Modeling for manufacturability of the design of parts with concentrators by the method of photoelasticity

Elmar Yagyaev¹, Leonid Shron² and Dmitriy Meniuk²

¹Crimean Engineering and Pedagogical University the name of Fevzi Yakubov, per. Uchebnyj, 8, Simferopol, 295015, Russian Federation
²Sevastopol State University, Universitetskaya st., 33, Sevastopol, 299053, Russian Federation

*elmar1875@gmail.com

Abstract. The article provides a methodology for the experimental determination of the concentration coefficients ασ and the gradients of the principal stresses. The effectiveness of the experimental method of photoelasticity is shown for studying the stress-strain state of parts of complex shape in the presence of stress concentrators, as well as for solving problems of brittle strength by methods of linear fracture mechanics.

1. Introduction

Increasing the requirements for the reliability of the operability of handheld power tools requires the development of a methodology for modeling the operation of parts, taking into account their design features and loading conditions. It should be noted that for such parts, the zones of the beginning of machine parts’ destruction are the zones of stress concentrations, for example, a jigsaw rod (see Figure 1).

The stress concentration has the greatest effect on the bearing capacity of machine parts and structural elements under alternating loads, under conditions of a corrosive environment, or in the embrittled state of the material. Despite the fact that stress concentrators significantly affect the strength parameters, the methods for calculating this effect are still not perfect enough, and the available data on the experimental values of the stress concentration coefficients are rather contradictory, and there is practically no information on the gradients of the first principal stress and the difference in principal stresses [1]. In this regard, the urgency of studying the influence of the geometrical parameters of the concentrator on the values of ασ and and the creation of reliable methods for their determination is obvious.

To date, extensive information has been accumulated on the effect of geometric stress concentrators, obtained by calculation and experimental methods [1–7]. The available data convincingly indicate a significant concentration of stresses in products with structural concentrators and its significant effect on their performance. At the same time, we have to admit that in the issue under consideration, many questions remain unclear. As already noted, the data of various authors on the degree of influence on the stress concentration of certain geometrical parameters of concentrators do not coincide, and sometimes contradict each other.
The purpose of the paper is to improve the design of critical parts of the power tool on the basis of reliable information about the stress state in the concentrator zone and methods of strength calculation using the example of a jigsaw rod.

2. Materials and methods
Stress concentration factors are determined by a variety of methods, including direct measurements with strain gauges, the use of elastic theory methods for finite element modeling, and the method of photoelasticity.

The study of stresses by the method of photoelasticity is not only a widespread method for studying the stress-strain state at the top of a concentrator, but also the distribution of stresses in its vicinity. This will make it possible to determine not only the stress concentration factors, but also the change in the stress-strain state around various geometric concentrators [6, 7]. The method is based on the use of birefringence of many transparent materials when they are deformed under load. An analysis of the interference fringes formed when deformed models of optically active materials are illuminated with polarized light makes it possible to qualitatively and quantitatively characterize the stress distribution in the model and to calculate the main parameters of the stress concentration. The photoelasticity method makes it possible to study the change in the stress-strain state on models, repeating all the geometric features of real parts and the conditions for their loading.

The part – the jigsaw rod – is made of 20Cr4 steel; the workpiece is obtained by stamping from sheet steel. The workpiece is quite simple in configuration; the processing of flat surfaces is not difficult. At the same time, grinding of the lateral surfaces of the rod with regulated values of four radii in the zone of the concentrator k is non-technical from the point of view of machining (see Figure 2 a). This process in the basic version required constant dressing of the grinding wheel, when processing the side surfaces, in order to form the required radii in the zone of the concentrator k. In this regard, it is necessary to conduct studies that will allow changing the concentrator zone without reducing the efficiency, which will increase the manufacturability of the design.

The studies were carried out by the method of photoelasticity. For this, plates with a thickness of $t = 4$ mm were made from an optically active material based on ED-6M epoxy resin. When making a radius of conjugation, in order to avoid residual stresses from "burning" in the process of drilling, the holes in the models were made on a vertical drilling machine with a manual drive and a spring feed mechanism, which ensured a low cutting speed and smooth feed. Oil was constantly fed into the cutting zone. To prevent chipping along the generatrix of the hole, at the time of entry and exit of the drill, pads made of organic glass were used.

First, in the plate, a U-shaped notch was made with a radius at the apex $\rho = 0.5; 1; 1.5; 2; 3; 4; 5$ mm and the fringe value of the model material was determined from the known values of the stress concentration coefficients $\alpha$ for such notches given in [8].

After testing the plates with a U-shaped cut, rod models were sequentially cut out of them (Figure 2 b).
This procedure for producing models made it possible to reduce the experimental errors associated with the spread of the optical properties of the material and the effect of residual stresses from mechanical processing. The study of the stressed state was carried out on a polariscope with a working field of 125 mm, in which sodium lamps serve as a source of monochromatic light. The distribution of the difference between the principal stresses, which is necessary to determine the concentration coefficients and the gradients of the difference between the principal stresses, gives a picture of isochromes, which was obtained by the method described in detail in [6, 9].

It is known from the theory of elasticity that the stress distribution in a plate under conditions of plane deformation or generalized plane stress state does not depend on the elastic constants of materials. Therefore, if it is possible to find the stress distribution for a plate (part) made of some isotropic material, then these results can be accepted for a model made of another isotropic material, provided that in both cases the magnitude, location of external forces and dimensions of the models are the same. In addition, optically active materials follow Hooke's law within fairly wide limits.

