Hip Replacement Failure Analysis and Design Improvement Techniques

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ABSTRACT

Hip replacements have been utilized widely to extend life and improve the quality of life for many individuals. This technology is driven to improve from both design and analysis perspectives. This paper will discuss how a hip implant was analyzed to determine the cause of an early failure case, and offer insight into how to improve the design. It was observed that fracture was caused by fatigue, through crack propagation from a laser etching acting as a crack on the surface of the stem. Plastic yielding, fracture, and fatigue failure theories have been used for the analysis. From the results, it has been determined that the failure was caused by final brittle fracture from a large crack which developed as a result of crack growth initiated from the laser etching. The results also showed that increasing the neck thickness and changing the etching location would increase lifetime of the hip implant. Therefore, with simple changes in the design, the problem of crack propagation caused by the laser etching could be solved.

INTRODUCTION

The hip replacement design process can be intricately complicated. It must meet unique geometry constraints to fit into the body of a human, it must have the material strength to withstand the various and uncertain forces of a hip, and it needs relatively high ductility to adapt to the strain in a human. In a specific case, a patient's hip implant fully fractured after only 5.75 years of use. This patient weighed 100 kg. The fractured hip implant was made of a DePuy Corial femoral stem with laser etching on the prosthetic neck. The femoral component was a size 12 Corial, high offset stem with a DePuy Biolox 32, þ9 ceramic femoral head. A 54 mm Duraloc 300 cup was inserted with a 54x32 mm Duraloc Marathon liner, as shown in Figure 1[3].

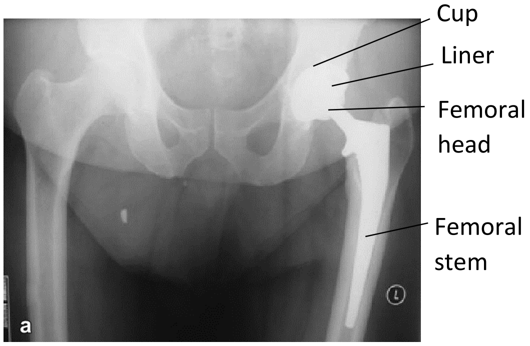

Figure 1: X-Ray of Patient with Hip Implant[3]

The expected lifetime of a hip implant is much more than 5.75 years, ideally lasting over 15 years. The work provided here will explain the results in determining the cause of fracture, as well as what methods can be used to eliminate the problem.

PROBLEM DESCRIPTION

In this case, the hip implant was modeled using the free body diagram shown in Figure 2, where N=4Mg, x=0.043 m, Θ=45°, and the cross section was modeled at A as a square with sides b=0.013 m. This was set up with only one force to simplify the problem, but was a conservative estimate of the force seen by a hip implant on a daily basis.

Figure 2: Simplified Free Body Diagram of Hip Implant

The hip implant fractured at A, which was also the location of the laser etching. The fractured hip showed beach marks[3], which theorizes failure was caused by fatigue. It was hypothesized that the laser etching acted as a crack, and propagated through the hip due to the cyclic stress caused by walking.

In order to analyze the hip implant as a material specimen, it was beneficial to model it on a differential perspective. Once modeled, equations were set up to mimic the cyclic loading of a human walking. An average of 5340 steps per day were used in order to find the amount of cycles per year[1]. From the problem description for the specific hip used, the following material properties were found: C=9x10^(-14) (m/cycle)/(MPa√m)^m, m=3, K_{IC} = 60 MPa√m, and σ_0=1200 MPa.

MODELING

It was necessary to find the maximum stress at the fracture site in order to set up the model of a material specimen at A. To find this, the internal stress caused by both the bending moment of the force component parallel to the cross section at A was calculated, along with the internal compressive stress caused by the force component into the cross sectional plane at A. The aforementioned stresses were solved using Equations 1 and 2[2]:

$$\sigma_{x,bending} = \frac{Mc}{I} = \frac{N cos\Theta X 0.5b}{\frac{b^4}{12}} \tag{1}$$

$$\sigma_{x,compression} = \frac{N}{A} = \frac{N sin\Theta}{b^2} \tag{2}$$

where x was the direction perpendicular to the cross section of the neck at A. Since the bending stress at A was in tension, and the stress from the force was in compression, combining the two stresses resulted in the following equation:

$$\sigma_{x,max} = \sigma_{x,bending} - \sigma_{x,compression} \tag{3}$$

The hip implant could then be modeled as a material crack specimen, shown below in Figure 3.

