CASE WESTERN RESERVE UNIVERSITY

GRADUATE STUDIES

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Date June 14, 1991

ESTHETICS AND ORTHODONTICS:

THE FABRICATION AND TESTING OF A SYNTHETIC

ESTHETIC ORTHODONTIC ARCHWIRE

BY

MARTIN C. WRITER

Submited in partial fulfillment of the requirements for the
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ESTHETICS AND ORTHODONTICS: THE FABRICATION AND TESTING OF A SYNTHETIC ESTHETIC ORTHODONTIC ARCHWIRE

Abstract

BY

MARTIN C. WRITER

Objectives were to obtain two potentially esthetic wire form composites and to manufacture, from raw materials, continuous fiber reinforced composites. Evaluations were performed on both the conventional manufactured and experimentally pultruded wires. Tensile and flexural properties were evaluated.

Commercial composite manufactures were contacted for readily available products. Experimental wires were manufactured utilizing a reaction injection moulding pultrusion technique. Wire forms were tested on an Instron device. A uni-axial tensile test and a three point bend test were performed on each wire. Experimental wire diameter data was evaluated by utilizing a travelling stage light microscope.

Conventionally manufactured composites demonstrated good tensile properties. Experimentally manufactured wires produced variable results. Tensile moduli ranged from 4.7 - 21.7 x 10^6 psi. Tensile yield strengths ranged from 87.0 - 192.4 x 10^3psi. The flexural modulus of elasticity for the experimental wires ranged from 5.8 - 14.8 x 10^6 psi. Flexural yield strengths ranged from 4.2 - 60.7 x 10^3psi. The flexural load at the 0.2% offset ranged from 0.020 - 0.191 Lbf. Wire diameters varied from 0.0165 - 0.0289 in.

While brittleness of fiber reinforced wire forms is a serious problem, these composites demonstrated properties similar to some wires currently used in orthodontics.

DEDICATION

This is dedicated:

To my wife Karen who aided me throughout my education, and without whose help andsupport this onerous task would not have been completed,

and

To Dr. George Georgiff, who inspired me to enter the dental and orthodontic profession.

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I would like to thank my wife, Karen, who was instrumental in helping me complete my thesis and my education, Emma Galante, without whose support and assistance my dental education would have been impossible, both my parents and in-laws for the interest and the support they have rendered during my education. Finally, I would like to acknowledge the faculty and staff at Case Western Reserve University.

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Introduction

The introduction and subsequent popularity of the new clear ceramic and crystal orthodontic brackets has demonstrated the need for increased esthetics of modern orthodontic appliances. Therefore, the addition of a complementing esthetic archwire is an exciting concept. The new generation of metal alloy wires such as nitinol and TMA have truly exceptional physical properties, however, because they consist of a metal base they have a silver, opaque color and are ecstatically incompatible with clear orthodontic brackets. Presently the most advanced literature regarding archwires has only evaluated the physical properties of the superelastic metal alloy archwires.

Other than white teflon-coated metal wires, a review of the literature and products presently available on the market demonstrate that only one clear or tooth colored esthetic archwire is currently in use. Teflon-coated wires are more esthetic than base metal wires, however, the teflon coating has been know to delaminate. Optiflex, the other commercially available wire, while being esthetic, is subject to fracture during normal orthodontic procedures.

Many possible synthetic material are on the market, however, they are not in the form of orthodontic archwires. Materials used in the production of fishing line, broom-bristles, and generally termed synthetic products are on the the market in non-orthodontic applications. Manufactures and researchers such as Composite Tec, Dupont, and the Bateile institute have developed and manufactured potentially adequate

materials, though these materials have not been used in the production of orthodontic archwires. The search for materials involves procurement of such materials from manufactures and alteration into round or rectangular orthodontic archwire from 0.012" to 0.022" in size. Once the materials are received they can be tested by a standardized technique to determine the probability of there actual clinical use.

The objectives of this research project are to:

1. Evaluate two commercially available synthetic materials that are already in wire form and could be used as or developed into an esthetic orthodontics archwire
2. Produce two wires from two other raw synthetic materials. These newly developed wires would have the potential to be developed into an esthetic orthodontic archwire. Such generally classified synthetic materials could be polymer, composite, or ceramic in composition.
3. In order to simulate actual orthodontic applications these wires, both the procured and produced wires will be tested against standard materials, such as stainless steel, and nitinol wires.
4. A Tensile Test and a Three-point Bending Test will be used to evaluate and compare the properties of these new materials. All materials to be utilized will be selected based on the following criteria: 1) they would be non-toxic in their final form and 2) they must be tooth colored or have the potential to be tooth colored or clear.

The research will comprised three phases. The first phase will include a search for materials that could be suitable for orthodontic archwires. The second phase will be the fabrication of glass and carbon filled composite wires utilizing both a polymer and an epoxy matrix. The third phase will encompass a laboratory comparison of the research developed potential wires with standard orthodontic archwire materials; stainless steel, and nitinol.

Statement of Thesis

Clear ceramic and crystalline orthodontic brackets give the patient the option of increased esthetics with their orthodontic appliances. They are much less visible than the standard stainless steel brackets. Currently there is only one archwire on the market that compliments these nearly "invisible" brackets. An appliance, that is generally invisible, is exposed by the silver gray metal archwire when it is tied into an almost invisible bracket. A patient wearing an invisible appliance, would realize enhanced esthetics with a clear or tooth colored archwire. An increase in patient compliance has been noted with use of esthetic appliances.

The literature overwhelmingly demonstrates that esthetics of the orthodontic appliance is one of the primary hindrances to adults receiving orthodontic treatment. Many advances have been made in the treatment of patients the development of nitinol wires has significantly changed orthodontics. While nitinol wires have superior properties to stainless steel, in the initial alignment phase of treatment, the drawback to the clinical use of nitinol archwires is their significantly increased cost. This

further justifies the research for finding a synthetic material that would have similar properties to steel or nitinol and possibly be provided at a lower cost. These new synthetic archwires should have physical properties that are similar to and or exceed those properties of conventional metal wires. Testing methods will include the Three-Point Bending test and a Tensile Test this will allow comparative testing of the new materials and will approximate their clinical effectiveness.

Review of Literature

Esthetics and Orthodontics

Orthodontics is traditionally one of the dental specialties most concerned with esthetic improvement as an outcome of treatment. Due to surgical and technological advances, previously unattainable results can be achieved.[1] In general, today's patients are seeking esthetic dentistry. Patients are informed consumers who have specific desires and goals. Furthermore, esthetic dental care has a great psychological impact upon a patient's life. Baldwin and Ast have stated that a large proportion of patients seeking orthodontic treatment do not seek care due to physical disorders.[2] Instead, patients seek treatment for cosmetic considerations.[3] Unquestionably, the single greatest factor responsible for the public's increased awareness and demand for esthetics is due to the media. There have been multiple documentaries, talk shows and printed articles on how an esthetic procedure has improved a patient's appearance ,and their life.

Patient's attitudes concerning dental esthetics have changed over the last 90 years. Currently, the new image is based upon wholesome-looking, cream colored, well shaped teeth. This is now the norm for an attractive dental appearance.[4] Today's patients want to know their options and both the long and short term consequences of those options. In the 1950's, the American Dental Association reported that, in the United States, some patients of limited financial ability to pay for extensive dental rehabilitation chose the option of dentures as a way to end dental

pain and to eliminate dental deviations from the "norm."[5] Patients have a strong and deep social imprinting dictating that to be successful one must be bright, healthy and have a perfect smile with sweet smelling breath[6].

Parents support esthetic dentistry due to their aspirations for their children. They attribute part of their children's success to the child's pleasing esthetic appearance. Esthetic dentistry is pursued with the belief that their child's current appearance may handicap them in pursuit of an improved status in the social stratum.[7] Finman has stated that although society has become "youth orientated," it is not youth itself that society wants but it is the energy, mental agility and the physical appearance of youth.[8]

In today's competitive society there is a definite pressure to conform to an artificial esthetic standard. If an individual has the desire to succeed, it is no longer a matter of choice, esthetics are a prerequisite.[9] This observation has been documented by the findings of Cushing et al. and Beder. Society considers a person who is attractive as more reliable and better qualified than a person who is deemed unattractive.[10,11] Considering these factors it is not surprising that slight rotations, mild crowding or mild spacing of maxillary anterior teeth can cause a patient great concern.[12]

Finally, in a survey by Linn, it was observed that a substantial majority of adults, irrespective of their socioeconomic status, regarded their dental appearance as being important, especially in interpersonal situations. Furthermore, a person's social class did influence the person's oral health. Those people of a lesser economically advantaged group were

less likely to have had their dental defects corrected even though they were cognizant of them.[13] Newman et al. found that a patient's satisfaction with their appearance and their self image was most strongly influenced by a patient's age, gender and the presence of discolored or restored teeth.[14] The previous observations concur with Katz's study on the relationship among eight orthodontic indices and one's self image.[15] Given the overwhelming body of evidence, stating that people associate success and a positive self image with pleasing esthetics, it is not immediately clear why all patients that deviate from the ideal do not undergo orthodontic treatment. This is especially true when financial arrangements can be made for the treatment. Furthermore, in a study Ingervall and Hegarg found that an increased motivation and interest in orthodontic care had a direct relationship to the resources available for orthodontic care.[16]

Searching the literature for factors that deter patients from receiving orthodontic treatment reveals many studies and many reasons for not receiving orthodontic care. Zachrison has reported that orthodontics can have detrimental effects on the patients overall dental health due to; dental caries, periodontal disease, occasional root resorption and pulp death.[17] Additionally, the psychological stress of undergoing orthodontic treatment may be a consideration. Maj et al. and later Lewis and Brown found that undergoing orthodontic therapy was stressful. In the study conducted by Maj et al, it was reported that 75% of the patients regarded the appliance appearance and bulk as being troublesome. Although, patients regarded their appliances as troublesome

the majority of the patients in this study felt their treatment was successful. Furthermore, the stress was more a relation of the patient's adaptation to their appliances than to discomfort or pain caused by their appliances. However, fifty percent of the patients surveyed expressed a fear that they would be excluded from their peer group due to the fact they were wearing an appliance. [18] Brown and Lewis found that in the British removable orthodontic appliance patients, a patient's anxiety levels were lower than those levels reported by Maj et al.

Gosney found that a parent's concern over their child's orthodontic treatment included factors such as time a parent would lose from work to transportation of the child to and from the orthodontist. Additionally, 85% of the parents were concerned about the amount of time that a child would be absent from school. On the average, a child will visit the orthodontist for twenty-one, 45 minute appointments during school hours. Furthermore, 62% of the children were concerned about the amount of time they would be missing school. Because over 60% of the patients in this study used public transportation, the cost of transportation and distance traveled were rated as relatively minor inconveniences.[19] Over half of the children, in this study, expressed some concern over their appliances. Some of their concerns were discomfort caused by the appliance and difficulty in speaking. Dietary restrictions were the third most common concern amongst children. During the study, visibility of the appliance was reported as a major concern only 20% of the time by males and 23% of the time by females. However, before orthodontic appliances were placed, 73% of the patients said they were suffering "a lot" of worry

about the visibility of their appliance. The children said however, that they would undergo orthodontic therapy if their dentist recommended treatment. Finally Gosney reported that well over half of the patients were teased about their appliances but only 12% were caused any anxiety by the teasing.

