Mechanical, microstructural characterization and redesign of a BMX bicycle frame

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Abstract

The high requirements of Bicycle Motocross (BMX) race conditions demands on the bicycle frame complex dynamic and static loads states by which it is expected that frames to experience high levels of stress and strain. To build efficient bike frames in terms of performance, weight and quality, it is necessary to analyse systematically its response against different loads. The aim of this work is to perform the design of a BMX frame for the national team of Colombia, including the microstructural and mechanical characterization of the initial bicycle frame as complement for the macrostructural characterization of the frame in static conditions. The components of the bike frame were exanimated using optical emission spectrometry, metallographic examinations, microhardness measurements and mechanical tests. It was found that significant differences of the grain sizes of the samples were reflected in the deformation values measured in the frame showing a high structural anisotropy. Despite this, the microhardness and mechanical resistance values the results show coherence between them. In Addition, safety coefficient of the four of the components of the bicycle frame was calculated finding that coefficient values was the calculated safe factor was 4.27. Copyright © 2018 VBRI Press.

Keywords: Bicycle, BMX, design, microstructure, structural characterization.

Introduction

Bicycle Motocross (BMX) is a kind of competition that uses bikes completely different from road and mountain. This sport is gaining popularity in the world, including Colombia, since actual both Women Olympic and World Champion is Colombian. This situation caused that the frame sponsor (Bicicletas GW) wants to improve it structurally. Due to the high requirements of BMX race conditions, frame is subjected to complex dynamic and static loads states. Therefore the frame would be expected to experience high levels of strain due to the elevated demands of mechanical resistance, power and efficiency [1–3]. To build efficient frames in terms of performance, weight and quality, it is necessary to analyze systematically its response against different loads in static (laboratory) and dynamic conditions (field). Despite this, the BMX bicycles are the less studied between the group of bikes used by different cycling disciplines. As consequence, there is poor scientific information about BXM bicycles.

Aluminum alloys are widely used in transportation applications because of their high properties such as good strength, formability, weldability and corrosion resistance [4]. For this reason the bicycle frames are made primarily from aluminum with hydroformed geometries because this process offers a better structural behavior while a good visual appearance is achieved. Commonly, each of the tubes has variable and different cross sections between a tube and another and such tubes have variations in thickness (double butted). The aim of this work is to perform a microstructural and mechanical characterization of the BMX bicycle frame that uses the national team of Colombia with the purpose of complement the frame characterization to enhance its functional performance from discussion of the relationship between the material and structural behaviour by means of the analysis of strain measured on an instrumented BMX frame in order to propose a new material selection for the optimized bicycle frame.

Experimental

For material characterization each of the components were identified as show in **Fig. 1**. The frame was sectioned for chemical composition, microstructure and mechanical behavior. The components were cut to carry out the chemical and microstructural characterization. A Bruker Tasman Q4 optical emission spectrometer was used for chemical composition. On the other hand, parts of the segments prepared and polished until mirror finish. Subsequently, the specimens were etched with Keller and Kroll reagent for 15 seconds. Finally, the samples were rinsed with deionized water and dried in a cold air stream. Microscopic observations were thereafter carried out by optical microscopy using an Olympus GX41 microscope. Microhardness measurements were carried out using an Instron 2100b microhardness testing machine with a Vickers indentation and a load of 300 g applied for 10 s. Tensile tests were performed in an Instron 5584 according to the ASTM E8 standard to obtain the yield strength (σ_y), ultimate tensile strength (σ_{UTS}), and Young´s modulus (E) values. Additionally, to find the strain values of four of the components (*down tube*, *chain stay*, *seat tube* and *top tube*) the BMX frame was instrumented with strain gauges (HBM-120 Ω) **(Fig. 1).** The loads were applied using a testing device which was custom designed and built for this work **(Fig. 1).**

Finally, based on the results, a new material was selected as well as the cross sections of the tubes based on the rigidity criterion thru the calculations of the inercy momentum of each cross section. Finally, a prototype was build and validated again in the test rig showed in **Fig. 1(c).**