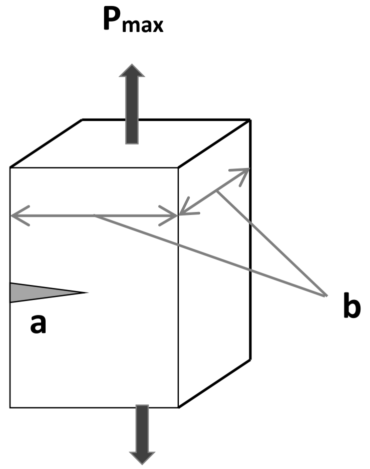

Figure 3: Free Body Diagram of Crack at A in Neck

where P_{max} was found by multiplying the maximum stress by the area of the cross section using the following equation:

$$P_{max} = S_{max} * b^2 \tag{4}$$

Finding the maximum force and modeling the problem in such a way allowed the fully plastic fracture to be found to allow for determination of brittle or ductile fracture. The fully plastic fracture was found using Dowling's equation[2]:

$$a_0 = b\left[P^* + 1 - \sqrt{2P^*(P^* + 1)}\right] \tag{5}$$

where P* was defined using Equation 6:

$$P^* = \frac{P_{max}}{bt\sigma_0} \tag{6}$$

It was then necessary to compare the value of a_0 to the crack length of brittle fracture, found from the following equation:

$$a_c = \frac{1}{\pi}\left(\frac{K_{IC}}{FS_{\max}}\right)^2 \tag{7}$$

where F was defined by Equation 8 on the next page:

$$F = 0.265(1-\alpha)^4 + \frac{0.857+0.265\alpha}{(1-\alpha)^{1.5}} \tag{8}$$

and

$$\alpha = \frac{a}{b} \tag{9}$$

which in this case was $a=a_c$ to solve for brittle fracture. Since this system of equations was circular, an iterative solver was set up on Microsoft Excel. K_{IC} was set up as a function of a_c and F, F was a function of a_c, and a_c was used as the iterative variable. a_c was altered until K_{IC} reached its value of 60 MPa$\sqrt{m}$. This method produced the failure of the hip due to brittle fracture. The fracture crack length, a_f, was found from comparing these values, as it is just the smaller of the two. Additionally, this value determines the mode of fracture in the hip implant neck.

Once a_f was found, it could be plugged into the following equation to solve for the initial crack length, a_i.

$$N_{if} = \frac{a_f^{1-\frac{m}{2}} - a_i^{1-\frac{m}{2}}}{C\left(F\Delta S\sqrt{\pi}\right)^m\left(1-\frac{m}{2}\right)} \tag{10}$$

where N_{if} was derived from the average number of steps in a day, and extrapolated to be the total number of cycles until fracture, using the following equation:

$$N_{if} = \frac{5.75\ years}{Hip\ Lifetime} * \frac{365\ days}{1\ year} * \frac{5340\ steps}{1\ day} * \frac{1\ cycle}{2\ steps} \tag{11}$$

Using the previous equations and variables, and utilizing Microsoft Excel, various data was generated: the mode of fracture, as well as the fracture length, and the initial crack length, along with various data that could be manipulated to solve various criteria.

RESULTS

As described in the previous sections, a hip implant was modeled as a material specimen undergoing uniform stress to determine an estimation of fracture due to crack propagation.