Adults seeking orthodontic care frequently request "braces that don't show" however, to some orthodontists, this patient is a crank and a nuisance.[20] Baum (1974), stated that conventional fixed orthodontic appliances were un-esthetic and implied that patients were immature if they felt that conventional un-esthetic orthodontic appliances were incompatible with their occupation or social status.

The basic underlying question to be answered is "why is an adult now seeking treatment?" Is it simply, many adults who were unable to have orthodontic treatment as a child would now like to have straight teeth? Breece and Neiburg attempted to answer this question by surveying 204 adult orthodontic patients. The patients surveyed were from both the private offices and the University Dental School. Females were more concerned with dental health, facial and dental appearance, general health, and mental health as compared to males. Additionally, women were more concerned with affordability of orthodontic care than were men. Evaluating the survey results as compared to education the results are more ambiguous. Highly educated individuals and minimally educated individuals seemed to consider dental health a less important motivating factor to sustain orthodontic treatment than did those with 9 to 16 years of education.

Adult opinions concerning why they did not begin orthodontic treatment were varied. Highly educated individuals were concerned with the amount of time involved with orthodontic treatment. Respondents without an academic degree or minimal education were more concerned with pain and discomfort. However, both groups overwhelmingly said that embarrassment from wearing appliances was the most important reason for not undergoing orthodontic treatment. This finding has been verified even when the adults knew they had a physiologic need for orthodontic treatment.[21] A summary of the literature revealed 6 reasons for an adult to undergo orthodontic treatment. These reasons are illustrated in Table 1.

Table 1--Top 6 Reasons Rated Important or Very Important To Adults Undergoing Orthodontic Treatment[22]

Reason For Seeking treatment	Important	Very Important
Straight Teeth	31.2%	61.4%
Dental Appearance	39.4%	53.7%
Dental Health	36.5%	52.7%
Facial Appearance	38.4%	44.8%
Healthy, Attractive Gums	36.9%	34.0%
Orthodontics for General Health	37.3%	31.4%

The chief reason that was claimed by patients for not having orthodontic treatment until adulthood was cost. Over 41% of the patients interviewed said that they were unable to afford treatment until adulthood. Only 11.2% had said that treatment had never been recommended until they were an adult. Therefore, most adults were aware they needed treatment and they treatment had been recommended but, they elected not to for various reasons.[23]

The primary concern of adults regarding orthodontic treatment were embarrassment and cost. If a truly esthetic appliance was used, according to Gosney, an esthetic appliance would remove over 40% of the barrier towards adult treatment. Today, these esthetic appliances are partially responsible for the fact that in many orthodontic practices adults constitute approximately 50% of the practice.[19]

In contrast to other observations, Turner found that the psychological drawbacks to orthodontic therapy were unfounded. Friends did not react poorly to patients wearing orthodontic appliances.[24] Furthermore, in another study it was found that 38% of the patients stated their appliances did not hinder them socially, once placed and an initial 4 week adjustment period had elapsed.[25]

As a summary of the literature is given on the following page, Table 2, illustrates some of the reasons' adults have given for not having orthodontic treatment.

Table 2--Reasons Adults Do Not Like Having Orthodontic Treatment[26]

Reason For Not Having Treatment	Percent
Embarrassment	41.7%
Lack of Information (Unaware of Adult Orthodontics)	27.4%
Expense	18.9%
Time and Length of Treatment	10.9%
Apathy	1.1%
Fear of Pain	0.0%

The major exceptions to these findings in the afore mentioned study were headgear and removable appliances. Over 85% of the adult patients said that headgear was uncomfortable, embarrassing and caused headaches. The patient's chief difficulty with a removable appliance was a speech impediment and difficulty eating. One surprising disadvantage that was reported, was that adults did not like the temptation of being able to remove their appliance. However, with respect to Hawley retainers, most patients found them less "troublesome" than fixed appliances.

Once an adult has become aware that he or she needs treatment, the adult considers their treatment needs for a considerable time interval before beginning treatment. In one study it was found that adults fell into two groups. The first group made the decision to proceed with

orthodontic treatment after considering their options for 1 to 3 years. The second group made their decision after thinking about it for 6 to 13 years. The range of time in this study was 2 weeks to 40 years.[27] The study also revealed that the general dentist was the person that was most responsible for educating, and finally convincing a patient that they would benefit from orthodontic treatment.

One area that the orthodontic profession has not dealt with effectively is the profession's attitudes and feelings with respect to treating adults. Brayer and Shapirs stated that orthodontic practioners were reluctant to treat adults for several reasons. They postulated that orthodontic practioners were projecting the patient's concerns about esthetics and were therefore hesitant to use appliances other than the conventional stainless steel appliances, that the practitioners felt comfortable with. Furthermore, doctors have assumed that adults would be more uncooperative. Finally, doctors were also hindered by their fear that the esthetics of the treatment result would be unacceptable to the patient.[28]

In summation, the desire for dental esthetics is not a fad but instead it is a new arena for the dental profession to explore and use new techniques and newly developed materials.[29] Both children and adult patients are requesting esthetic appliances. Development of such appliances would lead to increased patient compliance as well as an increase in patient clientele.

Orthodontics and Appliances

Dentistry, more than many other occupations, is highly dependent upon technology and advances in material. In the early days of orthodontics, gold was used in the form of bands and wires.[30] The development of the edgewise technique allowed an effective way to transmit force to teeth and correct various types of malocclusions. However, the disadvantage of this early system was the bulkiness of the appliances and the rigidity of the wire. These characteristics discouraged adults from undergoing orthodontic treatment. Furthermore, lengthy treatment time was another prohibiting factor. Finally, the discomfort associated with orthodontic appliances was the final barrier to an adult receiving orthodontic treatment. This was due, primarily, to the assumption that adults were more inflexible and less tolerant of pain than adolescents.[31]

World War II began a revolution in technology that forever changed orthodontics. Breakthroughs in metallurgy and advances in chemistry yielded refinements in the manufacture of stainless steel wires. These new wires, made of an austenitic alloy, were not only thin but also resisted deformation, and they allowed the development of more efficient orthodontic mechanics.[32] This advance allowed appointments to be spread out over a longer period of time. Thus, time was the first barrier to fall as a reason for adults to avoid orthodontic treatment.

From the late 1950's through the 1970's the technological breakthroughs in the plastics' industry was the next major advance in orthodontic technology. Buonocore investigated the adhesive properties

of methacrylate resins for dental use.[33] Since the 1950's, many composite resins have been developed that will bond an appliance, or a restoration, directly upon a tooth.[34,35] Thus, composite bonding materials allowed the bonded brackets to become a reality. After almost 60 years, bands were no longer the dominating aspect of a patient's face as they underwent orthodontic treatment.

With the arrival of direct bonding, and the use of bondable brackets becoming vogue, the brackets themselves began to change. The original double wide Siamese, or twin-bracket, began to give way to the mini-twin brackets. The Tweed single-bracket also began to be narrowed in a mesial-distal direction until rotational problems developed. The next generation of brackets were narrow brackets with rotation arms. However, all these brackets had something in common; they were made of stainless steel.[36]

Shortly after the development and commercialization of composite bonding agents, plastic (Lexan ® polycarbonate) orthodontic brackets were developed. These brackets were the first truly esthetic brackets that were available. This development allowed adult patients, who were concerned with esthetics, to have the choice of esthetic orthodontic treatment. However, due to problems with distortion, the orthodontic practioner was less than satisfied with the result. Additionally, due to problems with discoloration, patients were frequently dissatisfied with the appliance. In an effort to aid practioners, Goldstein and Burns stated

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Lexan ® registered trademark of General Electric Company, Inc. Corning, New York.

that the use of light forces, in combination with periods of removable appliance therapy was a way to minimize forces that would damage or dislodge the plastic or Lexan ® appliances.[37]

Though some ceramic brackets have been around since the late 1970's, the current generation of ceramic brackets became commercially available in the mid 1980's. The ceramic brackets are not a clay or china ceramic but instead they are a ceramic of sapphire, aluminum oxide. Sapphires are the second hardest substance known to man. These brackets are either of a mono-crystalline or a polycrystalline construction. In addition to being hard, they are chemically inert so they do not adsorb extrinsic stains nor do they discolor due to oxidation or UV exposure. Finally, these brackets are completely biocompatible and can be used in nickel sensitive patients.

While ceramic brackets are translucent or tooth colored, their crystalline structure makes them brittle and susceptible to fracture. Additionally, the surface hardness of these brackets is harder than that of enamel and because of this severe iatrogenic damage may occur to opposing dentition.[38] However, these brackets have better esthetics than plastic brackets and while they are susceptible to fracture, they will not distort. This combination has allowed both the orthodontist and the patient to be satisfied with this type of an esthetic appliance.[39]

In the late 1970's and the early 1980's, lingual bracket therapy became another treatment option for esthetic-minded patients. This choice, as with other esthetic options, had advantages and disadvantages. Adults liked their complete invisibility, since the brackets were placed

upon the lingual surface of the teeth. However, they did not like the speech impediments that frequently occurred due to the infringement upon tongue space. Orthodontic practioners did not like lingual appliances because working on the lingual surface required special pliers, working indirectly and the factor of increased variability in geometry of the dental arch when viewed from the lingual.

Most major orthodontic supply companies offer an esthetic bracket, however, an esthetic archwire has not successfully entered the marketplace. About the same time as the ceramic brackets were introduced, an 0.014" "White" wire from Lee was introduced. While the esthetic wire did alleviate some of the esthetic problem of traditional stainless steel, this wire was considered to have poor resiliency. Additionally, chipping of the teflon coating, and an increase in friction resulted in limited use.[40] Since that time Optiflex ™, has entered the market. Optiflex ™ is a clear, synthetic, initial aligning wire made of fiber optic material. This material is a fiberglass core in a nylon matrix. GAC has also introduced an esthetic archwire. They have introduced a version of their Sentalloy® wire. Spectra-Sentalloy® is a nickel titanium wire that has had an ionized coating of titanium nitrate applied to its surface and this coating gives the wire a whitish color.

Optiflex ™ Ormco Corporation, Glendora, Ca. 91740

Sentalloy® GAC International Inc. Centeral, Islip Ny 11722

Spectra-Sentalloy® GAC International Inc. Centeral, Islip Ny 11722

Considering the need for esthetic wires and the poor mechanical properties of current esthetic wires, the development of new esthetic wires with improved properties is important. The production of aligned fiber composite wires through the pultrusion process offers promise in this regard. A pultruded aligned fiber composite wire could be given any color. Wire properties could be varied depending upon the interplay of the fiber and its matrix.

Introduction to Reaction Injection Molding Pultrusion

Pultrusion Machinery

All parameters of the final product configuration can be controlled by changes in die design. For example, the experimental manufactured wire can be either round or rectangular in shape. Figures 1 and 2 demonstrate manufacture of a rectangular final product. By changing the aperture of the die, from square to round, a round product can be produced.

