Optimization and fast prototyping of polymer parts exposed to cyclic loading

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Abstract. Many mechatronic systems operate with parts made of polymers. This cost-effective solution is also easy to design. Manufacturing is trivial for producers who produce millions of parts. The solution is more complicated when the fatigue and loading is a significant factor. The paper describes the development of polymer parts that are loaded by cyclic operation. The number of cycles in a specific application can be around 1 million. The specific case also deals with a corrosion environment around these components. Gasses in the environment cause degradation of material and failure of parts made of specific polymers. This interaction limits the choice of suitable materials. The mechanism operates in two directions which define the opening of a valve and free turn. Two variants of elastic valves were analysed. Loading states were simulated by final element methods. Internal stresses and contact stresses were analysed. Results were compared with long-term test results. The material creep and other material properties define the function of elastic parts after thousands of cycles. The technology of mould fabrication was analysed considering simplification and general effectiveness of production. Prototype valves were printed by FDM 3D printer and tested. Prototype moulds were printed by SLA 3D printer, which produces high-temperature stable polymer. This procedure shows cost-effective prototype development and test procedures.

1. Introduction
The design of mechanical and electro-mechanical systems deals with many requirements. These products operate in varied environments, which can chemically affect the structure of used materials. It is a common problem of all types of materials like metals, polymers, composites, etc. Design of nontrivial structures requires system methodology, especially with loads, fatigue, and chemical stress. [1] Described electro-mechanical air switch operates with air which is relatively chemically neutral, but the complete application is situated in a corrosion environment. Polymers are relatively good corrosion resistant in general. This advantage defines suitable material. Long-term tests of producer show Polyamide PA6 and Polypropylene filled with glass fibres compatibility in the application. Mechanical properties of specified polymers are also suitable for allow loads. Jaziri’s team also refers about hysteresis of PET polymer in biomedical application [2]. These researches shows the crucial data about polymer parts applications. Test data of high speed tensile tests is also referred in this research [3]. Application of polymer parts in specific environments and loads is complex issue due to chemical resistivity and deformation characteristics of polymers in general [4]. Simulation and prediction with fast prototyping reflects producer requirements [5].
2. Polymers under cyclic loading

Polymer parts in mechanisms are loaded by many loading cases. Dimensions and shape design are produced concerning loading states, manufacturing technology, and costs. Cyclic loading is characterised by the number of loads: low cycle and high cycle loading state. Polymer parts under this loading change shape characteristics due to creep and hysteresis phenomena. Cyclic loading is also characterised by heat rise caused by dissipated mechanical force. [6] [7]

2.1 Hysteresis, creep, and fatigue

Base fatigue approach to the design of the cycle-loaded part is defined by Wohler’s theory [8] [9], which describes symmetric loading states. Smith’s theory and Haigh’s theory solve complex states with non-symmetrical stresses. [8]

Dang Van also deals with fatigue in multi-axial loading:

\[(t) + a \cdot p(t) \leq b\]  

(1)

where \(\tau(t)\) is maximal shear stress, \(p(t)\) is hydrostatic stress in time, and \(a\), \(b\) are material coefficients. Results show safety factor for \(10^7\) cycles. It is defined:

\[SF = \frac{b}{(\tau(t)+a \cdot p(t))_{max}}\]  

(2)

The Woehler theory describes fatigue behaviour with high cyclic loading states. This theory states the S-N curve. The critical state and number of cycles are dependent on the curve. It shows a limit number of cycles with constant amplitude of stress. Polymer parts fatigue is stated for defined number of cycles (usually \(10^7\)) [10]. Polymer fatigue behaviour is presumed and decried by curve III in the Figure 1.

![Figure 1 SN curve – origin I, modification II, presumed for polymers III](image)

3. Technology of manufacturing

3.1. Injection machine

The technology of manufacturing was developed with respect to customer requirements. The main requirement which reduces mould parameters is specified by inject machine – Babyplast 6/12. [11] This machine was required by customer.

| Table 1. Injection machine parameters. |
|---------------------------------------|
| piston diameter                      | 18 [mm]          |
| injection volume                     | 15 [cm³]         |
| injection pressure                   | 81.5 [MPa]       |
| stroke                               | 60 [mm]          |
| ejector force                        | 6.3 [kN]         |
| closing force                        | 6 [ton]          |
Optimization concerning technology of manufacturing is a vital part of the polymer-parts design. Technological properties of polymers, manufacturing of metal moulds, and parameters of injection machines are necessary data input. Presented parts were optimized, and injection processes were simulated. The projected injection material is Polypropylene filled with 30% glass fibre. Its shear velocity is 100000 [1/s], and it is a vital character for injecting process technology.

### 3.2 Prototype moulds

Figure 2 shows the prototype mould of a plastic part. It is printed by SLA (Stereolithography) method, which provides very good accuracy. Printed parts can resist high temperatures.

![Aluminium mould and SLA print of high-temperature polymer part](image1.jpg)

**Figure 2** Aluminium mould and SLA print of high-temperature polymer part

A highly productive method of prototype mould production is Jet Fusion. This technology uses powder polymer, actually Polyamide PA12 with glass fibres. Properties of the final part are suitable for mould design and allows injection numbers of prototype cycles (approx. 20-50). Printed mould can be seen below Figure 3.

