Testing, SEM-characterization and surface modification of gear wheels produced by additive and traditional technics

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Abstract. Both the comparative testing and SEM-control of crack surfaces for steel, polymer and 3D-printed polymer gears were carried out. Computer mechanical fatigue failure modelling correctness for steel wheels and in a less degree for polymer ones due to polymer inhomogeneous inner structure was shown. The SEM-characterization indicated that used type of fatigue failure modeling for 3D-printed polymer gears needs corrections due to the specific uneven gears surface shape, inner cavities presence and polymer deformation features as a result of both insufficient filament melting process, and microstructural polymer features. Surface fluorination aimed to 3D-printed gears friction ratio decreasing was tested. Gears modification was resulted to surface layer forming leading to wear halving to 0,3.

1. Introduction
Despite both serious and numerous theoretical and experimental research of machinery reliability parameters, mechanical failures are the most often reasons of part breakdown including gears wear. According to the statistics, failure of gears often leads to the longest downtime and maximum economic loss for factories [1-3,10]. One of the solutions of well-timed equipment maintenance is details and components 3D-printing for different machinery, printing ones among others.

3D printing has revolutionized many industries, recently expanding into industrial applications. It provides the ability to prototype quickly and cheaply [1-7, 10-14]. The latest up-to-date tendency is production of both micro-gears (having 0.1–1 mm outside diameter) and meso-gears (having 1–10 mm outside diameter) [2].

In the most cases 3D printing is used for prototyping only [1-7, 10], but details produced by additive technics can be used as a complete or temporary decision alternative for some components replacement (traditional gears, most notably) [2, 10].

3D-printers in the lowest price range are almost exclusively fused deposition modeling (FDM) printers. The high temperature heats the plastic into its melting temperature range, making the extrusion possible. The part is built one layer at the time, with the heated plastic coming out of the nozzle fusing to the previous layer. Such printers typically use hard polymers such as ABS or PLA, resulting in hard plastic parts [1].

While additive manufacturing (AM) offers numerous advantages to conventional manufacturing techniques, the cyclic behavior of AM parts must be understood before they can be safely used in different areas [3].
The viability of modern engineering structures and materials depends on actively designing against fatigue, which accounts for the majority of mechanical failures [2, 10]. It is often the research works are focused on testing the hardness difference between gear inner surface and bearing outer ring, analyzing the influence of interference fit tolerance on fretting slip distance, and exploring the influence of gear hub thickness on fretting slip distance [4]. It is known that at the stage of fatigue source generation, the roundness error of gear inner surface and the profile error of tooth surface can affect the radial clearance of the meshing gear pair. As a result, uneven load region on gear inner surface appears [5].

Profile measurements are common used method for surface performance estimation. In [11] such procedure was applied for 3D-printed patterns. It was found that surfaces produced by FDM process vary with respect to different layer thickness and build inclination. In case of 3D-printed gears a surface relief can cause additional loading areas appearance.

Another testing procedure of residual stress measuring in FDM parts made of ABS polymer – hole-drilling method with optical estimating – was described in [6]. One of the most important issues in the FDM process is the distortion of the part during the printing. This issue is due to the rapid heating and cooling cycles of the feedstock material that could produce accumulation of residual stress during part building up [6]. Authors pointed that once the entire model has been deposited the FDM part can show orthotropic material properties with behaviour similar to a laminate orthotropic structure.

An adaptable three-dimensional transient mathematical model of temperature variation with respect to space and time, during and after the FDM is described in [7] for PLA. Temperature management is a primary concern in FDM, as it has direct influence on the inter-layer bonding strength, rheological behavior, crystallinity of the polymer, deformation of the component and indirect influence on macro mechanical properties, surface quality, printability, etc. [1–7, 12]. In the work [8], both the spherical involute and the octoidal form systems for bevel 3D-printed gears are mathematically defined. Authors [4] showed the relationship between the load applied to a 3D printed sprocket and the number of cycles of continuous operation before a fatigue load related failure occurred and makes a conjecture on a range of load for “infinite life” of operation using torsional test analysis.

Dimensional inaccuracies of FDM part and were theoretically described in [13] including both deflection and heightening describing due to hydraulic pressure during extrusion. And in [12] authors examined influence of machine and materials parameters as well as process adjustment on mechanical properties and geometric accuracy including theoretical explanations of physical processes at the cooling stage.

SEM-methods are also widely spread for materials properties diagnostics in indeed different areas [2, 3, 5, 6, 15-17] and in a less degree for mechanical units as gears with vast majority of research dealing with steel ones for micropitting control. An interesting research heated in-situ SEM micro-testing device was presented in [15].

In our study both the computer visualisation and SEM-control of crack surfaces for steel, polymer and 3D-printed polymer gears were carried out.

