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INFLUENCE OF ANODIZED DEPTH ON FATIGUE LIFE FOR BICYCLE CRANKS

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ABSTRACT

Bicycle manufacturers are using new materials in order to improve the bicycle performance. In high-level cycling, magnesium, aluminium, titanium and carbon fibre, have replaced steel with the purpose of improving the weight / rigidity ratio.

Due to cost factors and ease of machining, aluminium is widely used in bicycle cranks manufacturing. In order to improve the external aspect of the final product and protect the external surface of the component, some surface treatments must be applied.

In the case of aluminium, anodizing is the most extended treatment, due to several factors as low cost, visual aspect, variety of colours and finishing. However, this treatment may reduce the fatigue resistance of the component.

In this work, the best compromise between anodizing depth and fatigue resistance performance of a bicycle crank has been analysed in order to provide an optimum solution to improve the performance of the component.

KEYWORDS: Fatigue life; Anodizing; Bicycle crank; Aluminium.

1. INTRODUCTION

High level cycling has experienced great technological advances in the last two decades. Not only professional but also amateur cyclist demand the maximum performance for every bicycle component. Therefore, manufacturers have to use increasingly sophisticated materials and designs in order to improve the weight / rigidity ratio.

High performance materials as carbon fiber, titanium or high-strength aluminium, as well as the use of Finite Element Analysis (FEA) in the design process, machining by numerical control (CNC) and surface treatments, are widely used by manufacturers in order to improve these components performance.

Aluminium is the preferred material because it is cheaper and easier to machine than carbon fiber or titanium. Furthermore its relationship weight / rigidity is better than the one the steel

However, manufacturers have to take into account the security of the cyclist. Unexpected failures of some components can cause serious injuries to users, so they have to be prevented.

To ensure that these components meet minimum strength and durability requirements, CEN (European Committee for Standardization) published the standard EN 14781:2006 (European Committee for Standardization, 2006). This standard states the safety and performance requirements that every component must fit from the point of view of fatigue failure.

Fatigue life depends significantly on surface condition. The fatigue life of a component decreases with an increase in surface roughness. In most cases, fatigue failure begins at the surface of the part. Roughness in this area is supposed to introduce stress concentrators that encourage the crack nucleation and accelerates the fatigue crack growth (Suraratchai, Limido, Mabru, & Chieragatti, 2008). This effect is more pronounced in high cycle fatigue.

Aluminum alloys of the 7000 series are attractive to be used as structural component because of their high fatigue strength, which is achieved by a proper material selection and heat treatment (in this case, T6), in order to develop fine strengthening precipitates. However, these precipitates usually cause localized corrosion such as pitting corrosion and intergranular corrosion, due to the potential difference between the precipitates and the matrix (Wei, Liao, & Gao, 1998).

The bicycle cranks studied in this paper, work under different environmental conditions. Thus, corrosion resistance of these components is an important aspect to be taken into account. To prevent corrosion failure and enhance corrosion resistance, anodizing is the most typical process used for aluminum alloys (ASM Handbook Committee. & ASM International. Handbook Committee., 1978). Despite the benefits in corrosion properties achieved with this process, anodizing has adverse effect on fatigue life of aluminum alloys (Chaussumier, Mabru, Shahzad, Chieragatti, & Rezai-Aria, 2013; Shahzad, Chaussumier, Chieragatti, Mabru, & Rezai-Aria, 2010). It is generally accepted that this reduction in fatigue life is directly attributed to the brittle and porous nature of oxide layer and tensile residual stress induced during anodizing process (Cirik & Genel, 2008). Moreover, localized corrosion, in the form of pits, emerges during pre-treatments and these pits accelerate crack nucleation during subsequent fatigue loading (Dolley, Lee, & Wei, 2000; Pao, Gill, & Feng, 2000).

Hemmouche et al. (Hemmouche, Fares, & Belouchrani, 2013) studied the effect of different tempers (naturally and artificially ageing (T4 and T6) and overageing (T7) conditions before sulphuric anodization. Their results showed a decrease in fatigue life of anodized specimens ~~as~~ compared with the untreated ones, this phenomenon been more pronounced in the T6 and T7 states.

The thickness of layer of anodized samples was different for the different tempers due to the size and the spacing of the precipitates (Fares, C., Belouchrani, M.A., Bellayer, S., Boukharouba, T., Britah, 2011). Fares et al. (Fares et al., 2015) demonstrated that sulphuric acid anodizing does not have significant effect on the static mechanical properties of a 2017A aluminium alloy, with the exception of ductility, which is significantly impaired. At high alternating stresses, they proved that the anodic film does not seem to have a pronounced effect on fatigue crack growth. However, the results obtained from fatigue testing at low alternating stresses showed that anodizing reduces significantly the fatigue life of the alloy. The decrease in fatigue life was attributed to the preferential dissolution of the matrix around cathodic particles, such as Al_2Cu which gave rise to the formation of cavities that acted as stress concentrators and promoted the nucleation of many small fatigue cracks. On the other hand, Shih et al. (Shih, Lee, & Jhou, 2014) showed that the fatigue strength decreases as the thickness of anodic aluminium oxide film increases.

Many sources in the available literature provide evidences that the reduction in fatigue life is not only due to the brittle properties of the aluminium oxide after anodizing process, but also to the film thickness, type of anodizing process and surface treatment prior anodizing. However, previous studies use general specimens in their experiments and fatigue bending conditions in one plane.

The novelty of this paper consists in the use of real parts in real work conditions with combined bending loads on various planes as well as torsion loads. These specimens thus involve results that are more realistic. The aim of this study is therefore to analyse the effect of the depth of anodizing on fatigue life of aluminium alloy 7075 T6 bicycle cranks, under the testing conditions of standard EN 14781:2006 (European Committee for Standardization, 2006).

In this particular application, the bicycle crank must be as light as possible but maintaining a high rigidity ratio and a fatigue life up to the minimum required by the standard. Starting from the performances of standard cranks, a new crank design will be optimized by reducing the weight, improving the weight / rigidity ratio and overcoming the established fatigue life.

To achieve this goal, it is necessary to select the best-anodized depth that allows to obtain a good crank protection with the best mechanical performances. The paper studies the deterioration in fatigue life due to different depth of anodizing in bicycle cranks and proposes an optimal value in order to improve the weight, rigidity and fatigue life ratio.

2. SULFURIC ACID ANODIZING

Natural oxide layer formed at the surface of aluminum components is not enough to ensure a sufficient resistance in severe environmental conditions. Anodizing process is widely used in order to increase the wear and corrosion resistance of materials.