Table 1: Values calculated from Excel showing behavior of hip implant at A

S_{max} (N)	**309.6**
P_{max} (MPa)	**52290**
a_0 (mm)	**5.882**
a_c (mm)	**4.078**
a_f (mm)	**4.078**
a_i (mm)	**0.1805**

Table 1 shows that the stress in the joint was just over 25% of the material's yield strength. The ductile fracture occurred when the crack propagated to 5.882 mm, whereas brittle fracture occurred at 4.078 mm, making the mode of fracture brittle, and fracture occurring when the crack propagated to 4.078 mm. Plugging these values into the lifetime equation, it was found that an initial crack of 0.1805 mm caused failure at 5.75 years, or 5.6 million cycles. This means that the laser etching only removed 0.1805 mm of material, and yet this was enough to cause brittle fracture after less than 6 million cycles. Figure 4 shows the minimum initial crack length necessary to achieve various hip implant lifetimes.

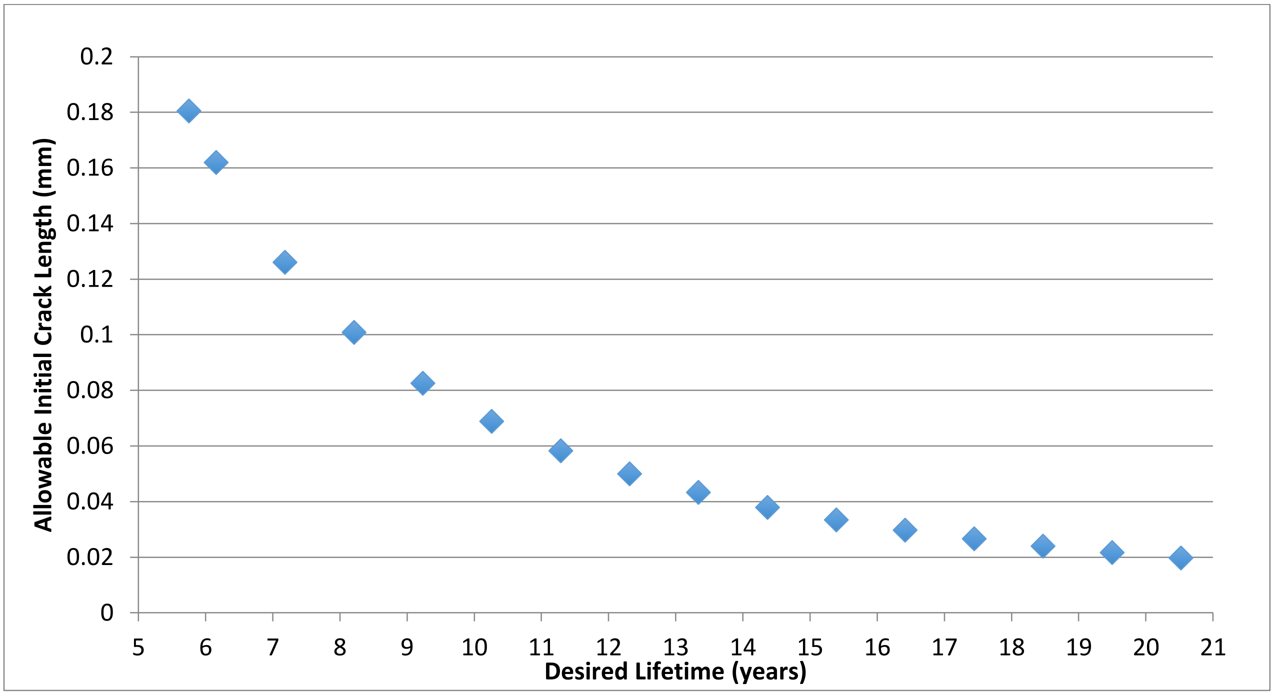

Figure 4: Theoretical Allowable Initial Crack Length vs. Desired Lifetime

This shows that in order to get extended life out of the hip implant from the perspective of crack propagation, the laser etching, or initial crack length at location A must be kept smaller and smaller. It was found that to achieve a lifetime of 15 years, the initial crack must be kept under 0.033 mm, and to achieve a lifetime of 20 years, the initial crack must be kept under 0.02 mm.

After the completion of the analysis and determination of fracture causation, variables were altered to determine causal relationships with lifetime. Figure 5 shows the effects of increasing the fracture toughness.

