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MEASUREMENT OF MECHANICAL PROPERTIES OF NC DRAGONFLY WING BY NANOINDENTATION

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ABSTRACT

This paper focus on measurement of indentation properties of veins of NC dragonfly wings. The wings were sliced into different locations on the wing and sandwiched between two glass slides using M Bond 610 and cured for 24 hrs. The edge of the sandwiched wing structure has polished and the required surface finish was achieved. The points to nanoindent were mapped on sample (veins and membrane) by microscope. Veins are composed of two layers, outer and inner layer. Outer layer is more stiff and hard whereas inner layer less stiff and soft. Materials of dried veins are non-homogenous and anisotropic. The average value of modulus and hardness of outer layer of veins are 13 GPa and 0.7 GPa where as for inner layer are 7 GPa and 0.4 GPa, respectively.

Keywords: NanoIndentation, Dragonfly Wing, Modulus of Elasticity.

1. INTRODUCTION

Micro air vehicle (MAV) is one of the most attractive field for research in present time for their extensive prospect of use in hazardous environmental exploration, reconnaissance, search and rescue. Insects have living and non living body parts, and they can fly, crawl, walk and jump, such concepts are useful in building autonomous Microsystems. Also, the cuticle of insect wings fulfills different demands, such as high stability combined with light weight and aerodynamically favorable construction. Multifunctionality is a common requirement in biological systems. Thus, birds and insects continue to advance flying systems utilizing advanced materials and structural concepts. Dragonflies are one such insect which have been widely investigated [US Army, May(1991), Herbert et al (2001)] to understand their aerodynamic properties and to build micro-systems based on their principles. Dragonfly wing have amazing wing characteristics that can provide exceptional flying and hovering capabilities. These wings can flap at the rate of 35 Hz and work together in such a way that it can accelerate from 0 to 60 mph in 1 second [1]. The authors measured and found the mass of the wings of a dragonfly is only 1-2% of its body mass, but the wings can stabilize their body and have a high load bearing ability during flight [2]. The lifting force of the insect wings is ten times greater than that of the wings of a plane with the same area [3]. The flight behaviors of insects are strongly related to the physical properties of wing [3-8]. If the wing properties are known then one can choose the right material to mimic the wings. The wing response to load or deformation while flying is directly related to wing mechanical properties.

Newman et al (1986) were measured the mechanical properties by tensile tests and found modulus was around 1GPa [9,10] but the tensile tests of samples were very small and difficult to perform and prone to erroneous result. The Nanoindentation test is the unique way to resolve above issue. The development of the nanoindentation technique has allowed highly localized hardness and modulus measurements to be performed on very small material volume. Hsin et al (2009), Song et al (2007), Sun et al (2010), Kempf (2000), Tong et al (2007) were measured nanoindentation on the dragonfly wing along the surface and the modulus and hardness were varied from 0.1 to 30.1GPa and 0.02 to 4..4GPa respectively [3-5,8,11]. Some of these study only focusing on membrane [3,4], veins[3-5], stigma[3,4,11], body cuticle [12]. This wide range of variation was due to measurement of properties on different parts of body and location of dragonfly wing. Lin et al measured the modulus of vein and found to be around 60GPa [6]. From the above literature, it was observed that all nanoindentation measurement was done on the surface of the wing. The purpose of this study is to find the modulus and hardness of the veins and membrane of the wing across the surface i.e.; on cross section of wings.

Biological branch and species name of the North Carolina (NC) dragonfly is Odonata and Lestes sp respectively [9] (Figure 1). The wing size varies from 20 – 25 mm in span and 5 – 6 mm in chord. Forewings are

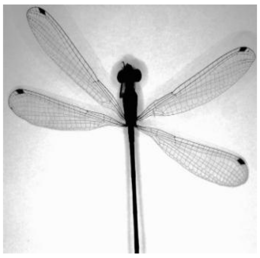

Fig 1. NC Dragonfly

larger than hindwings. The wings are mainly composed of vein and membrane. There are mainly three types of veins namely Costa, SubCosta, Radius and other veins are also present in wing system. A part from these Nodus and PetroStigma are two distinctive features (Figure 2).