Pultrusion machinery (Figure 1) is composed of many parts which includes the resin wet out tank, pre-forming fixtures, heated dies (Figure 3), a pulling section (Figure 4) and a cut-off saw (Figure 5). The resin wet out tank is a trough that contains rollers. The rollers force the reinforcing material under the surface of the resin mix to wet the fibers with resin. Additionally, a resin tank may have a pre- forming die that is used to

Figure 1

Conventional Pultruder

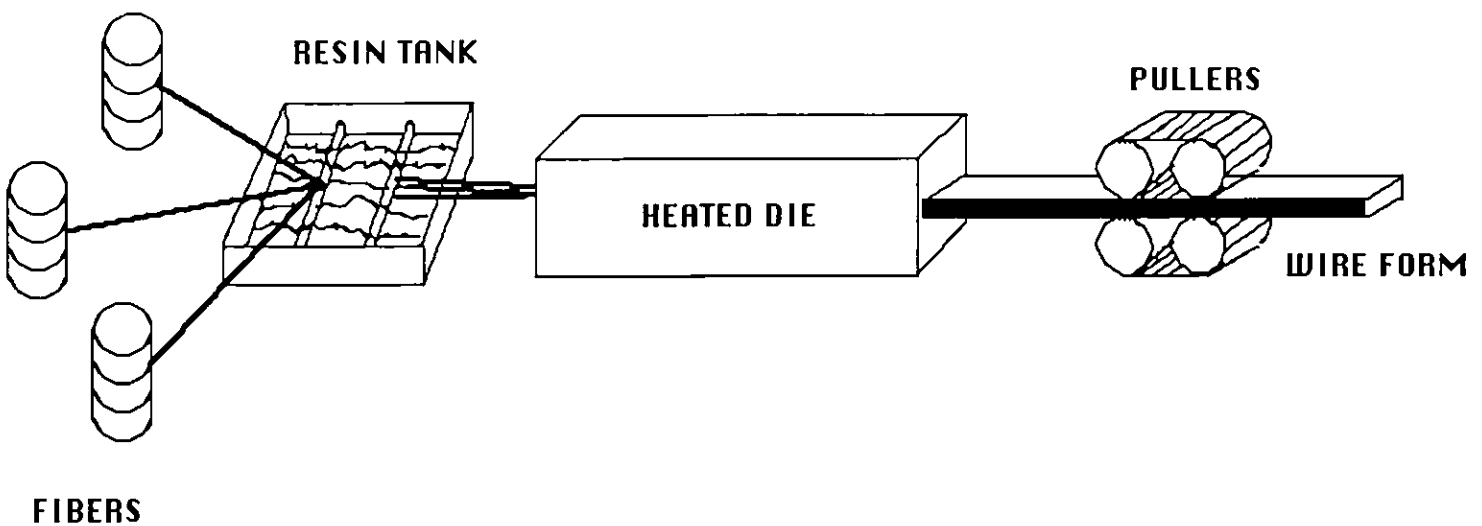
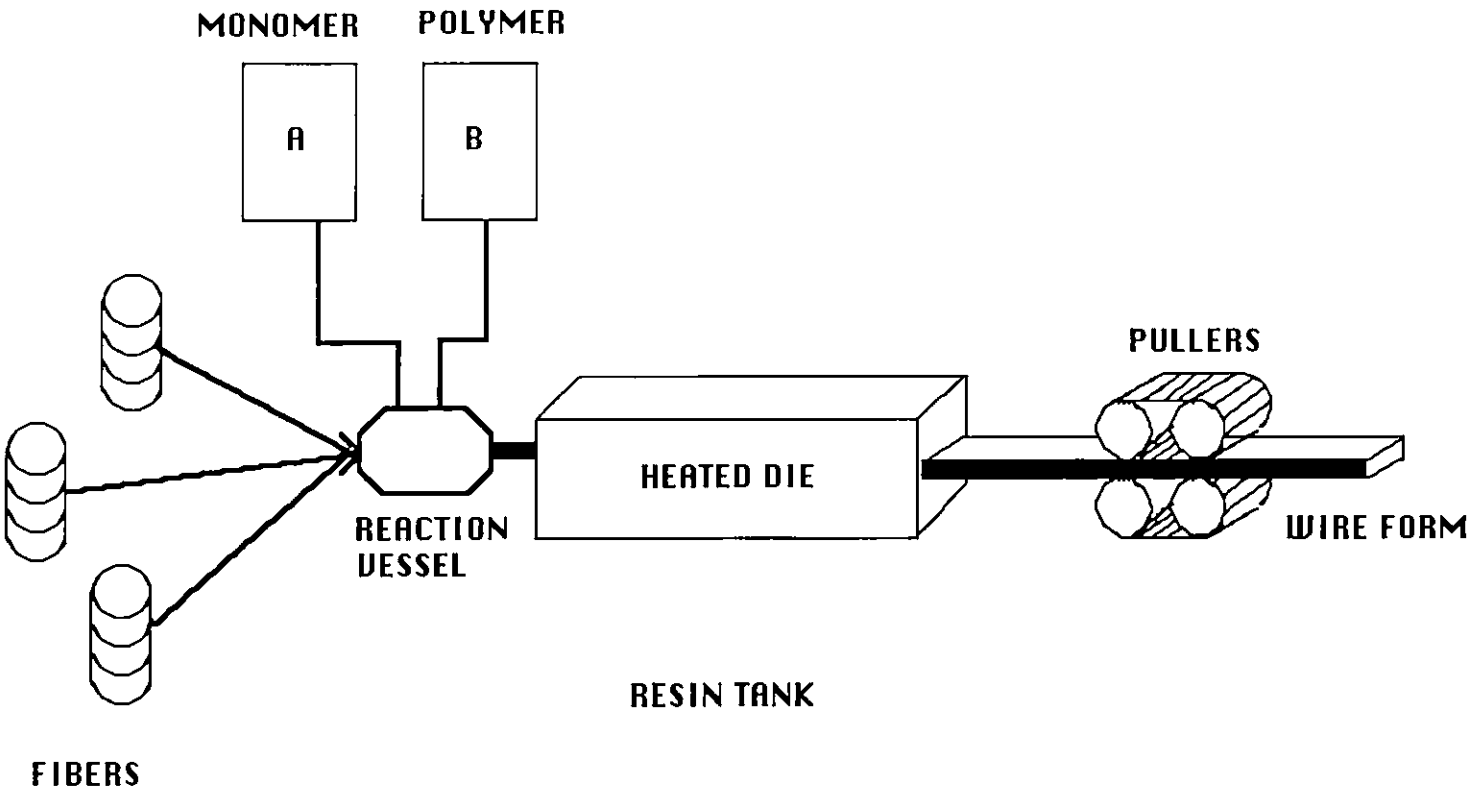


Figure 2

Conventional reaction Injection Molder



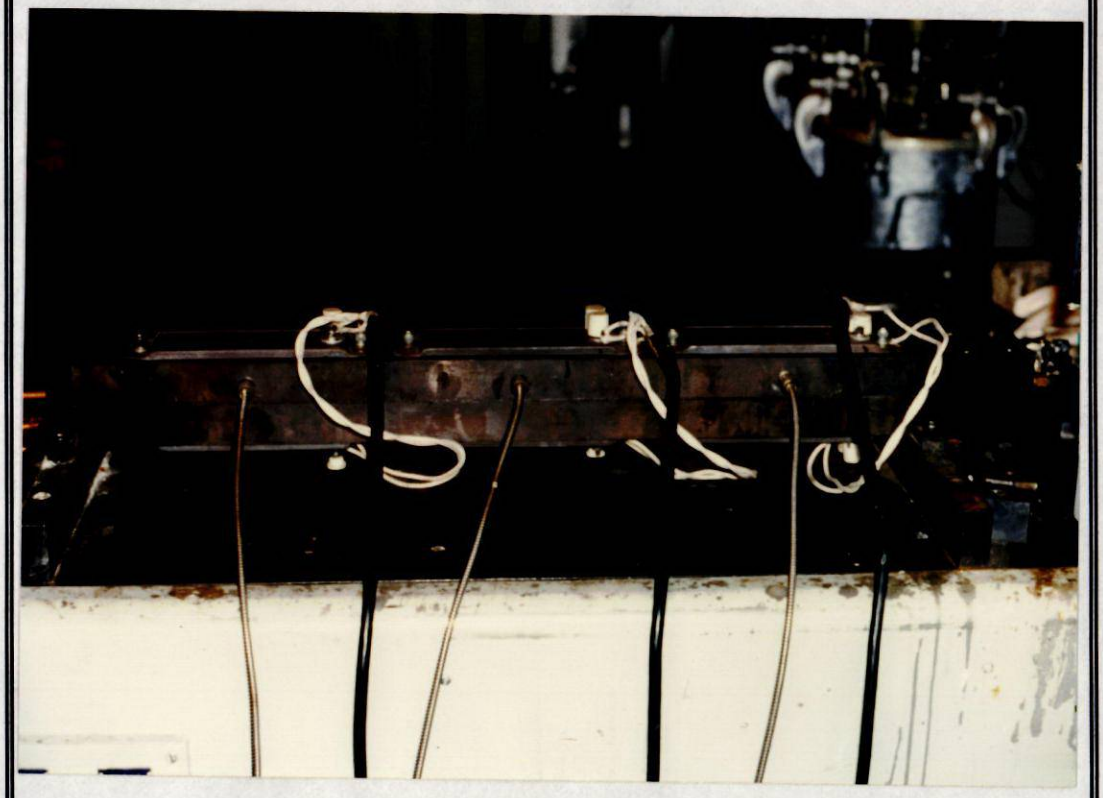


Figure 3. Heated Pultrusion Die



Figure 4. Grippers Engaging A Composite Wire-form



Figure 5. Cut-off Saw

remove excess resin from the product. Finally, the resin tank also has a comb that prevents fiber tangling. Reaction injection moulding pultrusion requires a slight modification of this basic design. Instead of a resin bath, there is a chamber where the reactive components are mixed, in this chamber there are rollers that insure good fiber wetout (Figure 2).

The next device, in the production line, is the pre-forming fixture. This device begins the consolidation of the reinforcement into its final shape. It is typically made from a resin product to allow easy cleaning. After passing through the pre-forming fixture, the uncured resin-reinforcement mixture is pulled through a heated chrome plated die. This section initiates the chemical cure for systems that utilize chemical cures. For systems that utilize a non-chemical set, this section provides an initial reduction in viscosity thus allowing a denser packing of the reinforcement and removal of excess matrix material.

The final sections include the pullers and the cut-off saw. Once the product has cooled appropriately, or has set chemically, it is engaged by the pullers. The pullers are a pair of continuous caterpillar belts that have pads that engage the pultruded product or a set of hydraulic pads that can be clamped and pulled parallel to the product. Finally, the cut-off saw is a saw that cuts the proposed product to the desired length.

Pultrusion - The Process

A relatively new processing method, reaction injection moulding pultrusion, (RIM)-Pultrusion, has been developed which has made possible the pultrusion of composites with high glass contents using a variety of matrices previously unavailable to pultrusion. This process, is fundamentally different from its predecessors, which has led to the production of continuous reinforced nylon-6/6 composites in a low temperature manner.

The new process replaces the pultrusion resin tank with a reaction vessel which feeds into the reaction injection moulding machine. (Figure 2) This change has led to many advantages over either process taken separately. In particular, the lower viscosity reactants used has resulted in improved fiber wetout. This in turn makes higher reinforcement contents possible. RIM-Pultrusion also features matrices with gelation times as fast as ten seconds. These matrices can be polymerized and cured at low temperatures. This process is continuous, and can produce high performance products with either a thermoplastic or thermoset material.

