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Deliverable D41.11: Report on graphite screening results at 750°C & 950°C.

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Summary

This document contains the results from the Graphite Irradiation Screening tests performed for the medium to high dose level INNOGRAPH experiments in the RAPHAEL-IP and completed for the 750 and 950°C nominal temperatures. The results have been compared with the lower dose Full PIE results completed in the RAPHAEL- IP. These results provide an initial indication of the behaviour ahead of the results from the Full PIE Tests being performed in ARCHER. The PIE tests to be carried out and the results of the assessment are to be reported in Deliverable D-41-12.

Approval

Rev.	Date	First author	SP leader	Project Coordinator
0	month/year	M Heijna (NRG)	D Buckthorpe; AMEC	S de Groot;NRG
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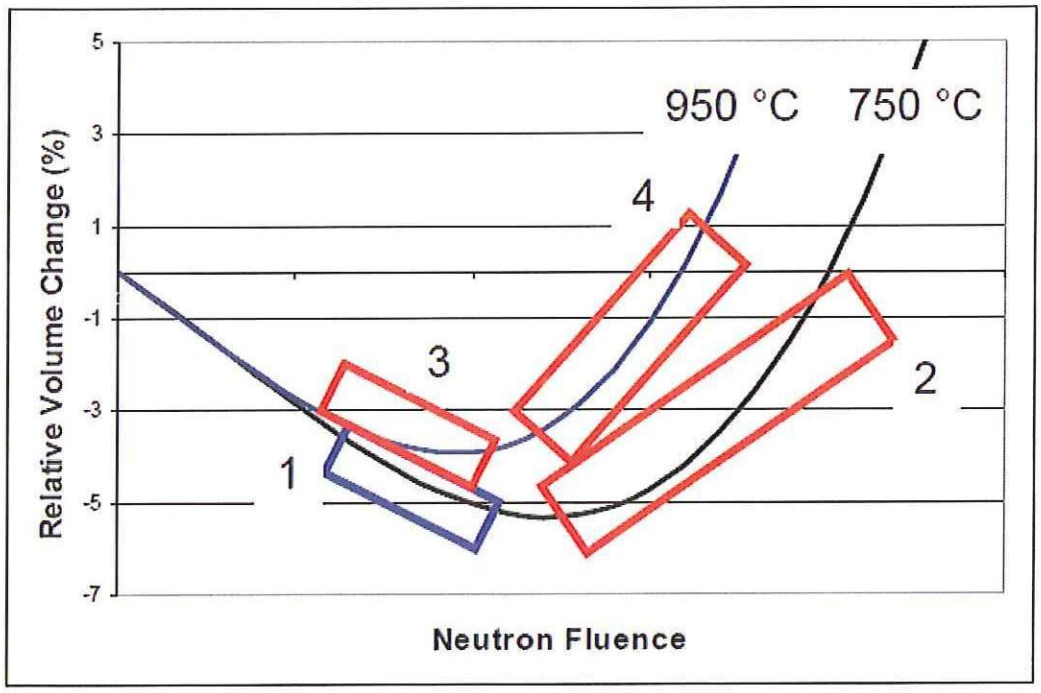
1 Introduction

This report describes the screening results of the Post Irradiation Examination (PIE) of INNOGRAPH-I B, the high dose irradiation experiment, irradiated at 750°C and INNOGRAPH-2B, the high dose irradiation experiment, irradiated at 950°C. The latter results were reported in RAPHAEL but have been included here for completeness. The results are plotted together in this report to show the complete data curves at 750 and 950°C. Screening measurements are performed on a selection of samples to get an idea of the behaviour of the interesting graphite grades. More PIE work is planned in the ARCHER programme to establish Full PIE curves at 750°C and 950°C which can be used to establish the Design Curves at these temperatures.

2 Background

Within the previous 6th Framework RAPHAEL-IP, irradiation experiments were performed at 750°C and 950°C in the High Flux Reactor (HFR) in Petten. In every experiment a few graphites were also irradiated at lower temperatures of 680°C and 850°C respectively. Four graphite grades have been selected to be tested as major grades. Two of those are produced by SGL Carbon and two by GrafTech. In addition, the minor graphite grades are listed to be included in the experiments with fewer samples. These also included graphite grades produced by Toyo Tanso. The following material properties were measured and compared before and after irradiation: specimen dimensions, mass, dynamic Young's modulus, coefficient of thermal expansion and thermal diffusivity. Density and thermal conductivity were calculated from the measured properties.

The diagram below shows schematically the expected volume change with neutron fluence at the two main irradiation temperatures. The boxes on the curves indicate the four different irradiation experiments.



Schematic overview of the Four Graphite Irradiation Experiments performed in RAPHAEL-IP

Box 1, the low dose irradiation at 750°C named INNOGRAPH-1A has been performed under HTR-M1 in the 5th Framework Programme and had a target dose of 8 displacements per atom (dpa) [1]. Box 2, named INNOGRAPH-1B is the high dose (up to ~25 dpa) experiment at the same temperature. Boxes 3 and 4, designated as INNOGRAPH-2A and INNOGRAPH-2B, represent respectively the low to medium dose and the high dose irradiation experiments at 950°C. In order to reach the target dose in as short a time as possible, the high dose experiments (INNOGRAPH-1B/2B) partly contain specimens, which have been irradiated in the low dose experiments. These high dose experiments had to be built in a hot-cell because of the radioactive loading. Capability to do this delicate work with manipulators is essential in carrying out this irradiation programme.

3 Test matrix

The selection of the graphite grades for the RAPHAEL programme is based on several factors such as thermal and mechanical properties, impurity levels and availability. The four major grades, produced by SGL Carbon and GrafTech are chosen in such a way that the graphites cover a variety of microstructures. The minor grades include graphites from three different manufacturers, SGL Carbon, GrafTech and Toyo Tanso. The minor grades include iso-moulded graphites and graphites based on needle coke. The list of major and minor grades is slightly different that the list in the 5th framework programme, due to the fact that in the four year period between the two lists new insights and grades were available.

Grade	Manufacturer	Coke	Process
PCEA	Graftech	Petroleum	Extrusion
PPEA	Graftech	Pitch	Extrusion
NGB-10	SGL	Pitch	Extrusion
NBG-18	SGL	Pitch	Fibro-moulding

Selected Major Graphite Grades

Grade	Manufacturer	Coke	Process
PCIB-SFG	Graftech	Petroleum	Iso-moulding
LPEB/BAN	Graftech	Needle	Extrusion
NBG-20	SGL	Petroleum	Extrusion
NBG-25	SGL	Petroleum	Iso-moulding
NBG-17	SGL	Pitch	Fibro-moulding
IG-110	Toyo Tanso	Petroleum	Iso-moulding
IG-430	Toyo Tanso	Pitch	Iso-moulding

Selected Minor Graphite Grades

4 Results from Screening Tests at 750°C (Box 2)

For the INNOGRAPH 1B Tests, in total 60 samples were measured for dimensions and mass, 30 samples were measured for Dynamic Young's Modulus (DYM), 18 samples were measured for the Coefficient of Thermal Expansions (CTE) and 16 samples were measured for coefficient of thermal diffusivity (Table 1). The irradiation experiment, test matrix, measurement techniques and results of the INNOGRAPH- 1A experiment are presented in Reference [2]. The peak dose of INNOGRAPH-1B was 13.5 dpa, resulting in a peak dose received by the reloaded samples of 9.9 + 13.5 = 23.4 dpa (INNOGRAPH-1A + INNOGRAPH-1B).

The results from the screening test at 750°C are shown in graphical form in a series of plots in Figures 1 to 13. The graphs include the data from the INNOGRAPH-1A irradiation experiment.

The results in Figures 1-3 show the volume change as a function of irradiation damage. It can be seen that there is an initial reduction in volume followed by a turnaround to increasing volume. The peak dose of the experiments is high enough for samples to go beyond cross-over (the point when the original volume is reached).

The results in Figures 4-6 show the length change in the samples. As for the volume change there is an initial reduction in length followed by a turnaround to increasing length. The peak dose of the experiments is high enough for samples to go beyond cross-over (the point when the original length is reached). A similar behaviour was observed for the specimen diameter. The anisotropic irradiation behaviour of the grades is also visible.

The change of dynamic Young's Modulus as a function of irradiation dose is plotted in Figures 7- 9. For nuclear grade graphites, there is a rapid initial increase in DYM after which a plateau is reached. (This initial rapid increase is not covered by the data). After about 5 dpa, a second increase in DYM occurs. At higher doses the DYM reaches a peak and then starts to decrease. The spread in results is high at these high dose levels, partly because of the material variability between the different grades, and partly because the large amount of irradiation damage results in larger measurement uncertainties. It will be interesting to measure samples between 10 and 15 dpa in the ARCHER programme, to determine at what dose the peak value of DYM change has been reached.