The analysis of both fundamental research and synthesis technologies for novel polymer materials processes are shown that traditional synthesis methods – polymerization and polycondensation – are near to visible possibilities exhausting; therefore the opportunities of novel unparalleled polymers synthesis versus characteristics of modern ones are significantly decreased [18-20] (excluding composites). Both surface and bulk modification is aimed at capability enhancement opportunities of existed polymers. As a specific task surface modification can be used to in-use polymer gears wear decreasing. Surface fluorination is widely applied for polymer modification [18] due to operational flexibility and processibility:

- Shape and size polymers items is limited a reactors size only;
- Polymers is modified at the room temperature and atmospheric or negative pressure;
- In majority cases initiation, catalysts and complex equipment are not demanded for fluorination;
- Toxic reagents and co-products can be neutralized by “chemical catcher” based on CaO [18]
So, in the research surface fluorination affection on 3D-produced gears tribological behavior was additionally examined (tribology coefficient for polymer-steel side friction and failure conditions, in particular).

2. Methods and materials
Numerous modelling of a wheel gears contact zone and wheel hydrostatic tension were realized by finite-element analysis using ANSYS software in a volume statement. The used methods cannot completely replace existing testing methods of gears but it can visualize potential fracture spots and failure development process.

The computational grid was constructed using tetrahedral regions. Statistical calculations were performed under the assumption of material isotropy, linear elastic material behavior as well as slight displacements. Also both in-use aggressive fluids action on gears and wheel shape inaccuracies were not taken into account (tested gears are used at alkaline sodium silicate (Na₂SiO₃) pH=13,0±0,5 at 25±3°C). The default load value on a wheel is ~1–1.5 kg. Calculation was not carried out for a wheel tooth, but for the whole gears.

For the given generic purpose of this study 3 gears types:
- traditional produced gears made of casehardened steel (Russian grade 20X3MBФ-III);
- powder-molding gears made of polyoximethylene-based ones;
- 3D-printed ones made of ABS,
were comparatively characterized using FE-SEM Jeol JSM 7500F at the acceleration voltage 1 kV (for polymer samples) and 10kV (for steel ones). The spatial resolution was at least 1 nm. The gears were Pt coated (about 10-12 nm, argon atmosphere) in order to avoid destruction as well as samples surface charging under an electron beam using magnetron AutoFineCoater JFC-1600 at the pressure about 10⁻¹ Pa.

A destroyed gear of a CtP-thermal plate processor (Glunz&Jensen Interplater 85/135, The Nauka RAS publishing centre) was designed using SolidWorks as an .STL file. Preparation procedures of the designed gear for 3D-printing was made in the Cura software (Ultimaker). 3D-printing was realized using A8 Anet printer and 1.75 mm ABS-filament from FD Plast.

ABS as polymer-base of a gear was chosen due to its high chemical stability to alkaline sodium silicate solutions. Printing parameters are presented in table 1, shape inaccuracy was determined as not above 1.2 %.

Fluorination of the 3D-printed wheel was realized by both the procedure developed in [11], and the findings of the RFFR-funding work (the grant №18-33-01093) for polymer films modification. Modification process was examined by IR-spectroscopy combined with attenuated total reflection method using FT-801 (Simex) instrumented by zinc selenide element.
Tribology coefficient and wear of initial and modified gears were defined in order to the technical specification (#4271-001-29034600-2004) using friction test machine MTU-21 at the contact mode by 200 rpm ring indenter rotation within 15 min. The indenter (45 steel, 6 grade of finish, R_a=1,3–2,0 µm) was pressed to sample surface at the force 35±2 Н and contact area 1.9 sm^2. Friction zone temperature was within 27±2 °С. Wear was gravimetrically tested using analytical balances ViBRA HT 224RCE.

### Table 1. Gears printing parameters

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| 1  Layer height            | 0.4 mm                                     |
| 2  Line wall thickness     | 0.8 mm                                     |
| 3  Filled density          | 100%                                       |
| 4  The first layer temperature | 250°C                                  |
| 5  Platform temperature    | 70°C                                       |
| 6  Filament diameter       | 1.75 mm                                    |
| 7  Stream                  | 100%                                       |
| 8  Printing speed          | 42 mm/s                                    |
| 9  Wall printing speed     | 21 mm/s                                    |
| 10 Moving speed            | 60 mm/s                                    |
| 11 Holdup generating       | backing arrangement – from the table,     |
|                            | backing overhand angle - 50°, backing      |
|                            | pattern – “Mesh”, backing density – 40%    |