Anodizing is an electrolytic process that produced amorphous aluminum oxide at the surface (ASM Handbook Committee. & ASM International. Handbook Committee., 1978). This surface treatment includes a degreasing step to ensure a clean surface. This step is followed by a pickling step to remove the natural oxide layer and to improve surface finish. But during pickling process, according to aluminum alloy and pickling conditions, several pits can be produced due to the dissolution of intermetallic particles or aluminum matrix (Liu, Li, Li, & Huang, 2009). After pickling step, the anodizing process takes place.

Anodizing is accomplished by immersing the aluminum into an acid electrolyte bath. The aluminum parts are the anode and current is passed between them and a cathode (mounted to the inside of the anodizing tank) through the electrolyte (sulfuric acid is most commonly used). In that way, oxygen ions are released from the electrolyte to combine with the aluminum atoms at the surface of the part being anodized. Anodizing is, therefore, a matter of highly controlled oxidation. Thus, a layer of aluminum oxide (alumina) is formed which covers the surface of the part. The oxide build up changes the surface of the aluminum, which then provides greater abrasion resistance as well as increased corrosion protection. The finish from sulfuric anodizing will not only build up the aluminum oxide on the surface (2 - 3μm thick), but will also penetrate into the material the same amount. This aluminum oxide is not applied to the surface like paint or plating, but is fully integrated with the underlying aluminum substrate, so it cannot chip or peel. It has a highly ordered, porous structure that allows for secondary processes such as coloring and sealing.

There are several types of anodizing, most commonly referred to as Chromic Acid Anodize, Sulfuric Acid Anodize, and Hard Anodize. Other less common types are phosphoric acid and titanium anodize. The sulfuric acid process is the most common method for anodizing. It is particularly suited for applications where hardness and resistance to abrasion is required. The porous nature of sulfuric acid films prior to sealing is used in the production of colored surface finishes on aluminum and its alloys. Sulfuric Acid

Anodizing have several benefits: it is less expensive than other types with respect to chemicals used, heating, power consumption, and length of time to obtain required thickness; more alloys can be finished; it is harder than Chromic Acid Anodize; and a clearer finish permits dying with a greater variety of colors.

It should be recalled that anodizing is responsible for a fatigue resistance decrease. Numerous researchers explain this phenomenon by the porous nature and the brittle behavior of the oxide layer, and the tensile residual stresses at the interface between oxide layer and substrate. While some others notice the presence of pits defects at the surface as responsible for too (Chaussumier, Mabru, Chieragatti, & Shahzad, 2013). According to previous studies (Hockauf et al., 2011), the crack transition is enhanced for thicker coating layers. Consequently, the coating thickness plays a crucial role for the overall fatigue strength. Thus, the aim of the anodizing process should be the production of coatings with minimal thickness, however, considering the requirements concerning wear and corrosion resistance.

3. IN- SERVICE LOADS IN THE CRANKS

Stress distribution in a bicycle crank is very complex. When the load is applied in the pedal by the cyclist, combined torsion and flexion loads appear in the crank in two different planes, producing the deformation shown in Figure 1 (the results shown in Figure 1, come from a finite elements simulation model performed by the authors (Calvo Ramos, Álvarez-Caldas, Quesada, & San Román, 2015)).

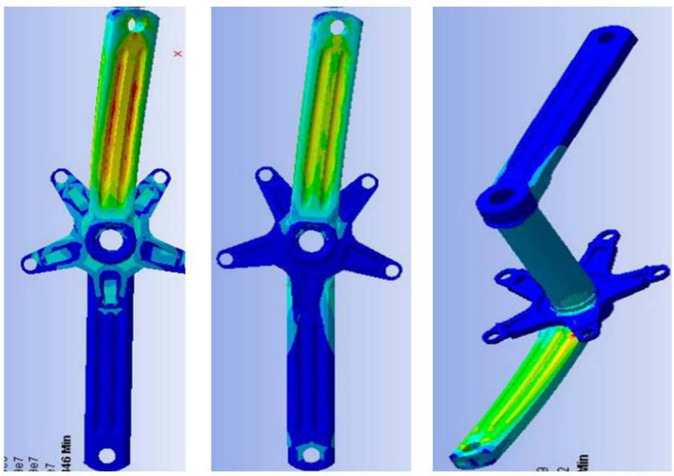


Figure 1. Deformed shape of the crank under in-service loads

4. FATIGUE- STRENGH TEST

According to chapter 4.12.7 of the standard (European Committee for Standardization, 2006), bicycle cranks have to overcome a fatigue- strength test. In such a test, the assembly (including the chain ring and the bottom bracket with its bearings) has to be fixed to an implement that represents the bicycle frame. The angle between the crank and the horizontal plane has to be 45 degrees, and the assembly has to be blocked with the chain so that the crank cannot turn.

Afterwards, a vertical sinusoidal load is applied in a point placed on the pedal axle at a distance of 65 mm from the crank. The load varies from 0 to 1800 N with a maximum frequency of 25 Hz. Figure 2 shows the test assembly. The crank is considered suitable if it overcomes 100.000 load cycles and no defect appears during the test.

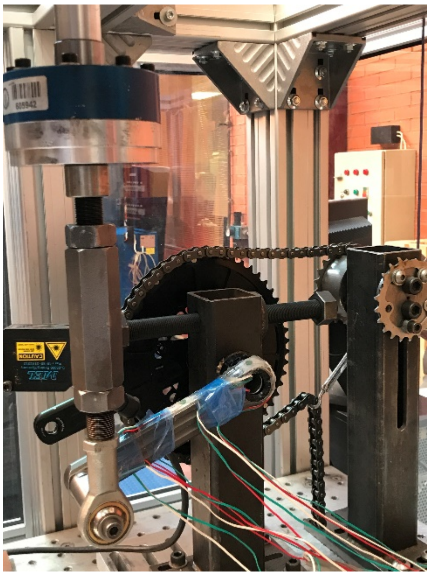


Figure 2. Cranks placed on test rig

5. TEST PROCEDURE

Under previous test conditions, 25 bicycle cranks have been tested. All cranks tested have been manufactured from the same aluminium 7075 T6 bar. All of them have been machined in the same CNC machine and the same working day. Moreover, the same surface treatment of anodized has been applied at the same time on all the cranks but with different depths of treatment.

For each depth of anodizing, five cranks have been tested, as indicated in Table 1. Additionally, five cranks without anodized treatment and five others with have been also tested and will be used as reference, and five standard cranks have been tested under the same conditions. These standard cranks are heavier than those used for the study and have an anodizing depth of 15 µm.

