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BENEFITS OF USING TI6AL4V ALLOY FOR CONNECTING ROD AND CRANKSHAFT OF A FOUR-STROKE ICE

Michał Hebzda

Krosno State College, Rynek 1, 38-400 Krosno, Poland,
Faculty of Production Engineering, Polytechnic Institute,
email: michalhebzda@gmail.com

Abstract: The article presents the process of designing a connecting rod and crankshaft made of titanium alloy Ti6Al4V in accordance with the assumed dimensions. The Engine unit will power a vehicle taking part in the Shell Eco-Marathon competition. The elements were subjected to FEM simulation for static and fatigue strength to check their trouble-free operation. The research has had positive effects, making further modification of the designed parts unnecessary. The energy needed to set in motion elements made of steel and Ti6Al4V alloy was compared, which results in a difference in fuel consumption.

Keywords: Shell Eco-Marathon, Crankshaft, Connecting rod, Titanium alloy, Ti6Al4V.

1. INTRODUCTION

The Shell Eco-Marathon is an international competition held every year in London. The main goal of the competition is to cover as much distance as possible on the equivalent of one litre of fuel or one-kilowatt hour. The "ROTOR" student scientific club has been participating in the Shell Eco-Marathon competition since 2016 in the category of ethanol-powered prototypes, achieving the following results: 2016 – 133 km/1 l, 2017 – 306 km/1 l, 2018 – 498 km/1 l, 2019 – 749 km/1 l.

In order to achieve further success, the team is working on designing a new four-stroke internal combustion engine. The connecting rod and crankshaft are one of the most important parts of the working engine that affect fuel consumption. The team plans to use Ti6Al4V alloy as the main engine construction material due to its low weight while maintaining high strength.

2. CHARACTERISTICS OF TI6AL4V TITANIUM ALLOY

Ti6Al4V (Class 5) is the most commonly used biphasic titanium alpha-beta alloy. This alloy contains 6% aluminium, 4% vanadium, 0.25% (maximum) iron, 0.2% (maximum) oxygen, with the rest being titanium.

This material shows much greater strength compared to pure titanium, while having the same stiffness and thermal properties. Among its many advantages, Ti6Al4V can be heat treated. In addition, Ti6Al4V is corrosion resistant, and easy to weld and machine compared to other titanium alloys. The yield strength of Ti6Al4V oscillates around 850 MPa.

Initially, the alloy was developed for the aerospace industry and is widely used in aerospace structural components. The density of Ti6Al4V corresponds to 50% of the density of nickel alloys and stainless steel. Therefore, the alloy is widely used because of its excellent strength-to-weight ratio. As a rule, it is used in an annealed condition at operating temperatures up to 400°C. However, this alloy can be heat treated to provide high strength in cross-sections up to 4 inches thick [Boyer, Welsch and Collings 1994].

3. CONCEPTUAL ASSUMPTIONS OF THE DESIGNED CRANK-PISTON INTERNAL COMBUSTION ENGINE-POWERED VEHICLE TAKING PART IN THE SHELL ECO-MARATHON COMPETITION

Based on the design of the crank-piston system of the Piaggio Fly 4T engine with a capacity of 48 cm^3, the crankshaft and connecting rod were designed. The main assumption of changing the design of the crank-piston system is to reduce the mass of moving parts, which have an impact on fuel consumption. The table presents the most important dimensions and properties of the connecting rod and crankshaft of the Piaggio engine.

Table 1. Main dimensions and properties of Piaggio engine

Steel Crankshaft	Steel Connecting rod
Total weight with crank pin 1940 [g]	Connecting rod length 90 [mm]
Crank radius 22 [mm]	Crankshaft crank radius 22 [mm]
Flywheel shaped connection	Piston diameter 39 [mm]
Multi-wedge connection of the drive train	Piston weight with pin and rings 53 [g]
The interference fit of crankshaft components	Piston pin diameter 13 [mm]
Bearing the main journals with ball and roller bearings	Connecting rod weight with bearings weight 140 [g]
Crank pin bearing - needle assembly	Connecting rod head width 14 [mm]
	Connecting rod end width 18 [mm]
	Maximum rotation speed 6000 [rpm]
	Speed at max torque 5000 [rpm] 523 [rad/s]

In order to reduce the masses of the parts of the crank-piston system, the dimensions and material of the connecting rod and crankshaft will be changed. The predefined main dimensions and mass properties are given in Table No. 2, which will be finally verified during FEM simulation.

