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Computational Engineering Analysis of Low-Cycle Loading for AMF-Active Micro Forceps 316 L-Stainless Steel Material by Finite Element Method

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Antagonistic contact on tips of active micro forceps produces surface stresses leading to fracture and wear finally leading to fatal failure. It was the aim of the present research to study the outcome of low cycle loading testing parts of active micro forceps materials involving either surface contact fatigue or flexural loading mechanisms. For this purpose, this research was focused on the mechanisms of the fatigue life of 316 L-type stainless steel active micro forceps in low cycle loading conditions. This could result in the fatigue failure of active micro forceps at stress levels below the yielding stress of material. Thus, researching the material and mechanical behaviors of an active micro forceps structure and force mechanism under low cycle loading is vital. Finite element method with accurate geometry and material properties was employed for a biocompatible forceps' tips in the computational modeling. To justify the data collected from Von Mises' yield condition, the Haigh diagram was developed to analyze fatigue wear. The low cycle loading behavior of the active micro forceps was analyzed in computational engineering tool of ANSYS LS-DYNA under operational load conditions in vitrectomy. The results of the analysis obtained from this research are helpful for micro component manufacturer and clinic surgery operation.

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1. Introduction

Microsurgery with active micro forceps (AMF) is very important practice but most challenging treatment at contemporary trends in surgical medicine. Forceps are the instruments that transmit forces from surgeon's hand to internal organs of retina of eye. Therefore, high stiffness is an important requirement for forceps [1]. Low cycle loading (LCL) of active micro forceps materials is recognized as a factor that contributes to material failure through either fractures or wear [2]. Since the process of such a failure occurs over time and may take thousands (or more) of cyclic load applications, it is characterized as a fatigue process in AMF. By focusing the attention on the material level of failure [3], mechanical damage represents the more relevant source of collapse, mechanical reliability issues [4]. For this research, a new finite element model of AMF with accurate geometry and material properties were developed to make realistic investigations of computational engineering on the mechanical fatigue behavior.

2. Material-method: low-cycle loading on active micro forceps

The objective of this work was to introduce a new scientific mean for investigating the quantitative responses of AMF made in 316 L steel to mechanical LCL at relevant conditions in computational engineering. LCL testing is critical for establishing the ultimate strength and reliability of joints, tips, and hinges within active micro forceps devices. 316 L stainless steel material for AMF is selected as material fatigue behavior for the investigation. This research was focused on micro part's material and mechanical design as divided in two areas: (I) simulation of the modeled forceps to undertake analyzing of the stresses occurring during working conditions within computational engineering environment, (II) tensile and LCL fatigue tests.

Little investigation has been done regarding to AMF on small-scale multi axial LCL fatigue behavior. Small dimensions of active micro forceps is great challenge to perform analysis and needs special environment for fatigue tests since the state of knowledge in macro technologies are not smoothly exchangeable to the micro domain [1, 4]. The size effects and changed parts behavior could justify this situation of AMF in this research. Although, size constrains (square cross-section of 2 mm $\times$ 500 μm diameters and are made of 316 L stainless steel of one forceps blade) change the mechanical properties as well as LCL fatigue behavior. LCL fatigue testing of 316 L steel was conducted according to ASTM F138 [5] and ensured a homogeneous metallurgical microstructure to superior corrosion and fatigue resistance.

When the material of AMF device is subjected to LCL followed by unloading and subsequent reloading, the response changes cycle by cycle until saturated. To model this behavior finite element simulation method was developed by employing ANSYS LS-DYNA workbench. In this research using the 3D finite element analytical results based on tensile strength deformation in AMF blade tips of 316 L stainless steel material device as shown in Fig. 1 when equivalent stress changes occur in one sec-

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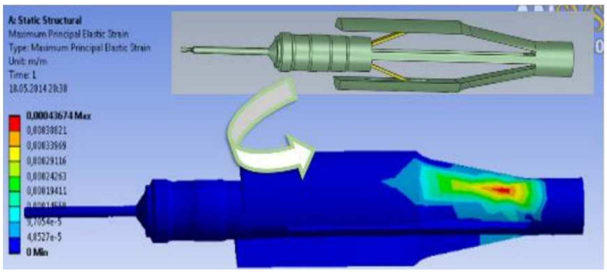

Fig. 1. Von Mises equivalent stresses.