Table 1. Tested items

Item	Anodizing depth
Crank # 1, 2, 3, 4, 5	Without anodize
Crank # 6, 7, 8, 9, 10	5 µm
Crank # 11, 12, 13, 14, 15	10 µm
Crank #16, 17, 18, 10, 20	15 µm
Standard Crank # 21, 22, 23, 24, 25	15 µm

A hydraulic cylinder, that has a load cell and a displacement sensor, controls the load that is applied in the test. A data acquisition system registers the values of the load applied by the cylinder on the pedal axle and the displacement of this cylinder. Each specimen has been tested until a crack appears. This fact is monitored and controlled by the acquisition system. Figure 3 shows tested cranks with different anodizing depth

Figure 3. Tested cranks with different anodizing depth

Before starting the fatigue test, a vertical rigidity measure has been performed in each tested item in order to verify that all cranks have the same performances.

Table 2 summarized the physical properties of the tested cranks. The first four types correspond to the new and lighter crank design with higher weight/rigidity ratio and different anodized depths. The last type corresponds to the standard crank initially designed by the manufacturer with an anodized depth of 15µm.

Table 2. Cranks physical properties

	w/o Anodized	5 µm	10 µm	15 µm	Std Crank (15 µm)

Item	Weight (g)	*VR	Weight (g)	VR	Weight (g)	VR	Weight (g)	VR	Weight (g)	VR
1	223,0	20.3	221,0	20.1	220,0	20.4	221,0	20	254	22
2	221,0	20.1	220,0	20.1	221,0	20.1	222	20.1	251	22,3
3	223,0	20.2	223,0	20.2	220,0	20.2	219	20.1	253	22,2
4	221,0	20.1	221,0	20.2	222,0	20.2	220	20.1	252	22,2
5	223,0	20.3	220,0	20.3	220,0	20.3	221	20.2	254	22,3
Mean	222,2	20.2	221	20.2	220,6	20.2	220,6	20.1	252,8	22,2
Std. Dev.	1,1	0.1	1,2	0.08	0,9	0.11	1,1	0.07	1,3	0,13

*VR= Vertical Ridigity (daN/mm)

It can be observed that the new crank design reduce a 13 % the weight of the component for the same anodized depth, as well as, the ratio rigidity / weight, increase a 3,6 %

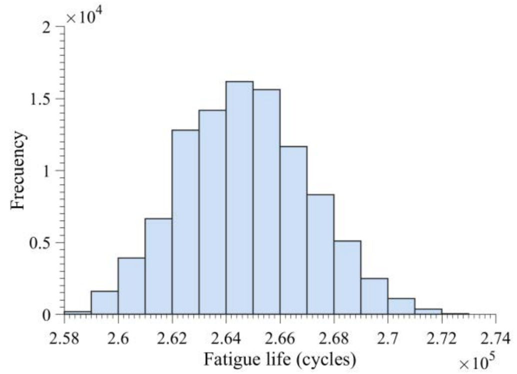
The relationship between the fatigue cycles until failure vs anodizing depth has been analysed. Table 3, shows the results of the performed tests.

Table 3. Test Results

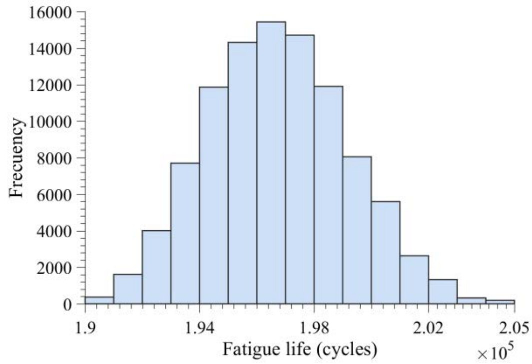
	w/o Anodized	5 µm	10 µm	15 µm	Std Crank (15 µm)
Item	Cycles	Cycles	Cycles	Cycles	Cycles
1	264.000	205.000	128.000	96.000	122.000
2	273.000	195.000	130.000	92.000	118.000
3	258.000	190.000	141.000	85.000	131.000
4	261.000	201.000	135.000	91.000	125.000
5	268.000	193.000	138.000	88.000	127.000
Mean $\bar{L}_f$	264.800	196.800	134.400	90.400	124.600
Std. Dev. $s\left(\bar{L}_f\right)$	2.362	2.446	2.160	1.662	1.721

The mean and standard deviation shown in Table 3 have been calculated using the non-parametric resampling technique known as bootstrap method (Efron, 1992). This techniques allows to generate a frequency distribution of the sample mean without make any assumptions about the distribution's sample (Ong, 2014).

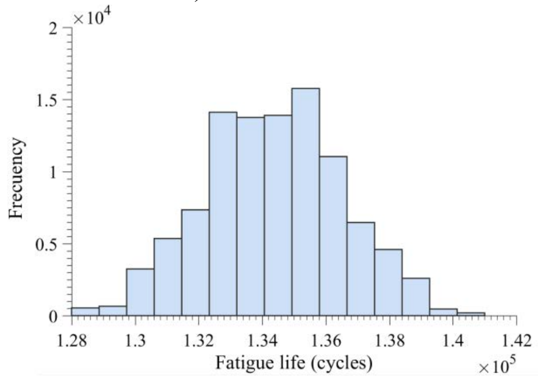
Figure 4, shows the probability density distribution of the mean of the four tested cranks, obtained from 100.000 bootstrap samples. It can be deduced that the distribution found follows a normal distribution tendency. This allows to verify that there is a tendency in the fatigue life of the alternative tested cranks.



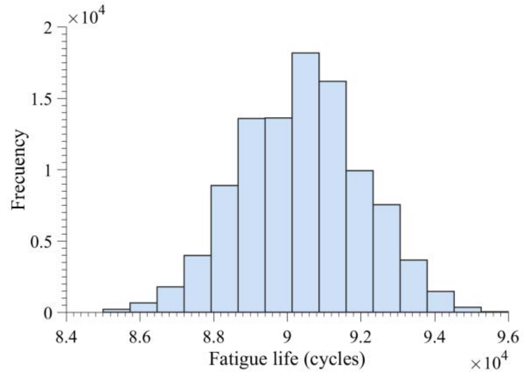
a) Without anodized



b) 5 µm anodized depth



c) 10 µm anodized depth



d) 15 µm anodized depth

Figure 4. Bootstrapping distribution of the fatigue life for the alternative tested cranks

According to the Guide to the Expression of Uncertainty in Measurement (GUM) (Joint Committee Guides Metrology, 2008) the experimental standard deviation of the mean, $s\left(\bar{L}_f\right)$, can be used as a measure of the uncertainty of $\bar{L}_f$. Moreover, a relative standard uncertainty of the fatigue life can be calculated $s\left(\bar{L}_f\right)/\bar{L}_f$ as an indicator of the quality of the results. Figure 5 shows the evolution of the relative standard uncertainty of the fatigue life $s\left(\bar{L}_f\right)/\bar{L}_f$ with respect to the anodized depth A_d.