The pultrusion process is the only continuous method of producing continuous fiber reinforced composites of variable lengths. To appreciate the full potential of the process, it is necessary to first understand the basic concepts involved. The process starts with the reinforcing material, rovings. The material may be fibers, mats, or weaves. During the fabrication process a carefully controlled uniformly low level of tension is required for proper reinforcement alignment. [41] These reinforcements are

impregnated with the matrix material in the second stage, it is important to achieve good fiber wet-out and matrix adhesion. Good fiber wet-out and matrix adhesion is essential because without this, the final product may contain matrix voids or be susceptible to non-uniform stress distribution. The resin wet-out tank may be heated or atmospherically controlled. By atmospherically controlling the resin wet-out tank, the resin can be subjected to a vacuum, thus allowing a reduction of voids in the final product. The batch life or the resin must be on the order of 30 hours or more for standard commercial purposes. In the heated die stage, the matrix is first gelled and then vitrifies around the reinforcement. Initially, the resin absorbs heat from the die, then the heat flux reverses as the reaction becomes exothermic, in the latter part of the die.

The next stage, the pullers, provide the driving force, as well as the name of the process ie. "pull"trusion process. The pullers are located at some distance from the die so that they clamp only after the product has established its modulus and cooled. Finally, the flying cut-off saw allows the pultruder to continuously produce any desired part length.

The pultrusion process is a relatively new technique and as such, there are only a few reviews on the subject. [42,43] The reviews that do exist are generally business oriented and were written to better clarify how particular advancements are advantageous to the industry.

Pultrusions have the inherent advantages of composites over metals; which are: improved strength to weight ratios, corrosion resistance, and easy finishing. However, the process does suffer from UV instability, lack of thin wall technology, poor post forming ability, and

higher processing costs when compared to metals. [44] Thin wall manufacturing is the ability to consistently produce thin (less than 0.5 mm thick) high quality products. Post-forming is the ability to shape a product after it has been manufactured. Because most current pultrusion matrices involve an irreversible chemical cure it is impossible to change the shape of the product after it has cured. If a thermoplastic matrix was developed post-forming would become a reality. However this matrix would have to have the ability to chemically bond to a coupling agent in order to produce a product that had properties similar to steel wires. A thermoplastic matrix is a matrix that can be shaped in a controlled fashion with the application of heat (300-500^{0}C).

MATRICES

The pultrusion process has been dominated by polyester matrices due to the absence of a viable alternative. In an effort to improve the properties and variety of profiles, many new resins have been explored. These resins generally are targeted at improving on the weaknesses of polyesters in the areas of flexural modulus, high-temperature stability, chemical stability, or shrinkage.[45,46]

The first attempts to expand beyond the basic polyester materials, were the developments of vinyl esters and epoxies. Although chemically somewhat similar, the vinyl esters provide better mechanical properties and chemical resistance than their isophthalic counterparts. Epoxies feature even better physical properties, including high temperature

stability. Epoxies were plagued, however, by their delicate chemistry and tackiness.

Since epoxies cannot build up molecular weight as fast as the anionically polymerized polyesters, they have slow gel times that translates to slow processing speeds and/or high heat requirements. In addition, early epoxies could not be even momentarily stopped in the die without seizing. Several different approaches were made to overcome these difficulties. Since the peak exotherm can occur before gelation, epoxies were liable to experience dramatic decreases in viscosity inside the die. This led to fiber compaction and sloughing of the resin rich surface. Kiernan et al.,[47] obtained good surface quality and better processability by adding fillers to the system to increase pre-gelation viscosity.

Kershaw et al.,[48] have explored specially modified epoxies for pultrusion. In 1983, pultrusion runs of two to three feet per minute were achieved with special curing agents. A system was also developed that could still be pulled after having been halted in the die for as long as four days. Other matrices that have been explored include methacrylates [49,50] acrylics [51], silicones[52] , phenolics [53]. The newest advances today is in the development of "B" stage epoxies and thermoplastic matrices for pultrusion.

A "B" stage epoxy is an epoxy that is only partially cured as it is pulled from the die. Due the fact that the epoxy is only partially cured the resinous product is able to be moulded after pultrusion or "post-formed." The desirability of the development of thermoplastic matrices is due to the

inherent post-forming and recyclability advantages over conventional thermosets.[54] Thermoplastics, due to their greater elongation ability, are also expected to make better use of the reinforcement properties of continuous filaments.

It has been necessary to develop special processing techniques for the thermoplastic resins. Early efforts in this area made use of solvent impregnation but suffered from two drawbacks. The proper amount of solvent used was a difficult choice; too little means the material was not pliable enough and too much translated into excessive time required to remove the solvent later on. In addition, employee health hazards needed to be taken into account. One simple method considered has been to pultrude the hot melted resin. This has been done with Polypropylene (PP) and nylon. This process would be well suited to Poly-ether-ether-ketone (PEEK).[55] Another process uses a radio frequency heater to melt the solid resin as the rovings pass through a fluidized bed.[56,57] Braiding of matrix fibers with the reinforcement has been explored, although special attention must be given to wet-out.[58]

The final aspect to consider when selecting a matrix is how the composite develops its final strength. Many early and most modern fiber laminates, composites, get their tensile and compressive strength from the frictional properties of the resin that surrounds the fiber and the frictional properties of the fiber itself. Studies indicate that upon initial loading of the laminate the adhesive bond between the fiber and the resin is broken. Therefore, it is the friction of the fiber moving in the resin matrix that contributes to the ultimate strength of the laminate.[59] While

many resins have been explored to serve as the matrix for a laminate the epoxies have shown their superiority over polyester and phenolic resins in testing.[60] Finally, an epoxies' interlaminar sheer ratio can be enhanced by the use of a silane coupling agent. This leads to the production of a wire that will demonstrate the mechanical properties of the fibers more effectively by relying upon the strength of a chemical bond versus a frictional coefficient to transmit stress throughout the laminate.

REINFORCEMENTS AND ADDITIVES

Just as polyesters dominate the resins available for pultrusions, glass fibers dominate the reinforcement arena. In addition to developing new fibers, researchers have emphasized improvement in fiber effectiveness. Work is also underway to examine other fillers and additives. Continuous longitudinal fiber reinforcement is the feature that allows pultrusions to exhibit superior mechanical performance. As such, it is important to insure that the fibers are of high initial quality and are properly incorporated into the resin matrix. It is desirable to avoid the presence of excess moisture in the fibers, or rovings, because water may change the cure features of the resin. In addition, water can lead to the formation of voids in the final product, if it is boiled off in the die. Moisture can also adversely affect the mechanical properties of pultrusions. Some processors have added preheating systems to control the effects of moisture. Care must also be taken to avoid crossing of fibers before the die entrance. Crossing of the fibers can lead to stress

concentrations in the profile. An attempt is usually made to achieve a uniform low level of tension on fibers as they enter the die.[61] A high tension will unnecessarily pre-stress the rovings and raise the pulling force requirement. Low tension will allow tangling of the fibers. Additionally differential tensions of the fibers in the product will prevent all fibers from working together to support a load.

Efforts have also been made to increase the percentage of fiber reinforcement. The theoretical hexagonal packing limit is 90.7 volume percent. Nevertheless the twisting of the fibers and their arrangement, in strand form, has set the practical limit at approximately 70 volume percent.[62] While increasing the fiber content improves product performance, it also makes processing more difficult. Higher glass contents raise the load on the pullers and makes it more difficult for the resin to impregnate properly all the fibers, i.e., poor wet-out. [63]

Fillers are put into pultrusions for a number of reasons. Fillers are added to the resin for cost savings and mechanical property enhancement. [64] In epoxy pultrusion, fillers are helpful in adjusting the viscosity of the resin prior to gelation.[65] Fillers are also used for their thermal properties, either to act as heat sinks for heat generated heat from the reaction exotherm or to distribute uniformly energy from the die.[66] These effects reduce the possibilities of thermal cracking and nonuniform cure. There has even been speculation on the possibility of using metal filaments in pultruded parts. [67]

The use of catalysts in pultrusion could be deemed part of the resin system, yet its effects are large and varied, therefore, it will be

considered here as a separate feature. The two most important factors in catalyst determination are the amount and the reactivity of the catalyst.[68] Generally, the proper amount of catalyst is determined empirically. The activity of the catalyst is related to temperature. These two factors are not totally independent, nevertheless, a large quantity of a slow catalyst will give different properties than a small amount of highly active catalyst. A highly active, or low temperature initiated catalyst, will lead to a faster cure but may also feature a less uniform cure than a slower system. In this case, concentration is an important factor in determining whether the cure will be complete or not since the catalyst may lose its effectiveness before it has diffused to all areas of the product. A catalyst that is only initiated at high temperatures may not begin reacting until the material is several inches into the die, This catalyst consequently has a decreased chance of creating a uniform cure. It is a common industrial practice to use multi-catalyst systems, consisting of both low and high temperature initiators to take advantage of both effects and achieve a better depth and more uniform cure. If a single catalyst system is used, it is best to rely on an initiator that begins working at low temperatures.

Finally, it is sometimes necessary to add a mold release agent to avoid high puller loads and die freeze-ups (seizure of the profile in the die).[69] A low profile additive may be added to aid in controlling shrinkage of the resin.[70]

Process Monitoring

Advances have also been made in the field of process monitoring, both for in-line and material quality control purposes. Specifically, differential scanning calorimetery (DSC) measurements can be used to check the reaction kinetics of incoming resins and to monitor the position of the peak exotherm in the die. [71] The peak exotherm has been found to be very useful in determining the general properties of the finished product. It is now possible to obtain in-line measurement of this and other processing data.[72] In addition, pioneering efforts have been made to measure the pressure profile inside the pultrusion die during production. The most important process parameter, and hence the one with the greatest potential for changing end product characteristics, is temperature.

The most obvious place to affect the wire form, by way of temperature, is in the die itself. High die temperatures have been shown to allow faster pulling speeds but also lead to a greater incidence of cracks in the final product. It is also possible that the outer shell of the profile will cure too fast in a hot die and form a skin of low thermal conductive material, effectively shielding the center of the composite from the heat needed for curing. Generally, a multi-zone heated die is employed with the entrance section cooler than the middle of the die. This initial zone has been termed the preheating zone, and later zones are denoted for gel and cure.[73] Other reachers have pointed out that a cooled tapered die entrance can be used to-decrease clogging of the die and improve wet-out.[74]

Other approaches exist to thermally change the composite besides changing the die-temperature. Preheating the resin and/or fiber reinforcement has been attempted. Preheating the resin is employed in an effort to reduce viscosity and improve wet-out.[75] Preheating the fibers is utilized to eliminate the detrimental effects of moisture on the curing resin and final product. This also allows the die to heat the resin and begin curing as opposed to wasting energy heating the reinforcements. However, it should be pointed out that in some cases the fibers are more effectively used as a heat sink for the reaction exotherm. In such instances, preheating would only necessitate a post-forming cooling phase.

The most dramatic changes have been made in the area of die and puller design. Tessier et. al, has published work on an ultrasonic pultrusion die which achieved superior fiber wet-out and higher fiber loadings by curing the resin with mechanical energy.[76] The vibrational energy not only cures the resin, but improves the flow of resin into the reinforcement, deaerates the resin, and reduces the friction at the die wall. These effects led to a 20% increase in transverse properties and a higher possible fiber volume fraction over standard epoxy pultrusion.