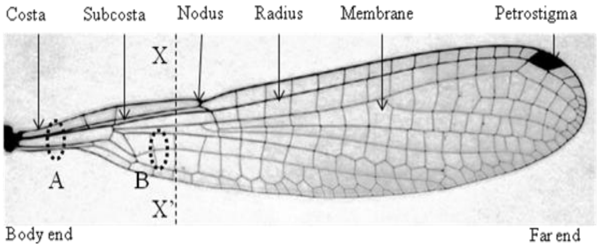

Fig 2. Sample wing

The nodus lies in the center of the leading edge of the wings and the stigma like a fuscous mark is situated near the tip. It was considered that the nodus and the stigma may not only improve the flexibility but also prevent fatigue fracture of the wings [18]. The stigma performs the balancing of the mass, stabilize at high speed flight and eliminate the airflow vibration. If the stigma is cutting off the dragonfly could still fly but the flight becomes unstable [11]. The basic framework of vein system of insect wings is made of chitin, a long chain, crystalline polymer the characteristics of which are similar to cellulose or technical materials [10]. The thickness of membrane varies from 1-5 micron, thicker at leading edge but thinner at far end and tailing edge. Table 1 shows the sizes of cross section of different veins of the dragonfly wing, which has sandwitch of elliptical cylindrical cross section.

Table 1: Cross section of different veins of the dragonfly wing

Segment of wing	**Major Axis 2a, µm**	**Minor Axis 2b, µm**
Costa	70-110	40-50
Subcosta	60-90	40-50
Radius	110-140	40-60
Other vein	30-80	20-40

2. MEASURMENT OF ELASTIC MODULUS AND HARDNESS BY NANOINDENTATION:

2.1. Sample Preparation:

Dragonfly wings were carefully separated from its main body and dried out at room temperature. The wing was sliced across at four locations on the wing span. Sandwiched specimens were prepared by placing a wing slice between two glass slides with epoxy-phenolic resin (M Bond^{TM} 610) layer to bond the wing (Figure 3).

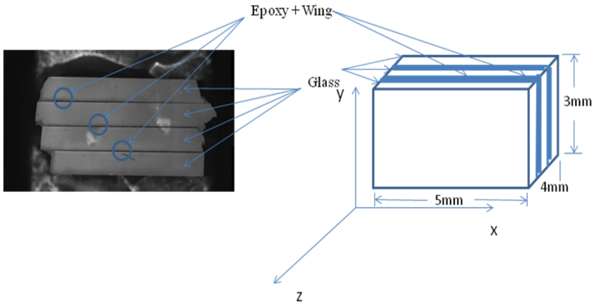

Fig 3. Sample (Sandwitch of glass, epoxy and wing)

The sandwich wing structure was cured at room temperature for 24 hours. The edge of the sandwich wing structure was polished using precision metal polishing machine (Figure 4) using different grades of diamond papers starting from 12 to 0.5 microns. During polishing, before changing the polishing paper grade, the surface finishing was examined using Axio Zeiss Imager M2M at different magnifications from 1.5X to 100X (Figure 5).

Fig 4. Photograph of Precision Metal Polishing Setup

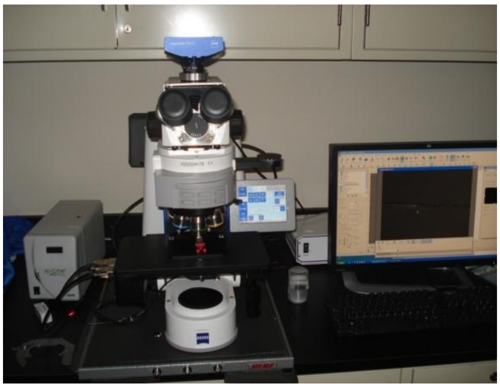

Fig 5. Photograph of Axio Zeiss Imager M2M

The points of indentation were initially mapped with the imager (Figure 5) on the cross section of specific vein (costa, subcosta & radius) so that it is easy to indent at selected points. A single cross section of dragonfly wing sample for nanoindentation is shown in Figure 6.

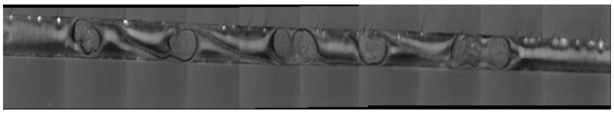

Fig 6. A complete cross section of dragon fly wing

From the images of ramon spectrum (Figure 7), it is clear that the veins are two layered outer layer and inner layer.

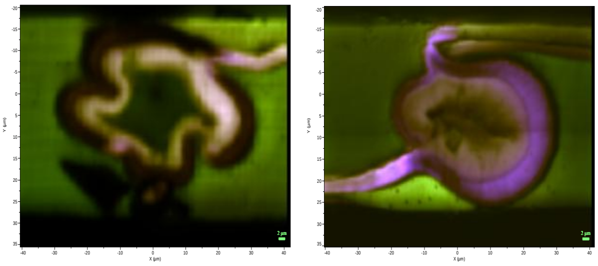

Fig 7. Ramon Spectrum Image of Veins

Before NanoIndentation test the sample mapped costa is shown in Figure 8.