![3D Printed mould of a part of the examined mechanism, printed by HP Jet Fusion technology](image2.jpg)

**Figure 3** 3D Printed mould of a part of the examined mechanism, printed by HP Jet Fusion technology

### 4. FEA analysis

Commonly used finite element methods are used for the optimization of the design. All CAD and CAE operations were performed by Siemens NX software package. Several variants of parts and loading cases were simulated. The mesh continuum consists of TET8 and QUAD10 quadratic elements, which can be used for contact stress identification with adequate accuracy. The material model is inherited from default material library.

Two basic states were identified: a lift of the valve and a free turn. Measured preload of the lifting spring was applied in contact solution. Von Mises stresses and contact forces were solved with respect to fatigue stress life identification.

#### 4.1. Variant 1

Free turn is realized in the direction shown in the Figure 4. Main problem is the bend of the deformed part. A secondary effect is contact wear.
Figure 4 State of trivial bend during the free turn

Lifting operation is characterized by buckling load and bend. It restricts the relief of material. A relative low force of preload reacts with cam by the friction contact. Contact pressure is low <5Mpa.

Figure 5 Lifting operation

Reinforcement for better lifting is exactly the opposite requirement for the free turn deformation. This contradiction induces the design of the second variant, which splits operations into two perpendicular directions.

4.2. Variant 2

Stress during the loading of the end of the support is concentrated in the bottom. It means that the risk of fatigue failure is also situated there. Improvement for better load distribution should be done. Obviously, the fatigue life is affected by edges and other stress concentrators. These should be blended or reconstructed.

Figure 6 Stress analysis during the free turn - Von Miesis results [Mpa]
5. Decrease of stress – optimization
Both variants deal with two problems. Namely, required deformation for the free turn and stability for the lift operation.
During the final element analysis, the stresses were observed. Decrease of stress enhances failure protection. It forms the approach for the shape evolution. The cam part should overcome the lift of the valve. It also should withstand the stress during the free turn. The enlarge of the deformed parts should decrease the stress based on the Hook law:

\[ \sigma = E \cdot \varepsilon \]  

where: \( \sigma \)-tensile stress, \( E \)-modulus of elasticity, \( \varepsilon \)-strain

However, enlargement of the deformed part means large deformation by the lifting operation, which is an unwanted effect.
Parts were optimized with respect to published studies [12] [13]. Optimization should decrease the residual deformation, which is a problem. Residual plastic deformation causes malfunction and failure of the mechanism. Decrease of stress and strain respectively decrease plastic deformation.

The hysteresis of the polypropylene part caused by the stress around 40MPa is relatively large, as shown in [12]. The measurement was performed by the temperature 20°C. The rise of the temperature caused an additional decrease of true stress. It means that relevant improvement is the decrease of operating stress, which is under 10Mpa.
5.1. Results for variant 1
First variant of part consists of extrude of 2D curve. It is plane optimization due to that. The goal is a low stress during the deformation and a suitable stability during the lifting operation. The optimal suitable shape was formed with optimal deep relief, and the simulation results respect the initial requirements.

![Figure 9 Relief increase](image)

5.2. Results for variant 2
Second modification is characteristic by multi-axis load, which is different in lift and free-turn operation. Relatively large deformation by the free turn is realized in perpendicular direction. It is possible to perform free turn deformation on a relatively long beam, which causes stress below 8Mpa. Constant-stress topology of beam causes better load distribution. Lifting operation is supported by tough part, and it causes suitable stress around 6Mpa. Contact pressure by lifting operation is negligible.

![Figure 10 Results of the optimized shape of lifting part, load by lifting operation, results [Mpa](image)

6. Prototype tests

6.1. 3D Print
A few 3D print methods were applied for the prototype production. The basic method is FDM which is based on melted filament application. The stereolithographic method was used for the prototype mould production. The most productive method is Jet Fusion, which uses plastic powder melted by radiative heat load.

Several prototype cam wheels were produced. These were made of the Onyx printing material and the PET polymer (polyethylene terephthalate). The Onyx is composite of PA6 (polyamide) and short carbon fibres.
The test procedure was proved in a simple way. Test bed consisted of spindle and mechanism. Approximately 8000 cycles / occurrences were tested. Wear of the contact faces can be seen in the Figure 13. Contact velocities were relatively high, and consequently, the surface of these faces was slightly melted. The species made of onyx material were damaged the least. The function of the mechanism was not disrupted.

6.2. Wear identification
Wear in FEA simulation was predicted. Stress on the contact path is very high due to critical edge to edge contact. The value of the contact pressure is dependent on trajectory and time; it can be seen on the left graph in Figure 14. Edges should be blended; otherwise they would be fast worn out, which however, does not fail the function.
7. Conclusion
The paper summarises many steps of the design of plastic prototype parts. The research deals with customer requirements and restriction of polymer parts. Cyclic loading, which causes unwanted plastic deformation, was investigated, and results were applied on the variants of cam parts. Prototype test was performed with respect to cyclic load and overall function in assembly. Development was performed with respect to fast prototyping. Two variants were offered to customer with fast prototyping of entire mechanism. Due to described methods, the development time was significantly shorted.

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