Strengthening of Poly Methyl Methacrylate (PMMA) through Electron Irradiation

Sung Ho Yoo, Hyung San Lim, Jun Mok. Ha, Sung Oh Cho
Department of Nuclear & Quantum Eng. KAIST , Daejeon306701, Republic of Korea
socho@kaist.ac.kr

1. Introduction

Irradiating polymers with electrons can result in cross-linking of numerous chains that make up the polymers or it can lead to formation of scissions. The former outcome can increase the molecular weights, strengths and melting points of the polymers while decreasing their solubility in solvents. The latter, formation of scissions, usually lead to decrease in molecular weights and strengths of the polymers while increasing their solubility. Poly Methyl Methacrylate (PMMA) was previously known to show the deteriorating mechanical properties when irradiated with electrons. This is true for low electron irradiation does, but it was found, through experimentation, that at high irradiation dose, PMMA demonstrates improved mechanical properties. With enough electron irradiation dose, the scissions can form new links amongst one another to achieve stability that surpasses that of the PMMA in pre-irradiation treatment state.

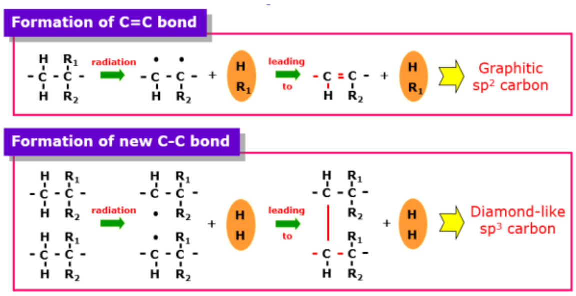

Figure 1. Polymer Strengthening Mechanism

As can be seen in figure 1, strengthening of PMMA stems from formation of carbonaceous materials, which are direct results of bonding amongst carbon atoms. Electron irradiation causes displacement hydrogen atoms leading to formation of radicals. These radicals form new bonds that give the irradiated PMMA superb mechanical properties. The commercialization of this technique could allow for cheaper, lighter and faster cars and improvements in other fields such as development in lens and displays.

2. Methods and Results

In this experiment, PMMA samples were placed in a vacuum chamber and irradiated with electrons with energy of 50keV. The independent variable of this research was the current density, which was freely manipulated to find the optimum irradiation dose for improving the mechanical properties of the PMMA samples. One of the key elements of this experiment was to observe improvements in the surface hardness of the PMMA samples, thus, pencil hardness testing method was used to roughly determine the change in hardness of the samples after irradiation treatment.

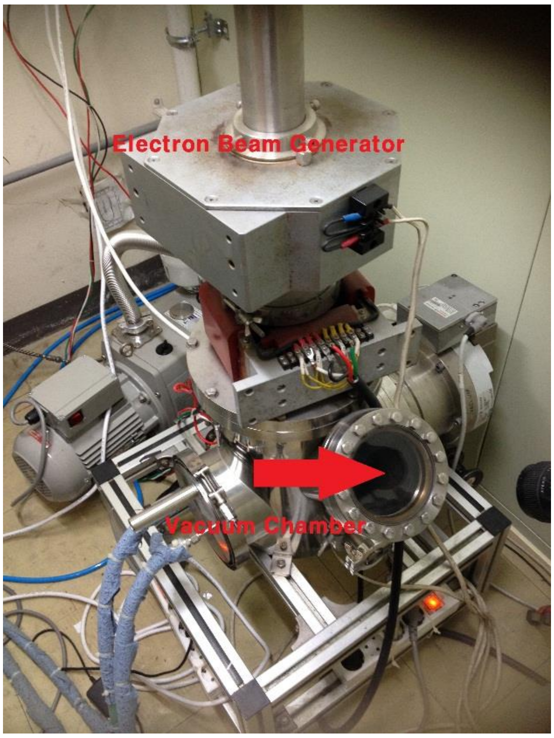

Figure 2. Electron Beam Device

Figure 3. Pencil Hardness Test Device

.