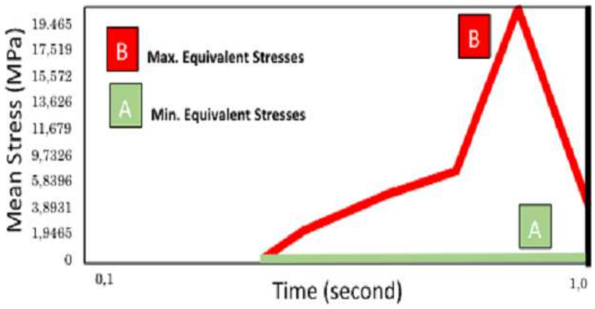

Fig. 2. AMF under stresses in second.

ond in Fig. 2. The stresses can be presented clearly using a color representation of the stress distributions in Fig. 1 and Fig. 3. The section plots revealed that the maximum von Mises stresses were primarily located at the force application areas in all the models. One of the important research area is the AMF tips related to tensile and fatigue stress distribution of the von Mises plasticity maximum distortion of 32 MPa found as shown in Fig. 1.

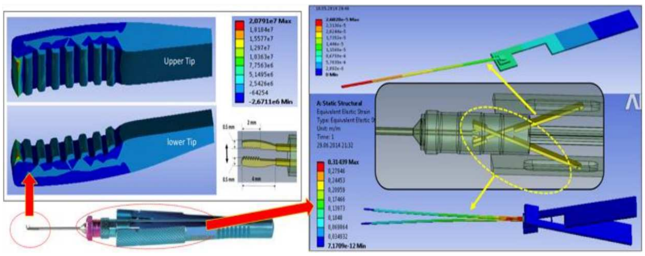

Fig. 3. Stresses occurring on forceps' tips and device hinge (inner parts).

The handle of the AMF was also analyzed to observe the surgeon hand holding whether tide or relax way of keeping the device during surgery in the eye retina. The analysis was limited to surgeon fingers force applied to forceps' handle. Figure 1 shows the maximum elastic strain occurring areas and also insight of the parts affected by the stresses given in Fig. 3.

Mechanical fatigue of AMF tips operating at high frequencies and whose motion is controlled by structural hinges as shown in Fig. 3 or elastic suspensions suffer from cyclic fatigue damage accumulation; crack initiation and propagation take place in the material and may cause the device failure. Finite element analysis (FEA) of elasto-plastic deformation was carried out to obtain the hysteresis loop and cyclic stress response of the material as shown in Fig. 4.

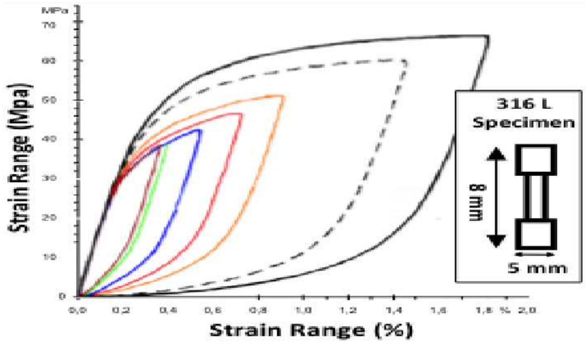

Fig. 4. Hysteresis loops compressive on AMF tips.

When AMF is subjected to an imposed cyclic plastic deformation, the highest and lowest stresses do not remain constant throughout the test. After a transitory stage where the highest stresses vary, they become steady for a long time.

As illustrated in Fig. 4, the tensile stress begins to decrease and associate with onset of cracking. Stress on tips of AMF was recorded as a function of strain, as obtained hysteresis loops that evolve and become stable provided that a stable regime exists. Figure 4 shows cyclic work hardening observed in 316 L austenitic stainless steel.

Isotropic and kinematic hardening was modeled in cyclic elasto-plastic 316 L stainless steel FEA to predict the first cycle hysteresis loop and initial few cycles of cyclic stress response of the material. Figure 4 shows the comparison of the simulated hysteresis loop for the first cycle obtained from FEA and experiment for $\pm 0.4\%$, $\pm 0.8\%$ and $\pm 1.2\%$ strain amplitudes, respectively. The outcomes of the analysis showed good agreement between the numerical simulation and the experimental results at $\pm 0.4\%$ and $\pm 0.8\%$ strain amplitudes. In Fig. 4, initial LCL response of the material was also predicted by FEA computational method.

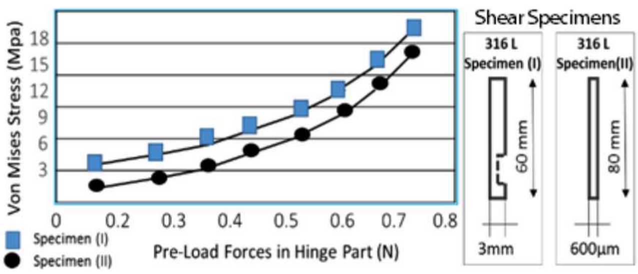

Fig. 5. Equivalent stresses in hinge parts.