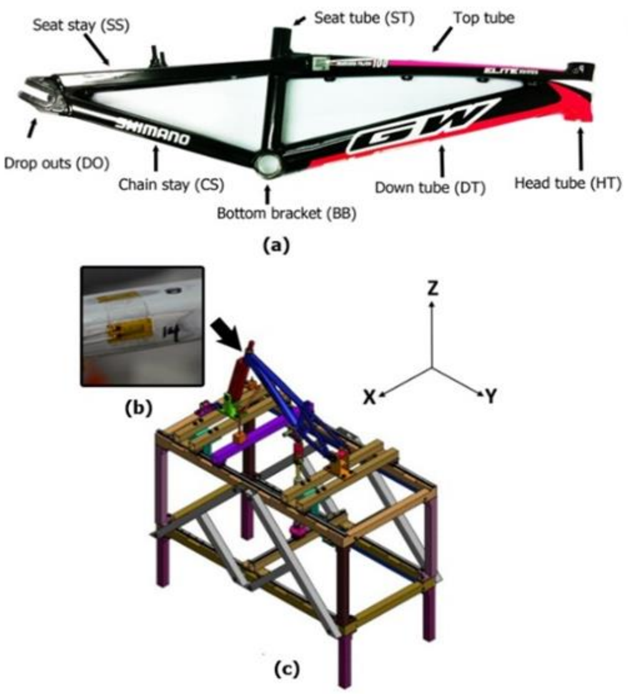

Fig. 1. (a) Components of the analyzed BMX frames (b) Strain gauge on the BMX frame (c) Test rig for the evaluation of the structural performance of bicycle frames.

Results and discussion

Materials/ chemicals details

The result of the chemical characterization shows the following composition (wt. %): Si: 0.614 %, Fe: 0.147 %, Cu : 0.185 %, Mg : 0.829 %, Cr : 0.072 %, Zn: 0.013 %, Ti: 0.027 % and Al: bal. Such values are representative of the whole set of characterized specimens and correspond to the composition of AA6061 aluminum alloy according with the ASTM B308 [5]: Si: 0.4-0.8 %, Fe: 0.7 % max. Cu: 0.15-0.4, Mg: 0.8-1.2, Cr: 0.04-0.35 %; Zn: 0.25 % max., Ti: 0.15 % max., Al: remainder.

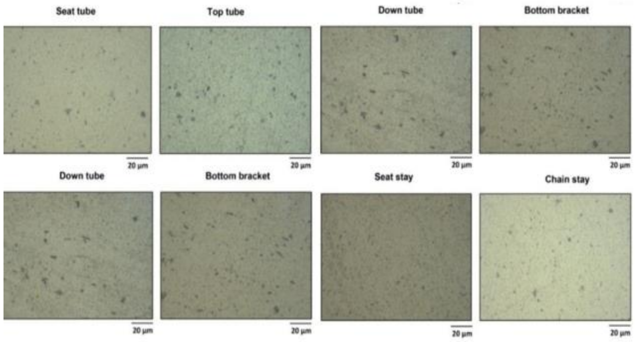

Fig. 2. Optical micrographs at 500 X after etching with Keller´s reagent.

Microstructural characterization

Fig. 2 shows that the microstructure for all the components was similar, being notable the presence of Mg_2Si precipitates which is the main component of 6XXX aluminum alloys series and is present due to the precipitation hardening for the period of artificial aging [6]. The presencee of such precipitates and the simitude of the microstructures is evidence that, besides being of the same material, the same heat treatment was carried out for all the components of the analized frame.

On the other hand, the analysis of grain size, shape and second phase particles distribution gives information related with the heat treatment performed on the components at the same time that show information about the plastic deformation of the material as consequence of the manufacturing process. To see this, samples of the cross sections (transverse - XZ plane) and top (longitudinal - XY plane) of the components were metallographically prepared. **Fig. 3** shows a representative sample of the grain distribution in longitudinal and transverse direction. The measured grain size for each component is described in **Table 1**.

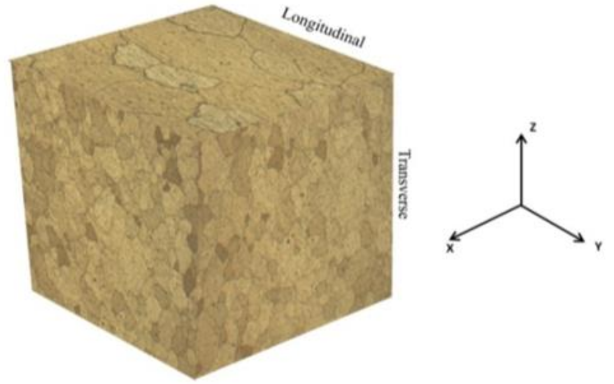

Fig. 3. Optical micrographs of the chain stay at 100 X after etching with Kroll´s reagent.