Composites

Composites are, by definition, a heterogeneous mixture of two or more physically distinct and mechanically separable materials. They are usually formed by mixing the separate materials in such a way as to

disperse one material throughout the other material. Furthermore, this is done in such a way as to maximize the properties of both materials.[77]

In fiber reinforced plastics, both the fiber and the resin combine to give the resulting product superior properties. Fibers have a very high strength and modulus. However, these properties are only developed with very fine fibers. Glass or carbon fibers must have a diameter in the range of 7 to 15 υm to exhibit these superior properties. Additionally, these fibers tend to be very brittle.[78] Plastics, on the other, hand can be either brittle or ductile and are usually very resistant to chemical degradation. When both fibers and resin are combined, in such a way, as to optimize the properties of both constituents; the resulting product will have strength and stiffness close to that of the fiber and with a toughness and chemical resistance close to that of the raw resin.[79]

There are many possible fibers to be used in a composite however, only three types of fibers will be discussed in this review of literature. The fibers that will be discussed are two type of carbon fibers (Figure 6), two types of glass fibers (E and S) (Figure 7)and ultra high molecular weight extended chain polyethylenes (Figure 8).

Allotropic carbon in the form of stacked small crystals is called turbostratic graphite. This form of graphite when formed into fibers under tension has a diameter of 7 to 9 υm. The carbon fibers are manufactured from either a rayon-based fiber or spun molten coal tar pitch. This mesophase pitch or "green yarn" is then heated at 2000 ^{0}C to induce carburisation. Tensile stress is needed during carburisation to prevent

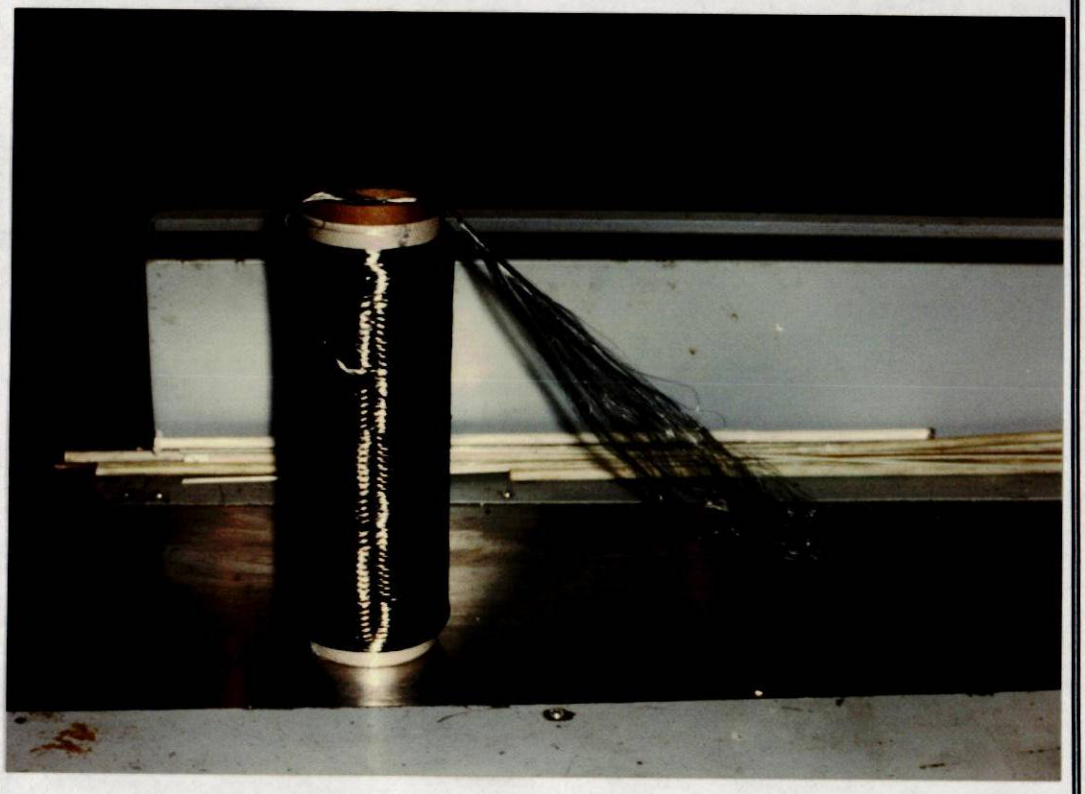


Figure 6. Carbon Rovings On A Cylinder



Figure 7. Glass Roving on a Cylinder



Figure 8. Extended Chain Polyethylene On A Cylinder

relaxation of the fiber and loss of orientation of the turbostratic crystals.[80] Depending upon conditions at the time of manufacture either type I or type II fibers are formed.

Type 1 fibers typically have a diameter of 7.0 to 9.7 υm and are designed to provide maximum stiffness, however, these fibers are relatively weak. Type II fibers have a diameter that ranges from 7.6 to 8.6 υm and are designed to have high tensile strength but at the expense of the flexural modulus, which is rather low.[81] Both fibers have properties well below their theoretical maximums. This is due primarily to flaws in crystal alignment and surface defects during manufacture.

Continuous filament glass fibers are formed by feeding raw materials into a reservoir tank and melting. The melt is then allowed to run through a series of metal plates, or bushings, that have several hundred holes drilled through them. As the glass extrudes through the holes the fibers are pulled together, sized, gathered, wound on spools and dried.

Sizing is the process of coating the individual glass fibers. This coating may be a lubricant, to prevent abrasion, or application of a coupling agent (e.g., silane) to create a chemical link between the glass fiber and it's matrix.[82] Size can also be used to bind fibers together to enhance the handling ability of the glass yarn and finally anti-static properties can be added to the fiber by appropriate anti-static agents. Most importantly however, the size must be compatible with the proposed matrix.

Filament diameter is controlled by several factors. The glass' inherent viscosity is dependent upon the composition of the glass and the temperature of the melting tank. Adjusting the viscosity of the glass in the melting tank is most easily influenced by the manufacture by altering the melt temperature. If the manufacturer can justify resetting or re-tooling the manufacturing equipment, the drawing hole's diameter and the filament winding speed may also be adjusted.

The following table allows for an elemental comparison of composition between E and S glass by weight percentage.

Table 3.--Composition Of Glass Used For Filament Manufacture[83]

(All Values Are In Weight Percent)

Chemical	E Glass	S Glass
SiO_2	52.4	64.4
Al_2O_3, Fe_2O_3	14.4	25.0
CaO	17.2	____
MgO	4.6	10.3
Na_2O, K_2O	0.8	0.3
Be_2O_3	10.6	____

The strength and the modulus of glass are determined by the three dimensional structure of the constituent metal oxides. Glass is, by nature, an amorphous structure, thus it is the molecular bonds that gives glass its strength. In glass there is a covalent bond between the silicon and the oxygen atoms. This leaves the oxygen atom with a slight electro-negative charge. It is the electro-negative charge that makes the ionic bonding between the sodium, and potassium, or another metallic oxide possible. This three dimensional structure can be varied by the addition of other metal oxides. The addition of other metal oxides changes the final properties of the glass by altering the molecular three dimensional configuration. By using other metal oxides to change the bonds strength and the number of bonds between the various constituent parts the strength of the glass can be increased or decreased.[84] Because of this three dimensional networking effect, glass has an added advantage of having isotropic properties. An isotropic property is a property that is the same both in the transverse direction and in the longitudinal direction.

Theoretically, glass has a very high tensile and compressive strength. However, due to surface flaws that occur randomly on a specimen, the theoretical properties of glass are not readily apparent. When glass is drawn into a fiber form, or filament, the same structural flaws occur. However, the flaws occur randomly so that a flaw in one fiber is not likely to be aligned next to a fiber with a flaw in the same position. Coupling the fiber together with a softer but tougher matrix, allows stresses to be transferred from fiber to fiber so that if one fiber fails, the other fibers will maintain the load. Properly made glass fiber

composites will have strengths approaching that of the theoretical strength of glass.[85] The strength properties listed in Table 4 are highly dependent on processing conditions and testing environment. Newly extruded or drawn E glass fibers that have been carefully handled and protected from humidity can have strength as high as 3.5 GN /m^2.[86]

Therefore, in order to take advantage of the fibers that are flawless, the flawless fibers must by isolated from the flawed fibers. Isolating the fibers provides protection from nicking, abrasion and the formation of de novo surface flaws caused by the failure of the flawed fibers. By using resin impregnation of the glass fiber bundles, it is possible to isolate individual fibers from one another and achieve higher tensile and compressive strengths in the glass laminate.

Ultra high molecular weight polyethlyene fibers are manufactured in a manner that is very similar to glass fiber manufacture. Raw chemical precursors are reacted to form polyethylene. The raw polyethylene is then dissolved in an appropriate solvent in a large mixing tank. To form fibers, the solvent/mixing tank has conventional melt spinning equipment attached. The solution in the tank is very viscous. As the material in the tank is drawn out through the spinnerettes the solvent is removed and the product begins to form highly orientated, semi crystalline fibers. X-ray diffraction studies indicate that as the crystalline content and the crystalline orientation improves the properties of the fiber also improve. Fibers produced in this manner from polyethylene are held together by the

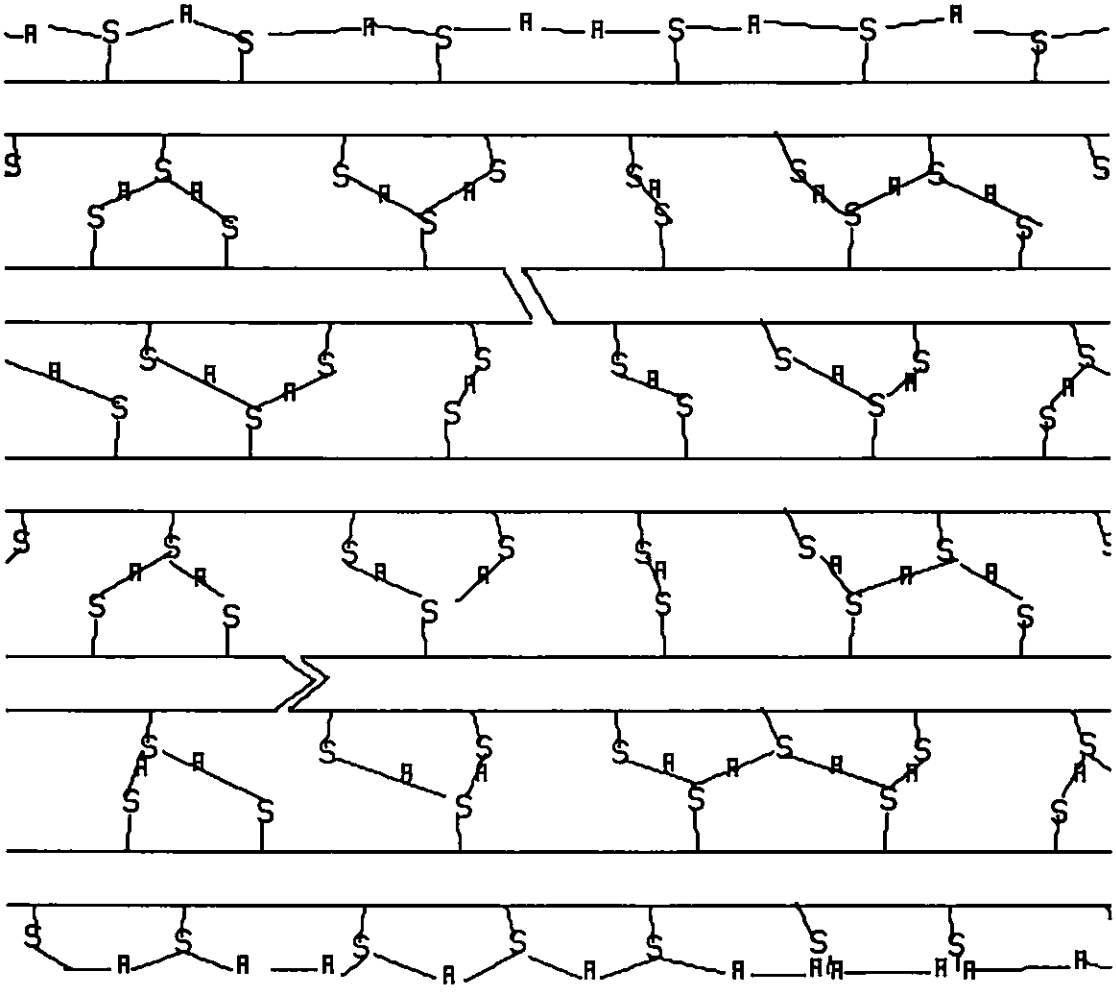


Figure 9. Diagrammatic Glass Laminate

Figure 9 is a diagrammatic representation of a glass laminate and demonstrates the shielding effect of the epoxy. An S represents the silane coupling agent that is ionically bonded to the glass fiber. The solid lines between letters represents a covalent bond. The R's represent a short organic molecule used to facilitate bonding.