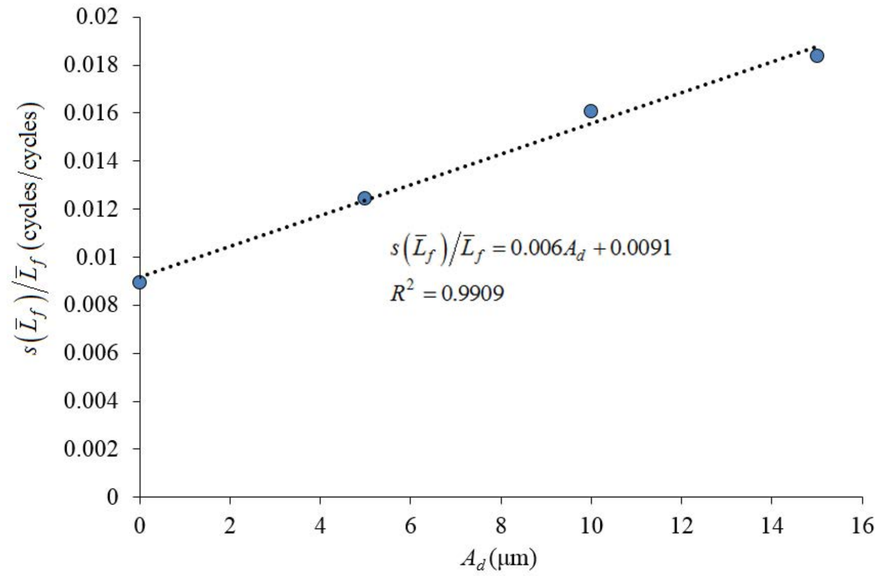


Figure 5. Evolution of the relative standard uncertainty of the fatigue life with respect to the anodized depth

According to Figure 5, there is a linear relationship between the relative standard uncertainty of the fatigue life and the anodizing layer. The lowest $s\left(\bar{L}_f\right)/\bar{L}_f$ value has been observed in the crank without anodized (close to 0.9%). In contrast, the greatest magnitude of the relative standard uncertainty corresponds to the anodized depth A_d =15 μm, with a value close to 2%. This informs that a greater dispersion of probable values of the fatigue life is expected as the depth of anodizing increases, so that the behavior of the crank is less predictable affecting to the quality and performance of the component. This could be due to the facts observed by (Chaussumier, Mabru, Chieragatti, et al., 2013; Hockauf et al., 2011).

They concluded that the decrease of the fatigue life could be due to the brittle nature of the anodize layer and the surface degradation of the anodized specimens, that produce stress concentration zone an early fatigue crack initiation. The random nature of the surface degradation due to a higher layer of anodized could be the main cause of the increase in the dispersion of the possible values of the fatigue life observed in Figure 5.

Figure 6 represents the mean values of table 3 and shows how the fatigue strength of the crank varies when the anodizing depth increases.

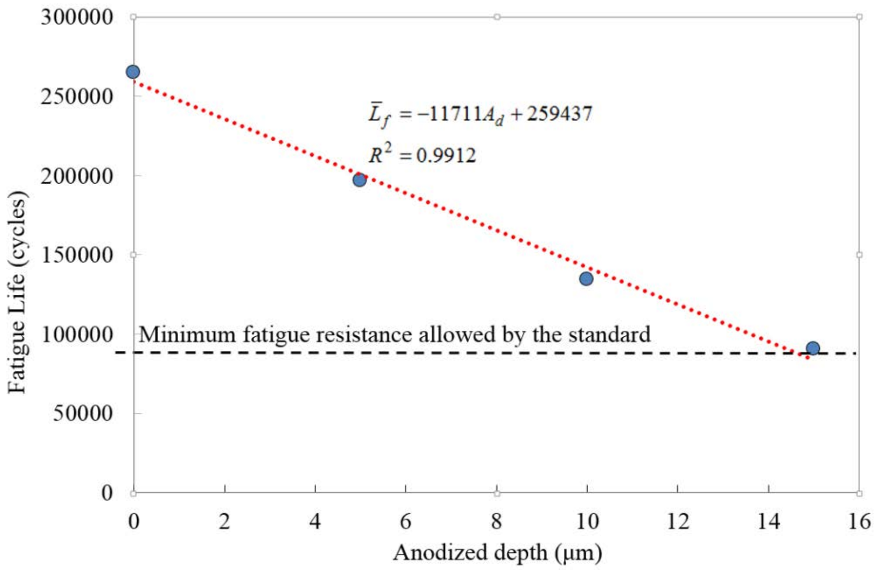


Figure 6. Performance of the tested cranks in terms of the fatigue life and the anodized depth

Figure 6 indicates that there is a strong lineal relationship between the fatigue life $\bar{L}_f$ of the crank and the anodized depth A_d, according to the regression factor R^2. The fatigue life of the crank with respect to the anodized depth can be calculated with the following linear expression:

$$\bar{L}_f = mA_d + c_o \tag{1}$$

Where: $m = -11711 \ (cycles / \mu m)$ and $c_o = 259437 \ (cycles)$

Expression (1) allows to determine the maximum anodized depth (2) that ensure the compliance with the minimum fatigue resistance allowed by the standard.

$$A_d = \frac{\bar{L}_f - y}{m} \tag{2}$$

It is important to consider that the value obtained by (2) is not unique, due to the probabilistic nature of the parameters involved in the calculus of A_d, i.e. the uncertainty of the variables. Applying the law of propagation of uncertainty to equation (2) and considering that there is no correlation between the variables (Joint Committee Guides Metrology, 2008), the combined variance of the anodized depth will be:

$$u_c^2(A_d) = \left[\frac{\partial A_d}{\partial \bar{L}_f} u\left(\bar{L}_f\right)\right]^2 + \left[\frac{\partial A_d}{\partial c_o} u\left(c_o\right)\right]^2 + \left[\frac{\partial A_d}{\partial m} u\left(m\right)\right]^2 \tag{3}$$

The probable value of the anodized depth A_d will be within the range $\left(A_d - \left[k \cdot u\left(A_d\right)\right]; A_d + \left[k \cdot u\left(A_d\right)\right]\right)$ where k is the coverage factor (Joint Committee Guides Metrology, 2008) for a certain probability of failure assumed by the manufacturer

The minimum value of anodized depth A_d assuming a probability of failure of 1 % will be then:

$$A_{d\_opt} = A_d - \left[k \cdot u\left(A_d\right)\right] \quad (4)$$

Where, k = 3 for a confidence level of 99,73 % (GUM).

According to equation (3) the uncertainties $u\left(\bar{L}_f\right)$, $u\left(c_o\right)$ and $u\left(m\right)$ have to be calculated. $u\left(\bar{L}_f\right)$ can be determined by representing the mean and standard deviation of table 3 considering that $u\left(\bar{L}_f\right) = s\left(\bar{L}_f\right)$ according to (Joint Committee Guides Metrology, 2008), as shown in Figure 7.

