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CHOOSING THE OPTIMUM MATERIAL FOR MAKING A BICYCLE FRAME

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This paper presents the results obtained following the Finite Element Method (FEM) simulations on a bike frame made of 3 different materials, Al6061, Carbon Fiber and Ti6Al4V, in order to identify the optimum material for the manufacture of the respective frame. The parts of the frame made of Al6061, Ti6Al4V will be joined using the WIG method (wolfram inert gas). Considering the results obtained and following the experiments we can see that the optimum material for making the bike frame is Ti6Al4V, but the main impediment for the large-scale use of the material is the high cost

Key words: materials, bike, FEM, stresses, displacements

INTRODUCTION

One of the major problems related to the design of any product is choosing the proper material to withstand all loads and stresses, either permanent or accidental, which may occur during its use. In order to reduce the time needed for the manufacture and trial of the products, a series of simulations may be conducted that could help the designers significantly reduce the number of possible materials the future products may be made of.

In general a bike may be defined as a road vehicle with two wheels, arranged one behind the other, set in motion by two foot pedals. It is estimated that riding a bike is three times more efficient than walking, whereas the speed is three – four times higher [1].

Cycling is divided into the following branches [2 - 4]: BMX; Trial; Street; Dirt; XC – Cross Country; Marathon; Tr – Trail; AM – Allmountain; Fr – Freeride; Dh – Downhill.

The size of the frame is represented by the length of the frame tube from the bottom bracket to the upper side of the seat tube; the sizes vary from category to category and from biker to biker.

Another special feature is at the Dh – Downhill frames, as they have full suspension meaning that the frame consists of the frame itself and a shock absorbing part (either pneumatic or hydraulic).

MATERIALS AND METHODS

At present the following materials are mostly used for making bike frames:

- Al 6061 alloy - for the bikes used in Trial, Street, XC, Tr, Am and Fr;
- carbon fiber - for the bikes used in marathons;
- titanium – it has been increasingly used for making bike frames.

The materials used for bike frames have a wide range of mechanical properties. The mechanical properties of common bike frame materials are listed in Table 1.

There is no material in the table that has advantageous properties in each category, which explains why manufacturers continue to fabricate frames using several different materials.

Among the aluminum alloys used for making bike frames, series 6000 is preferred - represented by aluminum alloys with magnesium and silicon. 6061 aluminum is the most used alloy in this series due to its good machinability. After its machining, the material is subject to a thermal treatment – hardening – to increase the strength properties.

The carbon fiber was initially employed in the automotive industry, on Formula 1 single-seaters, as it has a

Table 1 **Mechanical properties of common bike frame materials**

Characteristic \ Material	Al 6061	Ti6Al4V	Carbon Fiber
Young's modulus / $N/m^2 \times 10^3$	68,9	115	50 - 150
Yield Strength / N/m^2	260 - 290	880 - 1100	Varies
Tensile Strength / N/m^2	300 - 320	950 - 1170	250 - 400
Elongation / %	17	10	2,5
Density / kg/m^3	2,7	4,43	1,800
Weldability and Machinability	Excellent	Fair	Fair
Cost / € per kg	1,5	45	Varies

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reduced weight, has an increased strength and especially an increased safety level due to its capacity to disintegrate into small particles, thus absorbing the energy during a possible impact. The sports models took over elements from motorsport to reduce the weight and obtain improved dynamic performances.

Ti6Al4V alloy is the most used titanium alloy alfa+beta class and is also the most frequently used among the titanium alloys; it can be used in aeronautics, medicine and other applications which require relatively light weight, high strength (at stresses) and good corrosion properties.

EXPERIMENTAL RESULTS

The bike frame is made up to a great extent of tubes made by drawing (Figure 1).

The oval, square, rectangular etc. tubes are obtained by rolling or drawing of semi-finished products with circular section [7]. The dropouts are obtained by casting [8].

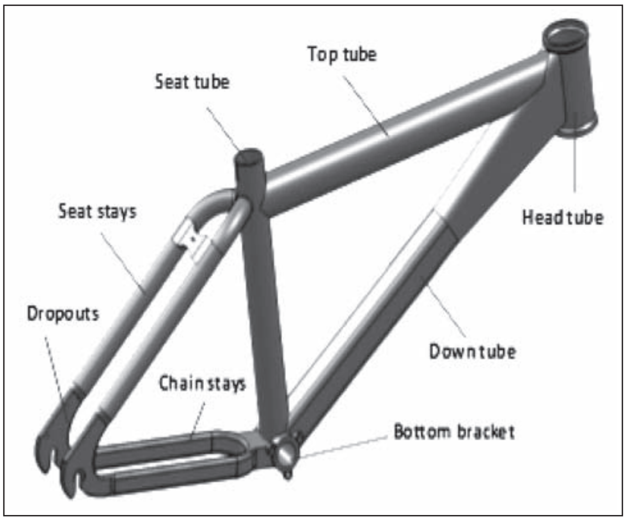

Figure 1 The parts of the 3D model of a bike frame

The assembly of the bike frame, made of 6061 and Ti6Al4V, is carried out by welding using the WIG method, with backing gas protection [9]. When the bike frame is made of carbon fiber, the parts will be assembled by bonding.

