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Monotonic and Fatigue Behavior of Five Clinically Relevant Conventional and Highly Crosslinked UHMWPEs in the Presence of Stress Concentrations

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Abstract

Five formulations of clinically relevant UHMWPE (conventional, moderately crosslinked annealed and remelted, and highly crosslinked annealed and remelted) were investigated in a physiologically relevant environment. Their monotonic stress-strain behavior in the presence of notches of two different severities and at two different displacement rates was examined using a custom developed video based system. It was found that both an elevation of yield stress and a truncation of orientation hardening took place. Additionally these changes were found to be material and elastic stress concentration factor dependent. The fatigue behavior of these materials was examined using the same geometries via a stress-life approach with failure defined as fracture of the specimen in the 1,000 to 100,000 cycle lifetime range. The results were modeled using the Basquin relationship ($\sigma = AN^b$, where σ =stress and N =lifetime, and A and b are experimentally derived constants) via maximum likelihood estimation methods to account for specimen runout (no failure at 250,000cycles). The conventional material was found to have a greater slope, b , and intercept, A , than the crosslinked materials as well as appearing to have less variance in its failure distributions.

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) has been used for bearing component of total joint replacements (TJR) for more than fifty years (Kurtz, 2009). Over one million people a year are treated for various joint problems with TJRs that use UHMWPE as the bearing material. Projections show increasing numbers of younger, more active, patients receiving TJRs, necessitating longer performance of these devices (Kurtz et al., 2007; Praemer et al., 1999).

Wear of UHMWPE components can be a significant problem due to formation of UHMWPE debris that can cause a biological cascade of events leading to bone resorption

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and periprosthetic osteolytic implant loosening (Ingham and Fisher, 2005). To combat this wear problem, crosslinking, using ionizing radiation was reintroduced in the 1990s (Kurtz, 2009) with precautions taken to reduce the amount of residual free radicals generated in the crosslinking process (to mitigate oxidative degradation). However, improved wear resistance is gained at the cost of a loss in ductility and fracture resistance due to the restricted mobility of the crosslinked polymer chains (Atwood et al., 2011). Both remelting, done above, and annealing, done below the peak melt temperature (T_m), have been used to combat residual free radicals. Remelting is highly effective at eliminating free radicals (McKellop et al., 1999), but has been shown to decrease crystallinity and lamellar thickness resulting in a decrease in yield stress, ultimate stress, and fatigue crack propagation resistance (Kurtz, 2009; Pruitt, 2005). Annealing does not adversely affect crystallinity (Kurtz, 2009; Pruitt, 2005), but does leave some free radicals, which can lead to oxidative degradation of the material (McKellop et al., 2000; Shen and McKellop, 2002).

Initially these highly crosslinked UHMWPE formulations were restricted to total hip arthroplasty, and now crosslinked UHMWPEs are also being used in total knee arthroplasty (Hodrick et al., 2008; Minoda et al., 2009). UHMWPE component designs contain stress-risers such as fillets, grooves, and undercuts. Therefore, it is of interest to analyze the behavior of crosslinked UHMWPEs in the presence of design-related stress-risers. Notched monotonic tensile tests of conventional and highly crosslinked UHMWPEs demonstrated that the triaxial stress state induced by the notch resulted in an elevation of axial yield stress (a phenomenon known as notch strengthening), a decrease in orientation hardening, and a change in the fracture micromechanism (Sobieraj et al., 2008, 2005).

However, neither of these two studies examined the effects of changing the elastic stress concentration factor (k_t) of the notch. Additionally, none of these works has addressed fatigue loading of UHMWPE in the presence of a notch. Therefore, the objective of this study was to study both the monotonic and fatigue mechanical behavior of conventional, moderately crosslinked, and highly crosslinked UHMWPE in the presence of 2 different stress concentrations. We hypothesized all the materials would show notch strengthening, a truncation of orientation hardening in the presence of a notch, and that these changes would increase with increasing notch severity. We also hypothesized that increasing notch severity and/or radiation dose would both decrease fatigue life.

2. Materials and Methods

Five UHMWPE materials (provided by Orthoplastics Ltd, Lancashire, England) were evaluated in this study. All the materials were made from ram extruded GUR 1050. The conventional material was sterilized at 30kGy in an inert nitrogen environment. Two moderately crosslinked materials were made by crosslinking with a radiation dose of 65kGy. Two highly crosslinked materials were made using a dose of 100kGy. Two types of thermal processing, remelting and annealing, were evaluated for each radiation dose. Remelting was performed above T_m at 150°C and annealing was performed below T_m at 130°C.