3. Results
The results of simulating and SEM-analysis are presented in fig. 3-20.
Following the modelling results (fig. 3, 4, 9,10, 15, 16) any inherent differences in failure patterns were not fixed at slight loading on examined gears, but according to SEM-analysis morphology of damaged ones is differently. Indeed, pitting, tips and tooth spaces tearing (fig. 5, area 4) and also local chippings of both active zones and teeth tips (fig.5, areas 2, 3), which are characterized by complex geometry and varied morphology – not only the steel grain structure (fig. 6, grains size are varied from 0,5 to 4 µm), but a layer-like one (fig. 7) were fixed for steel gears. The structures of active zones grains and fractures are differed from each other – within fractures the grains have a regular, elongated, plate-like shape for the most part. Such grains are interleaved with quite large homogeneous areas (as high as 50 µm). Morphology of the damaged steel gears corresponds largely to simulated patterns (fig. 3-4). It can be noted that a casehardening layer was also broken on top of all of this. In contrary to the previous case, numerous fractures of polymer gears produced by powder-melded technics were fixed near the tooth base line (fig. 11-12), tooth tips had also fractures but in a less degree. Macro-shapes of gears fractures are quite typical (fig. 9-10). They are compatible with the simulated patterns to a certain extent. Nevertheless, structure fractures inhomogeneity of polymer gears fractures, which is distinct from the steel ones, was detected. Random arranged textural features were found - ribbon, tubular, shapeless structures, and also micro size inner cavities (fig.13-14), which caused due to initially used material heterogeneity. Such cavities can cause early gear wear in an unpredictable area. So, simulation input data should be corrected.
Also it was found that more complex shape of 3D-printed wheel gears was not taken into account at the simulating: more precisely, a periodical relief (100-150 µm, close to semi-round shape) with respect to a reference line with 350µm-step in the printing direction (fig. 17), which comparative to the
layer height (table 1). Such gears shape is determined by layer-by-layer 3D-printing process. But additionally, interlayer cracks along the relief with depressions and overhangs (one-side, mainly). Figure 3. Normal stress field for steel gears

Figure 4. Tangential stress fields for steel gears

Figure 5. SEM-image of a fractured steel gear

Figure 6. Damaged steel wheel morphology (area 3)

Figure 7. Damaged steel wheel morphology (area 3)

Figure 8. Damaged steel wheel morphology (area 2)

accompanied by composition inhomogeneity were fixed for produced gears. Also numerous inner deep cavities of damaged gears were found at the interface of printed layers (fig. 17). All described defects are among FDM-printing procedure features. Both polymer deformation development and active surface fractures of wheel tooth tips were detected (fig 18-20). According to SEM-images polymer strands / fibers (1-3 µm thickness, fig.20), oriented
and elongated in a direction orthogonal to print and a parallel direction to gears rotation, respectively, are presented in damaged 3D-printed wheel gears.

Figure 9. Normal stress field for polymer gears  
Figure 10. Tangential stress fields for polymer gears

Figure 11. SEM-image of a damaged polymer wheel  
Figure 12. SEM-image of a polymer wheel, damaged near a bottom line of teeth

Figure 13. Chipping structure of a damaged polymer wheel  
Figure 14. Cavities structure of a damaged polymer wheel
Observed failure behavior is not typical for such rigid polymers as ABS or PLA, it can be brought about by the used filaments structure features and their morphological changes during storage. Additionally, wave-like structures (10-15µm “wave” thickness), oriented along printer head moving...
direction, and stochastically placed micro-cavities (fig. 19) were detected in the gears fractures. Their appearance can be caused by ABS filament inhomogeneity as well as layer-by-layer and dropwise FDM 3D-printing process and also polymer melting – cooling temperature differences. It should be noted, that authors [1] had pointed to the wheel tensioning force varied significantly from the intended preload value because of the uneven shape of the wheels, but the mismatch reasons were not defined.

The results obtained in this study add to research presented in [12, 13]. So, in case of statistically-valid failure data amount SEM-testing will allow to reasonably correct simulation (predict) parameters of traditionally and additive produced gears fatigue wear as well as to modify 3D-printing parameters, especially.

4. Modification
Static coefficient of friction and wear histograms for initial and fluorinated 3D-printed wheel gears are presented in fig. 21 and fig. 22, respectively.

According to IR-spectrums, any additional absorption bands were not found for produced (initial) ABS wheel gears but due to wheel fluorination new bands were appeared in 950-1300 sm⁻¹ and 1600-1850 sm⁻¹ spectrum areas. The first band is related to C-Fx – absorption bands overlapping (where x = 1, 2 и 3), the second bands group presence indicates different carbonyl groups bonding in a polymer chain due to some technological oxygen amount in gaseous fluorine. In general, IR-spectrums are evidenced about successful gears modification.

The correlation between wheel fluorination degree and both friction coefficient and wear decreasing is shown in fig. 21-22. So, friction coefficient was reduced from 0.5 to 0.3, also wear was about halved due to a fluorinated layer forming [18]. Based on the above it might assumed that ABS- fluorinated gears cycle life can be significantly improved.

Conclusion
In the study computer simulating and SEM-testing of crack surfaces for steel, polymer and 3D-printed polymer gears were carried out. Computer mechanical fatigue failure modelling correctness for steel
gears and in a less degree for polymer ones due to polymer inhomogeneous inner structure was shown. The SEM-characterization indicated the specific uneven gears surface shape with significant inaccuracies, inner cavities presence and ABS-polymer deformation features. It was shown that used type of fatigue failure modeling of 3D-printed polymer gears needs corrections. Surface fluorination aimed to 3D-printed gears friction ratio decreasing was tested. Gears modification was resulted to surface layer forming leading to wear halving to 0.3. Since the experiments presented in this paper only evaluate three different materials, further research is possible. Research work is under progress at the institutes of the authors investigating on manufacturing of good quality polymer gears and its surface modification.

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