When selecting the dimensions of the parts, the appropriate strength and rigidity of the parts were taken into account. In this case, the life of the parts is not important, because the engine will be used sporadically.

Table 2. Main assumptions of the designed parts

Ti6Al4V Crankshaft	Ti6Al4V Connecting rod
Connecting rod weight with bearings weight	Connecting rod length 120 [mm]
Crank pin mass	Crankshaft crank radius 25 [mm]
Crank radius 25 [mm]	Piston diameter 35 [mm]
Connecting rod end width 16 [mm]	Piston weight with pin and rings 49 [g]
Flywheel shaped connection	Piston pin diameter 10 [mm]
Shape connection of the drive train	Maximum exhaust pressure for ethanol 8.2 [MPa]
The interference fit of crankshaft components	Connecting rod head width 12 [mm]
Balancing of first order mass forces	Connecting rod end width 16 [mm]
Bearing the main journals with ball and roller bearings	Maximum rotation speed 5000 [rpm]
Crankpin bearing - needle assembly	Speed at max torque 4000 [rpm] 418 [rad/s]
Safety factor at least 2	The value of the radius to connecting rod length ”λ” $\lambda = r/l = 25/120 = 0{,}2083$
	Safety factor at least 2

Using the AVL BOOST program, the maximum pressure acting on the piston was simulated. Knowledge of the kinematics and dynamics of the crank-piston system made it possible to determine the forces acting on the crankshaft and the connecting rod. The crank pin material was defined as ŁH15 bearing steel. The masses of the designed parts will be determined with the help of the “Mass properties” module in Solidworks.

4. CONNECTING ROD AND CRANKSHAFT DESIGN PROCESS

Using the Solidworks program, the connecting rod and crankshaft models were designed in accordance with the assumed main dimensions. During FEM simulation, at the beginning stress, as a result of interference joints was determined. The tested parts were fixed in the place of bearing mounting. For static strength tests, gas forces acting on the piston crown and inertia forces were used. In the simulation of fatigue strength, objects were subjected to forces at a rotational speed at which the engine reaches maximum power [Shih 2011]. The minimum operating time of the parts was set at 14 million cycles, which corresponds to approx. 60 hours of operation.

