

# **IMPROVED EPOXY RESINS CURED BY ELECTRON BEAM IRRADIATION**

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## **ABSTRACT**

A Cooperative Research and Development Agreement (CRADA) sponsored by the Department of Energy Office of Science, NASA Langley Research Center, U.S. Air Force Research Laboratory, U.S. Army Research Laboratory, and several industrial partners has developed or improved several toughened cationic epoxy resins cured by electron beam irradiation. These resin systems have mechanical, thermal, and physical properties that are significantly better than earlier electron beam curable resins, and are comparable to many thermally cured, high performance, toughened and untoughened epoxies. Neat resin test results and comparative data on fracture toughness properties, tensile properties, thermal properties, water absorption values, cured resin densities and resin viscosities are discussed.

**KEY WORDS:** Electron Beam Curing, Polymer Composites, Epoxy

## **1. INTRODUCTION**

In 1999 a three year Cooperative Research and Development Agreement (CRADA) was initiated entitled, "Interfacial Properties of Electron Beam Cured Composites". The CRADA is sponsored by the U.S. Department of Energy Office of Science, U.S. Air Force Research Laboratory, NASA Langley Research Center, U.S. Army Research Laboratory, and several industrial partners.

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One of the goals of the CRADA is to develop improved electron beam curable cationic epoxy resin systems and composites that meet or exceed the performance and processing criteria established by the CRADA. These criteria are based primarily on the thermal, mechanical, and physical properties and processing characteristics from several autoclave cured, carbon fiber reinforced composites containing high-performance, untoughened and toughened epoxy resin systems. The resin systems that were considered in establishing the CRADA's criteria included Hexcel's untoughened epoxies 3502 and 3501-6 and Hexcel's toughened epoxies 8552, M73, and 977-6, as well as Cytec Fiberite's untoughened epoxies 934 and 976 and Cytec Fiberite's toughened epoxies 977-2 and 977-3. To accomplish this goal, particular emphasis is being devoted towards improving the toughness properties of electron beam curable cationic epoxy resins. Concomitantly, the toughened resin systems must possess an optimum balance of other important properties and processing considerations including: compression, tensile, shear, and flexural strength, modulus, and strain to failure properties; glass transition temperature and thermal stability; water absorption and chemical resistance; and several lay-up and electron beam processing criteria.

The CRADA has recently completed the formulation and testing of several electron beam curable, toughened cationic epoxy resins with encouraging results. This work is currently ongoing and the results achieved to-date are very promising.

## 2. BACKGROUND

Tough resin systems are critically important for use in many structural composite applications since they can significantly reduce the probability of catastrophic failure caused by impact damage compared with brittle epoxy resins. Additionally, toughness impedes the initiation and progression of damage leading to catastrophic failure. This is due to the fact that a significant decrease in the size of composite impact damage can be realized for composites containing increasingly tougher resins<sup>1</sup>. Brittle matrices are normally highly crosslinked resins having low strain capability and poor ductility, resulting in large reductions in composite compression-after-impact (CAI) strength even after experiencing low velocity impacts, and even if the damage is not visible. On the other hand, toughened resins can yield greatly improved composite CAI strength properties. However, improving composite CAI strength and toughness properties typically results in the reduction of one or more of the following:

- T<sub>g</sub>
- Hot/wet mechanical properties (e.g., compression strength)
- Modulus
- Processability

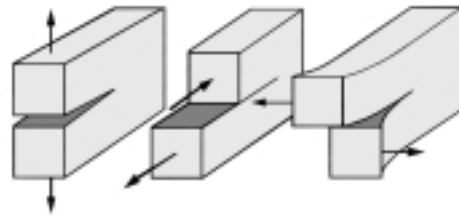
Fracture toughness is, by definition, one measure of the damage tolerance of a material containing initial flaws or cracks, or in other words, the resistance of a material to crack propagation. Fracture toughness can be quantified through the critical stress intensity factor,  $K_C$  or the critical strain energy release rate,  $G_C$ . In the case of linear elastic fracture conditions, for the case of plane stress  $G_C$  and  $K_C$  are related by:

$$G_c = \frac{K_c^2}{E} \quad \text{And for the case of plane strain:}$$

$$G_c = \frac{K_c^2}{E} (1 - \nu^2) \quad \text{Where } \nu \text{ is Poisson's ratio and } E \text{ is Young's modulus}$$

Fracture, or crack growth is by three modes of loading. Mode I ( $G_{IC}$ ,  $K_{IC}$ ) refers to the opening mode where loading is applied perpendicular to the crack path, while Mode II ( $G_{IIC}$ ,  $K_{IIC}$ ) is described as the sliding mode with in-plane shear loads parallel to the fracture surface and Mode III ( $G_{IIIC}$ ,  $K_{IIIC}$ ) consists of out of plane parallel loads as depicted in Figure 1 below. It should be noted that combinations of these fracture modes could occur simultaneously.

In general, Mode I has the lowest toughness of the three fracture modes and is often utilized to determine conservative allowable loads to prevent crack growth.



**Figure 1. Mode I, Mode II, Mode III**

Several important relationships between fracture toughness properties and other composite properties have been reported in the literature<sup>1</sup>. These include:

- Composite interlaminar fracture energy,  $G_{IC}$ , typically increases with resin strain-energy-release rate,  $G_{IC}$ . This effect is even more significant as the toughness of the resin decreases.
- Composite  $G_{IC}$ , usually tracks CAI strength.
- There is normally a close connection between composite  $G_{IIC}$  and CAI strength. Composite  $G_{IC}$  and  $G_{IIC}$  values commonly merge closer together as resin toughness increases.
- In general, CAI strength improves as resin strain-to-failure increases.
- As a general rule, as resin toughness increases higher CAI failure strain and higher composite  $G_{IC}$  result.
- High resin modulus is usually a prerequisite for achieving high composite compression strength.
- Maximizing either CAI strength or compression strength alone typically results in the reduction of the other. The goal is to maximize both properties by developing high modulus, highly toughened resins. However, as resin modulus increases it generally becomes increasingly more difficult to toughen and process.
- Fatigue normally lowers interlaminar fracture toughness.
- Poor fiber/resin interfacial adhesion commonly lowers interlaminar fracture toughness.