2.1 Experimental Methods

2.1.1 Monotonic Testing—Two notch geometries, a moderate and deep notch, were machined into cylindrical dog-bone specimens, both with an outer diameter of 8mm and inner diameter of 6mm. The moderate geometry had a notch radius of 0.9mm ($k_t=2.1$) and the deep notch a notch radius of 0.45mm ($k_t=2.7$). A smooth cylindrical geometry with a diameter of 8mm was used as a control in the monotonic testing (Figure 1). Specimens were soaked in a PBS bath at 37 °C for 8 weeks prior to testing. Following pre-soaking, the specimens were monotonically loaded to fracture, in air at 37 °C, using an Instron 4411 (Instron, Canton, MA). Two displacement rates (30 and 150mm/min) were used. Fifteen

specimens were used for each of the notched geometry conditions and seven to fifteen specimens were used for each of the smooth conditions for a total of 392 monotonic specimens.

Load data was collected with LabView (National Instruments, Austin, TX). Smooth specimen engineering strain was obtained using a non-contacting video extensometer (Instron, Canton, MA). For the notched specimens, engineering strain was obtained using a previously developed non-contacting video based method (Sobieraj and Rimnac, 2009). Custom written MATLAB (Mathworks, Natick MA) programs were used for the generation of both engineering and true stress strain curves.

2.1.2 Fatigue Testing—For the fatigue testing only the two notched geometries were tested. Prior to testing, specimens were soaked in a PBS bath at 37°C for 6–8 weeks. All tests were conducted under tension-tension loading with a sinusoidal waveform with a minimum tensile load of 30N (stress ratio $R=0.04-0.05$ for all tests) at 2 Hz on an Instron 8411 servohydraulic frame. The tests were conducted in a 37°C PBS bath. The intention was to capture lifetimes in the low-to-intermediate (1,000–100,000) cycle range. Load and crosshead displacement were periodically recorded up to failure using LabView. Cycles to failure were also recorded.

A total of 365 specimens were tested with an average lifetime of approximately 67,000 cycles (~9 hours/test). Failure of a specimen was defined as fracture. To make testing feasible, a lifetime of >250,000 (~35 hours) was considered runout, the specimen was removed, and the cycles at removal were recorded. There were at least four stress levels in each material geometry combination which had at least 6 specimens tested, to be able to acquire failure distribution data.

2.2 Analytical Methods

2.2.1 Monotonic Testing—For each of the specimens, a notch strengthening ratio was calculated (Sobieraj et al., 2005):

$$\phi_{\sigma} = \frac{\sigma_y}{\bar{\sigma}_{y,smooth}} \quad (1)$$

where ϕ is the notch strengthening ratio, σ_y is the true yield stress of an individual specimen and $\bar{\sigma}_{y,smooth}$ is the mean true yield stress of the smooth specimens tested at the same displacement rate.

A hardening ratio was also calculated for each of the specimens (Sobieraj et al., 2005):

$$\psi_{\sigma} = \frac{\sigma_u}{\sigma_y} \quad (2)$$

where ψ is the hardening ratio, σ_u is the true ultimate stress, and σ_y is the true yield stress for a specimen.

ANCOVAs were performed on the mechanical properties (true yield stress, and true ultimate stress and strain) and the hardening ratio:

$$X = \mu + \alpha [Material] + \beta [Notch] + \gamma [Rate] + \kappa [Material:Notch] + \lambda [Material:Rate] + \nu [Notch:Rate] \quad (3)$$

where X is the mechanical property or hardening ratio, Material is a categorical variable (one of the five formulations), Notch is a categorical variable (Smooth, Moderate or Deep),

Rate was treated as a categorical variable (30 or 150 mm/min), and the interaction terms between predictor variables are indicated by an “:” (e.g., Material:Notch).

Two reduced data sets were utilized to further explore the data. The first was a data set that only included the two notched geometries. The ANCOVA used was:

$$X = \mu + \alpha [Material] + \beta [Notch] + \gamma [Rate] + \kappa [Material:Notch] + \lambda [Material:Rate] + \nu [Notch:Rate] \quad (4)$$

where the definitions are the same as above, except that Notch now only has the possible values of Moderate and Deep. This ANCOVA was used for the three mechanical properties and the hardening and strengthening ratios.