electrostatic charges that are a result of the crystalline structure of the material. Because of the high degree of crystallization of the product the surface of the polymer is very inert.[88]

In order to facilitate chemical bonding to the fibers so that resulting composites have better physical properties the surface of the ultra high molecular weight polyethlyene fibers must treated. Treating of the ultra high molecular weight polyethlyene fibers is done by an electrically charged gas plasma. Fibers enter a reaction chamber with a controlled atmosphere. The atmosphere is then charged and free radicals are formed. The free radicals attack the fiber and leave the fiber surface with a reactive functional group. These reactive functional groups are then capable of interacting with a sizing compound or directly interacting with the matrix resin. Plasma treating of the fibers does result in a slight decrease in the actual tensile and flexural properties of the fiber, however, due to a dramatic increase in the binding ability of the matrix to the fiber, plasma treated fiber based composite properties are improved by approximately 20 to 25%. Therefore, treating the fibers with the gas plasma process is highly beneficial to the final product.[87]

When fibers made from ultra high molecular weight polyethlyene fail in a longitudinal direction, the fiber fails in a manner similar to steel in that, the fiber begins to elongate or neck. In this elongated region cracks begin to propagate and the fiber breaks. When the fiber fails in a transverse direction due to excessive bending the fiber begins to kink on the compression side of the fiber and stretch on the tensile side of the

fiber. The combination of these failure modes results in a disruption of the local crystalline structure and thus a permanent offset occurs.

Additionally, ultra high molecular weight polyethlyene fibers have a few beneficial properties that result from them being manufactures from an organic base. Ultra high molecular weight polyethlyene fibers have low water absorption. Ultra high molecular weight polyethlyene fibers absorb less than 1% of their weight when immersed in water. Composites made out of ultra high molecular weight polyethlyene fibers and a hydrophobic matrix can have water absorption values as low as 0.1%. Finally, ultra high molecular weight polyethlyene fibers have a specific gravity of 0.97 making them the only reinforcement that can float in water.

Table 4, on the following page, allows a comparison of the fibers used in the manufacture of a composite laminate, with respect to fiber size, tensile strength and tensile modulus.

Table 4--Mechanical and Physical Properties of High Performance Fibers[88,89,90]

Fiber Type	Fiber Diameter	Tensile Strength	Tensile Modulus
E - Glass	8 - 14 *u* m	3.45 GPa	72.4 GPa
S - Glass	8 - 14 *u* m	4 .58 GPa	86.2 GPa
High Strength Carbon	7.0 *u* m	3.53 GPa	230.0 GPa
High Modulus Carbon	6.5 *u* m	3.10 GPa	405.0 GPa
Ultra-high Mod Carbon	8.4 *u* m	1.86 GPa	572.0 GPa
Silicon Carbide Fiber	10-15 *u* m	2.5-3.0 GPa	180-200 GPa
Extended Chain Polyethylene	27-38 *u* m	2.94 GPa	169.2 GPa
Aramids	13 *u* m	2.75 GPa	124.1 GPa

101, 325 Pascals = 14.969 psi. at 1 atm pressure

Epoxy Resins

Epoxy resins are an amorphous glass like solid that becomes rigid once cured. Theoretically, once the epoxy is cured, the epoxy should be one large continuous and cross linked molecule. However, there is no real evidence for this theory.[91] Studies with electron-microscopy suggest that epoxies are an aggregate of three dimensionally branched networks of moderate molecular weight.[92] The ultimate size that molecules achieve during the curing phase is affected by temperature, monomer size, molecular reactivity and viscosity. Molecular reactivity is defined as the number of functional groups (epoxide rings) per unit of molecular weight.

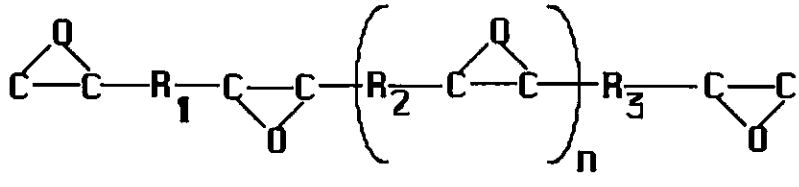


Figure 10. Prototypical Expoy molecule. Carbon atoms are represented by the letter C, oxygen atoms are represented by the letter O, an R represents a short length of carbon or sulfur molecules that bridge the epoxide groups and the parenthesis represent a repeating subunit.

Increasing the temperature of the curing epoxy results in an increase in thermal agitation of functional groups, thus allowing for increased polymerization by sterically hindered catalytic, functional,

groups. As the epoxy polymerizes the rotational and translational freedom of the functional groups is reduced therefore, the chance that a covalent bond is created with an adjacent molecule is reduced as temperature is reduced or viscosity increases.

Viscosity effects the degree of crosslinking in an inverse manner, as the resin's viscosity decreases the degree of polymer crosslinking increases. This is due to the amount of energy that is needed to accomplish proper orientation of the functional groups, which would result in a covalent cross-linking bond being formed. Energy to overcome problems due to high viscosity may be supplied in the form of heat.

Monomer size is related to ultimate molecular size by the number of reactive groups present on the entire monomer molecule. Compressive and tensile strengths of the epoxy improve as the distance between cross-linked molecules is shortened. This results from the shorter cross-linking distances, which implies a higher concentration of epoxide groups and therefore, statistically there is a greater chance that all or a larger percentage of the groups have reacted creating larger and more homogeneous molecule.

Epoxies, as previously described, are very glass-like, brittle, in their inflexibility, relative to most other polymers. This aspect would be detrimental to an orthodontic archwire. Flexibilizers and plasticizers can be added to the epoxies to decrease their brittleness. Flexibility is improved in an epoxy primarily by adding either long chain molecules that remain unreacted after the epoxy has cured or by utilizing a monomer that is long chained with few functional groups. Unreactable long chain

fillers are called plasticizers and long chain monomers are called flexibilizers.

Flexibilizers are of two varieties. The first variety is a monofunctional flexibilizer and the other is a polyfunctional flexibilizer. A monofunctional flexibilizer, as the name implies, has only one functional group. These are usually epoxidized vegetable oils containing 16 - 24 carbon atoms.[93] Because a monofunctional flexibilizer has only one functional group, the molecules tend to act as end-stop molecules and prevent cross-linking. Therefore, due to reduced crosslinking there is more freedom of movement of the aggregated epoxy molecules which results in added flexibility. Polyfunctional flexibilizers are more difficult to use in room temperature curing systems because they must be added in stoichiometric amounts.[94] However, polyfunctional flexibilizers do not weaken the structural integrity of the cured product as significantly as the monofunctional flexibilizers or the plasticizers. This is due to the fact that the polyfunctional flexibilizers do participate in cross-linking of the molecular aggregates. Therefore, because flexibilizers take part in the curing process and add some structural integrity to the final form, flexibilizers are the preferred method of adding flexibility to an epoxy. Finally, flexibilizers and plasticizers decrease internal stress, increase resiliency and toughness and some flexibilizers can be used to control shrinkage. However, flexibilizers and plasticizers decrease tensile strength.[95]

Epoxy Coloring Agents

While epoxies have the good strength and glass-like translucency their natural color is a yellow brown to black. Estheticlally, this a serious problem when this material is considered for use as a matrix for an esthetic arch wire. An esthetic archwire should be defined as being clear of tooth colored. Consequently, coloring agents must be investigated. The clarity of the archwire will be affected by the similarity of index of refraction of the various component parts.[96]

Coloring agents for epoxies fall into two categories that are primarily divided by particle size. The first category are dies which have a particle size under 0.1 micron and can form a solution or a low colloidal suspension. Pigments are coloring agents that have particle sizes above 0.1 micron which cannot form a true solution but instead form a high colloidal suspension. Coloring agents may be added to an epoxy directly and dispersed with the use of a high shear rotary mixer. Excessive loading of the epoxy with coloring agents will effect both depth and degree of cure. Organic dies are frequently the die of choice for coloring epoxies. They require concentration of only 0.5 to 1 percent whereas inorganic dies may require up to 3 percent to achieve adequate coloration.[97] Although, antimony oxide or titanium dioxide are inorganic dies they would be the dies of choice to impart a white color to an epoxy. However toxicological testing would have to be performed on a cured resin containing antimony oxide since antimony, in sufficient concentrations, is toxic.

Opaquing of epoxies is possible using metallic oxides. If a carbon fiber or silicon carbide fiber was used as the continuous reinforcement in

an esthetic archwire opaquing would be necessary due to the fibers natural color, black.

Federal Food and Drug Administration Requirements

The Federal Food and Drug Administration (FDA) has many requirements that govern the manufacture and introduction of a new medical/dental device into the American health care system. Guidelines for this process can be found in the Code of Federal Regulations (CFR) specifically, CFR 21:170-199 and CFR 21:800-1299.[98] These sections give the specific test and demonstration requirements that must be followed prior to distribution of the proposed product.

The first reference to a chemical related to Epon 828 is found in the CFR 21:173.5 entitled 'Subpart A- Polymer Substances and Polymer Adjuvants for Food Treatment.' CFR 21:173.60 specifically discusses the testing of a Dimethylamine-epichlorohydrin copolymer which is closely related to the epoxy that has been proposed for this research. Presently, the intended approved use for this product is a clarifying agent in beverage production, that can be removed by filtration. Acceptable levels of extractables in its current application is 50 parts per million when the product is refluxed for 3 hours in: water, 5% acetic acid, and 50% ethanol. Additional information on the epoxy can be found in CFR 21:177.0 entitled Subpart C-'Substances for Use Only as Components of Articles Intended For Repeated Use', Phenolic resins are addressed specifically in the subsection CFR 21:177.2410. The additional testing requirements specified in this

section are an extraction test using an 8% ethanol extraction and a *n*-heptane, spectrophotometric grade, extraction. In general, the extraction test is performed according to the following guidelines. In a clean 25mm x 200mm cuvet 10mls of solvent per square inch of material to be tested, are placed. After running the extraction for the specified period of time and at the specified temperature. The extraction solution is poured into a weighed platinum dish and evaporated. After evaporation is completed the dish is reweighed and the residue is determined. The weight of the residue is then divided by the surface are of the plastic sample and multiplied by 100 to yield the results in parts per million. The final extraction test is the determination of potassium per-manganate oxidizable extractives. Another extraction test is performed using water and para-methoxyphenol 1.0 ppm. The residue of this test is titrated by potassium per-manganate to determine the amount of oxidizable extractives.