Figures 10 and 11 show the results of the CTE measurements. For nuclear grade graphites, after a small initial increase in CTE, the CTE decreases as a function of dose until at a medium dose a plateau value is reached. (The initial small increase is not covered by the data). Performing more measurements between 10 and 15 dpa will give more information regarding the dpa value at which this plateau has been reached. -

Figures 12 and 13 show the results of the thermal diffusivity measurements. For nuclear grade graphites, there is a large initial decrease in thermal diffusivity, after which a plateau is reached. (The initial large decrease is not covered by the data). At higher doses, the coefficient of thermal diffusivity decreases further as can be seen from the graphs

Note – A very low dose experiment is to be carried out in ARCHER at 750°C. This will provide useful data where the rapid changes in DYM and thermal diffusivity occur, which will allow a better definition of the curves to be obtained.

5 Results from Screening Tests at 950°C (Box 4)

The results for the INNOGRAPH-2A tests are reported in the RAPHAEL Programme in Reference [3]. Screening results for the INNOGRAPH 2B tests have also been reported within the RAPHAEL-IP but are summarised here for completeness. Table 2 gives the test matrix of the INNOGRAPH-2B irradiation experiment. The pre-irradiated samples have been irradiated in the INNOGRAPH-2A experiment prior to their insertion in shielded facilities [3]. The INNOGRAPH-2B experiment was irradiated for 12 cycles, corresponding to 323 full power days. Measurements were taken in the first screening experiments where 60 samples were measured on dimensions and mass.

From these samples 30 samples were measured on DYM, 15 samples on CTE and 15 samples on thermal diffusivity. Criteria for the sample selection for these measurements cover most grades and select high dpa samples. However only low active (contact dose rate) samples could be selected to allow measurements in the glove boxes.

Table 3a and 3b show the results of the measurements on dimensions and mass. The tables also show the calculated volume and density and the results of the DYM measurements (if performed). The results before and after irradiation are given. As for the 750°C experiment, it was observed that a significant number of samples have increased volume and dimensions at high irradiation. The dosimetry results together with more PIE results are needed to obtain the dpa level at which cross-over occurs, and these will be obtained from the full PIE. Also the DYM values of the high dose samples are smaller than the highest DYM values of INNOGRAPH-2A. This suggests that the peak DYM for the 950°C irradiation is lower than that for the 950°C irradiation, and perhaps decrease at a faster rate thereafter. However, this cannot be confirmed until the full PIE has been carried out.

Table 3c shows the results of the CTE measurements both pre-and post-irradiation. Tables 3d and 3e show the results of the thermal diffusivity measurements. The values of the high dose (2B) samples are lower that the PIE results of INNOGRAPH-2A [3], which shows that both CTE and thermal diffusivity continue to decrease at higher doses..

6 Conclusions

The results of the Graphite Irradiation Screening tests performed on samples from the 750 and 950°C graphite irradiation experiments in RAPHAEL have been reported and summarised. The purpose of this report is to provide an initial indication of behaviour at high doses ahead of the results from the Full PIE Tests being performed in ARCHER. The PIE tests to be carried out and the results of the assessment are to be reported in Deliverable D-41-12.

7 References

[1] *J.A. Vreeling et al., Designing, loading, and assembling an irradiation experiment with radioactive samples, RAPHAEL DML 3.1: Progress on continuation of 750°C graphite irradiation test, 21457/06.77295/P, 26 October 2006*

[2] *J.A. Vreeling and B. Sakintuna "Graphite irradiation experiments at 750°C", NRG-21457/IO.101850, 2010*

[3] *J.A. Vreeling and B. Sakintuna, DML3.16 Post Irradiation Examinations of experiment at 950°C, full PIE of INNOGRAPH-2A, 21457/10/101644, 14 April 2010*

Table 1 Screening measurements on INNOGRAPH-1B samples (marked with X)

Sample	Grade	Orientation	Location	dpa	Dimensions	Massa	DYM	CTE	Thermal diffusivity
S031	NBG-10	WG	Centre	16.9	X	X	X	X	X
S033	NBG-10	WG	Centre	22.2	X	X	X	X	X
S038	NBG-10	WG	Centre	11.9	X	X			
S041	NBG-10	AG	Centre	21.1	X	X	X		
S042	NBG-10	AG	Centre	22.3	X	X	X	X	X
S043	NBG-10	AG	Centre	17.3	X	X	X	X	X
S053	NBG-10	AG	Centre	13.2	X	X			
S065	NBG-10	WG	Edge	21.7	X	X	X		
S068	NBG-10	WG	Edge	13.5	X	X			
S081	NBG-10	AG	Edge	10.1	X	X			
S094	NBG-25	AG	Centre	19.4	X	X	X		
S101	NBG-25	AG	Centre	13.1	X	X			
S108	NBG-25	WG	Centre	13.2	X	X			
S111	NBG-25	WG	Centre	15.2	X	X			
S130	NBG-25	AG	Edge	21.8	X	X			
S139	NBG-25	WG	Edge	23.0	X	X	X		
S468	NBG-18	WG	Edge	13.1	X	X	X	X	X
S476	NBG-18	AG	Edge	10.0	X	X	X	X	X
S512	NBG-18	WG	Centre	11.1	X	X	X	X	X
S514	NBG-18	WG	Centre	12.0	X	X			
S523	NBG-18	AG	Centre	13.2	X	X	X	X	X
S524	NBG-18	AG	Centre	11.4	X	X			
S568	NBG-17	AG	Edge	13.2	X	X	X		
S571	NBG-17	AG	Edge	10.8	X	X			
S579	NBG-17	WG	Edge	13.2	X	X	X	X	X
S580	NBG-17	WG	Edge	12.1	X	X			
S619	NBG-17	AG	Centre	8.3	X	X			
S626	NBG-17	WG	Centre	9.4	X	X			
T011	IG-110	AG	Centre	23.4	X	X	X		
T014	IG-110	AG	Centre	13.6	X	X			
T022	IG-110	WG	Centre	17.4	X	X			
T023	IG-110	WG	Centre	22.5	X	X	X		
T070	IG-430	AG	Centre	22.2	X	X	X		
T081	IG-430	WG	Centre	21.9	X	X	X		
U004	PCEA	WG	Centre	17.8	X	X	X	X	X
U005	PCEA	WG	Centre	22.4	X	X	X	X	X
U006	PCEA	WG	Centre	9.6	X	X	X		
U021	PCEA	AG	Centre	17.0	X	X	X	X	X
U022	PCEA	AG	Centre	21.3	X	X			
U023	PCEA	AG	Centre	22.2	X	X	X	X	X
U042	PCEA	AG	Centre	13.2	X	X			
U077	PCEA	AG	Edge	20.5	X	X	X	X	X
U078	PCEA	AG	Edge	9.5	X	X			
U104	PCEA	WG	Edge	13.0	X	X			
U123	PCIB	WG	Centre	18.2	X	X			
U148	PCIB	WG	Centre	13.6	X	X			
U166	PCIB	AG	Centre	13.4	X	X			
U167	PCIB	AG	Centre	12.0	X	X			
U191	PCIB	WG	Edge	23.4	X	X	X		
U197	PCIB	AG	Edge	23.6	X	X	X		
U236	PPEA	AG	Centre	19.9	X	X	X	X	X
U238	PPEA	AG	Centre	22.4	X	X	X	X	
U258	PPEA	AG	Centre	12.8	X	X			
U277	PPEA	WG	Centre	18.7	X	X	X	X	X
U279	PPEA	WG	Centre	22.2	X	X	X	X	
U287	PPEA	WG	Centre	13.1	X	X			
U298	PPEA	WG	Edge	9.2	X	X			
U306	PPEA	AG	Edge	11.2	X	X			
U354	LPEB	WG	Centre	13.2	X	X			
U364	LPEB	AG	Centre	13.0	X	X			

Table 2 Test Matrix for the INNOGRAPH 2B Experiment

Grade	Irradiated	Un-irradiated	Total
IG-110	2	2	4
IG-430	2	5	7
LPEB	3	6	9
LPIB	2	0	2
NBG-10	13	18	31
NBG-17	7	12	19
NBG-18	15	18	33
NBG-25	5	6	11
PCIB	5	6	11
PPEA	10	20	30
PCEA	16	18	34

Table 3a Results of Screening Measurements from INNOGRAPH 2B
(Dimension, Mass, Volume, Density & Dym: pre and post irradiated)