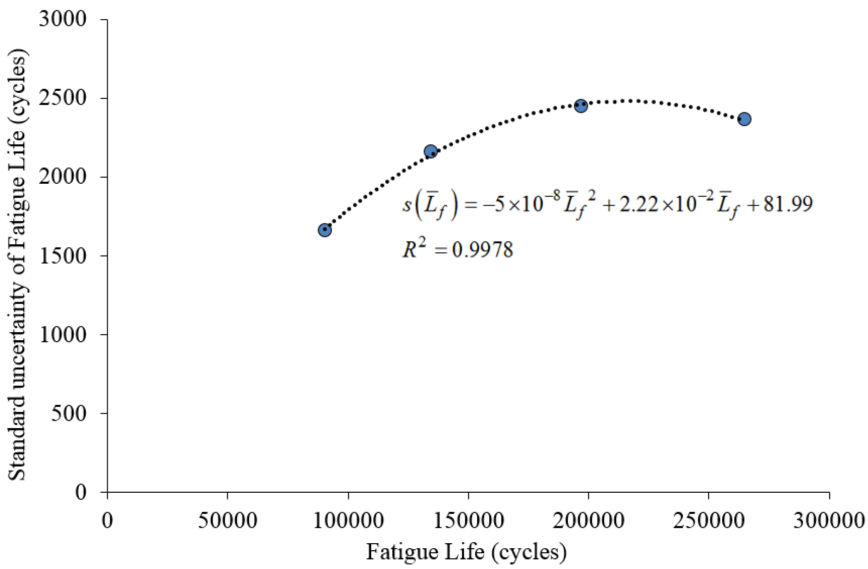


Figure 7. Evolution of the standard uncertainty with respect the fatigue life

Figure 7 indicates that the evolution of $s\left(\bar{L}_f\right)$ presents a second order polynomial behaviour with respect to the fatigue life resistance of the cranks. Therefore, with this polynomial expression it is feasible to find the value of the uncertainty for the minimum fatigue resistance allowed by the standard $\left(\bar{L}_{f\,\min} = 100000 \text{ cycles}\right)$.

Table 4 shows the optimum anodized depth (4) for a confidence level of 99.73 % for the new crank design and all the sources of uncertainty of equation (3). The uncertainties of the slope *m* and the intercept c_o where calculated following Gabauer´s recommendations (Gabauer, 2000).

Table 4. Optimum anodized depth prediction for the minimum fatigue resistance allowed by the standard

A_d (µm) (2)	$u(m)$ (cycles/µm)	$u(b)$ (cycles)	$u\left(\bar{L}_{f\,\min}\right)$ (cycles) From Figure 7	$u(A_d)$ (µm) (3)	$U_{99}(A_d) = 3 \cdot u(A_d)$ (µm)	A_{d_opt} (µm) (4)
13.61	780.50	7301	1802	1.11	3.33	10.28

The results of table 4 have been calculated considering the minimum number of cycles indicated in the standard $\left(\bar{L}_{f\,\min} = 100000 \text{ cycles}\right)$ and a confidence level of 99.73%. The minimum value of anodized depth A_{d_opt} is then 10.28 µm.

6. CONCLUSIONS

According with the results and analysis exposed in this paper, the following conclusions can be drawn.

The previous research demonstrates that the anodized depth reduces considerably the fatigue life of an aluminium part, and in particular for the bicycle cranks tested.

In this work, a linear relationship between the anodized depth and the fatigue life cycles has been found for this particular component. This has allowed to find the optimum anodizing depth value that allows to overcome the fatigue limit established in the reference standard with an acceptable confidence level.

In order to reduce the number of tests and increase the confidence level, the results have been calculated using uncertainty theory and bootstrapping techniques, minimizing thus the time and economical costs.

The reduction to 4µm of the anodized depth in the new crank design, allows to maintain the crank fatigue life performances while reducing the weight 13 %. Moreover, the stiffness to weight ratio improves 3 % from the standard cranks.