In summary, some of the attributes of high performance epoxy resins include:

- Highly toughened resins (Typically yields high composite CAI strength)
- High modulus resins (Generally yields high composite compression strength)
- High T<sub>g</sub> resins (Normally yields high service temperature composites)
- Easily processable resins

Historically, the typical methods used for toughening thermally curable epoxy resins has included:

- Addition of a 2<sup>nd</sup> phase toughener
  - o XTBN reactive rubbers (carboxyl-terminated butadiene acrylonitrile, CTBN, and amine-terminated butadiene acrylonitrile, ATBN, types)
    - Note: the acrylonitrile group in XTBN rubbers inhibits the cure of electron beam curable cationic epoxies
  - o Core shell rubbers
  - o Thermoplastics
- Addition of thermoplastics (single phase)
- Increasing length between crosslinks
- Interleafing
- Combinations of above

Rubber toughened epoxies (i.e. XTBNs) are generally not used in high-performance structural composites. Although XTBNs greatly improve CAI strength and strain, they fail to meet hot/wet compression strength requirements due to the rubber's low T<sub>g</sub> and low modulus<sup>2,3</sup>.

Core shell rubbers (CSR) are preformed particles containing an acrylic-based outer-shell and a rubber core. The outer shell may contain a reactive functional group to increase compatibility to the epoxy resin. The shell chemistry greatly influences the resin/CSR interfacial adhesion and is an important factor affecting the resin's fracture toughness. The fracture toughness mechanisms present in CSR toughened epoxies include localized matrix shear yielding (shear banding), particle cavitation, and rubber particle bridging across and behind the crack tip<sup>4</sup>.

The advantages of CSRs compared to reactive XTBN rubbers include: CSR particles having specific sizes are relatively easy to make; CSRs enhance toughness with less trade-off in thermomechanical properties; and CSRs offer superior UV-light and thermal-oxidative aging properties<sup>5</sup>. However, CSRs have relatively high initial viscosity and the particles tend to agglomerate.

Another approach that has been used over the years to toughen epoxies involves the use of chain extended polymers (increased length between cross-links). The Dow and Shell Chemical Companies' independently developed some of these types of resins during the 1980's. These materials are single phase, lightly crosslinked, toughened epoxy resins which are referred to as, "Crosslinkable epoxy thermoplastics" (CET resins)<sup>5</sup>, and "Lightly crosslinked thermosets" (LXT resins)<sup>5,6</sup>. Both the CETs and LXTs are tough, thermoplastic-like molecular structures made in-situ using "stiff-backbone" components and "flexible backbone" components. Advantages of

these materials include relatively high T<sub>g</sub>s, high modulus, and excellent inherent toughness. However, high temperatures (i.e. 150-200°C) are required for proper chain extension reactions to occur and the prepolymers are very viscous.

One of the more successful methods for toughening high performance, thermally curable epoxies is modification with engineering thermoplastics. There are several possible cured morphologies for thermoplastic toughened materials, with each possessing its own particular level of effectiveness. The various morphologies can result from homogeneous, single phase toughening, or second phase toughening, involving thermoplastic particulates (or epoxy particulates), or lastly, co-continuous, two-phase spinodal toughening.

The homogeneous, single-phase approach requires dissolving the thermoplastic into the epoxy, then curing of the system without phase separation. This method effectively reduces the epoxy's cross-link density, however it has generally provided only modest improvements for toughening thermally curable epoxy resins<sup>7,8,9</sup>.

There are two types of particulate, second phase toughening. The first type consists of an epoxy continuous phase and a thermoplastic discontinuous (thermoplastic particles) phase<sup>9,10,11</sup>. This morphology typically occurs at thermoplastic loadings of about 15% and less. An example of the particle sizes that have been reported for an amino-terminated poly(arylene ether sulfone) thermoplastic toughening material dissolved in an epoxy ranged from 0.5-2 microns<sup>4,10</sup>. A possible toughening mechanism with this morphology includes the localized yielding of the epoxy matrix initiated by deformation of the thermoplastic particles. This approach has generally provided only modest improvements for toughening thermally curable epoxy resins. The second type of the particulate, second phase toughening approach consists of an epoxy discontinuous (epoxy particles) phase and a thermoplastic continuous phase (phase inversion)<sup>9,10,11</sup>. In these types of systems the inherent toughness of the thermoplastic dictates the overall resin system's toughness. This morphology normally manifests itself at thermoplastic loadings exceeding 15-20%. The fracture of these materials typically occurs through ductile tearing of the thermoplastic matrix and debonding at the phase boundaries without fracture of the epoxy particles. This toughening approach has generally provided only modest improvements for toughening thermally curable epoxy resins.

The preferred morphology yielding high fracture toughness in thermally cured epoxies comprises a co-continuous, two-phase spinodal morphology<sup>9,10,11</sup>. This morphology consists of an epoxy continuous phase and a thermoplastic continuous phase. These phases are submicron in size and require thermoplastic loadings exceeding 15-20% (thermoplastic loadings of 30-40% are typically the norm for higher-performance epoxy formulations). The morphology, phase sizes, and the ultimate toughness are controlled by the thermoplastic backbone, its reactive end groups, its molecular weight, and the type of epoxy used in the formulation. The nature of the toughening mechanism operating with this morphology is not readily apparent other than a roughened fracture surface. In addition, the kinetics and thermodynamics of the phase separation process resulting during cure of these systems is complex.

