtained from forgings made in the Minsk Gear Plant from a steel circle Ø 110 mm, steel 45X (0.40% C, 0.65% Mn, 0.80% Cr). The forgings were manufactured using a specially designed die, which allows the arrangement of fibers to be closer to real structures, and a general-purpose crank press. The billets were heated by the induction method and in flame furnaces similar to the furnaces for heating the crankshaft billets.

The models were kept during heating in combustion furnaces for 80 and 120 minutes. The last value of the crankshaft's forging specification is considered to be the maximum allowable value. The temperature of the beginning of forging of the models was taken as 1000°and 1200°C, which practically corresponds to the real temperature of the beginning and end of forging of crankshafts. The models were made in the Minsk Motor Plant both from forgings that had only been normalized or normalized and improved after forging, and not heat-treated. During normalization, the forgings were heated to 900 + 20°C, then held in a furnace for 120 min and cooled in air. Thermal improvement provided for quenching: heating the forgings at 840 + 10°C, holding for 90 minutes and cooling in water, and then - high tempering: heating to 660°+ 20°C, holding for 120 minutes and cooling in air. Subsequently, the forgings were machined. The finished models were tested for hardness, fatigue resistance, and the microstructure of the material was determined. The test results for full-size crank models with a fillet radius of 4.0 mm are shown in Table 1.

Construction of fatigue curves (Figure 4) was carried out using the least squares method, the fatigue limit was determined from the expression [ ]

$$\overline{\sigma_{-1}} = \sigma_0 + d\left(\frac{\Sigma i \cdot n_i}{N} - 0,5\right) \qquad (1)$$

where d is the interval between load levels, i is the ordinal number of the load level, σ_0 is the value of the initial loading, n_i is the number of failures at level i, N is the smallest of the numbers of failure and non-failure at level i.

It has been established that the smallest resistance to fatigue fracture of models (1 250 Nm) is obtained after heating the blanks in a combustion furnace up to about 1 200°C and holding them longer than the standard time by 120 minutes at a forging temperature of 1 200°C. Application of normalization for such forgings does not lead to a change in the fatigue limit of the models, and the subsequent improvement increases the fatigue limit by about 8%.

The standard holding of the blanks in the furnace when heated to 1200°C provides the endurance limit for models made of non-heat-treated forgings by 16% more compared to their holding 120 min higher than the standard, which is 1 450 Nm. As it turned out, the normalization of such forgings reduces the fatigue resistance of the models to 1,350 Nm, and the subsequent improvement increases it to the initial value of 1,450 Nm.

Reducing the forging temperature to 1,000°C with standard holding of the blanks in the furnace reduces the resistance to fatigue fracture of non-heat treated models to 1,350 Nm. However, normalization followed by improvement increases the fatigue strength to 1,450 Nm, which corresponds to the optimal forging parameters. It should be noted that overexposure of the workpieces with such heating for 80 minutes provides the fatigue resistance of non-heat treated models equal to 1,450 Nm. Normalization of the forgings reduces this value to 1,350 Nm. No effect of subsequent improvement on the fatigue strength of models made from the corresponding forgings was found.

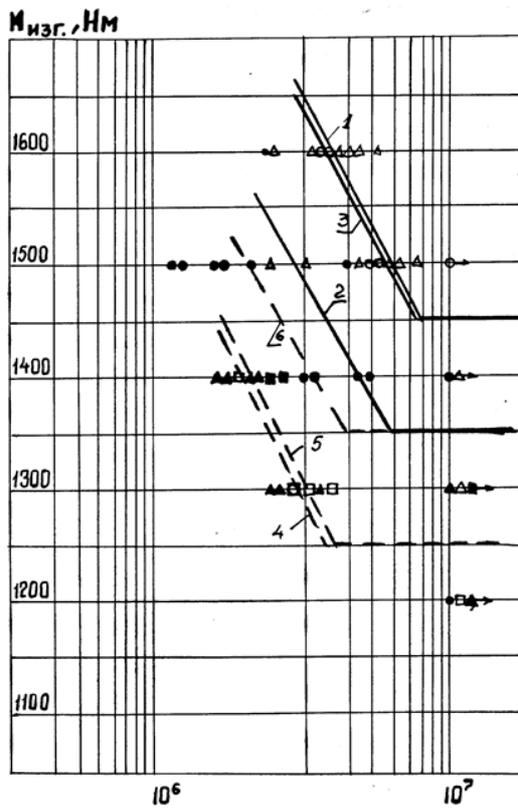*Table 1. Effect of heat treatment on the fatigue resistance of crank models.*