To determine the concentration coefficients $\alpha_\sigma$ and the maximum gradients of the first main stress $G_\sigma$, and the difference of the main stresses $G_\sigma (\sigma_1 - \sigma_2)$, it is necessary to know the stress at the top of the concentrator. The value of the maximum stress $\sigma_{1\text{max}}$ depends on the accuracy with which this order is determined.

The distribution of the difference in principal stresses in the concentrator zone is well described by an exponential function of the form:

$$\sigma_1 - \sigma_2 = a e^{-\epsilon r},$$

where $r$ is the distance from the top of the concentrator to the center of the isochromic fringe; $e$ is a base of natural logarithms; $a$, $c$ are coefficients determined by the least squares method.

Since $\sigma_2 = 0$ on the free surface, $\sigma_1$ will take on its maximum value.

The stress concentration factor $\alpha_\sigma$ is determined by the formula:

$$\alpha_\sigma = \frac{\sigma_{1\text{max}}}{\sigma_n},$$

where $\sigma_{1\text{max}}$ is the maximum stress at the top of the concentrator; $\sigma_n$ is nominal stress.

The nominal tensile stress is:
where $P$ is the load; $t$ and $b$ are the thickness and minimum width of the model, respectively.

To determine the value of the stress gradient at the top of the concentrator, we differentiate the expression with respect to $r$. In [6], the value of the gradient at the top of the concentrator is called the maximum gradient. The maximum gradient value is

$$
G_{(\sigma_1-\sigma_2)} = \left[ d\left( \frac{ae^{-cr}}{d}\right) / dr \right]
$$

The calculations usually use the maximum relative gradient $\bar{G}_{(\sigma_1-\sigma_2)}$, which is equal to:

$$
\bar{G}_{(\sigma_1-\sigma_2)} = \frac{G_{(\sigma_1-\sigma_2)}}{\sigma_{\text{макс}}},
$$

The approximate value $G_{(\sigma_1-\sigma_2)}$ can be determined from the expression

$$
G_{(\sigma_1-\sigma_2)} \approx \frac{\Delta(\sigma_1-\sigma_2)}{\delta},
$$

where $\Delta(\sigma_1-\sigma_2) = G_0$ is the fringe value of the model material; $\delta$ is the distance between two isochromes in the direction of the gradient, the maximum value of which is determined at the top of the concentrator $r = 0$.

3. Result and discussion

The obtained experimental values of the stress concentration coefficients give good quantitative agreement. The deviation of individual points does not exceed 5%. The analysis of the results obtained and calculations by the method [7] showed that the optimal radius of conjugation would be 1.5 mm with a weakening of the cross-section of 0.5 mm without reducing the efficiency of the rod. This made it possible to obtain a conjugation zone in the sheet stamping operation, which increased the manufacturability of the part and, as a result, excluded the operation of constant radial dressing of the grinding wheel.

4. Conclusion

(1) Application of the proposed method for determining the concentration coefficients and stress gradients made it possible to obtain reliable values of the concentration coefficients and stress gradients. In turn, this made it possible to use the calculated estimate of fatigue resistance in the interpretation of V.P. Kogaev to determine the optimal parameters of the concentrator.

(2) On the basis of the results obtained, the design of the rod has been improved due to the formation of the geometric parameters of the concentrator at the operation of sheet stamping, which in turn made it possible to exclude the operation of dressing the radius of the grinding wheel and to ensure the reliability and durability of the operation of the power tool.

5. References

[1] Shron L B 1995 Recommendations for the assessment of stress concentration in welded joints

Scientific-technical collection Sevastopol SevGTU 3 39–46

[2] Aleksandrov A Ya and Akhmetzyanov M Kh 1973 Polyatization-optical methods of mechanics of a deformable body (M.: Nauka) p 576

[3] Albaut G N, Baryshnikov V N, Pangaev V V, Tabanyukhova M V and Kharinova N V 2003

Determination of stress concentration factors in non-standard problems by polarization-optical methods Physical Mesomechanics 6 91–5
[4] Sedov A A, Doluda A O and Klimov M A 2016 Assessment of local stresses and deformations in parts with stress concentrators and analysis of damage under random cyclic loading according to various models of damage summation *Bull. of the Volgograd State Technical Univ.* 9(188) 69-74

[5] Tabanyukhova M V, Kharinova N V 2003 Stresses and their concentration coefficients in plates with rhombic cutouts *Proc. of NGASU Novosibirsk* 154-7

[6] Shron L B, Googe S Yu, Bogutskiy V B and Gordeeva E S 2016 Concentrators and stress gradients in welded joints with fillet welds *Sci. notes of the Crimean Engineering and Pedagogical University* 1(51) 118-23

[7] Kogaev V P 1977 *Strength calculations at stresses of time variant* (M.: Mechanical Engineering) p 232

[8] Peterson R E 1977 *Coefficients of stress concentration* (M.: Mir) p 302

[9] Shron L B, Bogutskiy V B and Yagyaev E E 2015 Analysis of the peculiarities of stress concentrators in the zones of initiation of fatigue cracks in joints with fillet welds *Sci. notes of the Crimean Engineering and Pedagogical Univ.* 2(50) 109-16