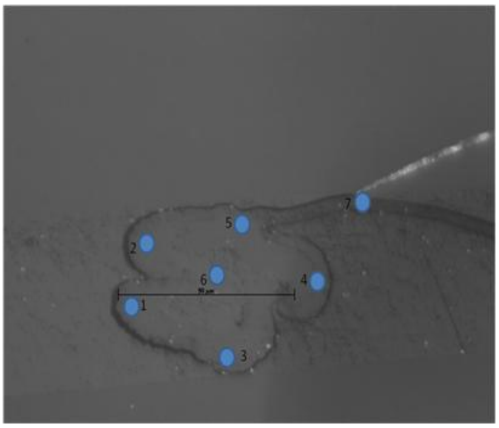

Fig 8. Indentation points of a costa

2.2 NanoIndentaion Test

The principal goal of nanoindentation test was to measure elastic modulus and hardness of the specimen from the indenter load and depth of penetration. Nanoindentation tests of the wings at cross sections were done by using a MTS NanoIndenter XP (Figure 9) (MTS System Corp., Oak Ridge, TN, USA). Berkovich diamond tip was used for these tests. The Berkovich geometry is generally preferred for measurement of hardness and elastic modulus. This is a three-sided pyramid that has an aspect ratio similar to that of the four sided Vickers pyramid. The Berkovich pyramid is a good choice for standard testing because it produces plasticity at very low loads, and minimizes the influence of friction.

Fig 9. Photograph of MTS NanoIndenter XP

The input parameters used in the nanoindentation test. For example, Poisson's ratio of dragonfly wing is unknown, so 0.3 was set as standard value. As the dragonfly wing is soft and brittle, the depth limit was set as 300 nm, allowable drift rate was 0.05 nm/s, surface approach velocity was set at 10 nm/s, surface approach distance to store as 1000nm and strain rate was set to $0.05s^{-1}$.

2.3 Computation of Elastic Modulus and Hardness from NanoIndentation

The elastic modulus and hardness were calculated by two different approaches, continuous stiffness measurement (CSM) and unloading curve.

2.3.1 Continuous Stiffness Measurement (CSM)

Modulus from continuous stiffness method (E_{CSM}) measures over the defined region of Load vs Displacement plot (Figure 10). Because the specimen material was soft, we choose the defined region is to be 100nm to 200nm.

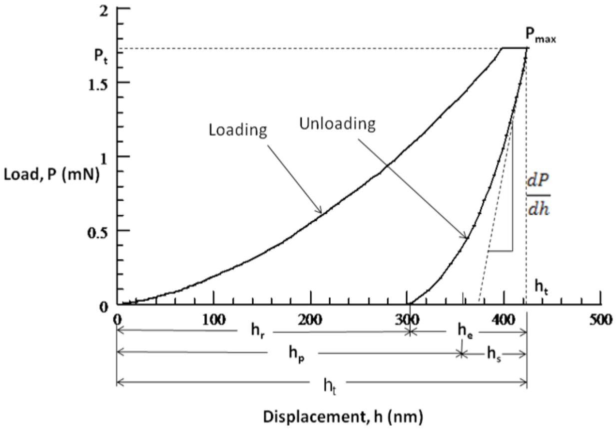

Fig 10. Indentation Load-Displacement curve

CSM option was chosen for the tests because it provides accurate measurements of contact stiffness at all depth and the stiffness values enable us to calculate the contact radius at any depth more precisely. It allows the continuous measurement of the contact stiffness during loading and not just at the point of initial unloads. This is accomplished by superimposing a small oscillation on the primary loading signal and analyzing the resulting response of the system by means of a frequency-specific amplifier. With a continuous measure of unloading slope of a loading cycle, one obtains the hardness and elastic modulus as a continuous function of depth from a single indentation experiment. CSM is average of a number of unloading curves during a continuous loading.

2.3.2 Unloading Curve Method

Measurement of unloading value was calculated from the slope of elastic unloading portion of Load vs Displacement curve (compliance curve) (Figure 10) at defined maximum depth.

The details of the calculation [11] are explained. For computing E and H of the wing, we assumed Poisson's raito of the wing to be 0.3, and the indentation parameters were: the modulus of indenter (diamond) E' is 1140 GPa and: poisson's ratio of indenter υ' is 0.07. And modulus of specimen is E and specimen hardness is υ.