Sample				Post irradiation							Pre irradiation						
				x (mm)	d (mm)	l (mm)	m (g)	V (mm^3)	ρ (g/cm^3)	E (GPa)	x (mm)	d (mm)	l (mm)	m (g)	V (mm^3)	ρ (g/cm^3)	E (GPa)
S358	NBG-10	AG	Edge	7.926	8.398	6.389	0.5427	346.0	1.569	19.9	7.685	7.984	5.956	0.5470	294.5	1.857	12.0
S649	NBG-10	AG	Centre	7.593	7.885	5.917	0.5348	285.5	1.873		7.709	7.990	5.994	0.5352	297.2	1.801	13.2
S652	NBG-10	AG	Centre	7.578	7.887	5.912	0.5358	285.1	1.879		7.707	7.978	5.970	0.5362	295.3	1.816	13.4
S359	NBG-10	AG	Edge	7.953	8.399	6.464	0.5474	350.8	1.561	14.3	7.694	7.997	6.036	0.5543	299.4	1.851	12.2
S077	NBG-10	AG	Edge	7.919	8.342	6.200	0.5250	332.4	1.580		7.977	7.996	6.008	0.5387	301.6	1.786	13.1
S646	NBG-10	WG	Centre	7.640	7.926	5.877	0.5334	286.6	1.861		7.716	7.997	5.980	0.5337	297.0	1.797	13.5
S648	NBG-10	WG	Centre	7.635	7.917	5.901	0.5308	287.2	1.848		7.703	8.000	5.991	0.5311	297.5	1.785	13.1
S062	NBG-10	WG	Edge	7.833	8.225	6.124	0.5360	319.7	1.677	28.2	7.687	7.987	6.030	0.5362	298.4	1.797	12.3
S360	NBG-10	WG	Edge	7.961	8.254	6.140	0.5290	324.8	1.629	22.4	7.700	8.004	6.016	0.5411	299.0	1.810	10.6
S362	NBG-10	WG	Edge	8.004	8.380	6.165	0.5311	334.6	1.587		7.691	7.990	6.055	0.5424	299.9	1.809	11.3
S382	NBG-10	WG	Centre	7.887	8.194	6.138	0.5400	319.7	1.689	27.5	7.768	7.990	5.978	0.5253	297.4	1.767	9.1
S420	NBG-25	AG	Edge	7.738	7.955	5.921	0.5391	292.1	1.846		7.703	8.002	6.014	0.5397	298.8	1.806	11.5
S438	NBG-25	AG	Centre	7.752	8.111	6.342	0.5387	322.6	1.670		7.783	7.992	6.014	0.5564	299.6	1.857	11.5
S446	NBG-25	WG	Centre	7.857	8.078	5.970	0.5366	303.6	1.767	33.1	7.702	7.986	5.952	0.5275	294.7	1.790	13.0
S448	NBG-25	WG	Centre	8.026	8.253	6.063	0.5361	321.8	1.666	28.8	7.688	7.986	6.046	0.5525	299.2	1.847	13.5
S519	NBG-18	AG	Centre	7.833	8.228	6.396	0.5474	334.1	1.638	21.8	7.699	8.015	5.992	0.5621	298.3	1.884	13.5
S870	NBG-18	AG	Centre	7.595	7.876	5.950	0.5421	286.6	1.892		7.684	7.982	5.995	0.5426	296.3	1.831	14.3
S880	NBG-18	AG	Edge	7.625	7.902	5.966	0.5407	289.4	1.869		7.690	7.988	5.984	0.5421	296.2	1.830	13.3
S883	NBG-18	AG	Edge	7.617	7.885	5.939	0.5402	286.9	1.883		7.703	7.987	5.984	0.5402	296.4	1.822	13.4
S475	NBG-18	AG	Edge	7.798	8.163	6.275	0.5440	323.2	1.683	21.6	7.688	7.994	6.005	0.5303	297.6	1.782	13.1
S473	NBG-18	AG	Edge	8.052	8.549	6.574	0.5383	368.5	1.461	16.6	7.648	7.987	5.984	0.5370	295.4	1.818	13.5
S462	NBG-18	WG	Edge	8.298	8.648	6.544	0.5467	379.2	1.442	16.0	7.691	7.983	6.005	0.5489	297.0	1.848	13.4
S463	NBG-18	WG	Edge	8.130	8.452	6.370	0.5417	352.9	1.535	17.4	7.687	7.997	6.027	0.5407	298.8	1.809	12.7
S464	NBG-18	WG	Edge	7.861	8.131	6.070	0.5462	312.0	1.751		7.696	7.997	6.013	0.5418	298.3	1.816	12.8
S506	NBG-18	WG	Centre	7.705	8.212	6.179	0.5447	318.9	1.708	27.7	7.697	7.981	6.038	0.5437	298.7	1.820	13.2
S566	NBG-17	AG	Edge	7.676	7.956	6.017	0.5589	295.8	1.889		7.718	8.012	5.992	0.5604	298.5	1.877	14.1
S562	NBG-17	WG	Edge	8.061	8.431	6.334	0.5486	348.2	1.576	20.2	7.751	8.008	5.975	0.5614	298.0	1.884	14.3
S578	NBG-17	WG	Edge	7.701	7.990	5.988	0.5583	296.7	1.881		7.740	8.013	6.028	0.5598	300.8	1.861	14.0
S598	NBG-17	WG	Centre	8.104	8.381	6.244	0.5597	341.0	1.641	24.9	7.745	8.015	5.989	0.5620	299.0	1.880	14.0
T044	IG-110	AG	Edge	7.999	8.185	6.333	0.5402	331.3	1.631	20.7	7.768	7.990	5.978	0.5253	297.4	1.767	9.1
T055	IG-110	WG	Edge	7.860	8.258	6.013	0.5246	316.3	1.658	24.1	7.574	7.973	5.988	0.5191	293.4	1.769	10.5
T087	IG-430	WG	Centre	7.782	8.296	6.122	0.5175	322.4	1.605	23.0	7.774	7.979	6.033	0.5339	299.6	1.782	11.2

Table 3b Results of Screening Measurements from INNOGRAPH 2B
(Dimension, Mass, Volume, Density & Dym; pre and post irradiated)