The weight pressing on the pencil was set at exactly 500g and pencil lead of various hardness was slid across the surface of the PMMA samples.

	Sample 1	Sample 2
Beam Strength	NA	50keV
Current Density	None	0.01μA/cm^2
Duration	None	270 minutes
Dose	None	1.29×10^{15} e/cm^2

	Sample 3	Sample 4
Beam Strength	50keV	50keV
Current Density	0.33μA/cm^2	1.2μA/cm^2
Duration	10 minutes	10 minutes
Dose	1.29×10^{15} e/cm^2	4.77×10^{15} e/cm^2

Table 1. Sample Conditions

Sample 1 (pristine PMMA) was set as the control sample and its surface hardness was determined to be below that of a 4H pencil lead (see Figure 4). The pencil hardness scale can be seen in Table 2.

Pencil hardness
with approximate U.S. equivalents

Softer (darker)										Harder (lighter)									
9B	8B	7B	6B	5B	4B	3B	2B	B	HB	F	H	2H	3H	4H	5H	6H	7H	8H	9H
								#1	#2	#2½	#3	#4							

Table 2. Pencil Hardness Scale

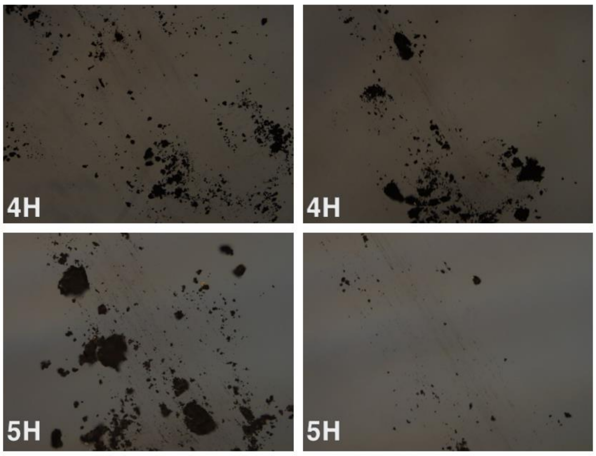

Figure 4. Sample 1 Pencil Hardness Test Results

Sample 2 (irradiated PMMA) was determined to have a surface hardness approximately equal to that of a 5H pencil (see Figure 5).

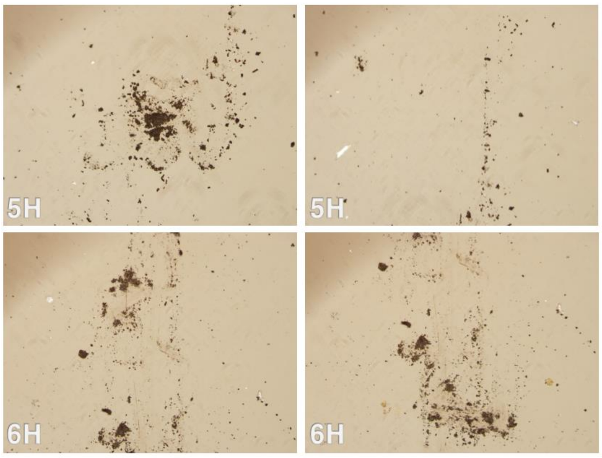

Figure 5. Sample 2 Pencil Hardness Test Results

Sample 3 was determined to have a surface hardness approximately equal to that of a 6H pencil (see Figure 6).