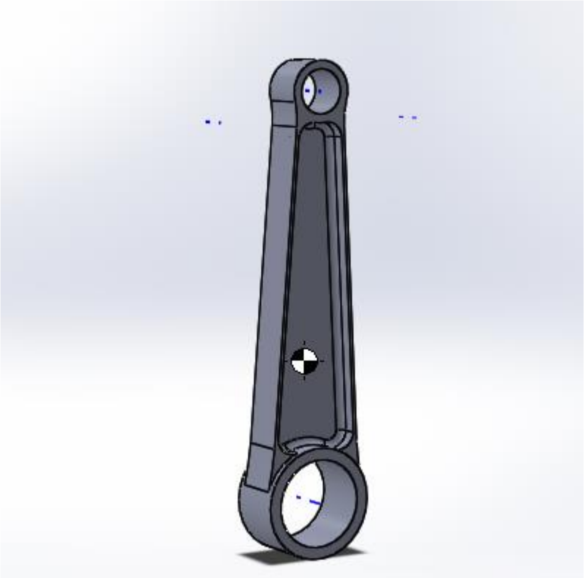

Fig.1. Connecting rod model made of Ti6Al4V alloy

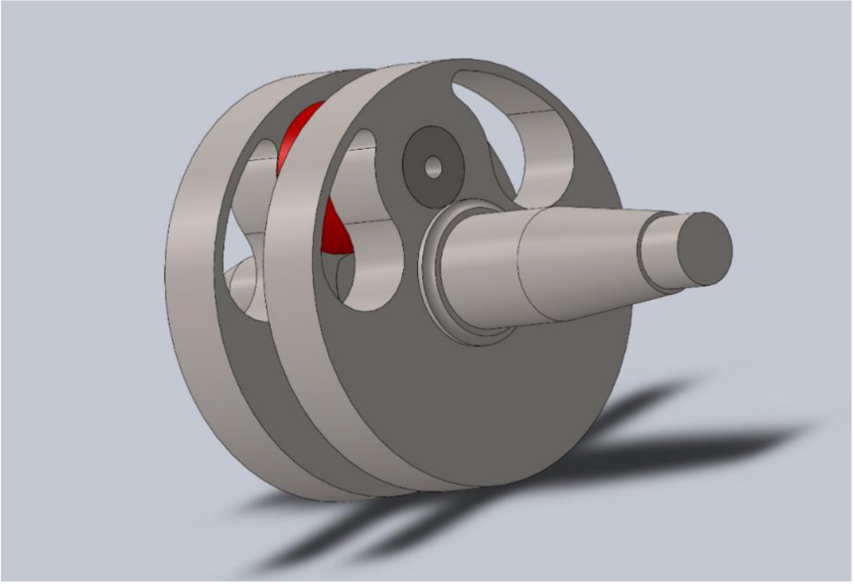

Fig. 2. Crankshaft model made of Ti6Al4V

The designed crankshaft is shown in Figure 2. Its dimensions are consistent with the assumed data. For balancing, a material allowance corresponding to the mass of the parts in rotation and reciprocating movement has been removed in the crankshaft discs.

The centre of gravity of the crankshaft has been moved to the axis of rotation [Hoag 2006].

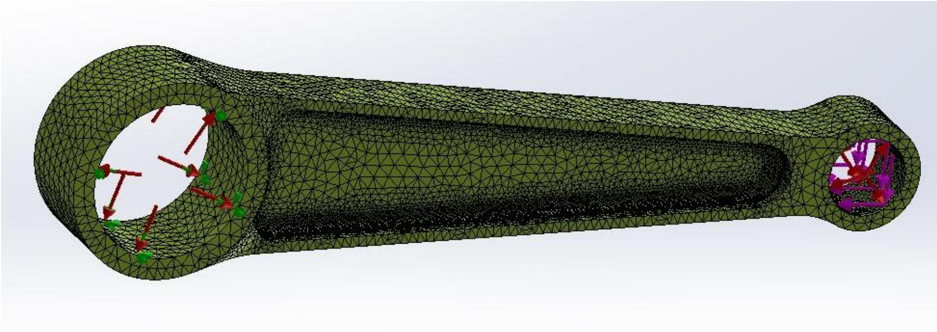

Fig. 3. The applied mesh for simulation purposes on the modelled connecting rod

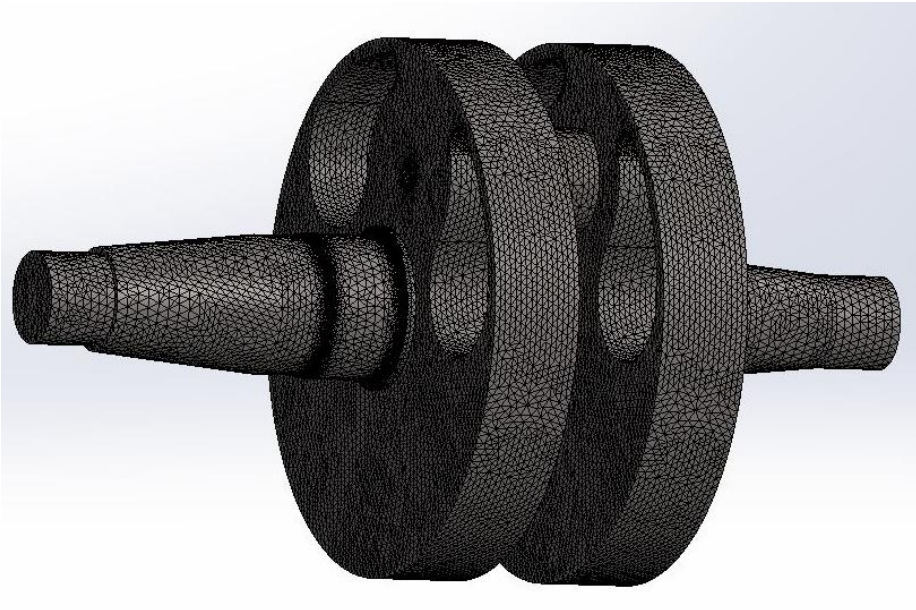

Fig. 4. The applied mesh for simulation purposes on the modelled crankshaft

A very fine mesh was created in both parts for FEM simulation using the "curvature-based mesh" option. This method allows the mesh to be thickened in places exposed to the highest stresses [Shih 2011].