Microhardness and tensile tests

Fig. 4 shows the microhardness results which are very similar for all studied components (standard deviation less than 3%). The results are according with the literature with hardness values between 90 to 110 Hv [7–9].

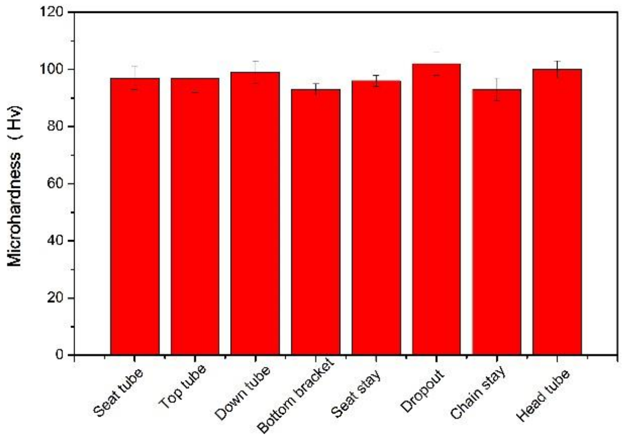

Fig. 4. Microhardness values obtained from different components of the BMX bicycle frames.

It is well known that hardness is related with the tensile strength of different metals. Such correlation allows the mechanical properties examinations in a relatively simple way [10,11]. For this reason the microhardness results were related with the ultimate tensile strength (σ_{UTS}) and tensile yield strength (σ_y) according the follow relationships [10]:

$$Hv = \sigma_{UTS}(1-n)\left(\frac{12.5n}{1-n}\right)^n \quad (1)$$

$$Hv = \frac{\sigma_Y}{3}(0.1)^{-n} \quad (2)$$

where Hv is the Vickers hardness, σ_{YS} is the tensile yield strength, σ_{UTS} is the ultimate tensile strength and n is a correlation factor which is 0.05 for 6061-T6 aluminum alloy [12]. Results of ultimate tensile strength and tensile yield strength obtained using the equation (1) is resumed in **Table** .

Table 1. Values of ultimate tensile strength (σ_{UTS}) and yield strength (σ_y) calculated from hardness measurements.

	ASTM grain size		Mean grain size (μm)		Calculated resistance from hardness measurements	
	Transverse (Z)	Longitudinal (Y)	Transverse (Z)	Longitudinal (Y)	**σUTS (MPa)**	**σ_y (MPa)**
Seat tube (ST)	5.0	4.1	65	86	304	261
Top tube (TT)	6.0	4.3	44	81	301	258
Down tube (DT)	4.9	2.5	65	150	308	264
Bottom braket (BB)	5.6	3.5	51	105	291	250
Seat stay (SS)	6.2	3.7	41	100	299	257
Dropout (DO)	4.7	3.4	69	108	317	272
Chain stay (CS)	4.9	3.9	65	91	288	247
Head tube (HT)	5.1	4.1	61	85	311	267

It is important to mention that tensile test were performed on machined samples from the *chain stay* component in order of verify compliance of equation (1) using the 0.05 value as correlation factor. It was found that that the correlation factor is suitable to make an approach of the mechanical properties (σ_{UTS} and σ_y) since the value by applying equation (1) is close (288 MPa) to the values of ultimate tensile strength obtained with the tension test (297 MPa). The Young´s modulus calculated from the tensile test is 67 GPa.

Structural test to the BMX frame

As mentioned before, gauges were placed parallel to the axis of the tube in order to analyze the strain in tension/compression. The frame was tested under five load conditions defined as *Bottom Bracket Vertical Load* (BBVL), *Fork Lateral Load* (FLL), *Chain Stay Lateral Load* (CSLL), *Fork Frontal Load* (FFL) y *Bottom Bracket Torsional Load* (BBTL). The results of this test are showed in **Table .** Positive and negative values correspond to maximum tensile and compression strains respectively.

Table 2. Maximum strain values for four of bicycle components at different test conditions.

