Numerical Analysis of Fatigue Degradation of Screw Pump

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Abstract: - In this article numerical analysis of fatigue damage of screw pump is discussed. The process of fatigue degradation of the screw is example of fatigue crack growth in notched bar under biaxial loading. This biaxial loading consists from axial tension loading and torsion for one screw systems and in the case of machines with several screws the loading consist from bending and torsion. The fatigue process was studied using computational methods. The screw pump used in this study were made from two different alloys and the effect of various surface layers on the fatigue resistance was also studied. The theoretical model is in a good agreement with experimental results.

Key-Words: - Fatigue Life, Finite Element Analysis, Screw Pump, Smith–Watson–Topper Criteria

1 Introduction

In some injection moulding machines are screw-type plungers used to force molten plastic material into a mould cavity. This screw plunger is an example of screw pump. This screw is placed in a heating chamber. The principle of the machine can be described as follows [1,2,3]:

(1) The plastic granules (for example Thermoplastic resin pellets) is sprinkled in heated chamber, see Fig.1.

(2) The forces caused by rotating screw pushed granulate to the mold cavity.

(3) The high temperature in the chamber caused melting of plastic material.

(4) The melted material is injected in the mold cavity.

(5) The injected material solidifies in mold cavity.

The whole process can be described more detailed as follows. The thermoplastics is supplied for moulding typically in pelletised form [1,2]. This pellets are fed through a hopper into a heated chamber with a reciprocating screw. Due the high temperature in the chamber the connections between polymer chains are weakened and viscosity of plastic melt drops. The rotating screw delivers the melted material forward. The pressure forces caused by rotating screw   adding a significant amount of frictional heating. This frictional heating reduces the required heating time. The molten material collects at the in the volume known as a shot. This volume of material is used to fill the mould cavity. The gathered molten material is injected in the forming cavity.
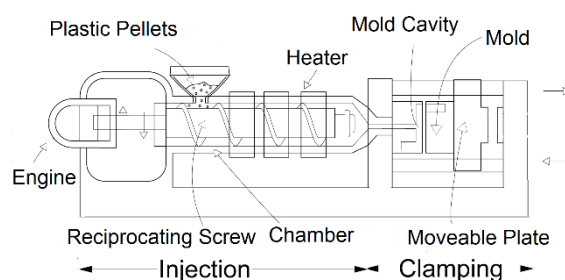

Figure 1. Principle of the injection moulding machine with screw pump.

The material in the cavity must be under the pressure until the material in the cavity entrance solidifies. The entrance in the cavity has small diameter compared to the other parts cavity. When the cavity is blocked by hardened material, the cold and stiff product is ejected from mould. This process is repeated many times and new pellets are dusted in the heating chamber. In mass production

this machines are executing thousands of work-cycles per day, month, year and fatigue damage of mechanical components, such as screw may occur. Therefore, it is important to study fatigue behavior of machine components [4,5,6,7]. Fatigue fracture of reciprocating screw in screw pump is serious breakdown. The fatigue failure of reciprocating screw is generally fracture of notched bar [6,7,8,9,10,11,12,13]. The prediction and calculation of fatigue life of notched specimen is different from the case of smooth specimens [9,10,11].

2 Fatigue Process Analysis

Now, when the principle molding machine was described, it is necessary to analyze fracture of screw occur. Some clogging of the working chamber with remains of blowout plastic appear, during prolonged repeating of the working cycle. This clogging (or additional friction caused by it) prevents movement of the screw. The screw is loaded by greater torque. If the machine used one screw in the working chamber, the screw is loaded with additional axial force (tension or compression according to the method of fixing the screw in machine). In the case of one multiple-axis technologies where carefully crafted screws rotate in opposite directions the individual screws are loaded by bending. In both cases, this additional loading caused by friction or clogging can caused fatigue damage in critical areas of mechanism. Typically, this is the place fastening the screw with a source of torque.