Sample				Post irradiation							Pre irradiation						
				x (mm)	d (mm)	l (mm)	m (g)	V (mm³)	ρ (g/cm³)	E (GPa)	x (mm)	d (mm)	l (mm)	m (g)	V (mm³)	ρ (g/cm³)	E (GPa)
U033	PCEA	AG	Centre	8.005	8.535	6.409	0.5345	357.3	1.496	12.2	7.683	7.991	5.876	0.5244	291.0	1.802	11.1
U034	PCEA	AG	Centre	7.710	8.164	6.211	0.5232	318.0	1.645	23.5	7.690	8.003	5.999	0.5355	297.8	1.798	11.0
U089	PCEA	AG	Edge	7.615	8.018	6.072	0.5447	300.8	1.811	36.2	7.692	7.991	5.980	0.5460	296.3	1.843	11.8
U035	PCEA	AG	Centre	7.706	8.144	6.233	0.5359	317.9	1.686	20.7	7.700	7.999	6.002	0.5383	297.9	1.807	11.1
U036	PCEA	AG	Centre	7.558	7.942	6.030	0.5364	293.4	1.828	34.9	7.691	7.990	6.012	0.5381	297.8	1.807	11.0
U074	PCEA	AG	Edge	7.697	8.123	6.302	0.5431	320.0	1.697	27.2	7.683	7.989	6.006	0.5446	297.3	1.832	11.4
U421	PCEA	AG	Centre	7.546	7.831	5.875	0.5330	279.7	1.906		7.715	7.992	5.960	0.5332	295.7	1.803	11.7
U431	PCEA	AG	Edge	7.542	7.841	5.928	0.5358	282.6	1.896		7.705	7.983	5.973	0.5360	295.7	1.813	11.5
U010	PCEA	WG	Centre	7.887	8.261	6.024	0.5313	317.7	1.672	24.5	7.698	7.988	5.972	0.5360	295.8	1.812	11.8
U011	PCEA	WG	Centre	7.808	8.182	5.999	0.5351	310.3	1.725	25.0	7.698	7.990	5.990	0.5378	296.8	1.812	11.5
U083	PCEA	WG	Edge	7.771	8.177	5.960	0.5415	307.2	1.763	32.2	7.706	8.006	5.963	0.5425	296.5	1.830	12.6
U084	PCEA	WG	Edge	8.025	8.600	6.233	0.5401	351.6	1.536	19.3	7.683	7.990	5.966	0.5410	295.3	1.832	12.4
U171	PCIB	AG	Centre	7.745	8.097	6.141	0.5461	311.4	1.754		7.679	7.989	6.006	0.5505	297.2	1.852	11.7
U164	PCIB	AG	Centre	7.849	8.008	6.065	0.5493	305.1	1.800		7.739	8.000	6.029	0.5538	300.1	1.845	11.9
U143	PCIB	WG	Centre	7.872	8.178	6.122	0.5543	317.7	1.745		7.678	7.996	6.038	0.5540	299.1	1.852	12.3
U146	PCIB	WG	Centre	7.979	8.302	6.228	0.5538	332.7	1.664	29.3	7.685	7.989	6.046	0.5552	299.3	1.855	12.4
U201	PCIB	WG	Edge	8.120	8.457	6.215	0.5462	344.5	1.585	24.7	7.685	7.992	5.957	0.5471	295.0	1.854	12.3
U203	PCIB	WG	Edge	7.749	8.047	5.976	0.5494	300.3	1.830		7.672	8.002	5.991	0.5493	297.1	1.849	12.6
U368	LPEB	AG	Centre	7.702	7.908	6.027	0.5490	293.9	1.868		7.779	7.981	6.023	0.5506	299.3	1.840	10.1
U358	LPEB	WG	Centre	7.687	7.937	5.984	0.5574	293.3	1.901		7.781	7.974	6.030	0.5589	299.2	1.868	10.5
U359	LPEB	WG	Centre	7.760	8.009	5.907	0.5581	294.9	1.893		7.764	7.998	6.012	0.5597	299.5	1.869	11.6
U399	PPEA	AG	Centre	7.568	7.868	5.917	0.5377	284.1	1.893		7.688	7.975	5.983	0.5380	295.5	1.821	14.2
U401	PPEA	AG	Centre	7.561	7.886	5.943	0.5364	286.2	1.874		7.701	7.991	5.988	0.5365	296.8	1.807	13.8
U303	PPEA	AG	Edge	7.739	8.156	6.155	0.5397	315.3	1.712	27.1	7.699	7.995	5.908	0.5426	293.0	1.852	14.0
U227	PPEA	WG	Centre	8.147	8.655	6.328	0.5380	363.4	1.480	17.8	7.643	7.977	5.994	0.5408	295.3	1.831	14.0
U295	PPEA	WG	Edge	7.838	8.189	6.016	0.5392	312.1	1.727	28.7	7.644	7.981	5.988	0.5412	295.2	1.833	14.2
U395	PPEA	WG	Centre	7.630	7.919	5.881	0.5364	286.2	1.874		7.672	7.978	5.988	0.5367	295.5	1.816	14.5
U396	PPEA	WG	Centre	7.639	7.920	5.877	0.5355	286.3	1.870		7.690	7.972	5.985	0.5356	295.4	1.813	14.5

Figure 3c Results of CTE Measurements from INNOGRAPH 2B

			Post irradiation				Pre- irradiation			
			Coefficient of Thermal Expansion ($10^{-6}K^{-1}$)				Coefficient of Thermal Expansion ($10^{-6}K^{-1}$)			
			30-120°C	30-200°C	30-750°C	30-950°C	30-120°C	30-200°C	30-750°C	30-950°C
S359	NBG-10	AG	2.3	2.4	3.5	3.8	4.4	4.5	5.1	5.7
S382	NBG-10	WG	2.0	2.2	3.3	3.6	3.9	4.2	5.3	5.5
S358	NBG-10	AG	2.3	2.6	3.8	4.1	3.9	4.3	5.3	5.5
S552	NBG-17	WG	2.0	2.2	3.4	3.7	4.5	4.5	5.5	5.7
S519	NBG-18	AG	1.7	2.0	3.4	3.7	4.4	4.6	5.4	5.7
S506	NBG-18	WG	1.9	2.1	3.2	3.4	4.3	4.4	5.3	5.6
S463	NBG-18	WG	1.8	2.0	3.2	3.5	4.3	4.5	5.5	5.7
S446	NBG-25	WG	1.2	1.5	2.7	3.0	3.5	3.6	4.6	4.8
U227	PPEA	WG	1.5	1.7	3.0	3.3	4.1	4.2	5.2	5.4
U303	PPEA	AG	2.2	2.4	3.4	3.7	4.7	4.9	5.9	6.1
U074	PCEA	AG	2.4	2.7	3.9	4.2	3.8	4.0	5.0	5.2
U083	PCEA	WG	1.5	1.8	3.0	3.3	3.4	3.8	4.7	5.0
U035	PCEA	AG	1.9	2.0	3.0	3.2	3.6	3.9	4.9	5.2
U033	PCEA	AG	2.2	2.4	3.6	3.9	3.3	3.7	4.7	5.0
U010	PCEA	WG	1.2	1.5	2.8	3.0	3.3	3.7	4.7	5.0

Figure 3d Post-irradiated Thermal Diffusivity Measurements from INNOGRAPH 2B

Sample			Post-irradiation Thermal Diffusivity (mm^2/s)									
			25°C	100°C	200°C	300°C	400°C	500°C	600°C	700°C	800°C	900°C	950°C
S382	NBG-10	WG	16.9	14.9	12.9	11.4	10.4	9.5	8.9	8.5	8.2	7.9	7.5
S446	NBG-25	WG	12.6	11.5	10.1	9.1	8.4	7.9	7.5	7.2	7.0	6.7	6.7
S464	NBG-18	WG	13.4	12.1	10.7	9.6	8.8	8.2	7.8	7.4	7.2	7.0	6.9
S475	NBG-18	AG	12.7	11.4	10.0	9.0	8.4	7.8	7.5	7.1	6.9	6.6	6.5
T044	IG-110	AG	9.1	8.3	7.3	6.7	6.1	5.7	5.4	5.2	4.8	4.7	4.5
U011	PCEA	WG	16.8	14.7	12.8	11.5	10.4	9.6	9.1	8.7	8.2	8.0	7.8
U034	PCEA	AG	13.5	12.0	10.6	9.5	8.7	8.2	7.7	7.5	7.1	7.0	6.6
U035	PCEA	AG	14.4	12.7	11.2	10.0	9.2	8.5	8.0	7.7	7.1	7.0	6.6
U036	PCEA	AG	24.8	22.4	19.1	16.7	15.0	13.7	12.6	11.8	11.2	10.7	10.4
U074	PCEA	AG	18.4	16.2	14.1	12.5	11.3	10.4	9.7	9.2	8.8	8.3	8.0
U083	PCEA	WG	21.8	19.6	16.7	14.7	13.2	12.1	11.2	10.5	10.0	9.5	9.1
U089	PCEA	AG	23.9	20.7	17.7	15.6	14.0	12.8	11.8	11.1	10.5	10.1	9.4
U143	PCIB	WG	10.5	9.5	8.5	7.7	7.1	6.7	6.3	6.1	5.9	5.7	5.6
U171	PCIB	AG	11.2	10.2	9.1	8.2	7.7	7.3	7.0	6.7	6.5	6.5	6.3
U303	PPEA	AG	12.0	10.7	9.4	8.4	7.8	7.3	6.9	6.6	6.4	6.1	5.8

Figure 3e Pre-irradiated Thermal Diffusivity Measurements from INNOGRAPH 2B

Sample			Pre-irradiation Thermal Diffusivity (mm^2/s)									
			25°C	100°C	200°C	300°C	400°C	500°C	600°C	700°C	800°C	900°C	950°C
S382	NBG-10	WG	115.6	86.2	61.1	46.3	37.5	32.0	27.6	24.6	22.0	20.4	19.4
S446	NBG-25	WG	103.0	77.6	56.0	44.0	35.9	30.2	26.5	23.4	20.9	19.4	18.6
S464	NBG-18	WG	109.2	79.7	56.7	44.0	36.3	30.7	26.9	23.5	21.3	19.5	18.7
S475	NBG-18	AG	104.6	75.5	53.1	40.4	32.6	28.0	24.2	21.6	19.4	17.6	17.0
T044	IG-110	AG	98.0	72.0	51.8	40.1	33.0	27.6	24.0	21.4	19.3	17.5	16.9
U011	PCEA	WG	129.9	97.9	69.4	52.4	42.2	35.8	30.6	27.5	24.5	22.0	21.2
U034	PCEA	AG	123.2	92.8	65.1	48.7	39.5	33.1	29.0	25.4	22.8	20.8	19.4
U035	PCEA	AG	128.5	93.9	67.4	50.5	40.9	34.8	30.2	26.5	23.9	21.8	20.8
U036	PCEA	AG	128.3	93.6	66.8	50.4	41.3	34.9	30.0	26.3	23.7	21.5	20.7
U074	PCEA	AG	126.4	92.7	66.1	49.9	40.3	34.4	29.6	26.2	23.7	21.6	20.5
U083	PCEA	WG	137.8	100.2	70.7	54.1	43.7	36.8	32.0	28.4	25.5	23.1	21.8
U089	PCEA	AG	124.4	92.4	65.7	49.6	40.4	34.2	30.1	26.3	23.3	21.5	20.6
U143	PCIB	WG	94.8	71.4	52.8	41.0	33.8	28.9	24.9	22.7	20.5	18.6	17.8
U171	PCIB	AG	91.1	69.9	51.1	39.8	32.3	28.0	24.2	21.9	19.6	17.8	17.5
U303	PPEA	AG	99.6	76.7	55.2	42.7	35.0	29.8	25.8	23.1	20.8	19.0	18.4