Method of blanks heating	Heating time of workpieces	Forging start temperature,°C	Heat treatment of forgings	Hardness, HB	Endurance limit, Nm
Flame oven	60	1 200	untreated	255…262	1 450
Flame oven	60	1 200	normalization	202…207	1 350
Flame oven	60	1 200	normalization + improvement	277…286	1 450
Flame oven	60+120	1 200	untreated	262…269	1 250
Flame oven	60+120	1 200	normalization	207…223	1 250
Flame oven	60+120	1 200	normalization + improvement	269…286	1 350
Flame oven	60	1 000	untreated	293…293	1 350
Flame oven	60	1 000	normalization	207…217	1 250
Flame oven	60	1 000	normalization + improvement	286…293	1 450
Flame oven	60+80	1 000	untreated	248…262	1 450
Flame oven	60+80	1 000	normalization	229…233	1350
Flame oven	60+80	1 000	normalization + improvement	262…269	1 350
Induction heating		1 200	untreated	241…248	1 350
Induction heating		1 200	normalization	229…235	1 450
Induction heating		1 200	normalization + improvement	262…269	1 450
Induction heating		1 000	untreated	235…241	1 350
Induction heating		1 000	normalization	192…196	1 450
Induction heating		1 000	normalization + improvement	212…226	1 350

Induction heating of blanks in the temperature range from 1000 to 1200°C does not affect the fatigue strength of non-heat treated models. However, this strength is 7% less than in the case of optimal heating conditions for billets in a combustion furnace and amounts to 1,350 Nm. It is characteristic that normalization of forgings made in the mentioned range of billet heating temperatures increases the fatigue resistance of the models up to 1,450 Nm. However,

the application of normalization with the subsequent improvement of forgings, the workpieces of which were heated to 1000°C, lead to a decrease in the endurance limit to the initial value (1,350 Nm). In the case of heating the workpieces at 1200°C, the effect of the mentioned heat treatment on the endurance limit was not found.

Thus, normalization of 45X steel forgings, the blanks of which were heated in flame furnaces during the standard time

and manufactured in the forging start temperature range of 1000... 1200°C, leads to decreasing of the fatigue resistance of the models compared to non-heat treated ones. The use of normalization followed by thermal improvement increases the endurance limit to the initial value obtained under optimal heating conditions for the workpieces.

Figure 4. The effect of heat treatment on the fatigue resistance of crankshaft models: 1 - heating time in a combustion furnace 60 min, heating temperature - 1200°C;

2 - heating time in a combustion furnace 60 min, heating temperature - 1200°C, normalization; 3 - heating time in a combustion furnace 60 min, heating temperature - 1200°C, improvement; 4 - heating time in a combustion furnace 60 + 120 min, heating temperature - 1200°C; 5 - heating time in a combustion furnace 60 + 120 min, heating temperature - 1200°C, normalization; 6- heating time in a combustion furnace 60 + 120 min, heating temperature - 1200°C, improvement.

The use of over-standard holding of blanks in flame furnaces, allowed for forging crankshafts (80 min) and more (120 min), ultimately reduces the resistance to fatigue failure of models, which could not be restored using normalization, as well as normalization with subsequent improvement. At the same time, changes were observed in the structure of the material: for improved models - sorbitic, for normalized - ferrite-pearlite.

The endurance limit of models, the workpieces of which were subjected to induction heating and heating in combustion furnaces at respectively optimal conditions, turns out to be practically the same. However, in the case of induction heating and in the process of manufacturing full-scale structures, it seems possible to do only by normalizing their workpieces.

4.3. Bench Tests of Models with Concentrators with a Small Radius of Curvature

The models with sharp concentrators of various geometries applied in the shaft journal were tested when loaded by pure bending.

The conducted studies allow to draw a conclusion about the prospects of research in this direction, since new knowledge about stress concentrators and their effect on the fatigue strength of full-scale parts may open up new reserves for increasing their fatigue strength.

This may indicate that under certain manufacturing conditions, the cheeks are deformed like a plate and, therefore, their ribs become already dangerous stress concentrators (Figure 5).
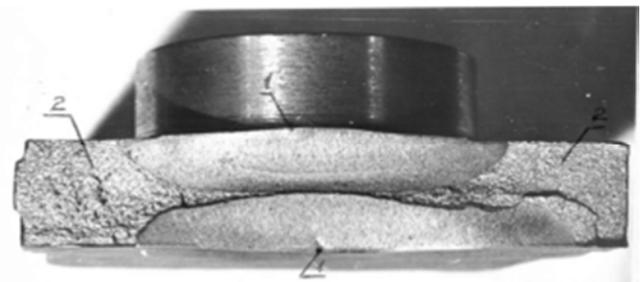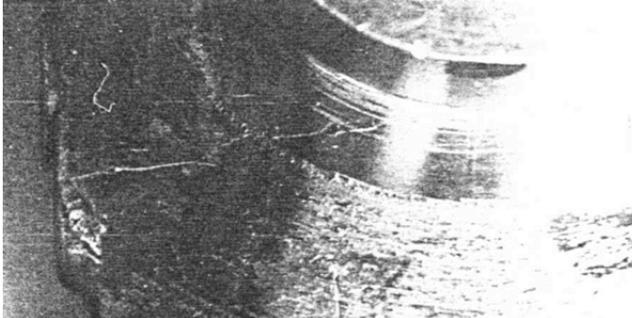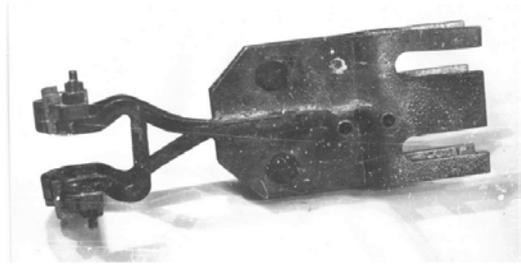