Component	**Strain (με)**				
	BBVL	**FLL**	**CSLL**	**FFL**	**BBTL**
Seat tube (ST)	89	-238	180	322	264
Top tube (TT)	-255	79	-277	207	-187
Down tube (DT)	307	389	-211	677	311
Chain stay (CS)	-214	-53	789	-327	-864

Solving for the relation for maximum stresses, assuming linear elastic Hookean behavior, considering the experimental founded value of 67 GPa of elastic modulus and yield strength value corresponding to the component with the maximum strain value (864 με**)** values for the yield strength of each component **(Table)** and considering the maximum strain value showed in **Table** , the calculated safe factor is 4,27. In addition, the strain values reported in **Table** show the highest values for the chain stay under BBTL and CSLL condition followed by the down tube under FFL condition.

The presence, size and distribution of the Mg_2Si precipitates in conjunction with the similitude of the microstructures is evidence that, besides being of the same material, the same heat treatment was carried out for all the components of the frame. This finding is consistent with the microhardness results that indicate that all the parts used for manufacturing the bicycle frame have a similar heat treatment. Additionally, the relationship between the results of the microhardness and tensile tests suggests that the heat treatment applied to material allowed recovery of the mechanical properties, homogenizing the components of the analyzed frame, which was expected for an aluminum alloy 6061 with a T6 heat treatment. Also, the microstructural characterization shows that some of the longitudinal sections have grain sizes greater compared to the transverse section. This can be explained due to that the effect of the deformation of the shape and size of the grains is produced by the recrystallization. The growth of the grain on the longitudinal section is due to the accumulated deformation energy due the manufacturing process which causes the deformation of the microstructure in that region. In contrast the intern zone (transverse direction) has less deformation than the surface therefore no recrystallization occurs and then the grain size is minor in Z direction.

On the other hand, the analysis of the relationship between the microstructure of the *top tube* and the structural characterization of the instrumented BMX frame shows that the grain size of the transverse section (XZ plane) and longitudinal (XY plane) are 44 µm and 81 µm respectively. This difference suggests major difficulty of movement along the transverse section (Z direction), compared with the longitudinal direction (Y direction) since there are major barriers to movement of dislocations. This is evidenced in the structural characterization of the frame since the lowest values of strain were obtained for FLL condition. Same situation was evidenced for the *chain stay* component. In contrast, the highest strain occurs to the *chain stay* component for BBTL condition (864 µε) condition. This behavior can be associated directly with the microstructure observed for this component, which has large grain size in longitudinal direction (91µm) compared with transverse direction (61 µm).

In addition, the safe coefficients of each component are very dissimilar depending of the type of load situation due to the microstructural differences at different directions which produce a high anisotropy in the material. This suggests that the frame could be lighter finding a better compromise between safety (less than 4,27), weight and functionality.

All the described results allowed to propose a change on the material selecting a material with more rigidity (68.9 GPa) and similar tensile strength (276 MPa) like AA6069-T6 in comparison with the AA6061-T6. It was found that a combination of 6069-T6 aluminum alloy, straight and curved tubing, with hydroformed sections of varying but complementary geometries in terms of sizes and profiles and point structural reinforcements in critical areas improve the overall stiffness of the frame up 10% and diminish the weight of the frame by 12%, while, according to the athletes consulted, also improved the appearance of the bicycle. Fig. 5 shows the final design of the BMX frame.

Conclusions

The grains showed in the micrographs of the longitudinal section are homogeneous which is coherent with the microhardness finding. In addition, grain size of the components observed in transverse is minor than the same for longitudinal direction. Such differences are reflected in the measured strain values explaining its structural anisotropy. The maximum stress observed was about 11 times lower than the yield stress of the material; this ratio could be decreased by reducing the weight of the BMX frame. The corresponding safe coefficients suggest that the frame could be lighter finding a better compromise between safety, weight and functionality. The establishment of a test protocol to optimize the design is important in order to make an approximation to the real conditions, however the human perceptions should be taken in account in future works. The information obtained from this work contributes to the understanding of the material and the structural behavior of bicycle frames providing a better basis for the design of a BMX bicycle frame.

Fig. 5. Final design of the BMX frame used by athletes of the Colombian delegation in the Olympic games of Rio de Janeiro 2016.

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