The selection criteria for the thermoplastics that are used in the co-continuous, spinodal approach include<sup>11,12</sup>:

- High toughness
- High performance (i.e. high T<sub>g</sub>, high modulus)
- Polyaromatic
  - Para linkages are preferred on the aromatic ring for high performance, but meta linkages enhance processability and solubility
- Good compatibility with epoxy resin(s)
  - Must have suitable reactive end groups (i.e. amine, epoxy, hydroxyl)
- Well defined molecular weight distribution
- Optimum molecular weight and/or loading level
  - Higher molecular weight thermoplastics and/or highly loaded thermoplastics are increasingly more difficult to process due to their higher viscosities
- Correct cured morphology

The type and distribution of the linking groups and the aromatic groups in the thermoplastic are very important in determining its T<sub>g</sub>, modulus, crystallinity, processability, solubility, and mechanical properties.

The co-continuous, spinodal morphology has been demonstrated to be very effective in toughening thermally curable epoxy resins, however, issues remain on whether this approach is viable for toughening electron beam curable epoxy resins. This is because the viscosity of the resin systems having the required thermoplastic loadings for optimizing toughness may be too high for electron beam processing and consolidation. Additionally, the spinodal formation that results during thermal cure may not be possible during electron beam cure due to incompatible phase separation kinetics.

Toughening composites by the interleaving approach is another method that has proven very successful for use with thermally curable epoxy resins<sup>13</sup>. Interleaving incorporates high strain, resin rich zones between prepreg plies, Resin A, and a separate resin which surrounds the fiber, Resin B. The interleaf approach consists of an inhomogeneous resin matrix where Resin A between plies is significantly different from Resin B surrounding the fiber bundles. Interleaving can produce extremely high, damage tolerant composites, but Resin B must also have high toughness. In addition, Resin A must have a rheology that is conducive to the particular processing and curing method that is used (i.e. electron beam or thermal).

The interleaving concept has inherent inhomogeneity and can lead to unusual crack propagation behavior<sup>13</sup>. Cracks in conventionally toughened composites typically move between laminate plies. However, in interleaf toughened composites the cracks can choose between a very tough interply zone and a lower toughness resin surrounding the fiber bundles, consequently, cracks may initiate between plies, but may switch to the fiber bundle and continue to grow inside the fiber zone.

The electron beam curable formulations considered and evaluated in the CRADA have included various toughening approaches discussed above as well as several others. These include the incorporation of various CSR's, thermoplastics, the use of chain extended resins, interpenetrating polymer networks, and interleaved prepregs.

### 3. EXPERIMENTAL

#### 3.1 Materials

**3.1.1 Electron Beam Curable Toughened Cationic Epoxy Resins** The electron beam curable resin systems were formulated by the Oak Ridge National Laboratory (ORNL) using commercially available epoxy resins, cationic initiators, toughening agents, and other additives<sup>14,15</sup>.

**3.1.2 Electron Beam Accelerator** The electron beam curing for the neat resin plaques evaluated in this work was performed by Acsion Industries, Inc. using their I-10/1, Pulsed Electron Linear Accelerator. The samples were irradiated under ambient conditions with no active cooling. The irradiation parameters included: Beam energy, 9.2 MeV; Beam current, approximately 66-88  $\mu\text{A}$ ; Pulse duration, 4-5  $\mu\text{s}$ ; Pulse frequency, 300 Hz; Scan width, 60 cm; Scan frequency, 2 Hz; Conveyor speed, approximately 0.15-0.17 cm/s; Power, 0.75 kW; Total dose, 100 kGy; Number of passes, 10; Rest period between passes, less than one minute; Average dose rate, 0.8 kGy/s; Instantaneous dose rate, 700 kGy/s).

**3.1.3 Fabrication and Electron Beam Cure of Test Plaques** The electron beam curable resin formulations were heated in an oven to a liquid state, poured into aluminum molds, cooled to room temperature, then electron beam cured to a total dose of 100 kGy at 10 kGy/pass.

**3.1.4 Fracture Toughness Testing** The electron beam cured neat resin plaques, measuring about 20.3 cm x 10.2 cm x 0.64 cm, were machined at YLA, Inc., into approximately 7.62 cm x 1.27 cm x 0.64 cm rectangular sized specimens, then machine notched and finally razor notched to generate a natural crack. The specimens were then tested at YLA, Inc. at room temperature in accordance with ASTM D 5045-93 to determine  $K_{IC}$  fracture toughness. The specimen geometry consisted of single-edge notch bend (SENB) specimens comprising a center-notched beam loaded in three-point bending. Five to ten specimens per material were tested to yield an average  $K_{IC}$  fracture toughness value.  $K_{IC}$  testing was also performed on thermally cured control resins, including Hexcel's 3501-6, which was thermally cured at Applied Poleramics Inc. using a cure schedule of 2 hours at 121°C followed by 4 hours at 177°C. In addition, two thermally cured, toughened epoxy resin systems, M73 and 8552, were supplied by Hexcel and subsequently tested at YLA. Literature data on several toughened and untoughened thermally cured epoxy resins were also included for comparative evaluation.

**3.1.5 Tensile Property Testing** The electron beam cured neat resin plaques, measuring about 22.9 cm x 12.7 cm x 0.32 cm, were processed and electron beam cured in the same manner as the fracture toughness plaques and machined by ORNL into dogbone shaped specimens having dimensions of approximately 20.3 cm x 1.9 cm x 0.32 cm having a gage length and width of 5.1 cm and 1.3 cm, respectively. The tensile specimens were then tested at room temperature at ORNL in accordance with ASTM D 638-99 to determine tensile strength, tensile modulus, and tensile strain to failure properties. Testing was also performed at the Air Force Research Laboratory (AFRL) on Hexcel's 3501-6 resin, which was thermally cured at Applied Poleramics Inc. using a cure schedule of 2 hours at 121°C followed by 4 hours at 177°C. The specimen

dimensions for the AFRL dogbone shaped specimens were approximately 6.4 cm x 0.5 cm x 0.07 cm having a gage length and width of 2.5 cm and 0.4 cm, respectively. Literature data on several toughened and untoughened thermally cured epoxy resins were included for comparison.

