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Project of Mars rover wheels based on structural infill using additive manufacturing

Projekt i wykonanie w technologii przyrostowej kół łazika marsjańskiego z wypełnieniem strukturalnym

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The process of designing and manufacturing tubeless wheels with structural infill for the Mars rover, which will take part in the University Rover Challenge competition, by the AGH Space Systems scientific club, is described. Some of Mars rover subsystems' are so unique, hence they should be manufactured from scratch. The algorithm for generating the structural infill has been proposed. The strength tests were conducted for the preliminary identification of material parameters, and their results were used as an input for FEM strength analysis. Wheels have been made of polymers with fused filament fabrication (FFF) additive technology, and then applied in the KALMAN rover.
KEYWORDS: Mars rover, 3D printing, FFF, URC competition, material tests

Due to the significant differences in atmospheric conditions on Earth and Mars and high costs of manned flights, no crew Mars expedition has been decided so far. In order to obtain data on the conditions prevailing on the Red Planet and lay the foundations for future manned missions, scientists and engineers decided to use autonomous vehicles which can carry out planned tasks without human support [1].

The Mars rover is a kind of space probe, an autonomous vehicle that when exploring alien planets is able to collect geological samples from hard to reach places. [2].

For several years, student competitions have been carried out, such as the University Rover Challenge (URC) and the European Rover Challenge (ERC), whose aim is to develop Mars rovers and test them in simulated conditions, similar to those found on Mars. Building such vehicles allows students to acquire knowledge in the field of designing machines, which can work in space. The scientific team of the AGH Space Systems prepares the Mars rover with the name KALMAN.

Due to the construction of the rover and the conditions of its operation, the essential element of the vehicle's construction are the wheels with the drive unit. The outer surface of the wheel comes into contact with the ground. Therefore, it should primarily provide adequate rigidity and strength under load, traction on the substrate and be resistant to deformation. Also included are the desert conditions in which the URC and ERC competitions take place.

The inspiration for the design and construction of wheels was used in off-road vehicles and quads, a tubeless tire with a honeycomb structure, adapting in shape to the conditions of vehicle operation [3-5].

Working conditions of the rover's wheel

Three forces act during the ride on the Mars rover's wheel (fig. 1):

- friction force from the ground, depending on the weight of the vehicle and the type of surface the wheel touches;
- driving force from an electric motor, transmitted to the driving wheel;
- force of the wheel pressure on the ground.

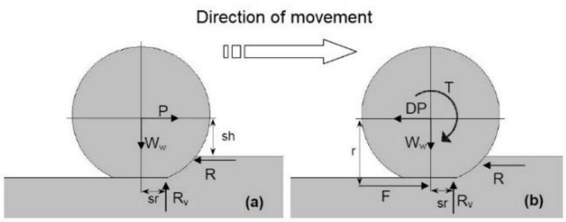

Fig. 1. Forces acting on the wheel: a) standing wheel in place, b) driven wheel [4]; *R* - friction force, *T* - engine torque, H_V - pressure, R_V - ground reaction force, *P* - wheel drive force, D_P - rolling resistance force, s_h - wheel immersion depth in the ground, s_r - wheel effect width with the ground

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Based on the analysis of the work of the Mars rover wheel, the following strength cases have been distinguished:

- the wheel rim is subjected to a load on bending, stretching and compression,
- the tire is subjected to compressive forces.

Goal of the project

In the previous project of the Mars rover - PHO-BOS, implemented by AGH Space Systems - wheels from the RC car model were used. Such a solution was not optimal due to limitations of a transmission mechanism, large deformations of the wheels under the applied load and a small surface of contact with the ground, so that the vehicle was in an unstable equilibrium.

After analyzing the available wheel solutions for vehicles with an own weight of up to 50 kg, it was decided to develop own wheel concept in order to meet the following criteria:

- increase the stiffness and durability of the wheels under the applied load and adhesion to the ground,
- minimize its own weight (total vehicle weight can not exceed 50 kg),
- enable the drive to be adapted to the rim structure and the maximum speed of 3 km/h, at which the vehicle can move during the competition.

Flexible plastics (i.e. elastomers) were used that meet the strength criteria for the assumed loads and working conditions. Tires and rims were produced using additive technologies based on the fused filament fabrication (FFF) method [6].