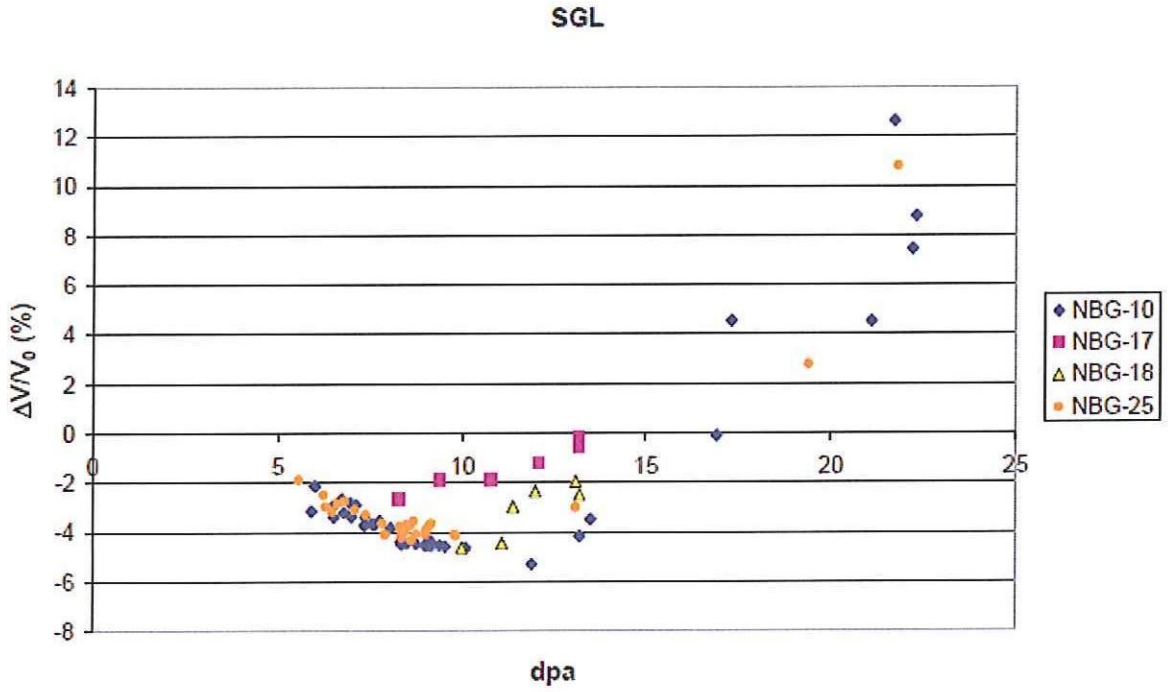


Figure 1 Volume change of the SGL grades

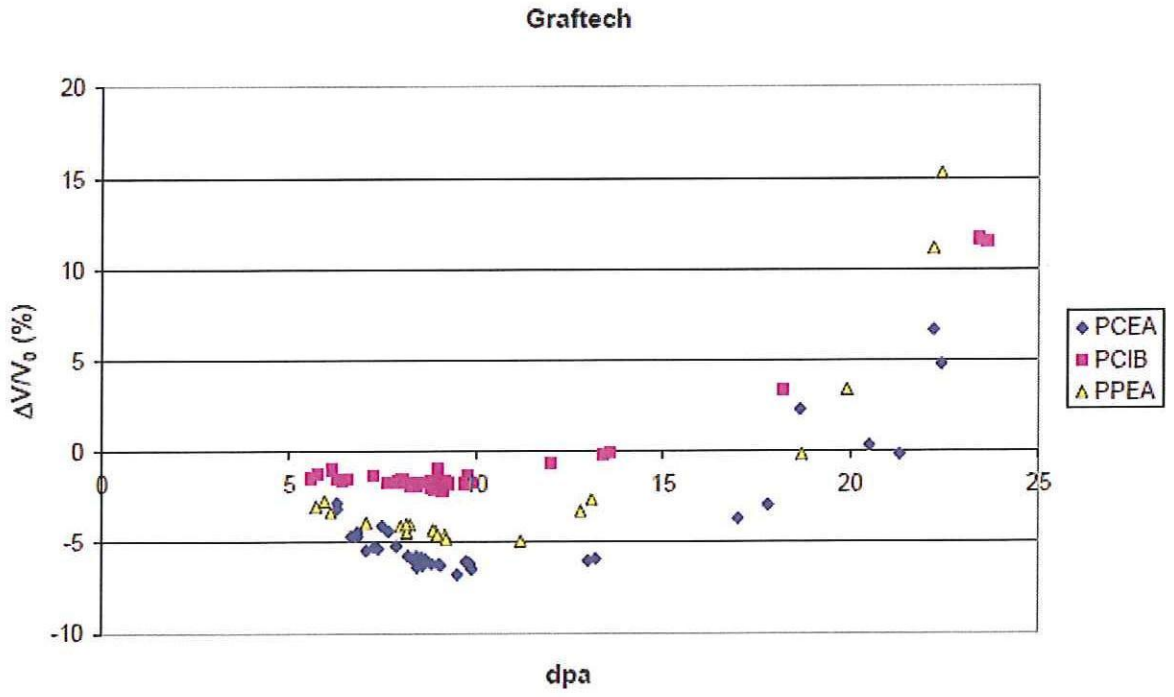


Figure 2 Volume change of the Graftech grades

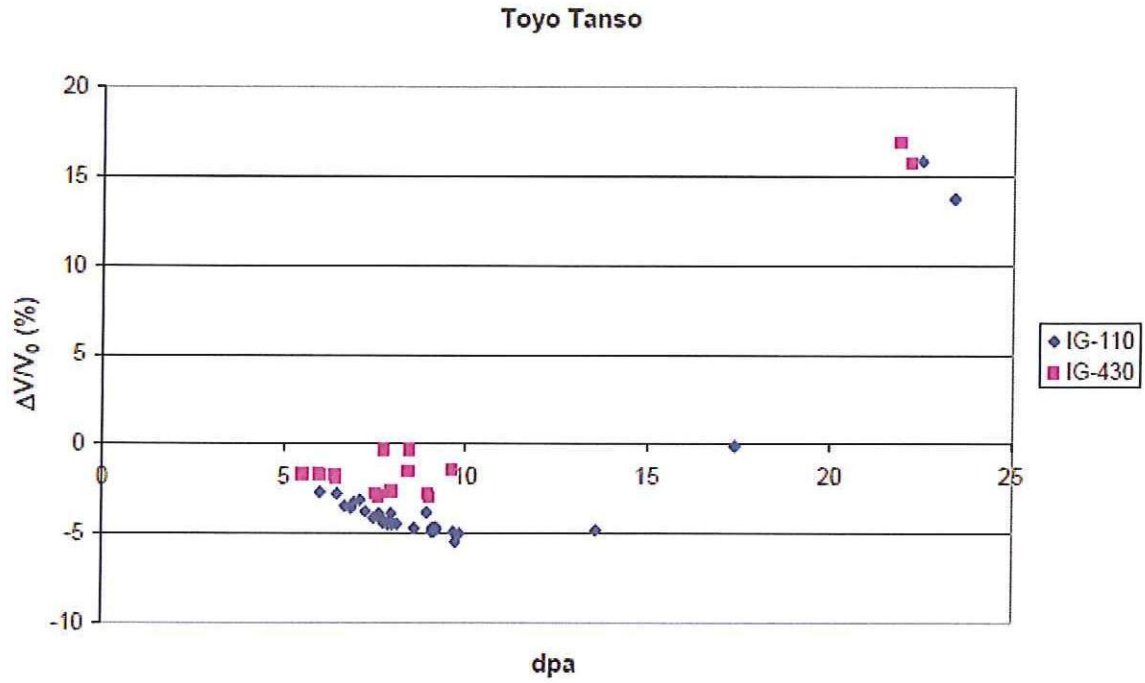


Figure 3 Volume change of the Toyo Tanso grades

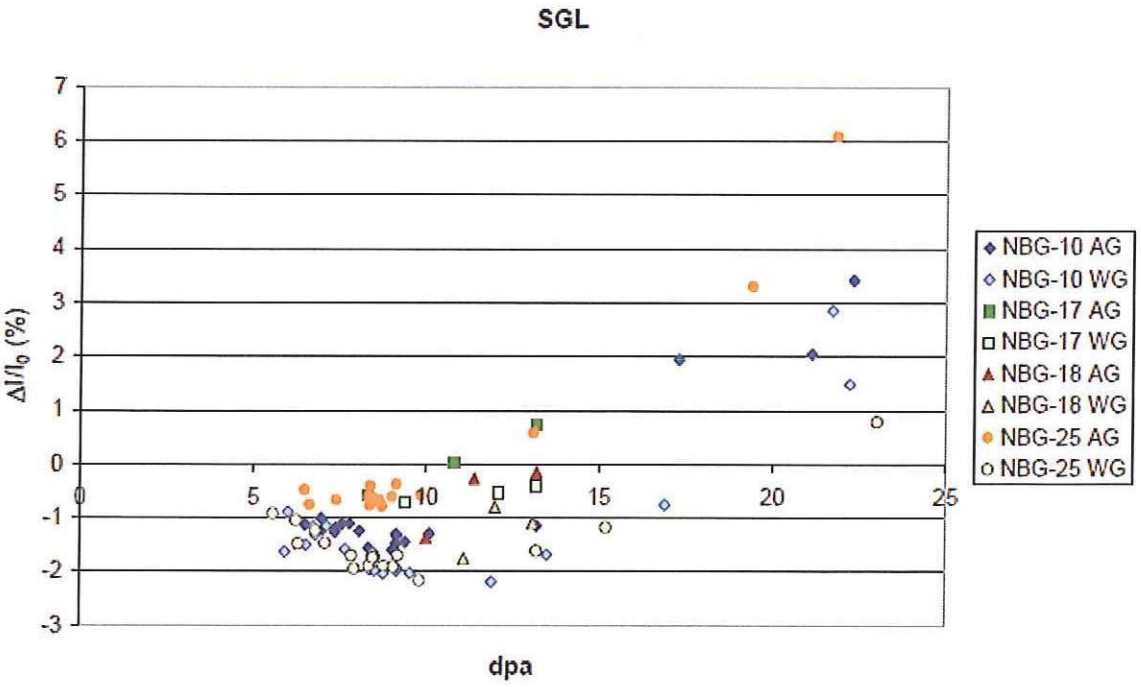