The designed bike frame must meet the client's requirements, for instance:

- weight strictly limited to 6 / Kg;
- resistance to the corrosion caused by environmental factors;
- resistance to mechanical shocks;
- no flaws are permitted;
- high dimensional precision
- to comply with the requirements of the standards in force related to safe design [10].

The FEM modeling process requires three types of input data: the geometry, the material properties and the loading. For the bicycle frame, "geometry" means the overall frame dimensions (such as tube lengths, intersection points and angles) as well as the tubing specifications (diameters, wall thickness, tapers, ovals, etc.).

In order to determine the operating behavior, a FEM methodology was developed to predict possible material or welds / bonds failure locations. The methodology consists firstly of establishing optimum dimensions for the frames. Then a solid model is designed and accurate material properties apply for the frames. Lastly FEM model is built, with localized meshing control.

Normally, the results of the structural FEM are provided in the form of displacements and stresses. Von Mises stress, also known as Huber stress, is a measure that accounts for all six stress components of a general 3-D state of stress (Figure 2).

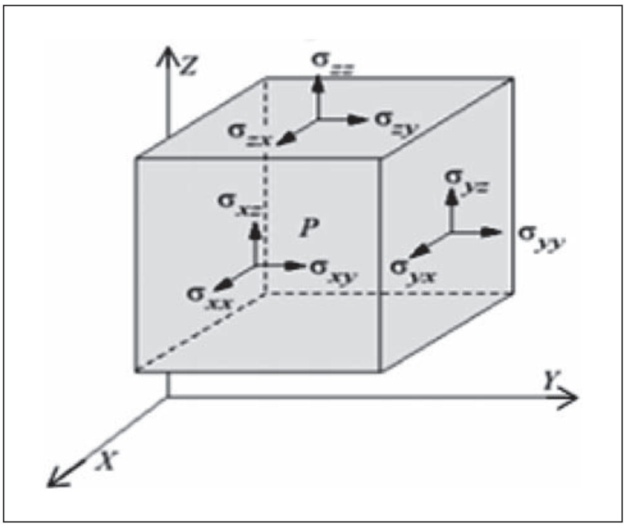

Figure 2 Stress components

One can notice that von Mises stress is a non-negative, scalar stress measure. Von Mises stress is commonly used to present results because of the structural safety for many engineering materials showing elasto-plastic properties (for example, steel or aluminum alloy) [11]. Von Mises stress σ_{vm}, can be expressed either by six stress components as:

$$\sigma_{vm} = \sqrt{0,5[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 3(\tau_{xy}^2 + \tau_{xx}^2 + \tau_{yz}^2)]} \quad (1)$$

Von Misses stress σ_{vm} can also be expressed by its main stress components as:

$$\sigma_{vm} = \sqrt{0,5[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \quad (2)$$

The areas for applying the loads were determined after the design in the specialized software and after obtaining the 3D model. The loading are presented in Figure 3.

Three variants of loads were considered for the FEA, which correspond to the real situations of normal use of the bike frame:

– Variant 1 simulates the forces exercised on the bike frame when the biker sits on the saddle without any other additional forces. The areas of the dropout and the head tube are considered restrained. The

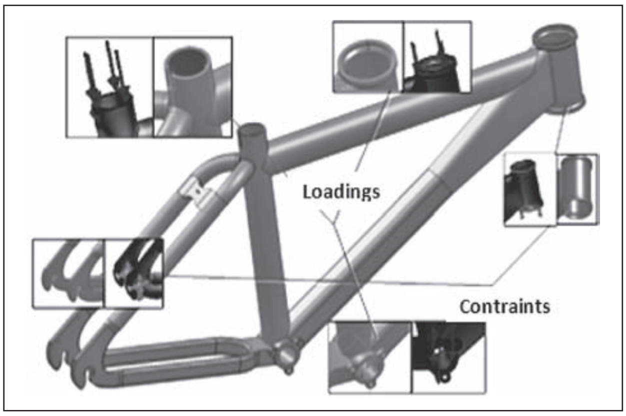

Figure 3 Loading areas on the 3D model for FEA analysis

force applied on the seat tube is equivalent to the biker's weight, respectively 900 / N;

– Variant 2 simulates the situation when the force applied on the bottom bracket is equivalent to the biker's weight (standing on the pedals), respectively 900 / N.
– Variant 3 simulates the case where the force applied is equivalent to the biker's weight and is distributed as follows: 600 / N on the bottom bracket and 300 / N on the head tube, respectively the upper part of the bottom bracket.

After making the 3D model of the bike frame the weight of each material was accurately computed. The obtained values were:

- the Al6061 frame: m_{Al} = 4 026,4 / g;
- the Ti6Al4V frame: m_{Ti}=4 604,46 / g;
- the carbon fiber frame: m_{CF} = 2 699,18 / g.