**3.1.6 Thermal Mechanical Testing Using Dynamic Mechanical Analysis** Dynamic Mechanical Analysis (DMA) was used to determine the dry and wet glass transition temperatures ( $T_g$ ) for the identical resin plaques discussed above. Wet  $T_g$ s were determined on specimens after being immersed in water at 70°C for 14 days. DMA testing was conducted by Acsion Industries, Inc., using a Rheometrics Solids Analyzer RSA II. The sample was placed in a dual cantilever tool, with an initial stress and strain of zero. The strain used for measuring the rheological properties was set at 0.1 percent. The temperature was raised at 2.5°C per step with a dwell time of 12 seconds. The frequency of the applied strain was 6.28 radians per second. Sample size was normally 3 mm x 7 mm x 55 mm. Measurements were obtained using the software provided by Rheometrics for the instrument.

**3.1.7 Percent Water Absorption Evaluations** The percent water absorption measurements were performed on several electron beam cured epoxy resins and on Hexcel's 3501-6 thermal cured epoxy resin after immersion in 70°C water for 14 days.

**3.1.8 Density Determinations** The cured resin density of the toughened, electron beam cured 798 resin system was determined using mercury intrusion and compared with literature density values on several thermally cured epoxy resins.

**3.1.9 Viscosity Determinations** The viscosity of the 798 electron beam curable resin was determined using a Brookfield Engineering Laboratories Viscometer, Model RV, using spindle SC4-21.

## 4. RESULTS AND DISCUSSION

During the early 1990's a significant amount of work was conducted on toughening electron beam curable cationic epoxies<sup>14,16</sup>. Much of this work focused on toughening a particular model system that comprised a diglycidyl ether of bisphenol A epoxy (Ciba Tactix 123) with 3 phr of a cationic initiator. A variety of toughening approaches were evaluated in this effort that ultimately resulted in a 125% increase in the fracture toughness,  $K_{IC}$ , properties compared to the untoughened model system. The  $K_{IC}$  values for these early toughened epoxies ranged from 0.42 to 0.92 MPa m<sup>1/2</sup> versus the  $K_{IC}$  for the model resin of 0.41 MPa m<sup>1/2</sup>. These results are approximately equivalent to  $K_{IC}$  values for Hexcel's 3502 and 3501-6 untoughened epoxies and Cytec Fiberite's toughened 977-3 epoxy which have  $K_{IC}$  values of 0.6, 0.8, and 0.9 MPa m<sup>1/2</sup>, respectively.

**4.1 Fracture Toughness Results** During the past two years further work has been conducted on improving the toughness properties of electron beam curable cationic epoxy resins as well as optimizing other important mechanical and thermal properties. The resin and testing origin information for these materials is shown in Table I. Figure 2 compares the fracture toughness properties of electron beam cured versus thermal cured epoxy resins. The  $K_{IC}$  values for the

electron beam curable epoxies are significantly higher compared to the earlier electron beam resins discussed above. These new or improved resins also compare more favorably to many of the thermally cured, high-performance, toughened epoxy resins that are widely used today. In addition, many of these systems exceed the minimum target value of  $0.9 \text{ MPa m}^{1/2}$  established within the CRADA. The  $K_{IC}$  values for this latest series of toughened electron beam curable resins ranged from 0.6 to  $1.6 \text{ MPa m}^{1/2}$  versus Cytec Fiberite's 977-3 and 977-2 toughened epoxies and Hexcel's 977-6, 8552, and M73 toughened epoxies that have values of 0.9, 1.1, 1.6, 1.6, and  $1.7 \text{ MPa m}^{1/2}$ , respectively.

**4.2 Tensile Property Results** Results on the tensile strength, tensile modulus, and tensile strain to failure properties of the electron beam and thermal cured epoxy resins are shown in Figures 3-5. The tensile strength properties of the electron beam cured resins exceed Hexcel's 3502 untoughened epoxy. Many resins also have strengths that are comparable or exceed Hexcel's two sets of published data on 3501-6 untoughened epoxy and some of the electron beam cured systems are also comparable to Cytec's 976 untoughened epoxy. However, the tensile strengths for these materials are still at least 8% below the CRADA minimum target value of 82.7 MPa. On the other hand, the tensile modulus and tensile strain to failure properties for the electron beam cured resins are quite comparable to most of the thermally cured, toughened and untoughened epoxy resins.

**4.3 Glass Transition Temperature Results** Results on the dry and wet  $T_g$  values for selected electron beam and thermally cured epoxies are shown in Figures 6-9. The  $T_g$  values for the electron beam curable resins are comparable to several thermally curable resins. The dry values for peak tan delta and peak loss moduli ( $E''$ ) for the electron beam curable resins ranged from  $178\text{-}382^\circ\text{C}$  and  $165\text{-}362^\circ\text{C}$ , respectively. The dry values for peak tan delta and peak loss moduli for the thermally curable resins ranged from  $185\text{-}270^\circ\text{C}$  and  $173\text{-}254^\circ\text{C}$ , respectively. The wet values for peak tan delta and peak loss moduli for the electron beam curable resins ranged from  $148\text{-}171^\circ\text{C}$  and  $125\text{-}143^\circ\text{C}$ , respectively. The wet value for peak tan delta for the thermally cured 3501-6 resin was  $220^\circ\text{C}$ , whereas the peak loss moduli for the thermally cured resins were  $151\text{-}160^\circ\text{C}$ . Note that the actual conditions used for conditioning the wet  $T_g$  samples (literature values only) were not available, therefore no comparisons should be made with this data.