Figure 4 Length change of the SGL grades

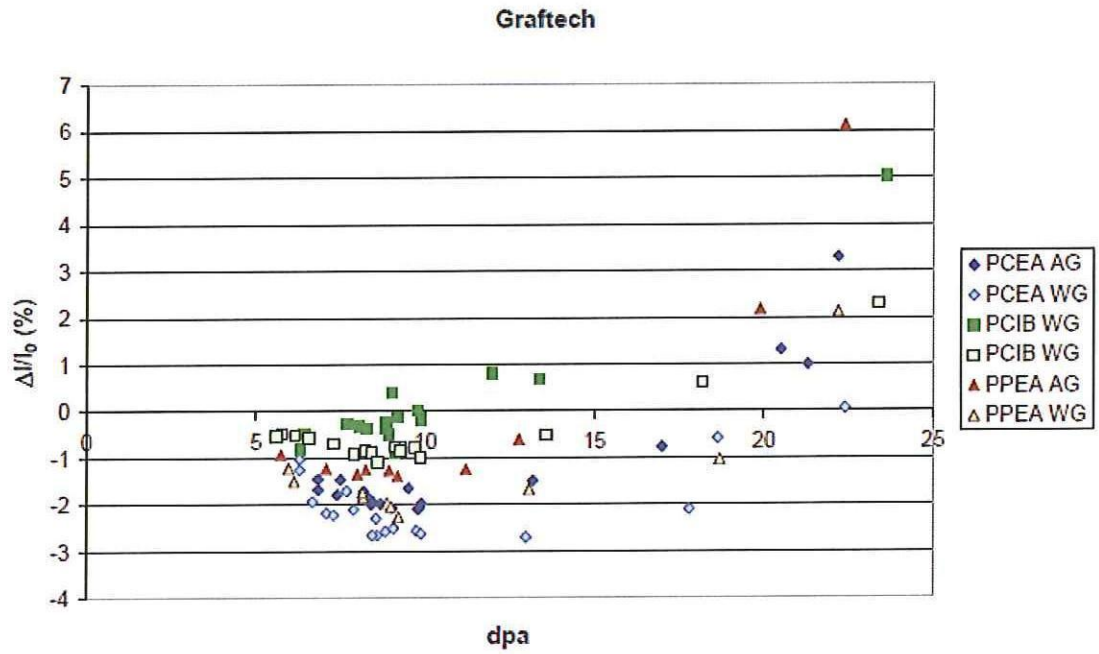


Figure 5 Length change of the Graftech grades

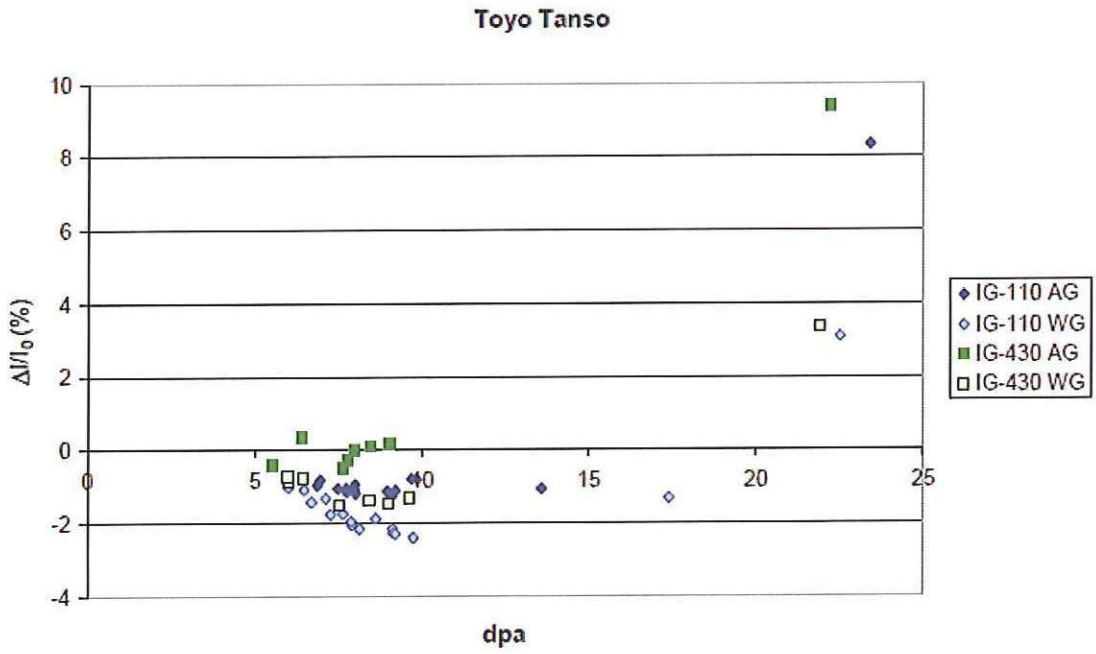


Figure 6 Length change of the Toyo Tanso grades

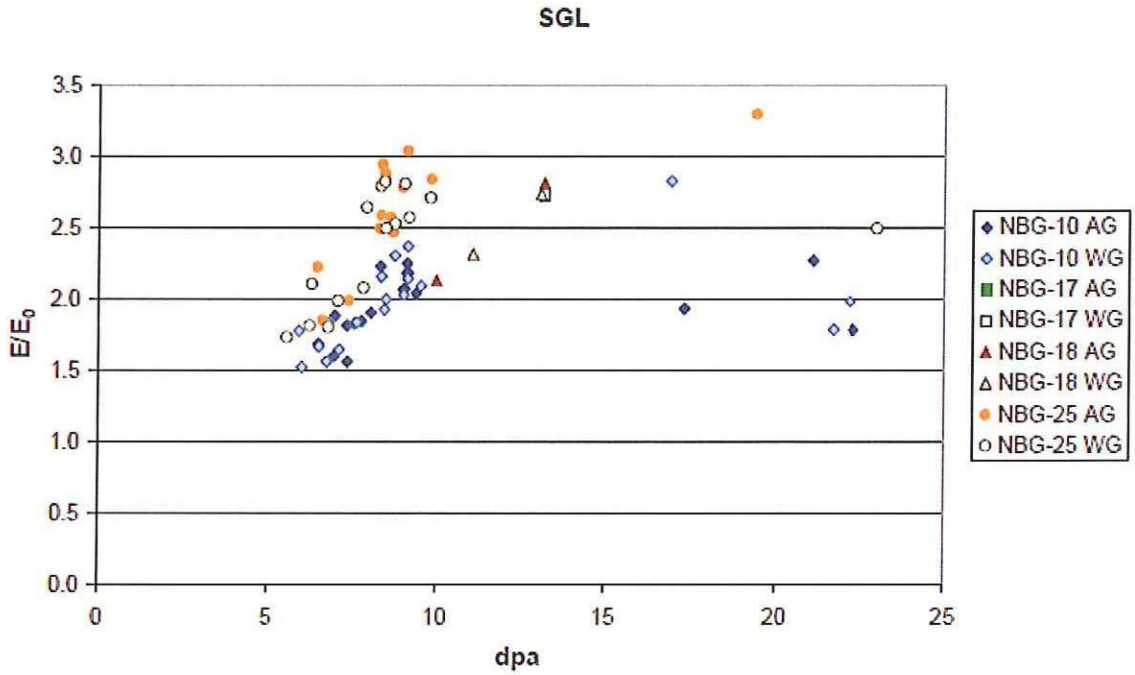


Figure 7 Change of Dynamic Young's modulus of the SGL grades