3 Material Characterization

Due to high working temperatures in the chamber, the parts of mechanism are manufactured from heat resistant steels. In this case high temperature steel 13CrMo44 was selected. Mechanical and physical properties of this steel are displayed in tables. Due to high working temperatures the creep characteristics must be considered in analysis.

D [mm]	$\sigma_{0.2\%}$ [MPa]	σ_T [MPa]	A [%]
up to 60	295	440-590	20
61-90	285	440-590	20
91-150	275	440-590	20

Table 1. Mechanical properties in hardened and tempered condition: where D is diameter of testing bar; $\sigma_{0.2\%}$ proof stress; σ_T is tensile strength.

100 ^{o}C	200 ^{o}C	300 ^{o}C	400 ^{o}C	500 ^{o}C
260	240	215	190	175
250	230	205	180	165
250	220	195	170	155

Table 2. Relationship between the $\sigma_{0.2\%}$ proof stress [MPa] and temperature [^{o}C].

Time [hours]	450 ^{o}C	480 ^{o}C	500 ^{o}C	520 ^{o}C	540 ^{o}C	560 ^{o}C
10^4	245	193	157	122	90	
10^5	191	133	98	77	46	

Table 3. 1% creep limit [MPa] vs. temperature [^{o}C].

Time [hours]	450 ^{o}C	480 ^{o}C	500 ^{o}C	520 ^{o}C	540 ^{o}C	560 ^{o}C
10^4	370	304	239	179	129	91
10^5	285	190	137	94	61	40
2.10^5	260	167	115	76	50	32

Table 4. Creep rapture temperature [MPa] vs. temperature [^{o}C].

4 Finite Element Model

For numerical analysis of stress-strain response to loading forces, the finite element models of screw were prepared. This models were created in Solid Works Software. For calculation two different type of model were prepared: (1) model of screw whole screw; (2) of semi-eliptical crack. This 3D-models were exported, meshed and solved to ANSYS software – see Fig.2. The model of crack was used for determination of stress-intensity factor along the crack-path [13,14].
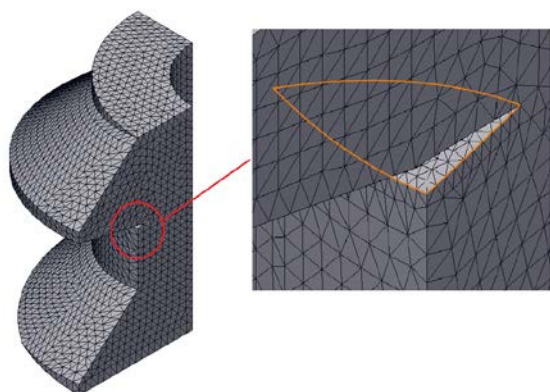
Figure 2. Meshed finite element model of crack at the bottom of the thread.

In the model (1) are analyzed two possible regions of fracture: bottom of bolt and the lubrication groove at the end of the shaft screw (at the bearings). The first model of screw is composed of 862.024 tetrahedral elements (type of element SOLID187). The model of crack on the bottom of the thread contains 542.028 tetrahedral elements and the model of the crack in the lubrication groove contains 482.068 elements. The need to use two different models for crack is given by different stress fields in their neighborhood. This differences in stress fields are caused by different profile of lubrication groove and the thread. Using a Finite Element Model of the thread the distribution of the von Mises stress at the bottom of the thread at the point maximal loading was calculated. The distribution of Von Mises stress at the bottom of the thread is shown at the Fig. 3.
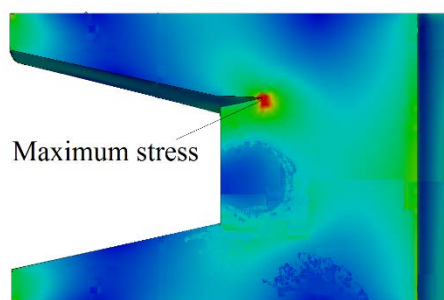

Figure 3. Von Misses stress in the thread and point of crack initiation.