Here, the total depth is h_t at maximum load P_{max}. The depth of the residual impression is h_r, the displacement associated with the elastic recovery during unloading is h_e, the depth of contact circle h_p, the distance from the specimen-free surface (at full unload) to the depth of the depth of radius of the circle of contact at full load is h_s. And the slope of the initial portion of the unloading curve is $\frac{dp}{dh}$.

Total Indentation depth, $h_t = h_p + h_s$

For Berkovich indenter, $h_s = \left[\frac{2(\pi-2)}{\pi}\right]\frac{P_{\max}}{dp/dh}$

So, $h_p = h_t - \left[\frac{2(\pi-2)}{\pi}\right]\frac{P_{\max}}{dp/dh}$

The projected contact area for Berkovich indenter,

$$A = 3\sqrt{3}h_p^{\,2}\tan^2(65.3°)$$

So, Hardeness, $$H = \frac{P}{A} \qquad (1)$$

Reduced Modulus, $$E^* = \frac{dP}{dh}\frac{1}{2h_p}\frac{1}{\beta}\sqrt{\frac{\pi}{24.5}} \qquad (2)$$

for Berkovich Indenter correction factor, $\beta = 1.034$

Finally, $$\frac{1}{E^*} = \frac{1-\upsilon^2}{E} + \frac{1-\upsilon'^2}{E'} \qquad (3)$$

Calibration test has been done on fused silica sample, manufacturer supplied data for fused silica was E=72GPa, H=9.6 GPa and Possions Ratio=0.17 where as the present mean measured value was E=71.4GPa and H=9.7 GPa.

3. RESULTS AND DISCUSSION:

Nanoindentaion was carried out for 6 samples and every sample is run for indentation tests of 4-14 indents depends on surface area. Table II shows the modulus and hardness measured from CSM and unloading curve for sample Costa05.

Table 2: Indentation results for Costa05

Sample ID	**E_{CSM} GPa**	**H_{CSM} GPa**	**$E_{unloading}$ GPa**	**$H_{unloading}$ GPa**
Outer Layer				
I-07	12.8	0.4	12.5	0.4
I-08	12.0	0.4	11.6	0.4
I-09	13.8	0.6	12.9	0.4
I-15	10.4	0.4	10.1	0.3
I-16	12.5	0.5	11.9	0.4
I-17	12.5	0.5	13.1	0.4
	12.3 (1.1)	**0.5 (0.1)**	**12.0 (1.1)**	**0.4 (0.0)**
Inner Layer				
I-04	8.5	0.3	7.9	0.3
I-12	8.8	0.4	8.1	0.4
I-13	6.0	0.3	6.4	0.3
I-14	8.0	0.7	7.2	0.5
	7.8 (1.3)	**0.4 (0.2)**	**7.4 (0.8)**	**0.4 (0.1)**
Resin				
I-03	4.7	0.2	4.7	0.2
I-06	3.5	0.1	3.6	0.1
I-10	4.0	0.2	4.1	0.2
	4.1 (0.6)*	**0.2 (0.1)**	**4.1 (0.6)**	**0.2(0.0)**

*standard deviation

From Table 2, E_{CSM} and modulus from unloading curve ($E_{unloading}$) for outer layer varies from 10.4-13.8GPa and 10.1-13.1GPa, respectively. Similary hardness from continuous stiffness method (H_{CSM}) and hardness from unloading curve ($H_{unloading}$) vary from 0.4-0.6GPa and 0.3-0.4GPa. The average E_{CSM} is 12.3GPA with standard deviation of 1.1 where for inner layer the average E_{CSM} is 7.8GPa with standard deviation of 1.3. For inner layer E_{CSM} and $E_{unloading}$ vary from 6.0-8.8Gpa and 6.4-8.1GPa, H_{CSM} and $H_{unloading}$ vary from 0.3-0.7GPa and 0.3-0.5GPa. Similarly we have all the cross-sections of veins (Costa, SubCosta, Radius) of all samples.

Table 3-5 shows the summary of measured modulus and hardness of different region of veins (outer and inner layer as shown in Figure 5) of costa, subcosta and radius. Summary of modulus and hardness of outer and inner layers of five costa vein are shown in Table III. The average modulus and hardness of outer layer measured from CSM varies from 11.9-13.3 GPa and 0.4-0.7 GPa, where as for inner layer it was 6.4-8.0 GPa and

0.2-0.4Gpa respectively.