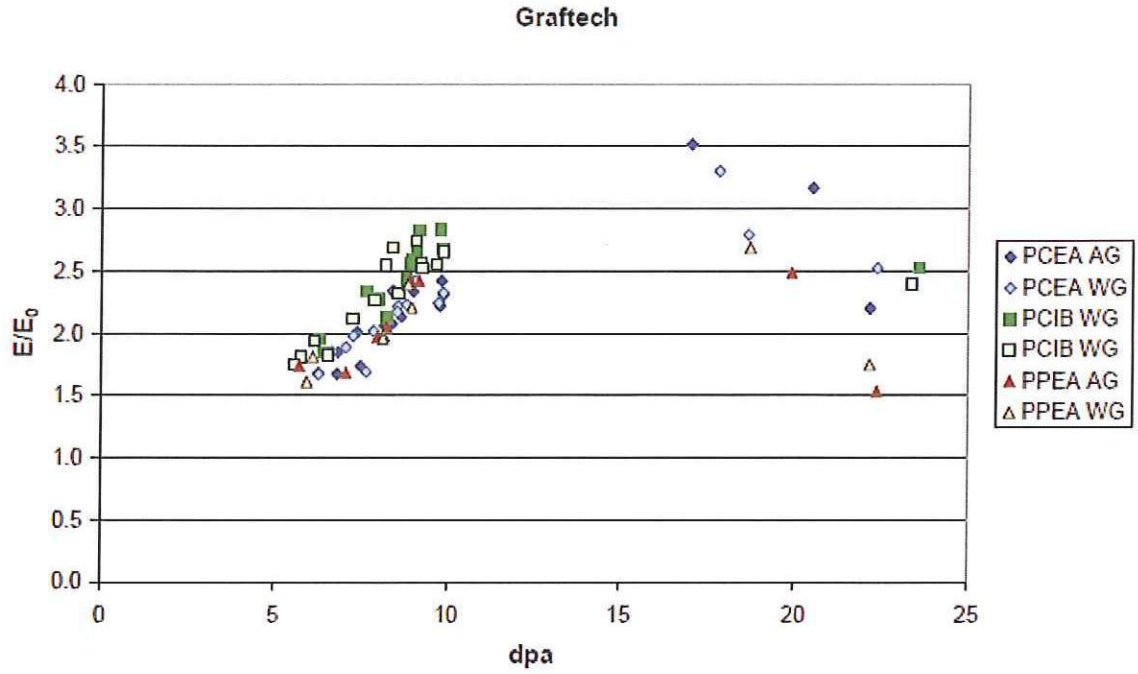


Figure 8 Change of Dynamic Young's modulus of the Graftech grades

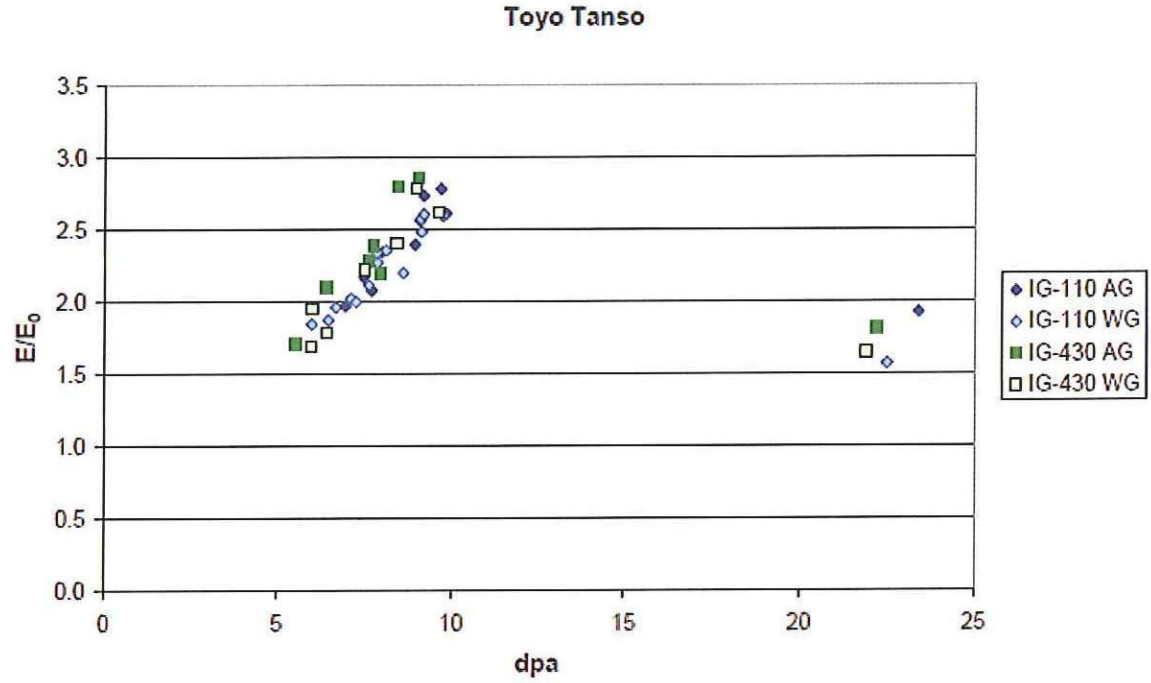


Figure 9 Change of Dynamic Young's modulus of the Toyo Tanso grades

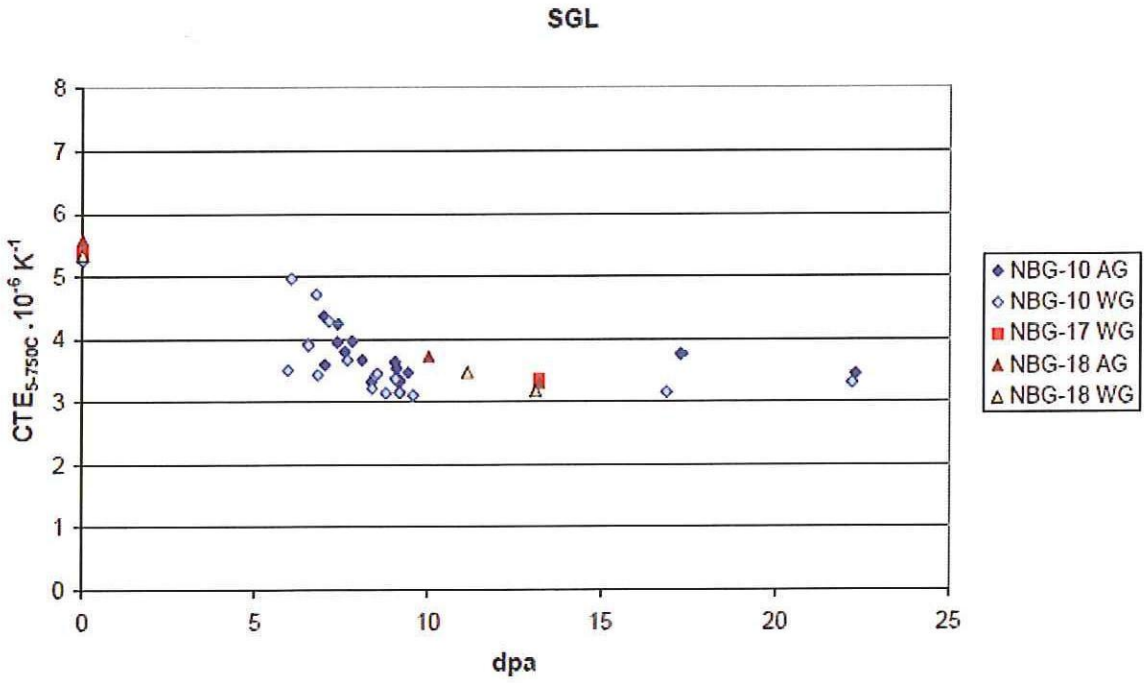


Figure 10 Change of CTE of the SGL grades