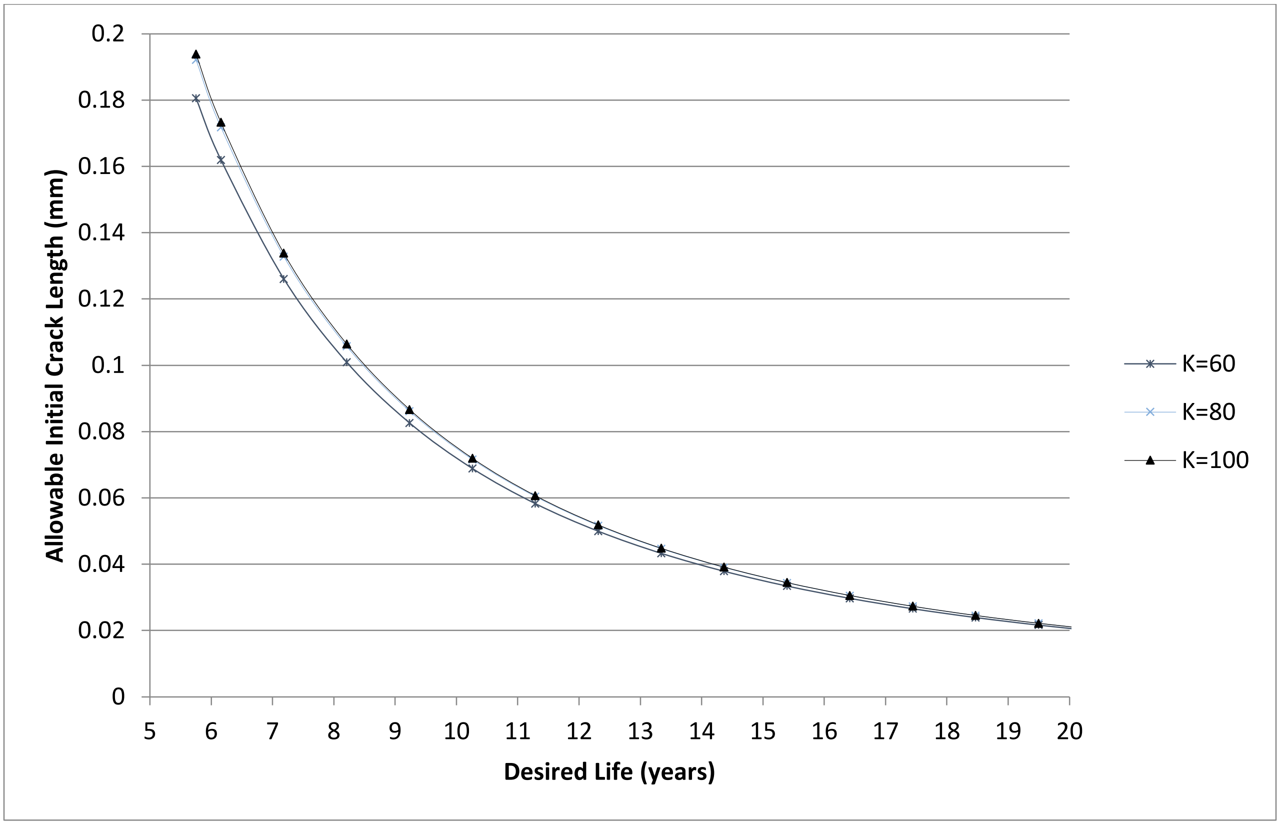

Figure 5: Values of K_{IC} and Theoretical Effect on Allowable Initial Crack Length vs Desired Life

Increasing K_{IC} to 80 MPa$\sqrt{m}$ barely changed the life of the hip implant. This new material would still only allow an initial crack length of 0.192 mm, and the laser etching of 0.1805 mm would only last about 6 years, only showing improvement by a few months. When the value of K_{IC} was increased to 100, the mode of failure was no longer brittle, and thus increasing K_{IC} further would not generate any benefit. When calculated with a_f equal to a_0, the results were, for all purposes, identical to a K_{IC} of 80. It followed that changing the composition of the material would not yield the desired results.