Table 3: Summary results for Costa

Sample ID	**E_{CSM} GPa**	**H_{CSM} GPa**	**$E_{unloading}$ GPa**	**$H_{unloading}$ GPa**
Outer Layer				
1	13.2(2.0)*	0.7 (0.2)	10.7(0.5)	0.5 (0.0)
2	13.3(0.7)	0.5 (0.0)	11. 0(1.9)	0.3 (0.0)
3	13.0(1.3)	0.7 (0.1)	10.5 (0.8)	0.5 (0.1)
4	11.9(0.1)	0.4 (0.0)	10.9 (0.4)	0.4 (0.0)
5	12.3(1.1)	0.5 (0.1)	12.0 (1.1)	0.4 (0.0)
Inner Layer				
1	6.6 (0.8)	0.4 (0.1)	7.1 (0.2)	0.3 (0.1)
2	8.0 (1.5)	0.4 (0.1)	7.8 (1.0)	0.4 (0.1)
4	6.4 (0.9)	0.2 (0.1)	5.6 (0.3)	0.2 (0.1)
5	7.8 (1.3)	0.4 (0.2)	7.4 (0.8)	0.4 (0.1)

* standard deviation

Table 4: Summary results for Subcosta

Sample ID	**E_{CSM} GPa**	**H_{CSM} GPa**	**$E_{unloading}$ GPa**	**$H_{unloading}$ GPa**
Outer Layer				
1	12	1.2	11.5	0.7
2	14 (1.3)*	1.0 (0.1)	11.7 (1.7)	0.6 (0.1)
3	15 (1.1)	0.7 (0.2)	10.9 (2.2)	0.5 (0.1)
Inner Layer				
1	9.5 (1.5)	0.9 (0.2)	7.1 (2.2)	0.4 (0.1)
2	5	0.2	7.6	0.3
3	6.3 (0.2)	0.3 (0.1)	6.5 (1.3)	0.3 (0.1)

* standard deviatio

Table 5: Summary results for Radius

Sample ID	**E_{CSM} GPa**	**H_{CSM} GPa**	**$E_{unloading}$ GPa**	**$H_{unloading}$ GPa**
Outer Layer				
1	12.4 (2.0)*	0.6(0.1)	12.6(2.7)	0.5 (0.1)
2	15.9	0.8	14.1	0.6
3	11.3 (1.01)	0.5 (0.1)	9.5 (1.3)	0.4 (0.1)
4	12.9 (1.1)	0.5 (0.0)	12.4(1.6)	0.4 (0.0)
Inner Layer				
1	6.7 (0.3)	0.3 (0.1)	6.4 (0.3)	0.3 (0.1)
2	8.9 (0.4)	0.7 (0.1)	7.4 (0.9)	0.3 (0.1)
3	5.6 (0.9)	0.2 (0.1)	5.6 (1.0)	0.2 (0.1)
4	7.3 (0.9)	0.3 (0.1)	7.4 (0.6)	0.4 (0.1)

* standard deviation

The deviation of modulus and hardness measured from CSM and unloading technique are due to calculation of those techniques done on two different region of the compliance curve. Thermal drift and nano-surface roughness also have contribution on this deviation. The modulus and hardness of veins are non linear in nature because of hard (high density) and soft (low density) region of wing structure.

Table 7: Summary results for Veins

Segment of wing	Modulus E, GPa		Hardness H, GPa	
	Outer Layer	Inner Layer	Outer Layer	Inner Layer
Costa	12.74	7.20	0.56	0.35
Subcosta	13.67	6.93	0.97	0.47
Radius	13.13	7.13	0.60	0.38
Average	13.18	7.09	0.71	0.40

From the summarized result it is clear that we can generalize the mechanical properties for veins, for mean modulus and hardness for outer layer is 13 GPa 0.7 GPa and mean modulus and hardness for inner layer is 7 GPa 0.4 GPa.

4. CONCLUSIONS

Veins are two layered outer and inner layer. Outer layer is more stiffer and hard whereas inner layer less stiffer and soft. Generally Costa undertake is mainly pressure, and its mechanical properties should be the largest. However in the NanoIndentaton test, the largest value of the modulus and hardness mainly appear in the radius. Materials of dried veins are nonhomogenous and anisotropic. The average value of modulus and hardness of outer layer of veins are 13 GPa and 0.7 GPa where as for inner layer are 7 GPa and 0.4 GPa, respectively.

5. ACKNOWLEDGEMENT

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7. NOMENCLATURE

Symbol	Meaning	Unit
P	Load	(N)
h	Displacement	(nm)
E	Modulus of Elasticity	(GPa)
H	Hardness	(GPa)
υ	Poisson Ratio	
β	Berkovich Indenter correction factor	

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