The Effect of Uniaxial Compression and Stress Relaxation on the Tensile Properties of UHMWPE

E. Abreu, A. Bellare
Department of Orthopedic Surgery, Brigham & Women's Hospital, Harvard Medical School, Boston, MA

Statement of Purpose: Wear of ultra-high molecular weight polyethylene (PE) components of joint replacement prostheses has received great attention for several decades since it limits in vivo life of these orthopedic implants. In recent years, it has been shown the radiation crosslinking induces a network structure into an otherwise linear, highly entangled, high molecular weight macromolecule, which makes it more wear resistant [1, 2]. The tensile properties of crosslinked PEs are characterized by lower maximum stress and maximum strain but with a higher strain-hardening modulus [3]. In this study, we used uniaxial compression and stress relaxation of PE in the melt state to determine whether it increases its network properties, i.e. higher entanglement density leading to higher strain-hardening modulus. The results showed that this melt-process significantly increased the strain-hardening modulus of PE compared to control PE, which is desirable from the standpoint of higher wear resistance.

Methods: Compression molded sheets of GUR 1020 (Ticona, Bayport, TX) PE with 0.1% vitamin E were obtained from MediTech Medical Polymers (Fort Wayne, IN). The sheets were machined into cylinders of 32mm height and 25mm diameter. The cylindrical specimens were heated to 158ºC using a Carver hydraulic press equipped with heating platens and compressed at a rate of approximately 10mm/min to a compression ratio of 15 and then allowed to anneal for a period of 3 hours in the compressed state (COMPR1) or subjected to multiple (=10) compressions and stress relaxation (COMPR2) followed by slow cooling to room temperature. Uncompressed PE served as control (CONTR). Tensile tests were performed on ASTM D638 type V specimens (n=8-10) using an ADMET tensile tester operating at a crosshead-speed of 10 mm/min. A Perkin Elmer Pyris differential scanning calorimeter (DSC) was used to measure crystallinity (X) and melting temperature (Tm) (n=3). The degree of crystallinity (X) was obtained using a heat of fusion, δh_f, of 293 J/g. Lamellar thickness (L) was calculated using the Gibb's Thomson equation [4]: $L=2\sigma_e T^0_m/[\delta h_f(T^0_m-T_m)]$ where σ_e ($=9x10^{-6}$J/cm) is the lamellar surface free energy and T^0_m (145.1ºC). The groups were compared by ANOVA with Fisher's LSD (or Bonferroni) *post-hoc* test with p-values less than 0.05 considered significant.

Results: Tensile tests revealed differences in the stress-strain behavior between the various groups of PE (see Figure 1). The initial linear elastic region of the PEs was nearly identical but the large strain behavior varied significantly. The maximum stress significantly decreased for the COMPR2 PE compared to the control PE while there was no statistically significant difference between the COMPR 1 PE and control PE (see Table 1). However, both compression techniques led to a significant decrease in the maximum strain ($p<0.001$) and an increase in strain hardening modulus ($p\leq0.001$) compared to the uncompressed control PE. COMPR1 PE had the highest strain hardening modulus since it was annealed and recrystallized in the compressed state, which is expected to trap it in an oriented state. Therefore, the entanglement network of this PE was already in a stretched state prior to tensile testing, resulting in a low maximum strain. COMPR2 PE was subjected to stress relaxation prior to tensile testing, thereby rendering it isotropic. Therefore, its strain hardening modulus was lower than COMPR1. But the combination of low crystallinity and higher strain modulus of COMPR2 PE compared to control PE indicates that it had a higher entanglement density, which is desirable for high wear resistance. Both compression processes also led to a significant decrease in the crystallinity ($p<0.001$), and lamellar thickness ($p<0.01$) with respect to the control PE (Table 1). The decrease in crystallinity is expected since the recrystallization after compression and annealing occurred without applied pressure compared to the compression molded controls, which are compressed under applied pressure, which leads to higher crystallinity.

Conclusions: In summary, uniaxial compression followed by stress relaxation can significantly increase strain-hardening modulus of PE, an indicator for high network density and high wear resistance, which are desirable for its application as a bearing material in total joint replacement prostheses.

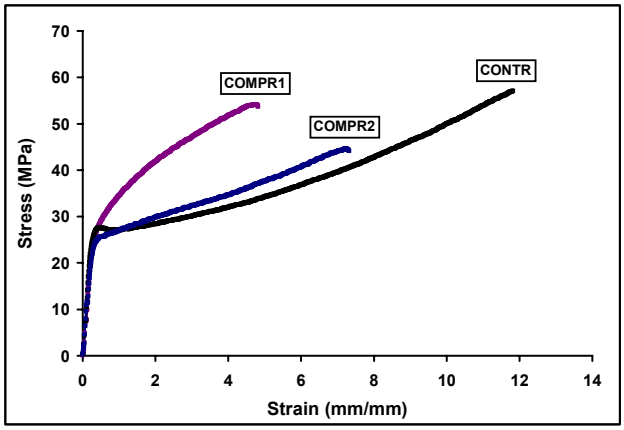

Figure 1. Representative stress-strain curves of control PE and PE after different compression treatments.

Table 1: Crystalline morphology and Tensile properties of various PEs (* significantly different than control)

PROPERTIES	CONTR	COMPR1	COMPR2
X (%)	49.7±1.2	42.8±0.4*	40.5±0.7*
L (nm)	36.6±2.7	26.6±3.5*	22.7±3.3*
Max Stress (MPa)	54.9±5.5	51.3±4.9	44.0±7.0*
Max Strain	12.0±1.4	4.9±1.4*	7.3±1.0*
Strain-Hardening Modulus (MPa)	1.51±0.46	4.96±0.72*	2.79±0.80*

References: [1] Muratoglu O, et al. Biomaterials 1999; 29:1463-70 [2] McKellop H, et al. J Orthop Res 1999; 17(2):157-67 [3] Gomoll A, et al. *J Orthop Res* 2002; 20:1152-56 [4] Hoffman JD Polymer 1983;24:3