Figure 6 shows the results of changing the thickness of the neck at A. It was increased by 5% each time, to generate thicknesses of 13.65 mm, 14.3 mm, 14.95 mm, and 15.6 mm; these thicknesses are shown below.

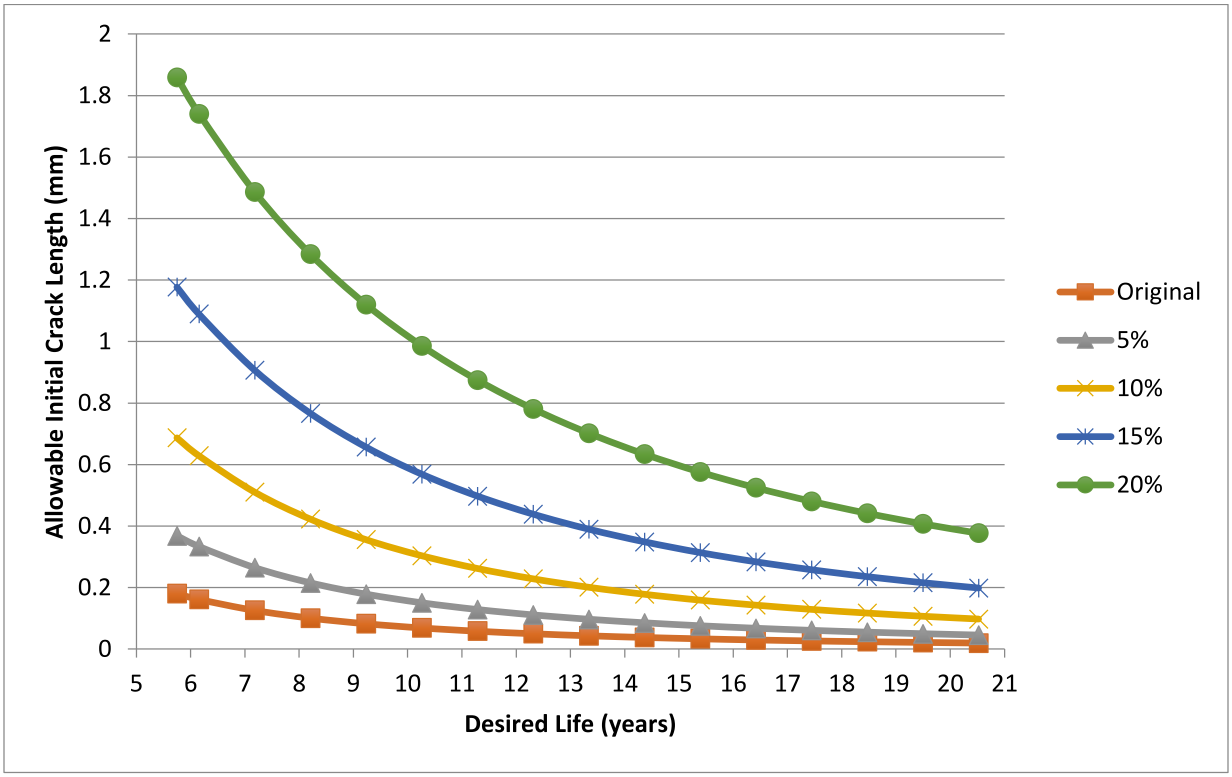

Figure 6: Theoretical Neck Thickness Effects on Allowable Initial Crack Length vs. Desired Life

As shown in Table 2, altering the thickness of the neck generated promising results. The lifetime of the patient's hip implant using the laser etching depth of 0.1805 mm is shown, the implication being that simple increases in the thickness of the neck could result in increasingly longer life. When the neck was increased 2.5 mm on each side, the initial crack length of the laser etching had no effect within the 20-year scope of the data.