In the first stage, appropriate construction materials were selected. The tire is in direct contact with the ground, which is why the Fiberlogy Fiberflex 40D material from Fiber-logs, based on TPE (thermoplastic elastomer) [7] was selected. It is characterized by high resistance to abrasion, cracking and dynamic loads. Its material properties allow the use of a reduced-size tire as a replacement for mass-produced wheels, eg for RC car models, thanks to the possibility of modifying its stiffness depends on infill density adjusted during design stage.. The rim was made of FormFutura's CarbonFil filament. It is a PETG copter (polyethylene terephthalate modified with glycol) reinforced with carbon fibers, offering a combination of elasticity and strength [8]. At the next stage, strength analyzes of materials were carried out in order to determine the wheel operation parameters.

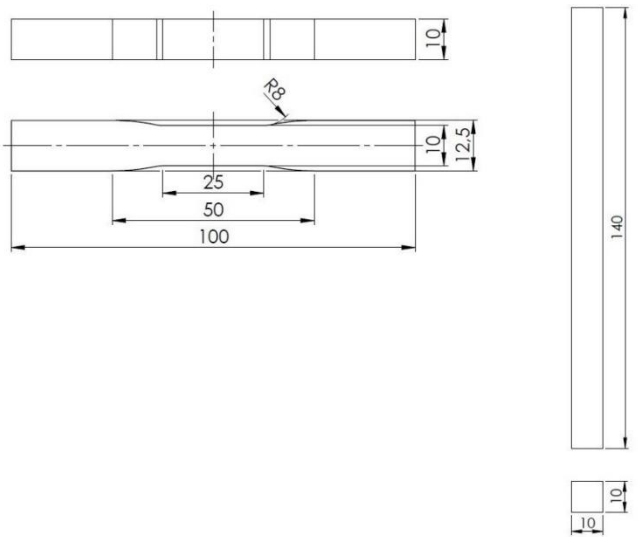


Fig. 2. Dimensions of the sample for tensil and flexural strength tests

Fig. 3. PETG material reinforced with carbon fiber: a) tensile strenght test with extensometer, b) flexural strenght test, c) compression test

Strength tests

Strength tests were aimed at determining the values of stresses and strains, elastic limits and Young's modulus depending on the filling used, the orientation of the model in the working chamber and the direction of printing.

Taking into account the working conditions of the rims, samples were designed and tested for tensile strength, compression and flexular strength, referring to the testing of their properties as fibrous composites. The samples for tensile resistance tests were in the form of paddles, in accordance with the PN-EN ISO 527-2: 2012 standard, and the samples for flexural strength were straight-pads with dimensions: 10 × 10 × 140 mm (fig. 2). The samples for the compression test were prepared in the form of a 10 × 10 × 10 mm cube made of CarbonFil material and in the form of a cylinder with a diameter of Ø30 mm and a height of 30 mm made of Fiberflex 40D material. CarbonFil fittings were printed with 50% and 100% honeycomb fill, and Fiberflex 40D - with 25%, 50% and 100% filling, with the same structure as the rim material. The use of different filling was aimed at selecting the best printout with optimal strength properties.

For samples to be reproducible, a set of fixed print parameters for both materials was established. The print parameters included: printing speed, substrate temperature, extruder temperature, nozzle type and cooling rate. Finished samples were subjected to durability tests (static and dynamic) using the INSTRON 8872 testing machine (fig. 3).

As a result of the research, an increase in the tensile strength and modulus of elasticity with the percentage of filling was observed. Tensile tests in the case of both types of fillings showed that in the range of 0÷45 MPa, the element operates in the elastic range at the deformation to 10% of the initial length. The Young's modulus for samples with 50% and 100% filling was determined from the curve of dependence on strain. At the fill of 50% Young's modulus equal to 2750

MPa was obtained, and for 100% - Young's modulus equal to 3150 MPa. The results obtained from the strength tests served as input data for the finite element analysis, which allows to determine the strength of the designed wheel.

Strength analysis by Finite Element Method (FEM)

The basic CAD model was made in the SolidWorks program. The geometrical dimensions of the tire and rims were determined based on the size of the 3D printer's working field and the maximum permissible speed of the vehicle, consistent with the competition regulations [9]. The tires used in off-road vehicles, such as ATVs, were the inspiration to design the tread of a rover tire. Figure 4 shows the tire and rim model.