**4.4 Water Absorption Results** The water absorption results for several electron beam cured epoxy resins (Table 1) were all relatively low, compared to thermal cured epoxies, and ranged in value from 2.2 to 2.7% versus 3.6% for Hexcel's 3501-6 resin.

**4.5 Density and Viscosity Results** One example of the more promising electron beam curable toughened epoxy resins evaluated thus far is the 798 resin. The density of the 798 resin is 1.14 g/ml which is 10-15% lower than the densities for several thermally cured toughened and untoughened epoxy resins, which ranged from 1.26-1.31 g/ml (Table 1), and well below the CRADA maximum target of 1.4 g/ml. In addition, the rheology for this material is broad enough to allow its use for making hot-melt prepregs and for use in VARTM and RTM applications. The viscosity values for the 798 resin at temperatures of 80, 100, and  $120^\circ\text{C}$  are about 1700, 400, and 100 centipoise, respectively.

## 5. CONCLUSIONS

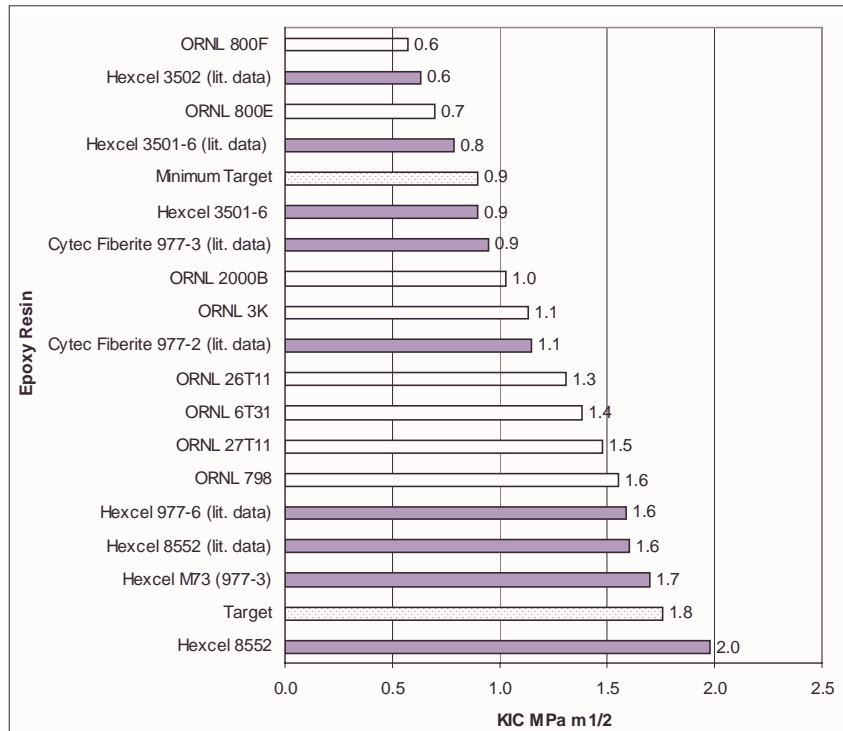
Several electron beam curable, toughened cationic epoxy resins have been developed or improved within the CRADA. These resin systems have mechanical, thermal, and physical properties that are significantly better than earlier electron beam curable resins, and in many cases are comparable to many thermally cured, high performance, toughened and untoughened epoxies. Specifically, these resins have improved fracture toughness properties, improved tensile strength, moduli, and strain to failure properties, high thermal properties, low water absorption values, low resin densities, as well as favorable rheological properties. Several candidate systems are currently being incorporated into carbon fiber reinforced composites for further evaluation.

## 6. REFERENCES

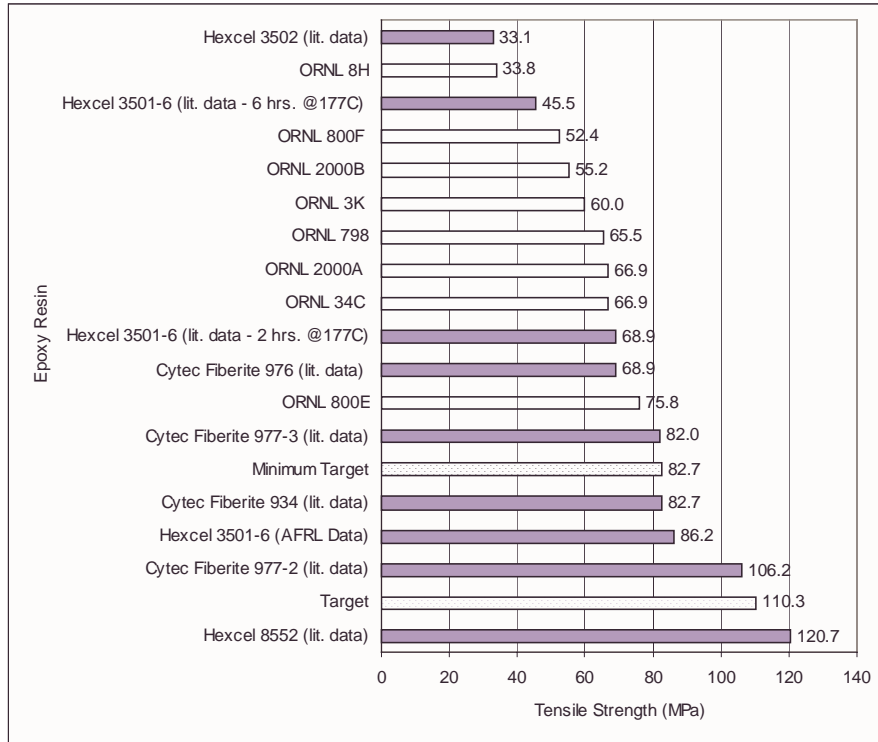
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**Table 1. Resin and Testing Origin Information**