The second reduced data set included only the crosslinked materials and was also examined via ANCOVA to determine the significance of possible effects of Radiation Dose and Heat Treatment on the three mechanical properties and the hardening and strengthening ratios. These two predictors replaced the Material predictor in the ANCOVA (interactions were not tested):

$$X = \mu + \nu [RadiationDose] + \tau [HeatTreatment] + \beta [Notch] + \gamma [Rate] \quad (5)$$

2.2.2 Fatigue Testing—The data were fitted with the logarithmic transform of the mean relationship commonly used in failure analysis (Lawless, 2003; Sarkani et al., 2007):

$$N = k\sigma^{-m} \quad \text{therefore} \quad \ln N = -m \ln \sigma + \ln k \quad (6)$$

where N is the lifetime, σ is the axial engineering stress amplitude, and m and k are constants. As data is commonly presented in S-N diagrams the more familiar Basquin relationship (Dowling, 1999) is easily related to the mean relationship:

$$\sigma = AN^b \quad \text{therefore} \quad b = -\frac{1}{m} \text{ and } A = k^{-\left(\frac{1}{m}\right)} \quad (7)$$

The easier to visualize (in terms of an S-N curve) constants of A and b will be presented in this work, but it should be noted that these are simply derived from the fitted values of the mean relationship.

Due to the fact that run-out samples did exist, a simple least squares solution to evaluate the S-N behavior was not sufficient. Instead, the method of maximum likelihood estimation (MLE) with unbiased estimators was used, as is commonly done in reliability testing (Lawless, 2003; Sarkani et al., 2007). The advantage of using MLE is that censored data (runout) is considered, rather than using other approaches that are commonly used that either ignore or count runout as a failure point (Sarkani et al., 2007). For this type of modeling the mean relationship is used in its log transform with the underlying failure distribution being a Weibull distribution at all applied stresses (Collins, 1993; Sarkani et al., 2007). Coefficient of determination (R^2) values were calculated using the generalized definition of R^2 proposed by Nagelkerke (Nagelkerke, 1991). The analysis was performed using code written in MATLAB.

To test for differences between the MLE models for materials at a given geometry, and to test for differences between geometries within a material the 2 groups of interest were pooled into a combined group and the MLE was conducted on this combined group. The log-likelihoods of the individual MLEs were then used in conjunction with the log-

likelihood of the combined MLE and the $\chi^2_{(2)}$ distribution, which was used to determine a p-value (Lawless, 2003).

3. Results

3.1 Monotonic Testing

In the smooth condition, all five of the materials demonstrated substantial ductility and orientation hardening (Figure 2). With the introduction of a notch, both materials demonstrated an elevation in the yield stress (notch strengthening) and a reduction in the ultimate stress and ultimate strain. Increasing the k_t of the notch further elevated the yield stress and also further decreased the ultimate stress and strain (Figures 2–5).

ANCOVA (equation 3) demonstrated that Material, Notch and Rate, and the Material:Notch interaction all significantly affected true yield stress, true ultimate stress and strain, and the hardening ratio (Table 1). The Material:Rate interaction was only significant for the true yield stress. The Notch:Rate interaction was found to be significant for true yield stress, true ultimate stress, and the hardening ratio, but not for true ultimate strain.

Evaluation of the first reduced data set (that which only included the notched data) by ANCOVA (equation 4) showed that Material, Notch, Rate, and the Material:Notch interaction were significant predictors for true yield stress, true ultimate stress and strain, and both the hardening and strengthening ratio (Table 2).

The ANCOVA of the second reduced data set (only the four crosslinked materials) again showed that Notch was again a significant predictor for all three properties and both the hardening and the strengthening ratios. Rate was significant for yield stress, ultimate stress, and the strengthening ratio.

Radiation Dose had a significant effect on true ultimate stress and strain and the hardening ratio. Heat Treatment had a significant effect on true yield stress, true ultimate strain, and the hardening and strengthening ratios (Table 3).

By combining the information gained from these analyses (equations 3–5) with the data itself, several general trends can be observed in the mechanical behavior of these five UHMWPE materials. However, it is important to remember that while these general trends were found to be statistically significant, it is possible for a specific comparison of two test conditions to not be significantly different.