Table 2: Theoretical Lifetime from Increasing Neck Thickness

b (neck thickness, mm)	Lifetime (years)
13 (original)	5.75
13.65 (5% increase)	9
14.3 (10% increase)	14
14.95 (15% increase)	20
15.6 (20% increase)	20+, possibly infinite life

Figure 7 shows the effect of changing the location of the laser etching. The majority of the stress at location A resulted from bending stress in the neck. This was generated from the moment from the force and the distance to the etching. Changing the location of the etching allowed for a reduction in the moment, which reduced the maximum stress in the neck joint of the hip implant.

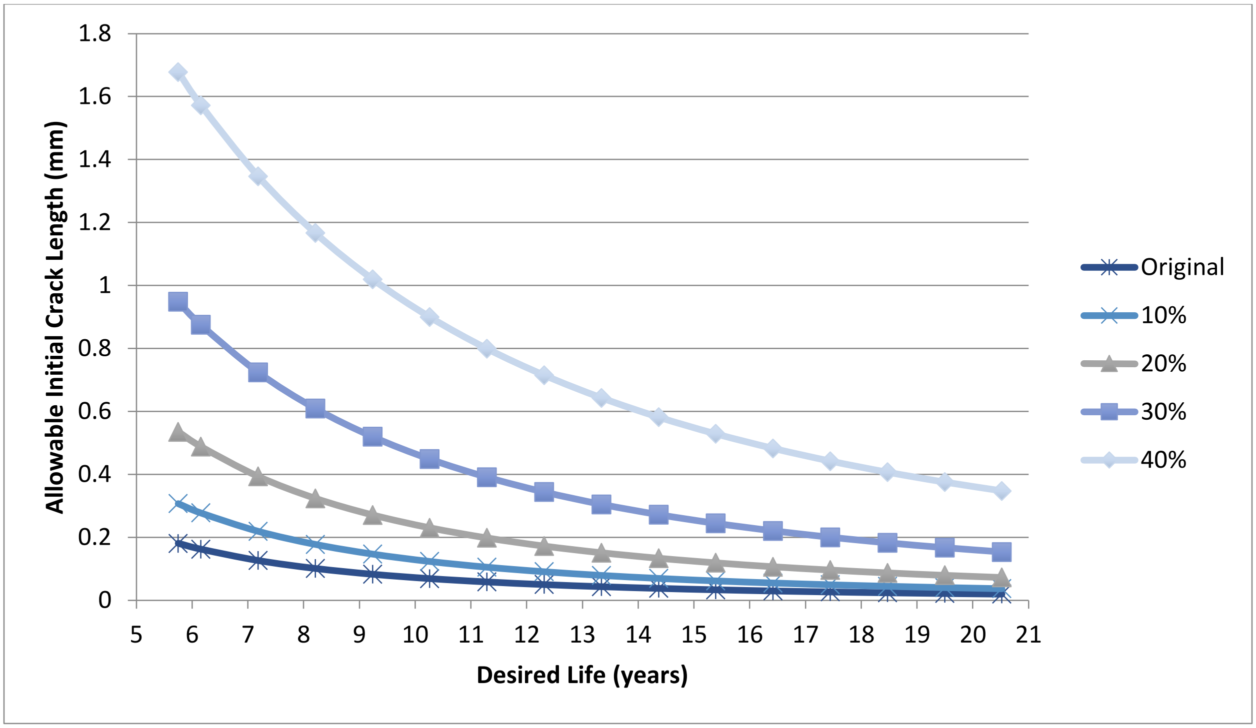

Figure 7: Etching Location's Theoretical Effect on Allowable Initial Crack Length vs. Desired Life

It was evident here that this change also had a significant effect on the lifetime of the hip implant. Table 3 shows that with only a 10% change in the location of the etching up the neck would give the hip implant another 3 years of use. Moving the etching a little over 10 mm resulted in a lifetime of almost 20 years, which is an improvement over the original of a factor of 4.