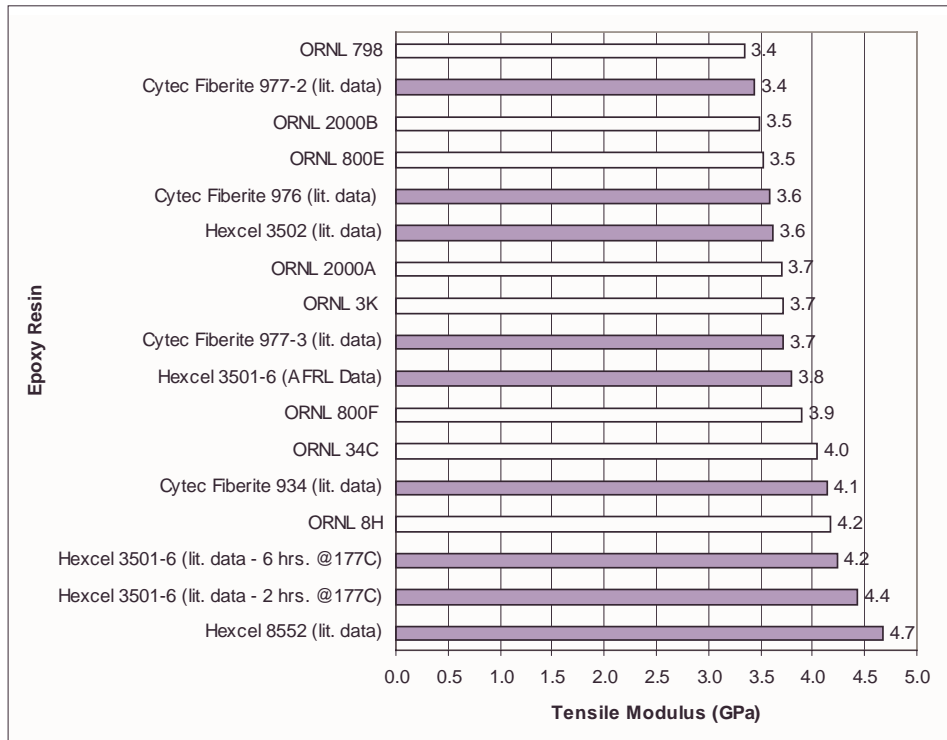
Resin and Testing Origin Information	Epoxy Type	Source of Tensile Data	Source of K <sub>IC</sub> Data	Source of Tg, % H <sub>2</sub> O, and density data
Hexcel 8552	Thermally curable toughened epoxy	Hexcel	Hexcel	Hexcel (Tg and density)
Hexcel 977-6	Thermally curable toughened epoxy		Hexcel	Hexcel (Tg only)
Hexcel 3501-6 (cured 6 hrs @177C)	Thermally curable untoughened epoxy	Hexcel	Hexcel	Hexcel (Tg and density)
Hexcel 3501-6 (cured 2 hrs @177C)	Thermally curable untoughened epoxy	Hexcel		
Hexcel 3502	Thermally curable untoughened epoxy	Hexcel	Hexcel	Hexcel (Tg and density)
Cytec Fiberite 977-2	Thermally curable toughened epoxy	Cytec Fiberite	Cytec Fiberite	Cytec Fiberite (Tg and density)
Cytec Fiberite 977-3	Thermally curable toughened epoxy		Cytec Fiberite	Cytec Fiberite (Tg and density)
Cytec Fiberite 934	Thermally curable untoughened epoxy	Cytec Fiberite		Cytec Fiberite (Tg and density)
Cytec Fiberite 976	Thermally curable untoughened epoxy	Cytec Fiberite		Cytec Fiberite (Tg and density)
Hexcel 8552	Thermally curable toughened epoxy		YLA	Acision (Tg only)
Hexcel M73 (977-3)	Thermally curable toughened epoxy		YLA	Acision (Tg only)
Hexcel 3501-6	Thermally curable untoughened epoxy		YLA	Acision (Tg and % H <sub>2</sub> O)
Hexcel 3501-6	Thermally curable untoughened epoxy	AFRL		
798	Electron beam curable toughened epoxy	ORNL	YLA	Acision
27T11	Electron beam curable toughened epoxy	ORNL	YLA	Acision (Tg and % H <sub>2</sub> O)
6T31	Electron beam curable toughened epoxy	ORNL	YLA	Acision (Tg and % H <sub>2</sub> O)
26T11	Electron beam curable toughened epoxy	ORNL	YLA	Acision (Tg and % H <sub>2</sub> O)
3K	Electron beam curable toughened epoxy	ORNL	YLA	Acision (Tg and % H <sub>2</sub> O)
800E	Electron beam curable toughened epoxy	ORNL	YLA	
800F	Electron beam curable toughened epoxy	ORNL	YLA	
2000B	Electron beam curable untoughened epoxy	ORNL	YLA	Acision (Tg and % H <sub>2</sub> O)
34C	Electron beam curable untoughened epoxy	ORNL		
2000A	Electron beam curable untoughened epoxy	ORNL		
8H	Electron beam curable untoughened epoxy	ORNL		Acision (Tg only)