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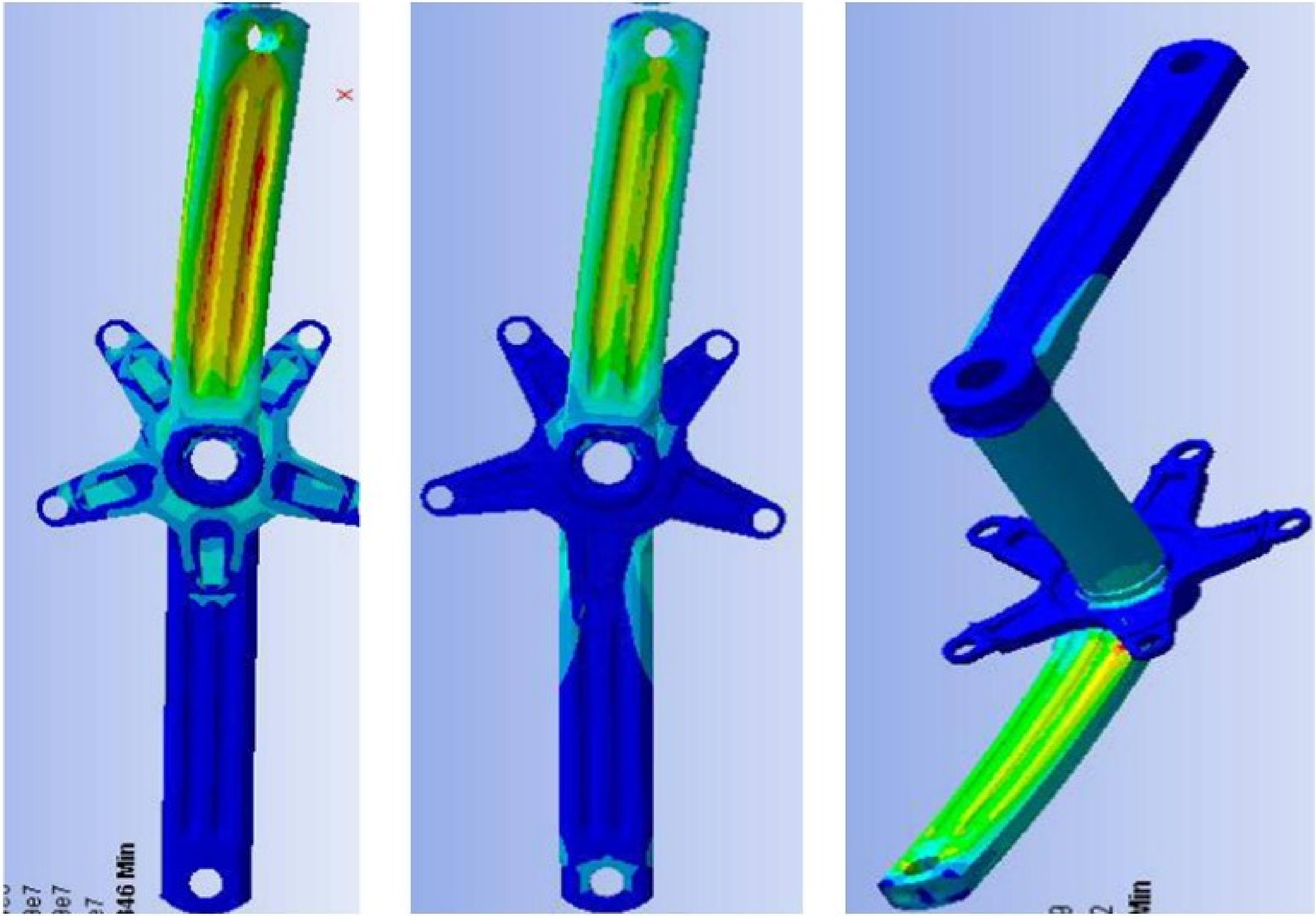
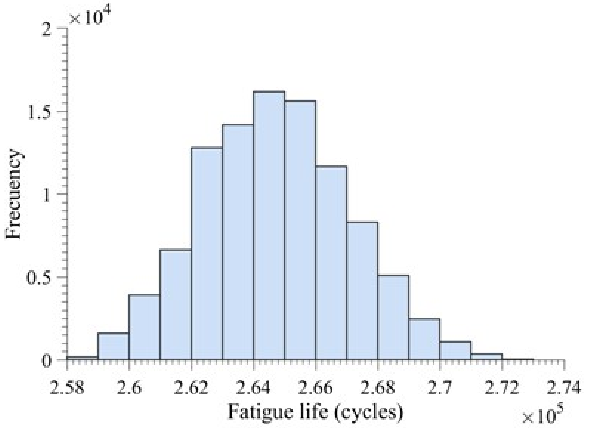
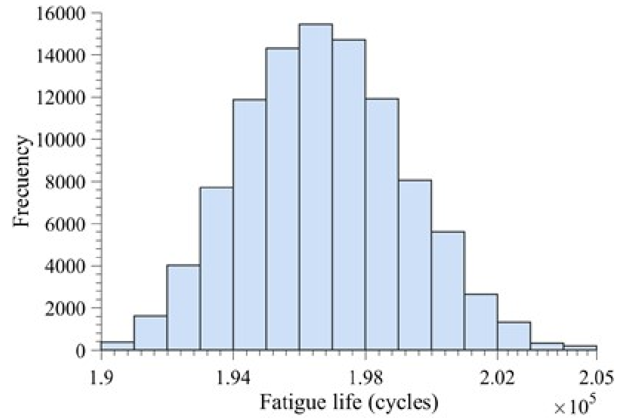