a)
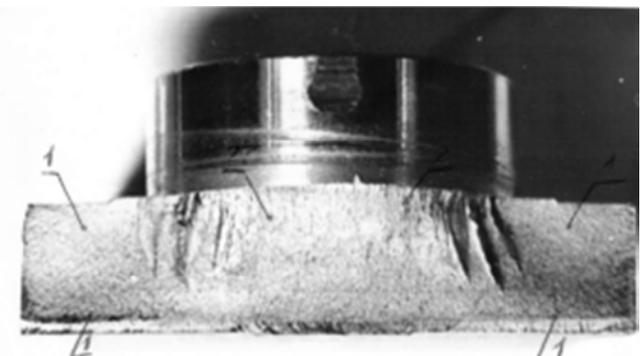
b)

Figure 5. Destruction of models: (a) with a fillet radius r = 4.0 mm (1 - the beginning of the appearance of a crack; 2 - the final stage of fracture); (b) with a fillet radius r = 0.15 mm (1 - the beginning of the appearance of a crack; 2 - the final stage of fracture).

In this case, the endurance limit of crankshaft models made using the proposed solutions to a greater extent, compared with existing designs, depends on the width of the cheeks. Therefore, in the case of the practical implementation of such solutions, significant reserves for increasing the fatigue strength can be incorporated in the optimal choice of the width of the cheeks, as well as strengthening of the peripheral sections of the cheeks using local hardening. Despite the indicated differences in the distribution of maximum stresses

and fracture processes, the endurance limit of models with a fillet radius of 4.0 and 0.15... 0.6 mm is practically the same. Therefore, 0.4... 0.6 mm can be taken as the critical radius of a fillet. This nature of the destruction makes it relevant to use local hardening (Figures 6, 7) in order to increase the fatigue resistance of the models. The studies of models subjected to local hardening of the cheeks with various technological conditions were carried out (Table 2).

Figure 7. *Inductor for local hardening of crank models.*

In addition, of considerable interest is the creation of concentrators that are the source of directional crack propagation.

The conducted studies allow to draw a conclusion about the prospects of research in this direction, since new knowledge about stress concentrators and their effect on the fatigue strength of full-scale parts may open up new reserves for increasing detail's fatigue strength. Nevertheless, it is evident, that final conclusion on application of such solutions must be done only after investigation of summary effect of stresses concentration, conditioned due to the full complexity of the actual design.

Figure 6. *Crack arising during high-cycle loading of a model with a critical fillet radius and local hardening.*

Table 2. *Effect of fillet radius on fatigue resistance of full-size crankshaft crank models.*

№№	Radius of crankshaft filet, mm	Ultimate bending moment of full-size models of the crankshaft crank (cheek width - 120 mm), Nm	Ultimate bending moment of crankshaft crank models with a cheek width of 90 mm, Nm	Ultimate bending moment of crankshaft crank models with a jaw width of 120 mm and local hardening, Nm
1	5.9 … 6.2	1 750	1 650	2 350
2	3.7 … 4.1	1 550	1 450	2 450
3	1.9 … 2.0	1 150	950	2 550
4	0.4 … 0.6	1 450	850	2 750

5. Conclusion

As a result of the studies carried out, it was found that with a decrease in the fillets radii of the crankshaft crank models, the maximum normal stresses increase, and the endurance limit decreases, which corresponds to established practice. In the case of the transition from the cheek to the neck at an angle of 90° with a radius of less critical one, the stresses are reduced, which can be explained by the strong influence of the local deplanation of the sections of dangerous sections. The studies performed allow us to conclude that research works in this direction are promising, since new knowledge about stress concentrators and their effect on the fatigue strength of full-scale parts can open up new reserves for increasing detail's fatigue strength. Nevertheless, final conclusion on application of such solutions must be done only after investigation of summary effect of stresses concentration, conditioned due to the full complexity of the actual design.

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