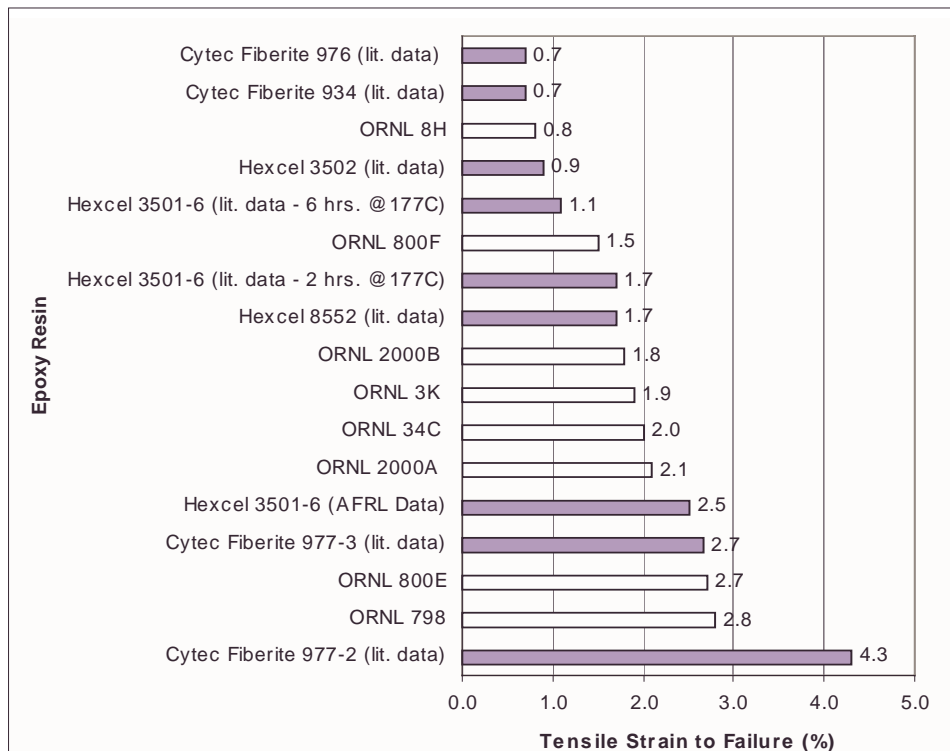
**Figure 2. Fracture Toughness (Mode I) Properties of Electron Beam and Thermal Cured Epoxy Resins**



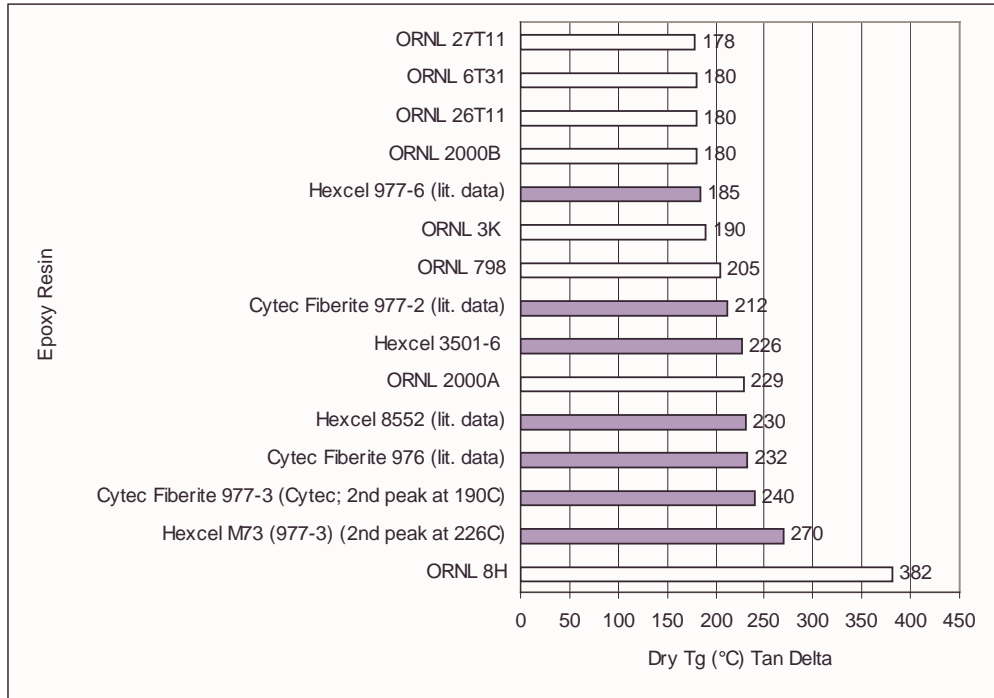
**Figure 3. Tensile Strength of Electron Beam and Thermal Cured Epoxy Resins**



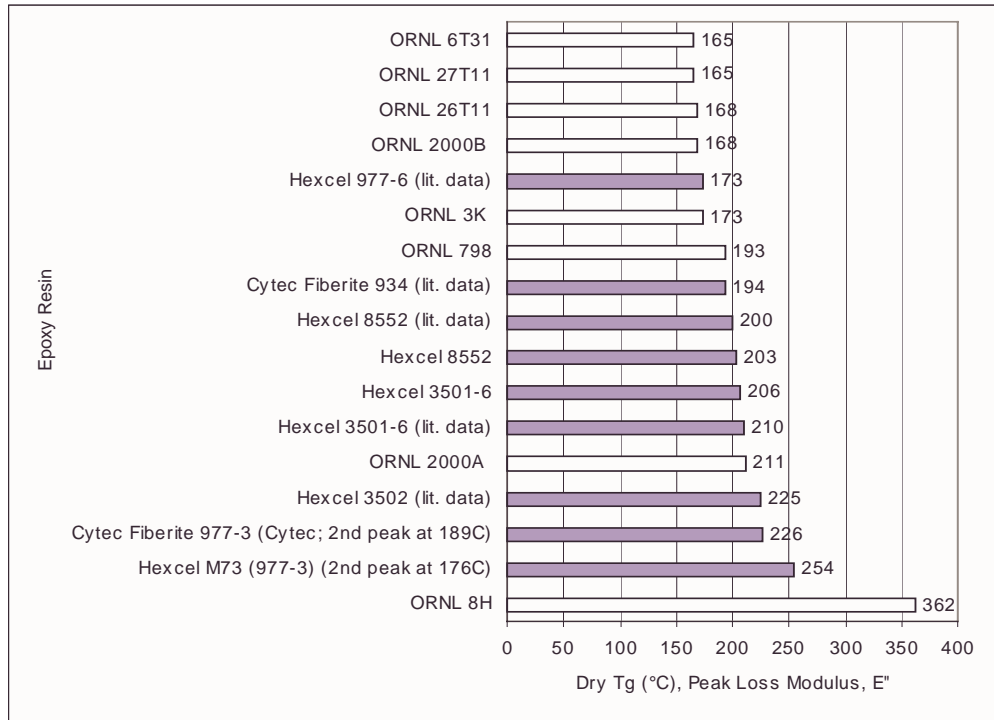
**Figure 4. Tensile Modulus of Electron Beam and Thermal Cured Epoxy Resins**