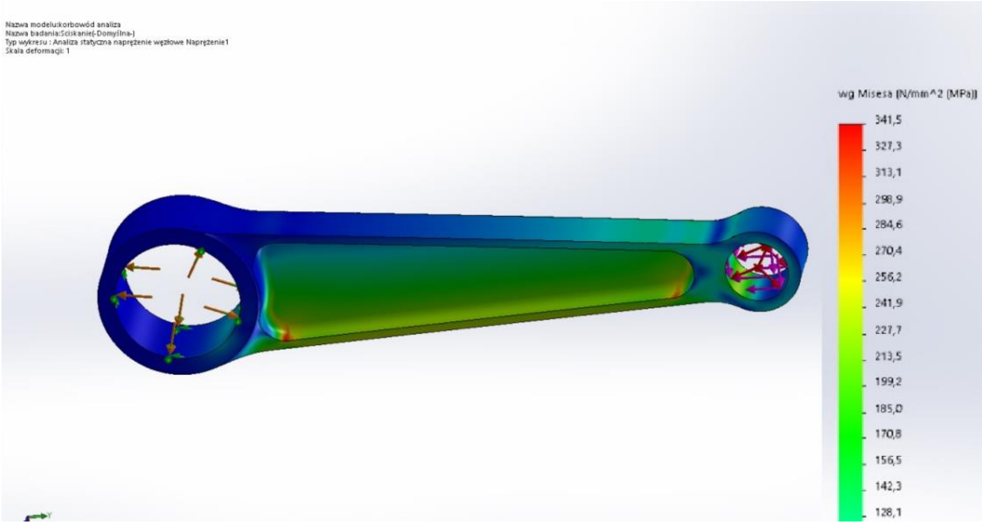

Fig. 5. Simulation results of static strength of the designed connecting rod

During FEM simulations, the following connecting rod loads were taken into account during operation [SAE International 2004, Hoag 2006, Isermann 2014]:

- compressive force from gas forces and inertia forces from reciprocating parts;
- buckling from compressive force (slenderness factor $\lambda \approx 30$);
- rankine's buckling theory was used;
- bending by inertia forces;
- stretching by inertia forces.

The test showed good static strength of the designed element. The maximum stresses occurring are 341.5 [MPa], which meets the given conditions.

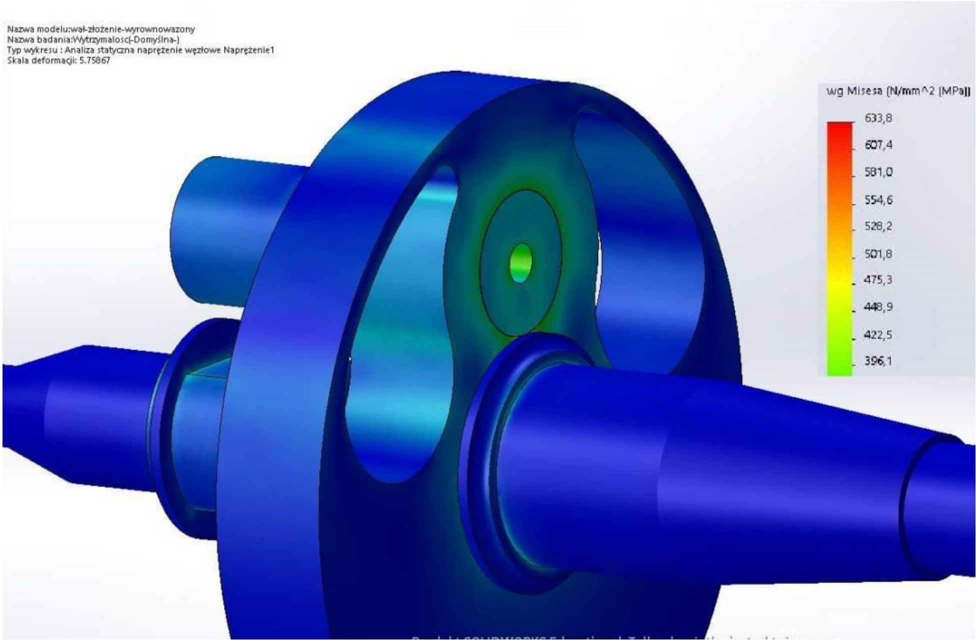

Fig. 6. Simulation results of static strength of the designed crankshaft

During FEM simulation, the following loads acting on the crankshaft during operation were taken into account[SAE International 2004, Hoag 2006, Isermann 2014]:

- press fit crank pin – shaft disc;
- press fit connection of main journals with shaft discs;
- tangential and normal force acting on the crank pin (components of gas forces);
- centrifugal force of parts in rotation.

The results show the highest stresses arising during crankshaft operation. The highest stresses arise where the crank pin connects to the crankshaft disc. They do not exceed the assumed allowable stresses.

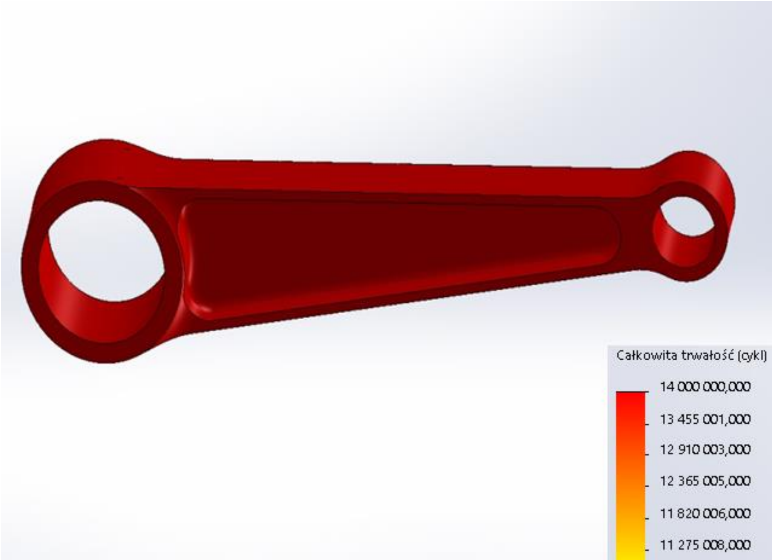

Fig. 7. The simulation result of the connecting rod fatigue strength with Ti6Al4V

The studies show sufficient fatigue strength. The connecting rod exposed to gas and centrifugal forces will not be damaged during 14 million working cycles.

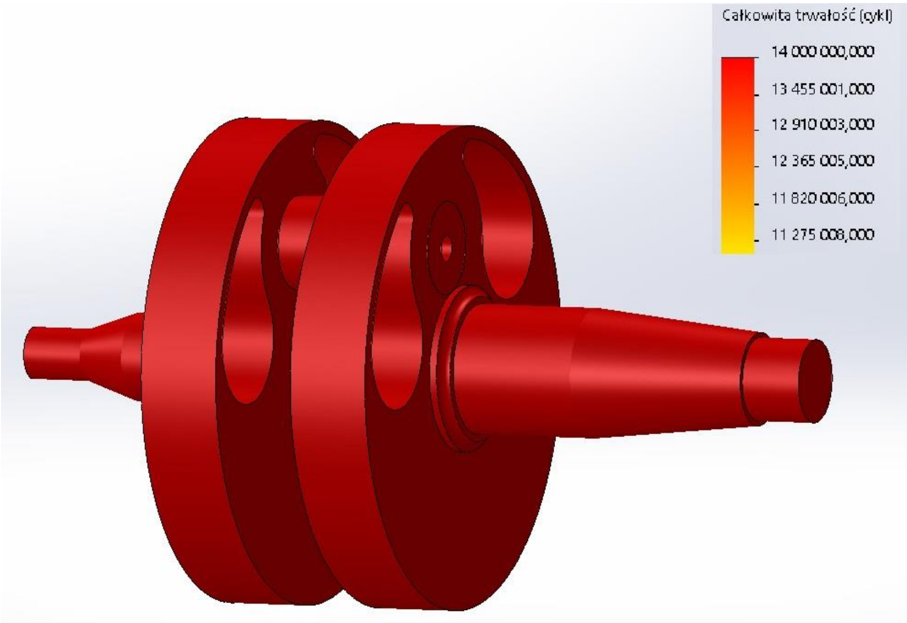

Fig. 8. Results of the crankshaft fatigue strength simulation

The simulation shows the designed element, which is subjected to all of the forces during operation. The study proves that the crankshaft should withstand over 14 million working cycles. This amount is sufficient, considering the very short working time the engine will be subjected to.