605942

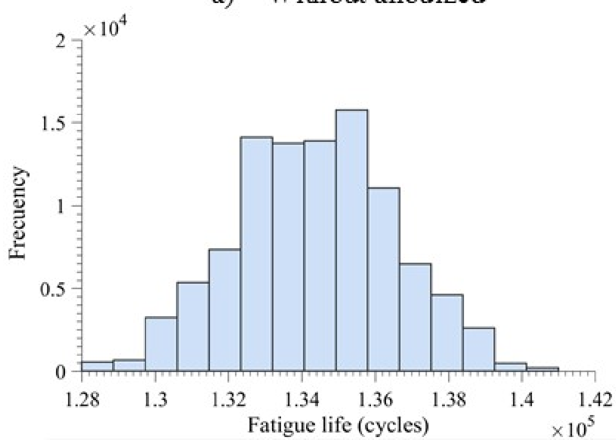

Without Anodized
10 µm depth
5 µm depth
15 µm depth



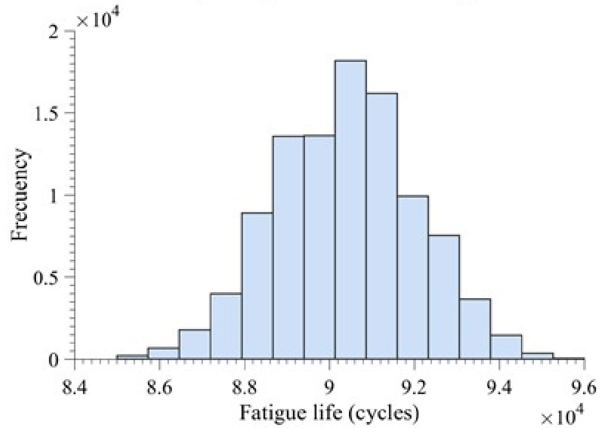
a) Without anodized



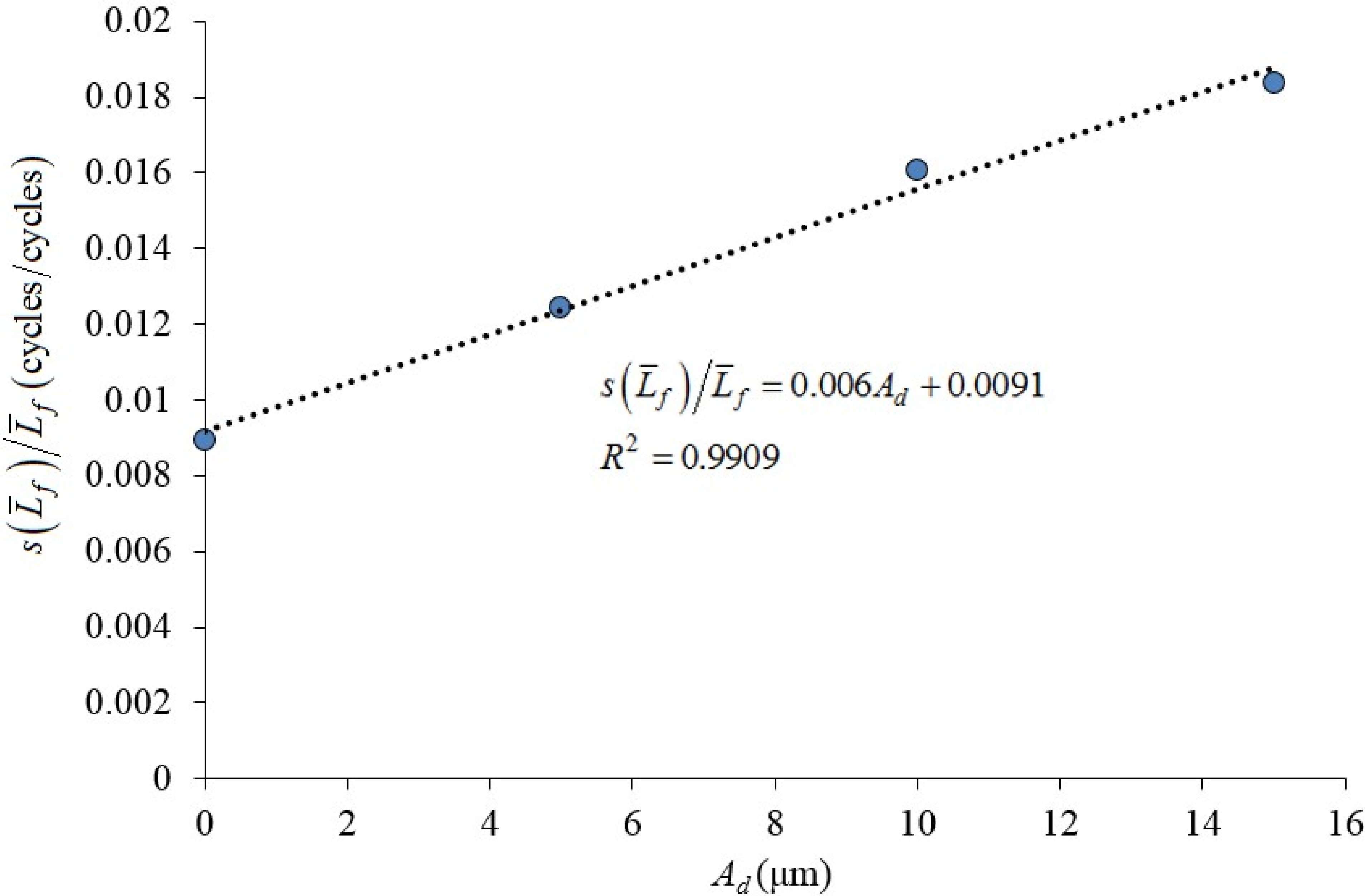
b) 5 µm anodized depth



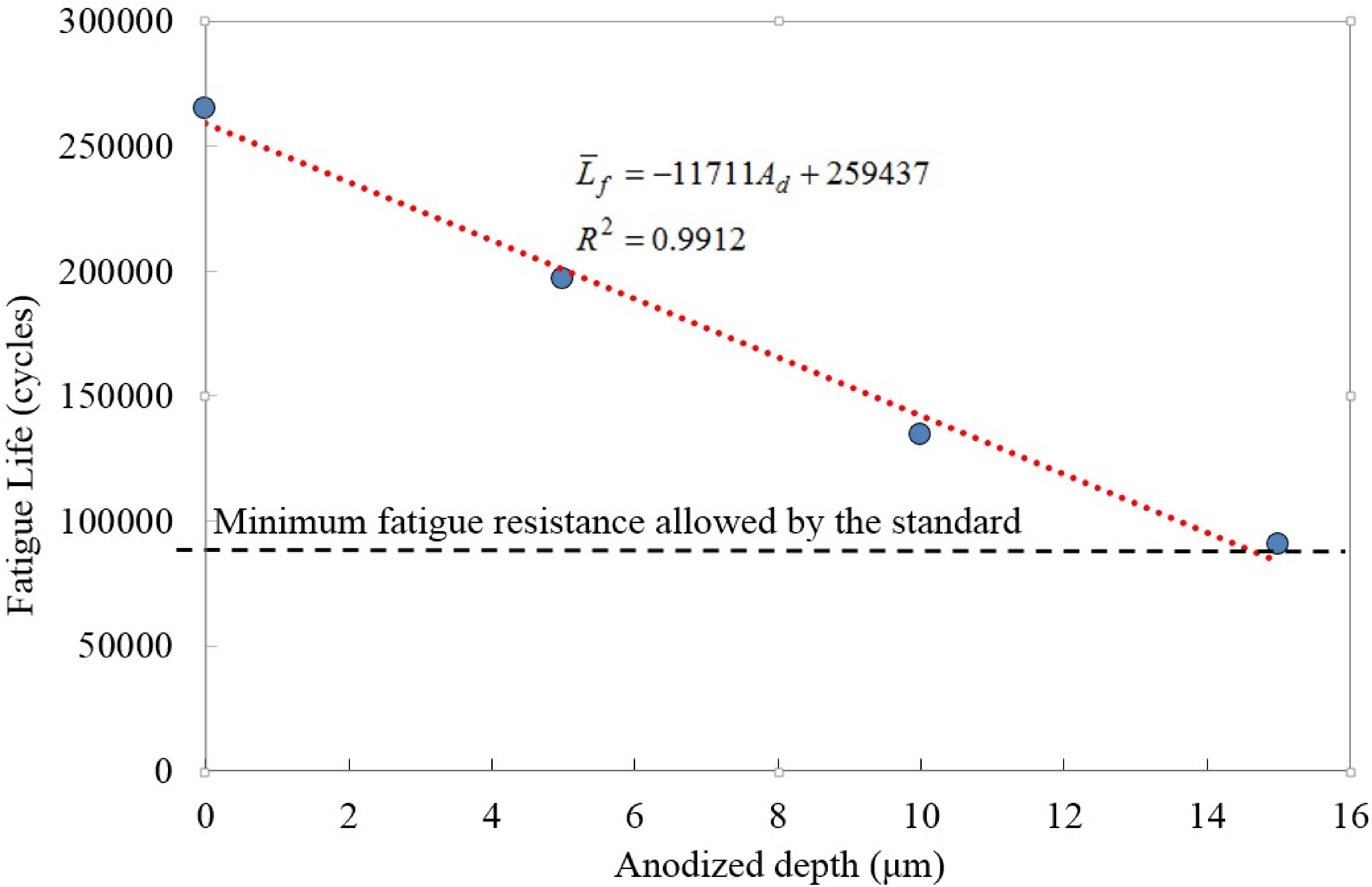
c) 10 µm anodized depth



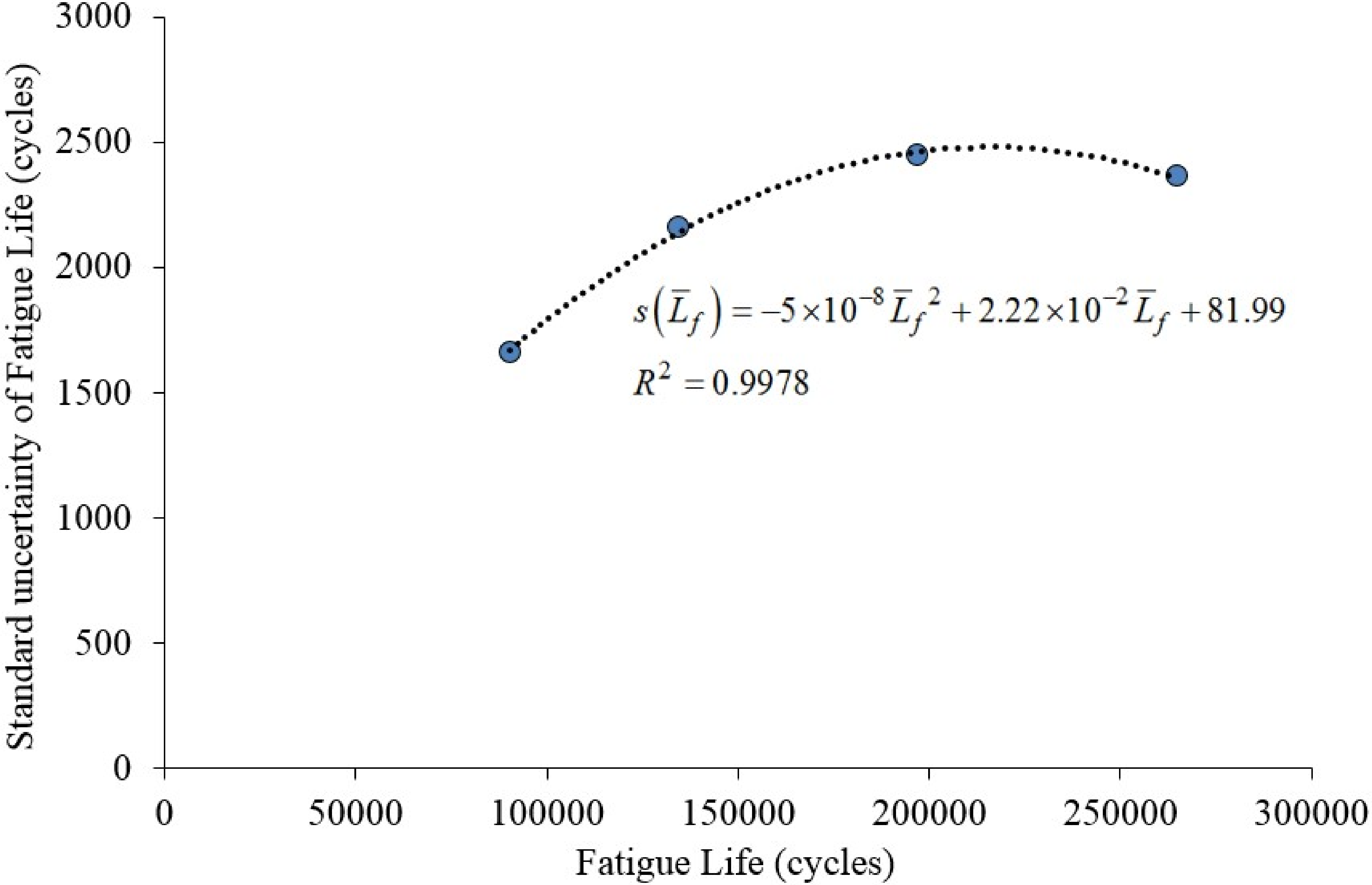
d) 15 µm anodized depth



$s(\bar{L}_f)/\bar{L}_f$ (cycles/cycles)
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
2
4
6
8
10
12
14
16
A_d (μm)
$s(\bar{L}_f)/\bar{L}_f = 0.006A_d + 0.0091$
$R^2 = 0.9909$



300000
250000
200000
150000
100000
50000
0
0
2
4
6
8
10
12
14
16
Fatigue Life (cycles)
Anodized depth (μm)
$\bar{L}_f = -11711A_d + 259437$
$R^2 = 0.9912$
Minimum fatigue resistance allowed by the standard



3000
2500
2000
1500
1000
500
0
0
50000
100000
150000
200000
250000
300000
Standard uncertainty of Fatigue Life (cycles)
Fatigue Life (cycles)
$s\left(\overline{L}_f\right) = -5\times10^{-8}\,\overline{L}_f^{\,2} + 2.22\times10^{-2}\,\overline{L}_f + 81.99$
$R^2 = 0.9978$

Table 1. Tested items

Item	Anodizing depth
Crank # 1, 2, 3, 4, 5	Without anodize
Crank # 6, 7, 8, 9, 10	5 μm
Crank # 11, 12, 13, 14, 15	10 μm
Crank #16, 17, 18, 10, 20	15 μm
Standard Crank # 21, 22, 23, 24, 25	15 μm

Table 2. Cranks physical properties