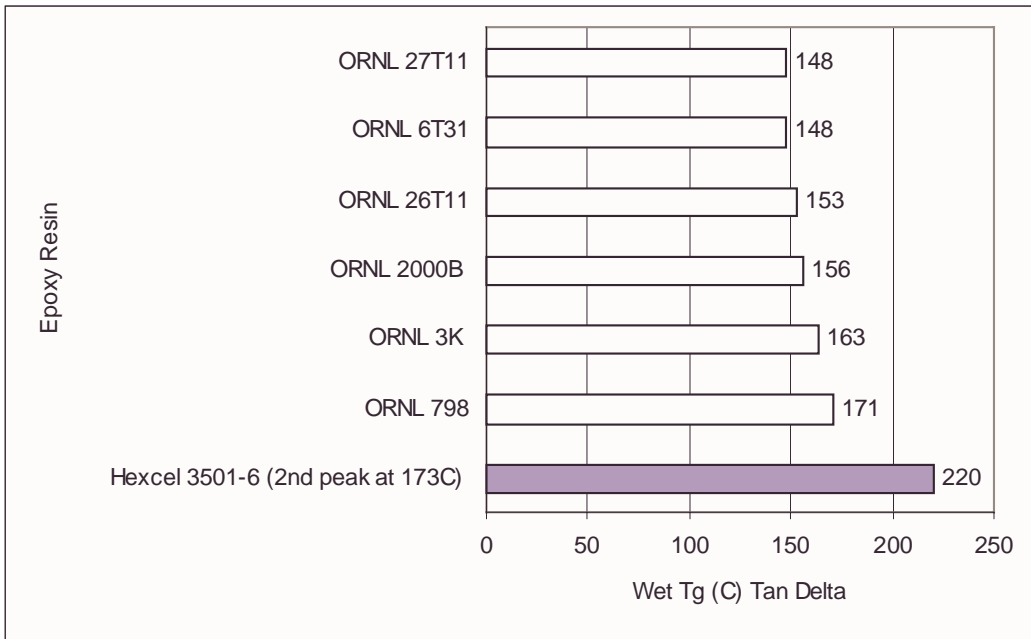
**Figure 5. Tensile Strain to Failure of Electron Beam and Thermal Cured Epoxy Resins**



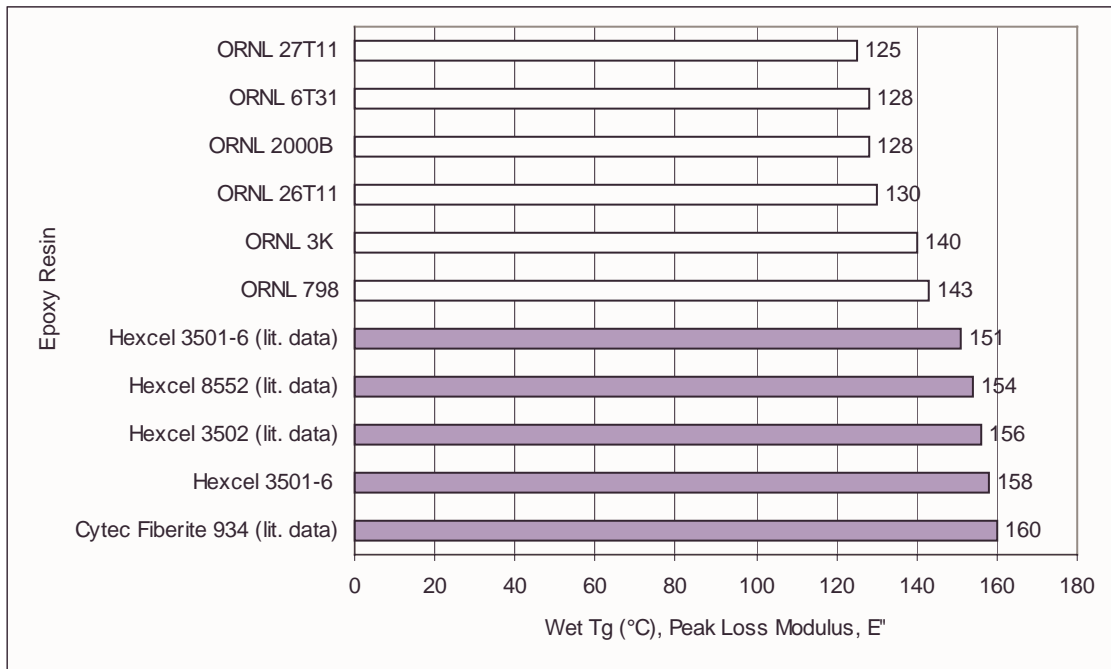
**Figure 6. Dry Tg (Peak Tan Delta) of Electron Beam and Thermal Cured Epoxy Resins**



**Figure 7. Dry Tg (Peak Loss Modulus, E'') of Electron Beam and Thermal Cured Epoxy Resins**



**Figure 8. Wet Tg (Peak Tan Delta) of Electron Beam and Thermal Cured Epoxy Resins**



**Figure 9. Wet Tg (Peak Loss Modulus, E'') of Electron Beam and Thermal Cured Epoxy Resins**