With regard to specific differences between materials, the conventional material had the highest yield stress with the annealed materials slightly lower and the remelted materials having the lowest yield stresses (Figure 3). All of the crosslinked materials showed a decrease in ultimate stress compared to the conventional material, and the 100kGy materials tended to have a lower ultimate stress than the 65kGy materials (Figure 4). The crosslinked materials had a lower true ultimate strain than the conventional material whereas the remelted materials showed a trend of higher true ultimate strain than the annealed materials. Materials irradiated at 100kGy had a lower ultimate strain than those irradiated at 65kGy (Figure 5). For notch strengthening, the remelted materials had a higher ratio than the conventional and the annealed materials (which had comparable values to each other) (Figure 6). For the hardening ratio, the conventional and the 65kGy remelted material had comparable values. Annealed materials had lower hardening values, and increasing radiation dose lowered the hardening ratio for both crosslinked materials (Figure 7).

With regards to differences in the specimen geometry, the yield stress increased with notching and increasing the severity of the notch caused a further increase (Figure 3). Notching decreased both the ultimate stress and strain, and increasing notch severity caused a further decrease (Figures 4 and 5). Increasing the severity of the notch increased the strengthening ratio (Figure 6). Notching decreased the hardening ratio and increasing the notch severity caused a further decrease (Figure 7).

Increasing the rate from 30mm/min to 150mm/min was found to increase the yield stress, the ultimate stress, and the notch strengthening ratio (Figures 3, 4, and 6). Increasing the rate was also found to decrease both the ultimate strain and the hardening ratio (Figures 5 and 7).

3.2 Fatigue Testing

The majority of the material/geometry test groups had some specimens with runout (Table 4) with only the conventional UHMWPE in the moderate geometry having no runout specimens. Additionally, the conventional material was better fit by the mean relationship (equation 6) than the crosslinked materials as indicated by the higher R^2 values. The conventional material also had the least spread to its data, that is to say at a given stress level the range of lifetimes seen for the conventional material was tighter than for the other materials. (Table 4, Figures 8 and 9).

The conventional material had both a steeper slope, b , and a larger intercept, A , than all of the crosslinked materials in both the notched conditions (Table 4, Figure 9). There were no general trends in the relationship of the values of b and A within materials or geometries of the other materials. Within each material, with the exception of the 65kGy remelted material, there was a significant difference in the moderate and deep notched conditions within a material (Table 5). In the moderate notch geometry the conventional material was found to be significantly different than the other 4 materials and the 65kGy remelted and annealed materials were significantly different from one another (Table 5). No other differences were found significant in the moderate notched condition between materials. For the deep notched condition, again the conventional material was statistically significantly different from all the other materials as was the 100kGy annealed material (Table 5). None of the other material comparisons were found to be significant in the deep notched condition.

4. Discussion

The objective of this study was to investigate the effects of notching and increasing k_t on the material properties and the notch strengthening and hardening ratios as well as to investigate fatigue of UHMWPE in the notched condition. A novel experimental design was used for the testing of notched fatigue life of different UHMWPEs that incorporated MLE statistical methods in order to facilitate a practical research protocol.

The major limitation of this study is that it is an *in vitro* study that used simplified geometries and loading conditions relative to the *in vivo* environment. Nevertheless, the use of simplified geometry and loading scenarios can be a useful approach (Collins, 1993) and in this case provides insight into the role of UHMWPE material formulation in combination with implant design on the mechanical performance of UHMWPE bearings designs used in joint replacements. Another limitation is that smooth specimens were not tested in the fatigue testing portion of this work. Preliminary experiments found smooth specimens to slowly lengthen and become translucent indicating a process of chain orientation (Sobieraj et al., 2005). It was not thought that this essentially new, highly oriented material state was clinically relevant and, therefore, only notched specimens were tested.

The hypothesis that all the UHMPE materials would show notch strengthening, and a truncation of orientation hardening upon notching and that these changes would increase with increasing notch severity was confirmed. As expected, the conventional material showed the highest yield and the greatest ductility. This is consistent with previous reports on UHMWPE (Kurtz et al., 2002; Sobieraj et al., 2005).

The finding that heat treatment significantly affected yield stress while radiation dose did not can be explained from the morphology of the polymers. Both bulk crystallinity and lamellar thickness have been shown to be determinant of the yield stress in polyethylenes in general. The heat treatment alters the bulk crystallinity by causing lamellar thickening in the case of annealing and by causing an overall decrease in the bulk crystallinity in the case of remelting (Sobieraj and Rimnac, 2008). Therefore, it is an expected result that heat treatment affects yield stress, and that the annealed materials have a higher yield stress than the remelted materials.