The numerical calculations of strength of the rover rims were carried out in the Hypermesh program, based on data obtained from the samples. As the boundary conditions, degrees of freedom (RBE2 elements) corresponding to the rotation and displacement of the wheel along the X and Z axes were taken so that the wheel could rotate about its own axis. At purple points (RBE3 elements), shown in fig. 5, a force of 100 N was applied in each hole that was transferred from the hub to the rim.

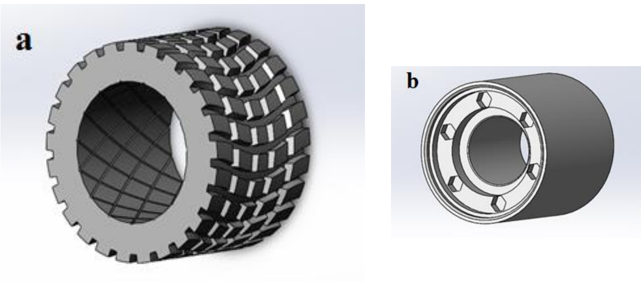
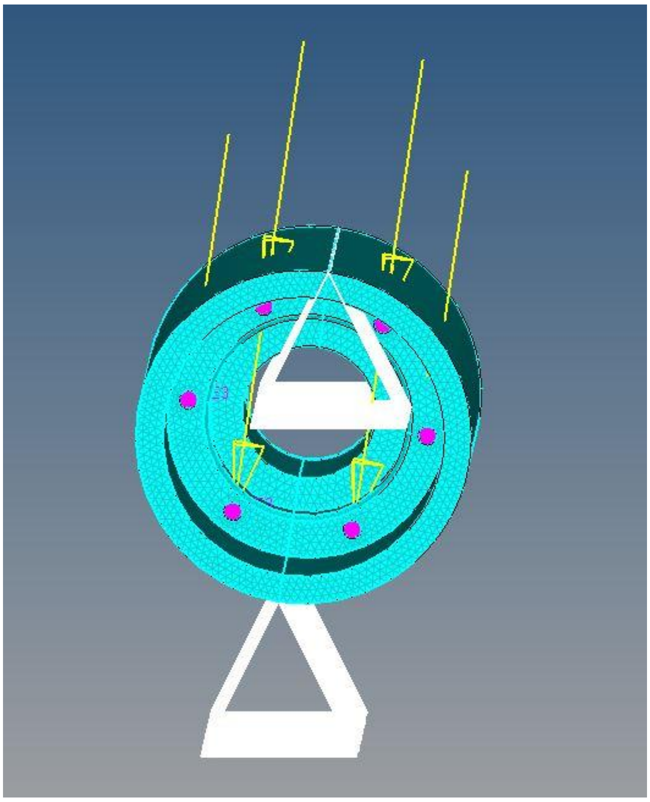


Fig. 4. CAD models: a) tires, b) rims

a)



b)

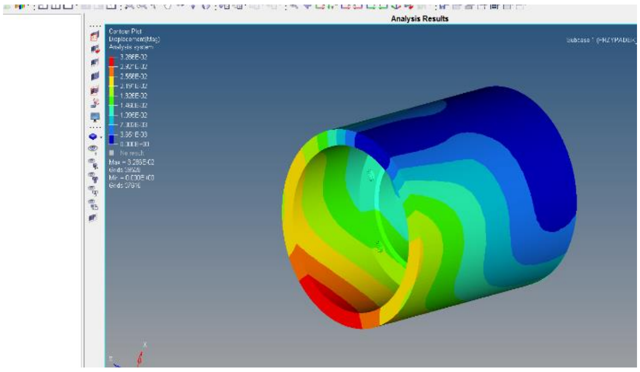


Fig. 5. Assigning boundary conditions (a), analysis of data obtained from simulation (b)

Numerical FEM numerical analyzes were performed on the basis of input data from samples with different infill volume. An optimization criterion was adopted based on minimizing the weight of the rim while maintaining permissible stresses and deformations and taking into account the safety factor. It was decided to use the data from the tensile test for a sample with 50% fill. After analyzing the results (figure 5b) it was determined that the maximum deformation of the rim diameter is 1.4 mm (8% of the initial value), with a maximum stress of approx. 8 MPa. This is an acceptable deformation for the rim material. Based on the data from the experimental trials, it was found that the simulation data was in the elastic range of the CarbonFil material.