	w/o Anodized		5 µm		10 µm		15 µm		Std Crank (15 µm)	
Item	Weight (g)	*VR	Weight (g)	VR	Weight (g)	VR	Weight (g)	VR	Weight (g)	VR
1	223,0	20.3	221,0	20.1	220,0	20.4	221,0	20	254	22
2	221,0	20.1	220,0	20.1	221,0	20.1	222	20.1	251	22,3
3	223,0	20.2	223,0	20.2	220,0	20.2	219	20.1	253	22,2
4	221,0	20.1	221,0	20.2	222,0	20.2	220	20.1	252	22,2
5	223,0	20.3	220,0	20.3	220,0	20.3	221	20.2	254	22,3
Mean	222,2	20.2	221	20.2	220,6	20.2	220,6	20.1	252,8	22,2
Std. Dev.	1,1	0.1	1,2	0.08	0,9	0.11	1,1	0.07	1,3	0,13

*VR= Vertical Ridigity (daN/mm)

Table 3. Test Results

	w/o Anodized	5 µm	10 µm	15 µm	Std Crank (15 µm)
Item	Cycles	Cycles	Cycles	Cycles	Cycles
1	264.000	205.000	128.000	96.000	122.000
2	273.000	195.000	130.000	92.000	118.000
3	258.000	190.000	141.000	85.000	131.000
4	261.000	201.000	135.000	91.000	125.000
5	268.000	193.000	138.000	88.000	127.000
Mean $\bar{L}_f$	264.800	196.800	134.400	90.400	124.600
Std. Dev. $s\left(\bar{L}_f\right)$	2.362	2.446	2.160	1.662	1.721

Table 4. Optimum anodized depth prediction for the minimum fatigue resistance allowed by the standard

A_d (µm) (2)	$u(m)$ (cycles/µm)	$u(b)$ (cycles)	$u\left(\bar{L}_{f\,\min}\right)$ (cycles) From Figure 7	u (A_d) (µm) (3)	$U_{99}\left(A_d\right)=3\cdot u\left(A_d\right)$ (µm)	A_{d_opt} (µm) (4)
13.61	780.50	7301	1802	1.11	3.33	10.28