For ultimate stress the radiation dose was found to be a significant predictor (while heat treatment was not). Increasing crosslinking density has been shown to decrease ultimate stress (Kurtz, 2009). Therefore, since irradiation dose determines crosslinking density the finding that the ultimate stress is decreased with increasing radiation dose is an expected result. Further, fracture in thermoplastics is a combination of chain disentanglement, chain scission, and plastic deformation in the amorphous phase (Karian, 2003), therefore, it would not be expected that alterations in crystallinity would significantly affect the force to break/disentangle these chains or to alter the flow behavior of the amorphous phase.

The ultimate strain was dependent on both heat treatment and radiation dose. The finding that radiation dose was a significant predictor is due to the fact that crosslinking decreases the ductility of UHMWPE by causing chains to be more restricted from free motion by linking them together (Kurtz, 2009). The reason that heat treatment was significant is more subtle; the crystallinity of the remelted materials is reduced, and therefore there is a larger amorphous content. It can be expected that the increased amount of amorphous material will, therefore, allow for a greater strain to be achieved at a given radiation dose.

Taken together the findings support that yield is predominantly a phenomenon of the crystalline domain, and that the ultimate properties are dominated by the amorphous regions in this family of UHMWPE materials.

This is the first study known to the authors that has examined the effect of altering k_t on the axial stress-strain behavior of UHMWPE and that examines this in several clinically relevant formulations of UHMWPE. As shown in previous works by this group (Sobieraj et al., 2008, 2005), notching increased the true axial yield stress and decreased the true axial ultimate stress and strain. In this study it was found that increasing the k_t not only further increased the yield stress, but also further reduced the ultimate stress and strain.

With regard to fatigue testing, the method used in this study was to conduct experiments to failure, not to a 12% failure strain criterion as has been done by other investigators (Medel et al., 2007; Puertolas et al., 2006). The crosslinked materials all had improved fatigue behavior in that the stress levels in the higher lifetimes were higher than for the conventional material. This improved fatigue behavior of the crosslinked materials is consistent with the findings of Puertolas et al. (2006) and Baker et al. (2003). Both of these studies conducted smooth (unnotched) specimen S-N tests on various conventional and crosslinked formulations of UHMWPE and found higher lifetimes (in these studies failure was defined as attainment of a specific strain level) at a given stress level for the crosslinked materials. Baker et al. hypothesized that crosslinking may serve to strengthen the amorphous phase of

the polymer, thereby minimizing fatigue-induced void formation which is a precursor to flaw generation.

The conventional material showed a higher R^2 than the other materials. This implies that the other materials either have significantly more variance in their S-N distributions, or that the Basquin relationship is not an accurate estimate of the S-N behavior of these materials. Simple observation of the data and the resulting linear regressions and MLE solutions (Figure 8) suggests that there is a higher variance of the S-N data for the crosslinked materials. There are several possible reasons this variation. There could be variability in radiation dose that the specimens received, resulting in a variation in crosslinking, however these differences should be small, and unlikely to explain all the variation. Another potential explanation is that the crosslinked materials have a higher sensitivity to machining flaws associated with the notching procedure.

5. Conclusions

This work showed that both notch severity and UHMWPE formulation are significant contributors to the behavior of UHMWPE in the vicinity of a stress concentration. This was found both under monotonic and cyclic loading conditions, in which the crosslinked materials appear to show improved overall S-N characteristics when judging mean behavior, but at the expense of what appears to be greater variability in their behavior.

Therefore, UHMWPE formulation must be considered in the design of the stress riser features of components, including undercuts, fillets, and locking mechanisms. For example, a locking mechanism that is acceptable for a conventional UHMWPE acetabular liner may not be appropriate for a highly crosslinked one.

Lastly, there has been limited research into the behavior of 2nd generation highly crosslinked polyethylenes in the presence of notches (Sobieraj et al., 2008). In this regard, the authors know of no such studies on vitamin-E enhanced crosslinked polyethylenes. Therefore, given the findings of this study, this is an area that may warrant investigation in these new materials, given their current adoption by the arthroplasty community, and their incorporation into designs with larger heads, thinner liners, and multiple bearing surfaces in THA and TKA.

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Figure 1.
The geometries used in this study. All have an outer diameter of 8mm and an inner diameter of 6mm.

Figure 2.

Representative axial true stress-strain curves for the five formulations of UHMWPE (all are at 30mm/min).

Figure 3.
True axial yield stress. Left: 30mm/min. Right: 150mm/min.

Figure 4.
True axial ultimate stress. Left: 30mm/min. Right: 150mm/min.

Figure 5.
True axial ultimate strain. Left: 30mm/min. Right: 150mm/min.