In the section of the CFR entitled Subpart B-'Procedures for Domestic Device Establishments' (CFR 21: 807.20) guidelines for product development and marketing are listed. According to this section all proposed products must be listed with the FDA within 30 days of production. These products shall be listed with the FDA on a FD-2892 (medical listing form). After the FDA has received this form the FDA will classify the proposed device as either Class 1, Class 2, or Class 3. Class 1 is defined as any device that is defined as having sufficient general controls to provide reasonable assurances of safety and effectiveness this device cannot be used as a means of life support. Class 2 has the Class 1

definition with the additional caveat of these devices will eventually have sufficient controls to assure reasonable assurances of safety and effectiveness. Class 3 is any device that subject to the Class 2 classification with the addendum of this device will be an implant into the body or a body cavity and/or this device is used in life support. Clearly, this implies that an esthetic archwire may be considered as a Class 3 device and thus is subject to the most stringent guidelines.

After classification of the proposed device the manufacturer may elect to file a 501K form (pre-market notification) which would be appropriate for esthetic archwires. A 501K form establishes, via the testing described previously and supplementary physical testing, data that the proposed product is essentially equivalent to products that exist on the market. If the FDA accepts this pre-market notification production and distribution of the new product may commence. If the FDA does not concur with the manufactures supposition then a well controlled double blind study must be performed according to the specifications that are delineated in CFR 21: 860.7. After submission of this data if the FDA agrees with the manufacturer upon the devices safety and effectiveness production can commence.

Orthodontic devices are listed in the CFR under section 872:3765 and they are listed as Class 1 devices. However, pit and fissure sealants which are closely related to the epoxies that are to be used in the production of the experimental esthetic wire-forms are listed as a 2 device. Therefore, the status of the proposed esthetic archwire is not clear. Before further

research into product development commences a classification ruling from the FDA would be advisable so that appropriate testing can be undertaken.

In summary, while the resinous component part of the experimental manufactured wires have approval in other uses, they are not approved for intra-oral use in the proposed form. Both the epoxy and the fiber reinforcement must be classified and approved prior to human testing.

Materials and Methods

Phase 1 - Evaluation of Epoxy Set Times

Due to manufacture hesitation in quoting set times and temperatures with the epoxy combinations that were proposed for this investigation, trial epoxy mixes were evaluated. Aluminum weighing boats were fabricated from aluminum foil. Samples of Epon 828® weighing approximately 2 grams were placed into each boat. Catalyst was added according to the ratios listed in Tables 5, 6, and 7. The Epon 828 was preheated in a preheated convection oven equilibrated at 70^{0}C for 2 minutes until a temperature of 40^{0}C was reached. The temperature of the catalyst was evaluated by means of a standard 100^{0}C laboratory thermometer. Catalyst was added to the base and the solutions were mixed thoroughly. Samples were placed in the convection oven to cure.

Table 5--Initial Epoxy Curing Evaluation Ratios
Single Catalyst
(Resin:Catalyst)

Material	Ancamine K61.B	Ancamine 1916	Capcur 380
Epon 828	1:1	1:1	1:1
Epon 828	3:2	3:2	3:2
Epon 828	2:1	2:1	2:1

Table 6--Initial Epoxy Curing Evaluation Ratios

Dual Catalyst Trial 1

(Resin:Catalyst)

Material	Ancamine K61.B & Ancamine 1916	Ancamine K61.B & Capcur 380	Ancamine 1916 & Capcur 380
Epon 828*	1:1:1	1:1:1	1:1:1
Epon 828	2:1:1	2:1:1	2:1:1
Epon 828	3:1:1	3:1:1	3:1:1

Table 7--Initial Epoxy Curing Evaluation Ratios

Dual Catalyst Trial 2

(Resin:Catalyst)

Material	Ancamine K61.B & Ancamine 1916	Ancamine K61.B & Capcur 380	Ancamine 1916 & Capcur 380
Epon 828*	1:1:1	1:1:1	1:1:1
Epon 828	1:2:2	1:2:2	1:2:2
Epon 828	2:3:3	2:3:3	2:3:3

* These runs were duplicated to serve as control groups between the two runs.

State of cure was evaluated every two minutes by bending the aluminum boat. If the epoxy separated from the boat or the film of epoxy fractured, the time of cure was noted and the trial was annotated as successful (P= passing). If at the end of 10 minutes the epoxy was no longer liquid but it had not cured completely the results were recorded as marginal (M=,marginal). If the epoxy had not cured in 10 min the results were recorded as a failure and the experiment was stopped (F=failure). Once approximate set times were established Phase 2 of the fabrication of the composite wire forms was initiated.

Phase 2 - Fabrication of Composite Wire-forms

Dies were fabricated by two separate vendors. The Case Western Reserve University School of Dentistry Machine Shop obtained a 1/4" sweg lock fitting from Crawford Plumbing supply. This fitting was then center drilled with a #75 bit which corresponds to a finished diameter of 0.025." The entrance and exit ends of the die were polished using standard dental gold finishing rubber wheels. The second set of dies were fabricated by Electron Beam Technologies, Inc. Electron Beam Technologies, Inc. center welded a stainless steel tube of 0.020" inside diameter to a copper tube having an outside diameter of 0.125". The first die fabricated had an overall length of 39", and a molding section of 12". This was done in order for the die to be enclosed completely within the heating element. The second die was 2.5" long and a molding section of 6". This was designed so that its placement could be varied within the heating element to vary the reaction conditions. The rovings, fibers, were threaded through the first

die by passing a guide wire through the die and then attaching a fibril. Once the fibril was pulled through the die, additional fibrils were passed through the die by braiding the additional individual fibrils with the main fiber and pulling all the fibers through the die. The die was then placed into the heating chamber and clamped into place. The epoxy bath was positioned in front of the die. Fibers were wetted by painting of the roving with an epoxy covered glass rod. A polished glass rod was used in order to minimize fiber damage during the coating procedure. (Figure 11) As with the previous epoxy cure trials, the Epon 828® was preheated in a convection oven to approximately 40^{0}C. Next 15 grams of Epon 828® was weighed out into a glass petri dish. Catalyst was then weighed out in a 1:1 ratio and the chemicals were mixed thoroughly and then applied to the rovings. The carbon roving was supplied by the Thornel division of Amoco Performance products. (Thornel 6K Carbon, PID 222008, T650/42, Grade 000NT) The Spectra ® Roving was supplied by Allied Signal Inc. (PID Spectra 1000 Plasma Treated 650den) The Glass roving was supplied by Owens Corning Fiberglass Corp. (PID B650E)

The coated rovings were then pulled into the die and cured.(figures 12 and 13) Rovings were pulled through the die at 8" to 13" per minute. The die was 39" long. Speed was varied in response to the gel time and the temperature of the die during the specific run. Die temperature varied from 70^{0}C to 180^{0}C depending upon the fiber used. Samples were pulled until fuzzing was obvious or the roving failed. Fuzzing occurs when



Figure 11. Petri Dish With Epoxy For Roving Coating



Figure 12. Coated Rovings Entering The Heated Die

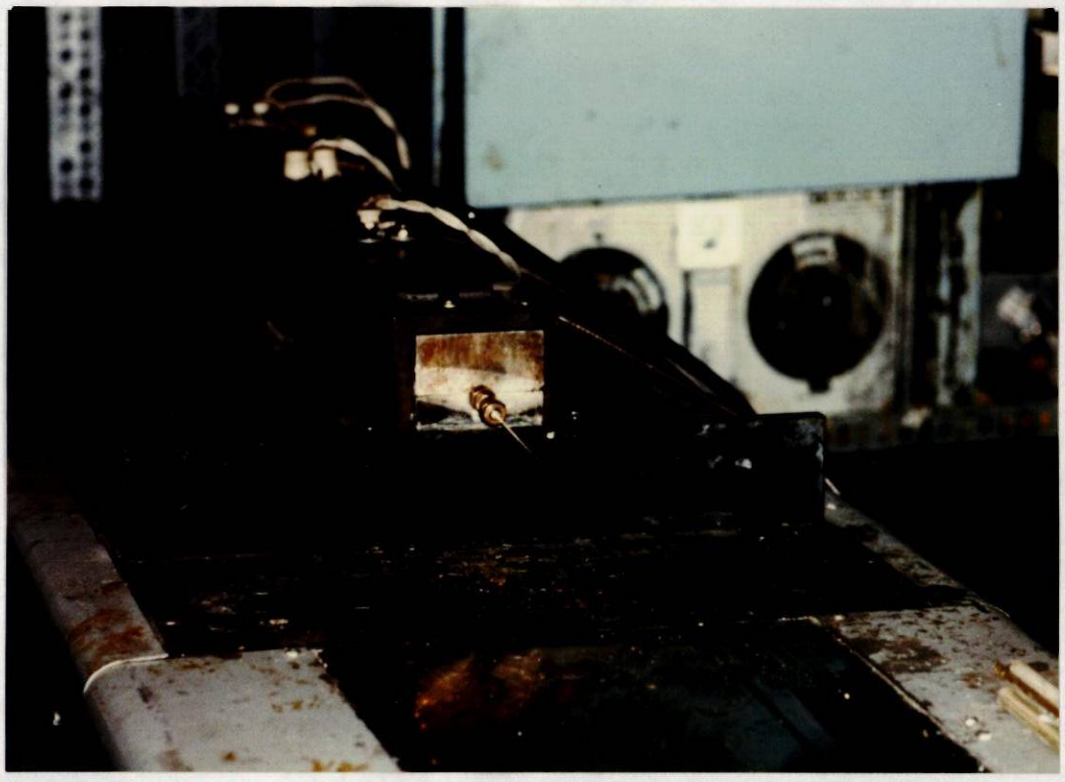


Figure 13. Cured Composite Wire-form Exiting The Die

individual fibers break and begin to collect at the entrance of the die. Fuzzed fibers can damage other passing fibers by nicking and tangling.

The next phase of this experiment was to be the fabrication of polymer resin wires, however, due to mechanical difficulties, this section of the experiment was eliminated. Laboratory fires were accidentally caused on several occasions when the samples of Mindel®, Radel®, Udel® (obtained from Amoco Performance Products, Inc.) were heated.

Wire Testing Methodology

Three runs of each of the testing conditions describer herein were performed upon the materials summarized in Table 11. The tests that were performed were a uniaxial tensile test to material failure and a Three-point-bend Test up to the occurrence of the maximal bend stress or obvious specimen slippage was performed. Values for the tensile modulus of elasticity (Et), the yield strength at the 0.2% offset and the corresponding strain at the 0.2% offset were reported from the tensile data. The values for: the flexural modulus of elasticity (Ef); the yield strength at the 0.2% offset; the corresponding strain at the 0.2% offset; the load corresponding to the 0.2% strain and the deflection corresponding to the 0.2% strain offset were reported with the use of the approximated

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Mindel®, Amoco Performance Products, Inc.
Radel®, Amoco Performance Products, Inc.
Udel®, Amoco Performance Products, Inc.

flexural stress-strain diagrams. Representative stress-strain diagrams for tensile data, approximated flexural stress-strain diagrams for bend test data and load-deflection diagrams which allowed for evaluation of clinically significant parameters for the bend test data are given. No wires were heated and all tests were performed at room temperature, approximately 27^{0}C. The testing protocol used here is modeled after that developed by Dr. Matthew Johnson (CWRU Department of Orthodontics 1990).