Experimental tests of samples and FEM analysis of the rim used in the Mars rover allowed determination of stress state of the loaded component. Based on the analysis, the optimal filling of the geometric model of the rim was chosen - 50%.

Developing an algorithm to fill a structured tire

An algorithm for structural filling of the tire was developed. In additive technologies, the direction of applying building material and the filling of the interior of the model (FFF technology) are important, which influence the strength of the element [10, 11]. It was decided to modify the tire's filling. Reducing the percentage of filling affected mainly its rigidity, the way of matching the surface of the ground and the amount of deformation depending on the obstacles to be overcome.

It was assumed to make a wheel of two parts - separate tires and rims, printed from other components. In the case of a tubeless tire, it was decided to use a honeycomb print that would allow for better durability properties by modifying stiffness. The virtual model with the generated structural filling is shown in fig. 6. Due to this construction, the objects achieve high strength while maintaining low mass [8].

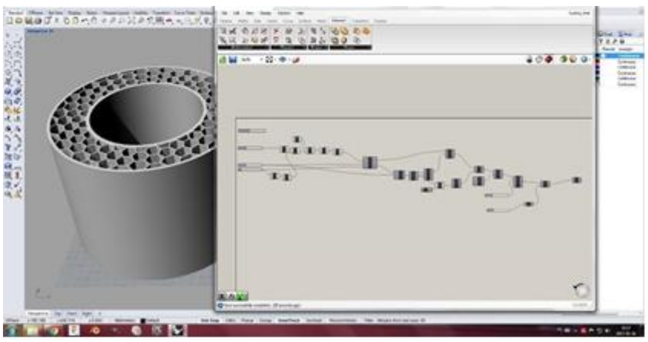


Fig. 6. Algorithm enabling the generation of tire filling, developed for the needs of the KALMAN rover project

While designing the algorithm, algorithmic techniques were used to minimize the mass of the tire, while at the same time changing stiffness in different areas, based on compression tests of Fiberflex 40D samples [12]. The stiffness of the tire increases with the decreasing diameter of the tire, because the area in contact with the ground has a lower density of the filling than the area located on the rim.

Creating the Mars rover wheels

After completing the stage of generating the structural filling for the rover tire and rim as well as choosing the parameters of 3D printing, elements were manufactured. Grooves were designed in the tire structure to make a glue connection between the tire and the rim (fig. 7). A set of four tires and rims was printed within approx. 120 hours. Then they were glued together. As a result, the weight of a single wheel was 1.06 kg (fig. 8).

a) *b)*

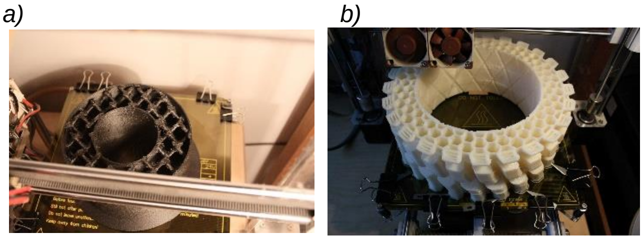


Fig. 7. The 3D printing process: a) rims, b) tires - with visible grooves for glue

Fig. 8. Ready wheels of the KALMAN rover

Conclusions

Due to the cooperation with Crystal Cave in the scientific circle of AGH Space Systems, the project of wheels of the KALMAN Mars rover with the use of modern additive technologies has been successfully completed (fig. 9). The vehicle equipped with such wheels will be ready to participate in racesof the Mars rovers URC 2018.

The shape of a honeycomb infill can be obtained immediately using the FFF method. By modifying various parameters, such as density of filling in a selected area, a finished element was obtained, which did not require any additional finishing by machining.

This solution is also suitable for use in mobile robotics when it is necessary to make a component for a specific purpose and specific working conditions. It is a good solution for unit production due to the low cost of input materials and the possibility of carrying out many iterations in order to select the most favorable variant.

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