5 Fatigue Life Calculation

The model of crack formation and propagation is based on Navarro approach [16,17,18,19]. In this model Paris-Erdogan law was used for description of propagation phase of fracture process. For further calculation must be the stress intensity factor SIF determined. The SIF at the forehead of crack is depending on the distance from the bottom of the thread or bottom of lubrication groove. In order to determine the stress intensity factor SIF the second finite element model was prepared. This model represents semi-elliptical crack. In the case of crack at the bottom of the thread, the crack grows along the edge of the helix, with an inclination 16.5°, which corresponds to the thread pitch, see Fig. 4.

In the case of crack in the lubrication groove is the inclination 0° (the cracking plane is perpendicular to the screw axis.

The elliptical crack is characterized by two axes *a* and *b*. The major axis b is tangential to the thread and the secondary axis a is perpendicular to the axis of the helix, respectively to the axis of screw

The determination of SIF at the front of the crack is based on *J*-integral method [20]. The SIF is a function of the crack length *a*. This relation between *ΔK* and length of crack *a* can be determined by repeated simulations. The length of the crack at the beginning of simulation is set to 5 μm. This length is apparently much smaller than the threshold length of crack for the propagation phase.
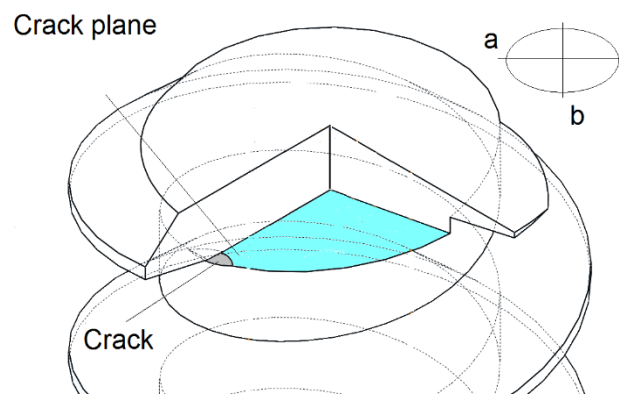

Figure 4. Crack geometry – Crack at the bottom of the thread.

The first option is to use Paris law. Assuming that the SIF depends on the crack length of each test analyzed, the law takes the form

$$\frac{da}{dN} = C\Delta K(a)^n \qquad (1)$$

where a is the crack length. This crack growth law is very simple but it has the disadvantage that it does not take into account the crack growth threshold, nor the behaviour of short cracks, making it unrealistic. Therefore, we consider the complicated relationship

$$\frac{da}{dN} = C\big(\Delta K(a) - \Delta K_{th,\infty}\big)^n \qquad (2)$$

This model uses a crack growth law for long cracks, i.e. introducing a threshold for long cracks, $\Delta K_{th,\infty}$. This law is more realistic but it does not show the behaviour of short cracks. This relationship is used to describe propagation phase of fatigue process.

For modeling of fatigue process is necessary to determine σ-N curve. It is obvious that the screw is under multiaxial loading. In this case the curve σ-N is expressed by parameters obtained from any multiaxial fatigue criteria.

In this work Smith–Watson–Topper criteria was chosen, because it was successfully used for description the fatigue behavior of processed metals under high temperatures (however, this temperature is under temperature typical for damage caused by creep).

The criterion defined by Smith et al. [21] is applied to materials in which cracks grow practically from the beginning in mode I. In this case the fatigue parameter, usually called Smith–Watson–Topper (SWT), is expressed as

$$SWT = \sigma_1^{max}\,\frac{\Delta \epsilon_1}{2} \qquad (3)$$

Where $\Delta\varepsilon_1$ is the maximum range of principal strain and σ_1^{max} is the maximum normal stress in the plane where the maximum range of principal strain is produced. The parameter is applied according to the following equation [18,19,21]:

$$SWT = \frac{\sigma_f^2}{E}\big(2N_f\big)^{2b} \qquad (4)$$

When the load cycle is not proportional, as occurs in fretting, it is more complicated to apply this parameter as a reset of the rotation of the principal directions. In this case, the SWT parameter is defined as the maximum, among all possible directions, of the product of the strain amplitude times the normal maximum stress [19,21]:

$$SWT = \Big(\sigma_{max}\,\frac{\Delta\epsilon}{2}\Big)_{max} \qquad (5)$$

In this way there is greater simplicity and the results turn out to be the same as those obtained with the first Eq. (4). It is useful used equivalent stress as damage parameter for this criteria.