5. COMPARISON OF STEEL PARTS PARAMETERS TO TI6AL4V TITANIUM ALLOY PARTS

The main assumption of the project was weight reduction, which results in a reduction of the energy needed to put the parts of the crank-piston system into motion. During the race, the engine is started about 20 times. Knowing the moment of inertia of the crankshaft and connecting rod, the amount of kinetic energy needed to set the part in motion was calculated [SAE International 2004].

The kinetic energy for a steel crankshaft and connecting rod is:

$$E_{ks} = 417.21\ [J]\ (1)$$

and the energy for a Ti6Al4V crankshaft and connecting rod is:

$$E_{kt} = 168.73\ [J]\ (2)$$

which gives us about a 60% reduction of kinetic energy. In order to estimate the reduced fuel consumption, the efficiency of the Piaggio engine was used for calculations. The efficiency of an engine cannot be determined at the design stage.

The adopted efficiency is:

$$\eta = 0.28\ (3)$$

The sum of the kinetic energy difference between the energy of the Piaggio crank-piston system and the designed system is:

$$E_k = 867.8\ [J]\ (4)$$

The calorific value of ethanol is: 21 200 [J/ml]

The estimated difference in fuel consumption of the engine with a connecting rod and crankshaft made of titanium alloy is:

$$\frac{867.8\ [J]}{21200\ [\frac{J}{ml}]} = 0.041\ [ml]\ (5)$$

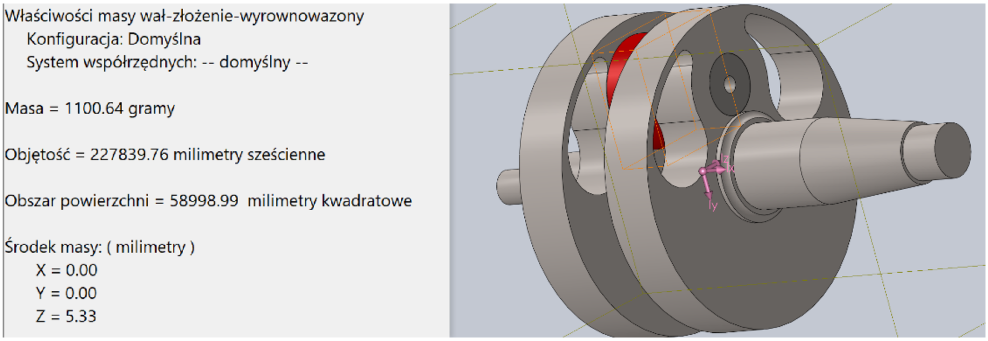

Fig. 9. Results of the crankshaft fatigue strength simulation

Due to the change of dimensions and the change of material from which the parts were made, the mass of the crank-piston system was reduced by almost 50%. The red element in Figure 9 is the equivalent of the connecting rod, piston with pin and rings as well as the bearing masses.

6. CONCLUSIONS

The main goal of the "ROTOR" team is to achieve the best possible result during The Shell Eco-Marathon competition, which is why the team decided to create an engine of their own design, the main elements of which will be made of Ti6Al4V titanium alloy. By using parts of the crank-piston system made of Ti6Al4V alloy, whose energy needed to set it in motion is much lower compared to the mass-produced Piaggio Fly 4T engine crank-piston system, lower fuel consumption was estimated. In addition, the weight of the entire car has been reduced, which will positively affect the final result during the competition. The disadvantage of this construction is the high cost of production due to unit production of parts and the high cost of Ti6Al4V compared to steel.

Using the Solidworks program, simulations of the static and fatigue strength of the designed parts were performed. The results confirm the well-chosen dimensions of the parts and their resistance to forces, which will result in a long and reliable working time.

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