Figure 6.
Hardening ratio. Left: 30mm/min. Right: 150mm/min.

Figure 7.
Notch strengthening ratio. Left: 30mm/min. Right: 150mm/min.

Figure 8. Representative S-N curves. Left: conventional material with moderate notch ($R^2=0.86$). Right: 100 kGy Remelted material with moderate notch ($R^2=0.28$). These are the two conditions with the highest and the lowest values of R^2 .

Figure 9. Bar charts of the Basquin relationship values of b (slope) and A (intercept) for the fatigue Maximum Likelihood Estimation (MLE).

Table 1

P-values for ANCOVA (equation 3).

Predictors	<i>True Yield Stress</i>	<i>True Ultimate Stress</i>	<i>True Ultimate Strain</i>	<i>Hardening Ratio</i>
<i>Material</i>	<0.001	<0.001	<0.001	<0.001
<i>Notch</i>	<0.001	<0.001	<0.001	<0.001
<i>Rate</i>	<0.001	<0.001	0.035	0.005
<i>Material:Notch</i>	0.001	<0.001	<0.001	<0.001
<i>Material:Rate</i>	<0.001	0.073	0.282	0.480
<i>Notch:Rate</i>	<0.001	0.003	0.879	<0.001

Gray shading indicates significance

Table 2

P-values for ANCOVA (equation 4).

Predictors	True Yield Stress	True Ultimate Stress	True Ultimate Strain	Hardening Ratio	Strengthening Ratio
<i>Material</i>	>0.001	>0.001	>0.001	>0.001	>0.001
<i>Notch</i>	>0.001	>0.001	>0.001	>0.001	>0.001
<i>Rate</i>	>0.001	>0.001	0.045	0.17	>0.001
<i>Material:Notch</i>	0.038	>0.001	>0.001	>0.001	0.002
<i>Material:Rate</i>	>0.001	0.39	0.45	0.82	>0.001
<i>Notch:Rate</i>	0.16	0.2	0.96	0.62	0.46

Gray shading indicates significance

Table 3

P-values for ANCOVA (equation 5).

Predictors	True Yield Stress	True Ultimate Stress	True Ultimate Strain	Hardening Ratio	Strengthening Ratio
Radiation Dose	0.347	>0.001	>0.001	0.12	>0.001
Heat Treatment	>0.001	0.139	>0.001	>0.001	>0.001
Notch	>0.001	>0.001	>0.001	>0.001	>0.001
Rate	>0.001	>0.001	0.12	0.02	0.39

Gray shading indicates significance

Experimental parameters for the fatigue testing as well as the results of the MLEs. Stress levels gives the number of different stress levels at which samples were tested.

Table 4

Material	Geometry	Total Samples	Runout Samples	Stress Levels	R ²	A (MPa)	b
Conventional	Moderate	29	0	6	0.863	16.17	-0.038
	Deep	27	1	6	0.804	16.31	-0.037
65kGy Annealed	Moderate	32	2	5	0.432	14.19	-0.021
	Deep	31	2	5	0.536	13.84	-0.020
65kGy Remelted	Moderate	45	10	10	0.387	13.69	-0.017
	Deep	36	4	7	0.445	13.79	-0.023
100kGy Annealed	Moderate	44	10	9	0.543	14.38	-0.019
	Deep	38	3	7	0.588	15.43	-0.029
100kGy Remelted	Moderate	48	6	9	0.280	14.19	-0.022
	Deep	35	3	9	0.579	13.47	-0.019

Table 5

P-values for comparisons of MLEs.

	Conventional	65kGy Annealed	65kGy Remelted	100kGy Annealed	100kGy Remelted
Conventional		<0.001	<0.001	<0.001	<0.001
65kGy Annealed	0.004		0.03	1	0.196
65kGy Remelted	0.007	1		1	1.000
100kGy Annealed	<0.001	<0.001	0.006		0.076
100kGy Remelted	<0.001	0.532	1	<0.001	
Moderate vs Deep	<0.001	0.006	0.102	<0.001	0.006

Gray shading indicates significance. The material comparisons are in the top part of the table. Above and to the right of the blackened diagonal squares are the p-values for the moderate notch material comparisons (the top right cell is comparing the conventional material to the 100kGy remelted when both have a moderate notch). Below and to the left of the blackened diagonal are the p-values for the deep notch material comparisons (the cell in the second row first column is comparing the conventional material to the 65kGy annealed material when both have a deep notch). The last row of the table includes the p-values for the geometry comparisons within a material.