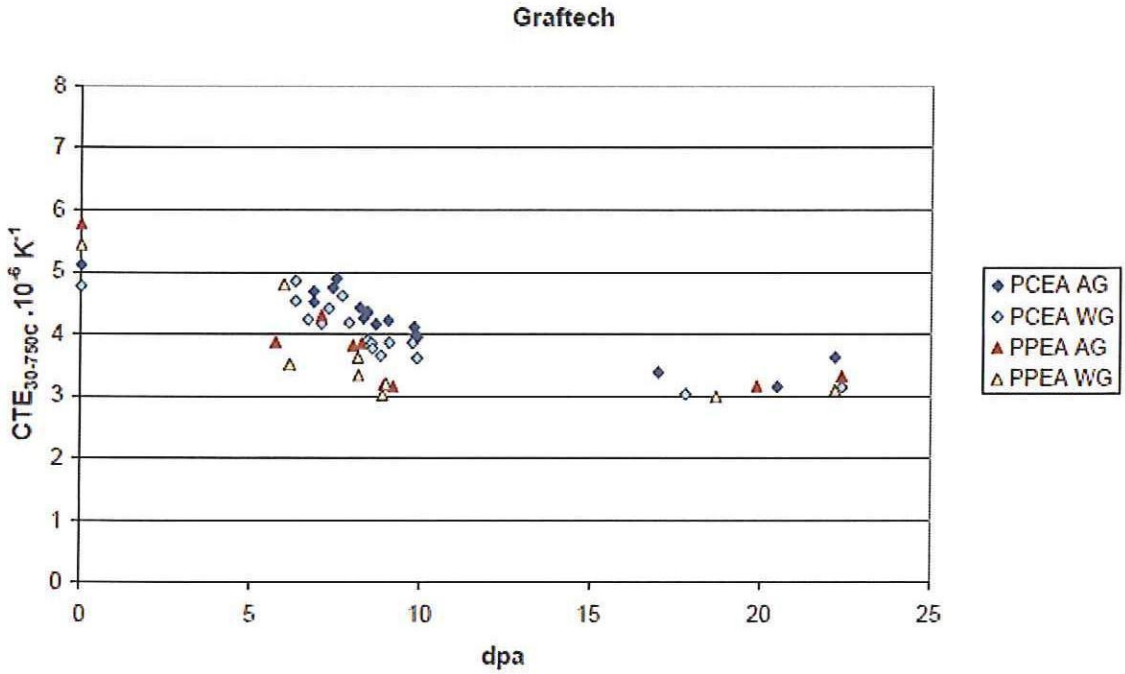


Figure 11 Change of CTE of the Graftech grades

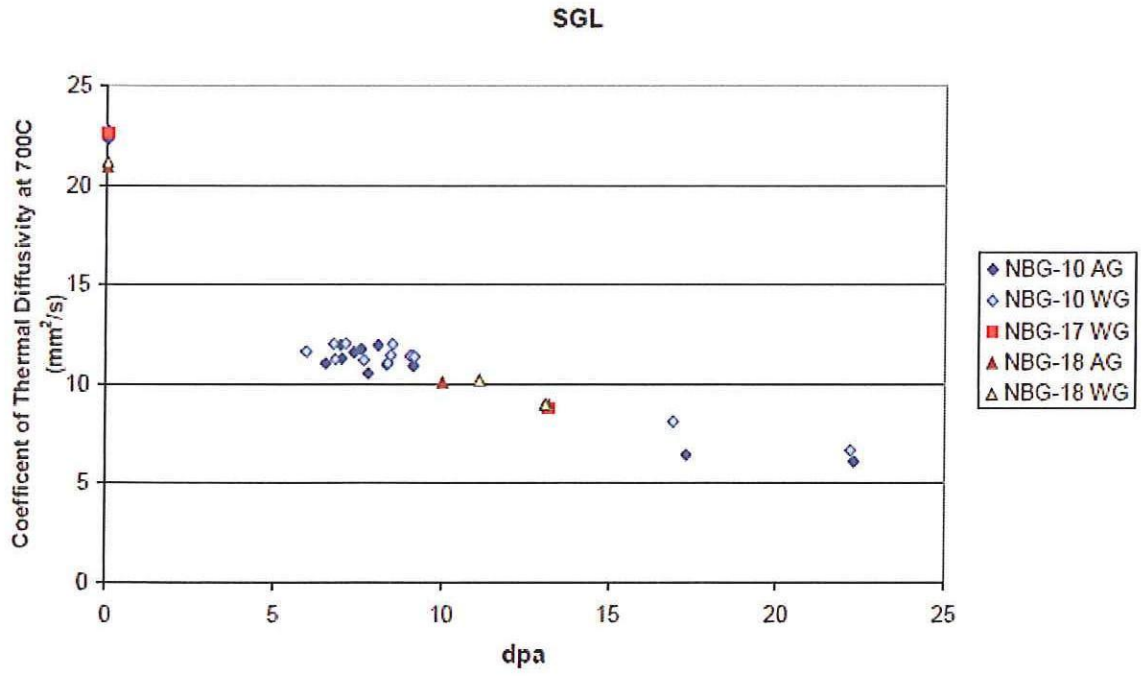


Figure 12 Change of thermal diffusivity of the SGL grades

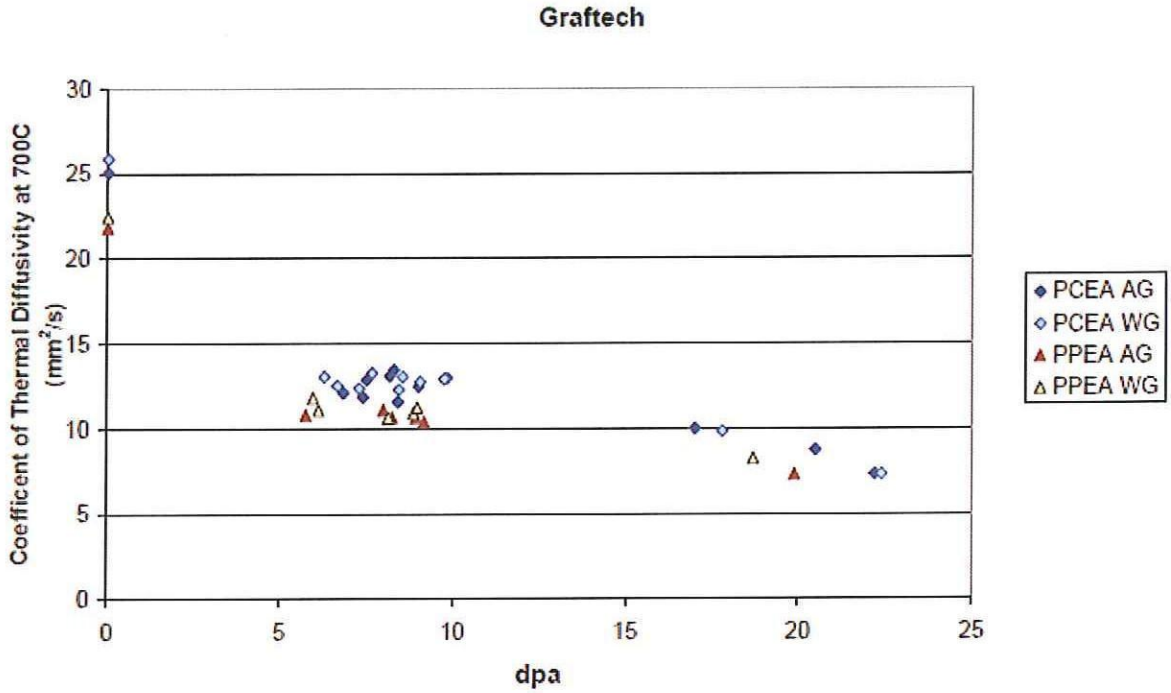


Figure 13 Change of thermal diffusivity of the SGL grades