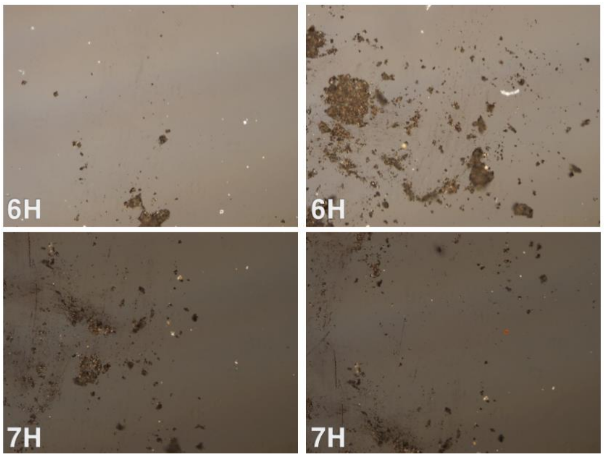

Figure 6. Sample 3 Pencil Hardness Test Results

Sample 4 was determined to have a surface hardness greater than that of a 9H pencil (see Figure 7).

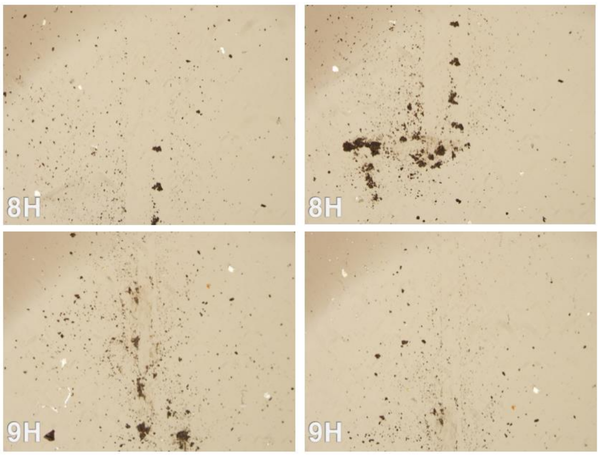

Figure 7. Sample 4 Pencil Hardness Test Results

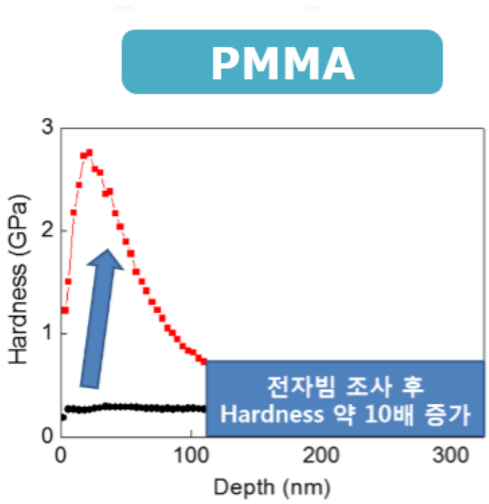

Figure 7. Nano-indenter analysis [1]

Material	Hardness (GPa)
Pristine PMMA	0.290
Copper	0.396
Nickel	0.638
Zirconium	0.903
Cobalt	1.043
Molybdenum	1.53
Uranium	2.450
Irradiated PMMA	**2.800**
Tungsten	3.430
Diamond	115.000

Table 2. Hardness Comparison

3. Conclusions and Further Works

The results demonstrate a general trend of increase in surface hardness with increase in radiation dose. However, in the case of sample 2 vs. sample 3, equal dose irradiation did not result in the same surface hardness result showing that current density also played a role in increasing the hardness.

With higher irradiation dosage and beam strength, hardness of irradiated PMMA could be increased to a much greater extent. Electrons with 50keV of energy can only penetrate around 30µm of PMMA, thus increasing the beam energy could potentially allow for hardening of not just the surface of the PMMA samples, but the whole samples themselves.

Furthermore, Pencil Hardness Test is a method to roughly analyze a material's hardness and does not provide an accurate feedback on the mechanical properties of the material of interest. Hence, a more thorough and effective method of measuring data from the use of equipment such as IZOD Impact Tester, Strain-Stress Tester and Haze Meter will be utilized in the future.

REFERENCES

[1] Sung Oh Cho*, Hye Young Jun "Surface hardening of poly(methyl methacrylate) by electron irradiation", Nuclear Instruments and Methods in Physics Research B 237 (2005)