Figure 5 shows the tensile stress amplitude with number of cycles at total strain amplitudes. Results were used to plot S–N curves in order to estimate the fatigue limit of the material in presence of mean and alternate stress conditions in Fig. 6. The effects of the elastic modulus of the AMF were examined. It was found that both total strain energy and total reaction force increased as the elastic modulus of the AMF was increased from 0.36 MPa to 35 MPa. The results are plotted in the S–N curve shown in Fig. 6. 316 L stainless steel undergoes hardening under LCL. As a critical research issue, the mechanical strength of the structural integrity of high-stressed hinges of AMF for force posts was crucial to avoid fracture collapse. In addition to this, another complication was observed as the data from S–N curves also capture the device-to-device variability, concerned by the uncertainties of material characteristics and manufacturing processes.

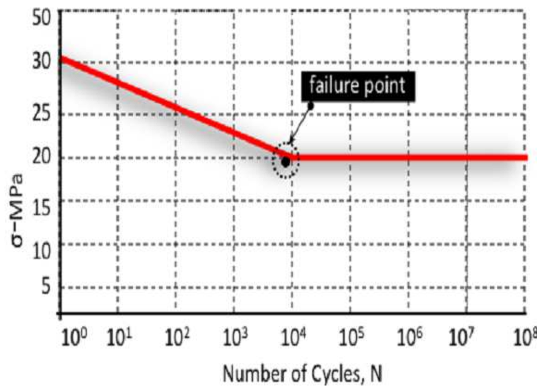

Fig. 6. S–N fatigue data life diagram.

Figure 6 shows the S–N curves for standard hinge specimens (inner parts of AMF) tested under different stress ratios at room temperature. Test structures are designed for a LCL of specimen: frequency of 15 Hz pull-in or instantaneous mechanical collapse. Stress variations for shear test structure diagram show performance of fatigue test from very low stress level to stress level of the same order of magnitude of the static tensile strength of the material in Fig. 6. The fatigue limits were observed to increase with increasing the stress ratio. Finite element simulation results are presented in Table. Specimen (I) and (II) plate's vertical maximum deflection and corresponding von Mises equivalent stress are extracted for different static force values.

TABLE

Shear specimen deflection.

Specimen (I)		Specimen (II)	
Von Mises stress [MPa]	deflection [μm]	Von Mises stress [MPa]	deflection [μm]
3	0.013	3	0.054
6	0.022	6	0.091
12	0.083	12	0.126
15	0.168	15	0.253
18	0.209	18	0.508

3. Conclusions

This article presents a new method of FEA of cyclic loading behavior related to fatigue analysis carried out using ANSYS LS-DYNA computational engineering software. The models developed in this study could unfailingly calculate the cutting, gripping strength of AMF in retina tissue. The relative AMF application force to the surgeon's hand is modeled by FEM using design parameters in Figs. 5, 6. New evidence that supports the LCL fatigue hypothesis was gained for AMF in this research.

Permanent deformation were detected by analytical methods: as a change in generation of excessive stresses of holding strain of hinges in AMF and as a change in 316 L stainless steel material microstructure. The analytical results of the AMF were closely related to the results of mechanical experimental tests with the correlation coefficient of 0.96 for both total strain and total reaction force. The three-dimensional nonlinear finite element models developed in this research were affected by the cyclic loading condition, the material property of the retina tissue and the frictional coefficient between the tips and the hinges of AMF. The finite element models, as computational engineering tool, may support manufacturers to consider new designs for AMF before manufacturing and assist surgeons to select suitable devices for their patients' eye surgery.

Acknowledgments

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References

[1] D.H. Bacon, L. Edwards, *Int. J. Fatigue* **48**, 39 (2013).

[2] T.M. Ahmed, A. Alfantazi, *Eng. Failure Anal.* **16**, 1432 (2009).

[3] S.G. Hong, K. Lee, S.B. Lee, *Int. J. Fatigue* **27**, 1420 (2005).

[4] L. Liu, N.H. Loh, *Powder Technol.* **206**, 246 (2011).

[5] ASTM F138, Standard Specification for Wrought 18Chromium-14Nickel-2.5Molybdenum Stainless Steel Bar and Wire for Surgical Implants (UNS S31673), ASTM International, West Conshohocken 2013.