Table 3: Theoretical Lifetime from Various Etching Locations

X (distance to etching, mm)	Lifetime (years)
43 (original)	5.75
38.7 (10% decrease)	8
34.4 (20% decrease)	12.5
30.1 (30% decrease)	19.5
25.8 (40% decrease)	20+, possibly infinite life

DISCUSSION

The generated data shows the trends of how the hip implant was affected by altering the physical properties and various geometric variables. Today, many people utilize hip replacement technology, and learning how to improve the methods for designing and analyzing them is a crucial step for the future. The data presented was beneficial not only in explaining how the hip implant fractured and some of the initial conditions that must have occurred to cause it, but it also gave a clue into how the specific hip implant could be improved.

Increasing the fracture toughness yielded essentially no results, and should not be a consideration due to the effects it will have on the strength and ductility of the hip. Further studies should be done to determine what other chemical material properties could be altered without negatively affecting the required strength and ductility of a hip implant.

Changing the thickness of the neck generated beneficial results, as the lifetime increased greatly, with only a small increase in the dimensions of the neck of the artificial hip. This, by itself was seemingly a good choice for improving the lifetime of the hip. However, many hips are custom made, and must first fit inside the human they will be used in. Without knowing enough information in this specific case, it was hard to ascertain whether this was still a good choice. If a tolerance of the thickness were small enough, this solution would not be feasible.

Moving the etching location also produced advantageous results. By moving the etching only a few millimeters, the lifetime was extended to almost 4 times that of the original scenario. Additionally, this solution seemed to have no negative effects on the functionality of the hip. More research would need to be performed to confirm this, but if the original etching was put in an arbitrary location, and moving it had no ill effects, this solution would be the most advantageous.

Ideally, the most beneficial solution would be a combination of increasing the neck thickness and moving the etching location, as they both trended in the direction of increasing the life of the hip.

Another factor to consider in the solution was one of time. The hip implant in this case was created over 10 years ago, with the limitations of the knowledge and technology of that time. Currently, the technology exists to laser etch metal with only removing .0025 millimeters, which would have a lifetime of almost 20 years even with the original conditions of the problem. Additionally, there is currently a laser technology that oxidizes the metal instead of removing material, and is used in many medical devices[4]. The implication of this is there would no longer be a crack at the location of the laser writing, and the lifetime would be infinite from the perspective of crack propagation. However, more research needs to be done to determine if either of these is feasible for the application of the hip implant.

This experiment was beneficial to find a solution for the problem of crack propagation caused by laser etching in hip replacements. More significantly, this experiment showed how a complex problem could be modeled as a simple materials problem. The implication of this is that many problems in design and quality could be alleviated without a large amount of time and computer simulation.

An important point to note is that all values discovered are highly theoretical. They are based on a greatly simplified model of forces on an individual's hip joint, in conjunction with many assumptions that prevent this model from being too realistic. This is simply a model used to find potential design and safety improvements in regards to crack propagation. In order to confirm the validity of the theoretical claims, further studies should be done. Initially, FEA testing should be done, as it would be efficient and cost effective. This would give a way to test an increased amount of changes fairly quickly, and without having to spend additional money. Beyond this, actual testing could be done. However, FEA still has trouble performing fatigue testing, and testing prototypes takes a long time due to the nature of cyclic testing. Additionally, these testing environments also do not perfectly mimic the forces a patient may encounter on a daily basis. However, these tests would help to confirm the accuracy of the model.

Further research could also be conducted with manufacturers of the hip implants to see the progress that has been made over the past 10 years.

CONCLUSIONS

The hip implant fracture was successfully analyzed using the data in conjunction with equations and modeling. Using a materials perspective, internal stress at the location of fracture was found by simplifying the problem into a standard materials specimen model. Using basic materials equations, the mode of fracture was determined, which in this instance was brittle fracture. Estimating the average amount of steps in a day, the approximate initial crack length of the hip implant fracture case was established. Finally, by changing the variables of the problem, favorable design results were found. Using the information found, it was confirmed that both changing the neck thickness of the hip implant, and moving the etching location closer to the cup yielded increased life for the implant. Additional research is needed to find the optimized solution for this case, and whether any of the proposed changes are feasible. Further research also needs to be done on the current technology of laser etching and whether or not crack propagation in hip implants continues to be a problem with the current technology.

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