The fracture mechanics is used for calculation of the number of cycles needed to propagate a crack to length a_{FR}. The length a_{FR} is the crack length at the time of final rupture. The following equation expresses the number of cycles [18,19,22,23]:

$$N_i\big(\sigma_{eq}, a\big) = N_{Total}\big(\sigma_{eq}\big) - \int_a^{a_{FR}} \frac{da}{C\Delta K^m} \qquad (6)$$

The subscript *Total* means the total number of cycles. The subtrahend in this equation is obtained from Paris-Erdogan law. Limits of integral are a – some crack length during fatigue process and a_{FR} – the length at the time of final rupture.

Another phase of the fatigue process is described by the curve a-N_P. The curve can be obtained by integration of growth law for any crack length to failure. Propagation stage of fatigue process can be described by the equation (7):

$$\frac{da}{dN} = C\left(\Delta K^m - \left(\Delta K_{th,Long}\left(\frac{a^{KT}}{a^{KT} + a_0^{KT} - d_0^{KT}} \right)^{\frac{KT}{2}} \right)^m \right)$$

where $\Delta K_{th,Long}$ is the growth threshold for long cracks, a_0 is the El Haddad parameter [24,25] and d_0 is the average distance to the first microstructural barrier.]. This parameter is defined by equation:

$$a_0 = \frac{1}{\pi}\left(\frac{K_{th,Long}}{\Delta\sigma_{FL}} \right)^2 \qquad (8)$$

where $\Delta\sigma_{FL}$ is the material fatigue limit.

The KT factor (threshold for long cracks $\Delta K_{th,Long}$, – see Eq. 7) is obtained from the Kitagawa–Takahashi diagram [25, 26].
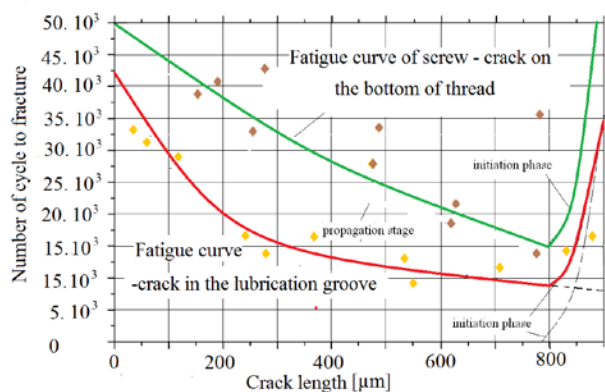
Figure 5. Theoretical curves of fatigue life for M = 400N. and temperature 300°C.

The complete fatigue life can be obtained by merging of *a-N$_i$* curve (number of cycles to length) and *a-N$_p$* curve (number of cycles to rupture), if both curves are known, they can be merged. Merged curves can be used for description of the entire fatigue life of specimen. This curve for total life of screw is shown in Fig. 5. From this picture is clearly visible, that the initiation life is much smaller than propagation life.

6 Results and Discussion

Theoretical fatigue curves for temperature 300°C are shown in Fig. 5. Also the fatigue experiments for V and U notched bars are shown in this figure. Bars with U notch have same behaviour as lubrication groove and V notched bars (angle 60°) corresponds to the bottom of thread. Results for The U-notched specimens are very closed to the model. Due to the higher von Misess stress in the lubrication groove it failure occurs most probably in this region of screw. The model of fatigue damage of screws pump is described in this paper. Comparison of experimental and theoretical model shows considerable agreement with reality.

Acknowledgment

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