The stress and displacement values for each case were analyzed after applying the restraints and the forces in the above mentioned areas and after running the finite element analysis program.

Based on the FEM results, there were three main areas on the bike frame with a susceptibility to failure, in all three loading cases [12]. These areas were the top tube near the weld/bond to the down tube, on the down tube near the weld/bond to the seat tube, and on the down tube near the weld/bond to the head tube, Figure 4.

The values of the stresses and deformations resulted after running is presented in Tables 2, 3, 4.

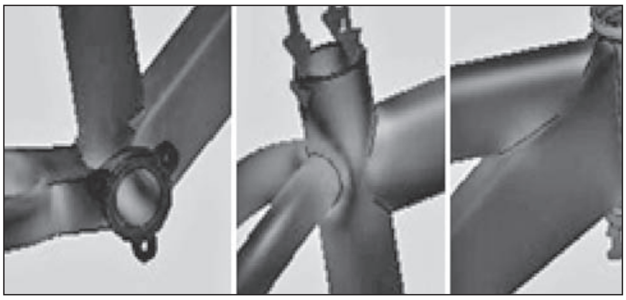

Figure 4 FEA results showing tensile and correlation to failure location

Table 2 **Values of the stresses and of the displacement obtained for the first loading variant 1**

Material \ Characteristic	Von Mises Stresses / N/m^2 x e^{+007}	Displacements / m x e^{-005}
Al6061	1,36401	4,73783
Ti6Al4V	1,44527	3,34074
Carbon fiber	1,60392	1,92872

Table 3 **The stress and displacement values obtained for the second loading variant**

Material \ Characteristic	Von Mises Stresses / N/m^2 x e^{+007}	Displacements / m x e^{-005}
Al6061	1,25107	4,13653
Ti6Al4V	1,34558	3,14053
Carbon fiber	1,61491	1,82767

Table 4 **The stress and displacement values obtained for the third loading variants**

Material \ Characteristic	Von Mises Stresses / N/m^2 x e^{+007}	Displacements / m x e^{-005}
Al6061	1,21087	4,23658
Ti6Al4V	1,24656	3,15069
Carbon fiber	1,51391	1,78888

Three criteria were established and analyzed for the choice of the optimum material out of the 3 materials taken into account for making the bike frame:

- *Cost*. This category includes the costs for obtaining the frame parts, the costs for joining the frame, the costs for the fixing devices for the assembly, the labor costs, etc.;
- *Weight*. This criterion was also analyzed as a lighter frame also implies a smaller effort when riding the bike when all the other bike parts are identical;
- *Mechanical strength of the frame*. This criterion was analyzed due to the shocks the frame is subject to during riding.

Each criterion was granted a weight, k_i, from 1 to 3, according to its importance and to the client's requirements, as follows:

– Cost: 2;
– Weight: 1;
– Strength: 3.

Note: 1 – important criterion;
2 – very important criterion;
3 – decisive criterion.

Each material analyzed based on the criteria and by comparison to the other 2 was granted a grade, N_i, from 1 to 3; the grades are:

1 – satisfactory;
2 – good;
3 – very good.

For each material the points are calculated according to:

$$\sum N_i \cdot k_i \text{ (material)} = N_1 \cdot k_1 + N_2 \cdot k_2 + N_3 \cdot k_3 \quad (3)$$

It is considered that the material with the highest sum $\sum N_i \cdot k_i$ is the optimum material. By replacing the values in formula 1 we obtain:

$$\sum N_i \cdot k_i \text{ (Al6061)} = 1\cdot 2 + 2\cdot 1 + 2\cdot 3 = 10 \quad (4)$$

$$\sum N_i \cdot k_i \text{ (Ti6Al14v)} = 2\cdot 2 + 1\cdot 1 + 3\cdot 3 = 14 \quad (5)$$

$$\sum N_i \cdot k_i \text{ (carbon fiber)} = 3\cdot 2+ 3\cdot 1+1\cdot 3 =12 \quad (6)$$

Table 5 was drawn up with the help of the grades, weights and obtained results.

Table 5 **Grades and weights**

Material \ Criterion	Cost	Weight	Mechanical strength	$\sum N_i \cdot k_i$
Al6061	1	2	2	10
Ti6Al4V	2	1	3	14
Carbon fiber	3	3	1	12
Weight, ki	2	1	3	-

Taking into account the 3 criteria, according to Table 5, the optimum material for the bike frame is Ti6Al4V.

CONCLUSIONS

For the experimental research we analyzed 3 types of materials used for making the bike frames in terms of their strength under the specific stress conditions. In the design stage, FEM is a useful prediction instrument related to the operating behavior as well as to the highly stressed areas of the created 3D model.

Considering the results obtained and following the experiments we can see that the optimum material for making the bike frame is Ti6Al4V, but the main impediment for the large - scale use of the material is the high cost.

For the validation of the created FE model further tests will be conducted on real models and the obtained results will be compared. Furthermore, the created 3D model can be used for carrying out the standard trials that are specific to the analyzed product type.

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