Protocol for Tensile Test

The Instron Model 1125 Universal Testing Machine was used for all Trials. A 1000 pound Instron Reversible Load cell was used to detect changes in the load. The load cell was calibrated with standard weights at zero, mid-range and full-scale. The load cell had variable full scale calibration ranges (sensitivity) of 1000, 500, 200, 100, 50, 20 pounds. The full scale calibration range was selected for each material so that the ultimate tensile strength would occur in approximately in the middle or upper third of the graph. This was done so that the sensitivity of the load cell was maximized for each specimen type.

The average error for each of the full scale calibration load ranges used, 200, 100, 50, and 20 pounds, were ± 0.0116 lbs (±5.3g), ± 0.023 lbs (±10.4g), ± 0.028 lbs (±12.7g) and ±0.0129 lbs (±5.9g), respectively. The graph drawn from the chart recorder of the Instron Universal Testing Machine produced during each experiment was used only to assist the

operator in selecting the appropriate load cell full scale calibration range (sensitivity). Actual data collected in determination of the modulus of elasticity (E) and Yield strength (YS) at 0.2% offset was determined from data acquired by means of a Macintosh IIx ® computer and the Analog Connection Quicklog ™ Laboratory and Factory Data Acquisition Program. Data was stored by means of a Macintosh IIx ® Computer. Data worksheets were analyzed by means of the Microsoft ® Excel Program, Mystat ® statistical analysis program, Statview 512 ® statistical analysis program, and Odessa Data Desk®. Data received from the Instron Strain Data Unit was provided to the data acquisition system in terms volts with a range of 0 to 10 volts. This s information was converted mathematically to stress and strain units. Thus 0 lbs corresponded to 0 volts and the full scale load for a given sensitivity setting corresponded to 10 volts. One data point was selected at 0.5 second intervals by the data acquisition system. This rate was chosen because it allowed for ample data points to be collected in the linear region of the graph.

An Instron Extensometer, a light weight gauge, was used to measure the elongation of the specimen. The extensometer had a 10% travel, or a 10% maximum strain (Figure 14). The specimen clips of the extensometer had to be modified to allow the accurate testing of the small diameter wires. The extensometer was designed with large notches to hold the specimen. For these tests, the plastic fittings of the spring loaded specimen holders were rotated 90^0, and a new notch was cut into the plastic fitting, this new notch facilitated specimen clamping.[99] This notch was approximately 0.012".

The extensometer was calibrated before testing of the wires by use of the Instron High Magnitude Fixture Extensometer Calibrator. The extensometer was calibrated and the appropriate strain magnification ratio was selected so that the specimen being evaluated would undergo a tensile failure, break, before the maximum strain range had been exceeded. A strain magnification ratio setting of 400:1 on the Instron Strain Data Unit, or a full scale extension of 0.05" was used for all wire samples. The linear portion of the stress strain graph for all the materials tested was within the 10% or 0.1" elongation range. The extensometer was zeroed after each run to insure accuracy in data acquisition. The average error in recording the elongation for the full scale strain calibrations (sensitivity) used for the 0.05" (strain magnification ratio 400:1) was $\pm 2.9 \times 10^{-5}$ in ($\pm 7.4 \times 10^{-4}$ mm).

The data was received in terms of voltage and was then converted with the following formulae to provide a unit corrected stress strain plot. The ordinate (vertical axis) of the plot or stress, σ, is defined by the following equation,

$$\sigma = (a * U_{\sigma})/A$$

where σ = stress, the converted ordinate data, psi.

a = data acquisition conversion factor, lbs/ volts

U_{σ} = voltage from the meter detecting load, volts

A = cross sectional area of the wire being tested, in^2

The abscissa (horizontal axis) of the stress-strain curve, ε, is given by the following equation.

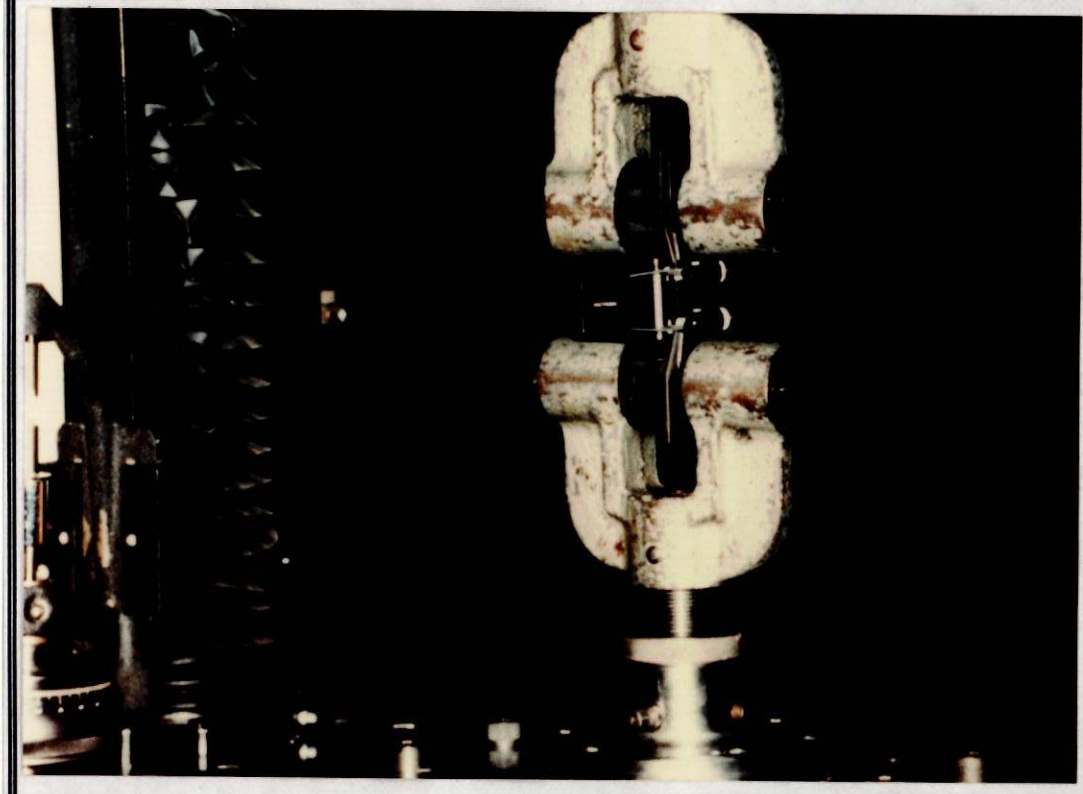


Figure 14. Extensometer Attached To The Instrom

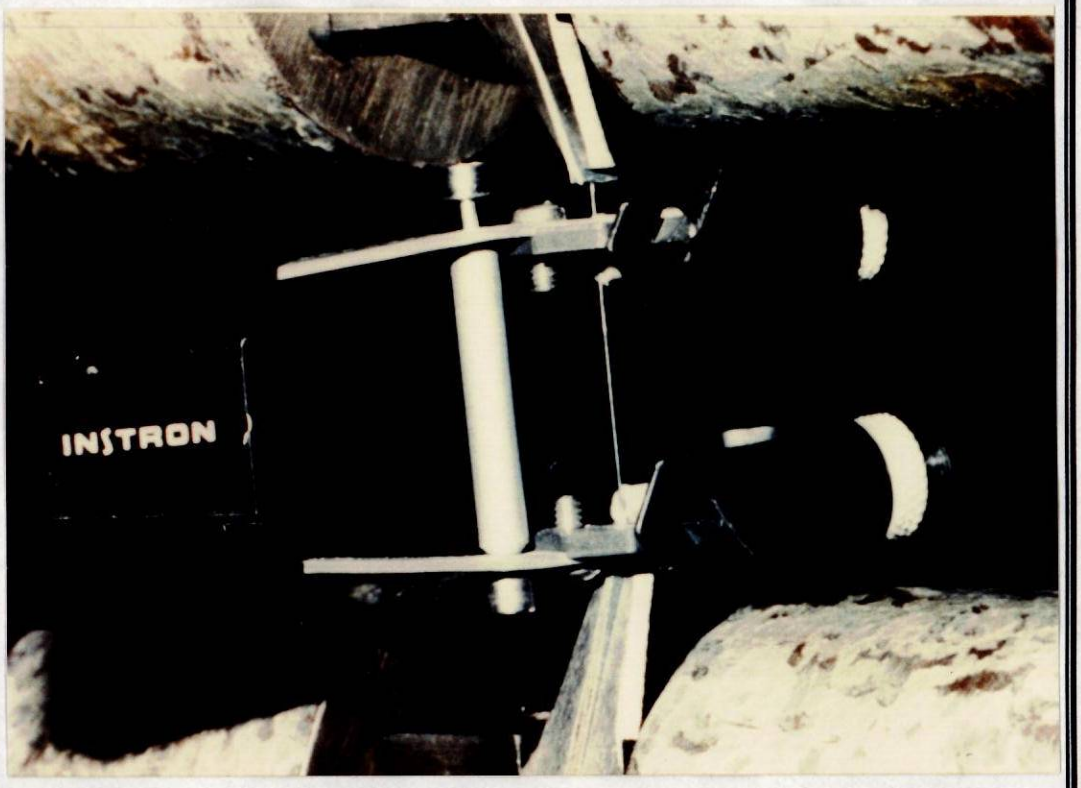


Figure 15. Close Up of Grippers And Extensiometer

$$\varepsilon = \ln (L/L_0)$$

where L= the characteristic gauge length, in

L_0= the original gauge length, in

and,

$$\varepsilon = \ln [(L_0 + U_\varepsilon * b)/L_0]$$

or when simplified,

$$\varepsilon = \ln [1 + (U_\varepsilon * b)/L_0]$$

where ε = strain, the data acquisition conversion factor, in/volt

b = the data acquisition factor, in/lbs

U_ε = voltage from the meter detecting change in length, volts

L_0= the original gauge length, in inches

A pair of Instron 1000 lbs capacity screw action tensile test grips were modified to permit testing of the small diameter wire specimens. (See figure 15) The lower grip as originally received from the plant was attached to the Instron tensile test grip by a loosely fitting pin in a slot. This design allowed slight upward movement of the grip until the pin was engaged. Since the weight of the grip was approximately 10 lbs, when a load developed that exceeded the weight of the lower grip, the lower grip was lifted by the

specimen in tension, until the pin engaged. This produced a "bump" or artifact on the stress strain curve. This artifact made the interpretation of the final results more difficult. To circumvent this problem, the lower grip was modified with a jam nut that would secure the lower grip and not permit any upward movement during the testing runs.

The grip was attached to the load cell by a multidirectional, self-centering (universal) hinge. This clamp insured uniaxial loading of the clamped specimen. Because serrations on the grippers caused wire deformation and or cutting of the specimen during tightening of the grips and while loads were being applied to the specimen, smooth grippers were substituted. Four Instron 2" ^{100} smooth flat grip faces were used to hold the specimen during testing. The grip faces allowed for a maximum of 2 inches of wire specimen to be compressed between each grip. To prevent slippage of the specimen in the grips and to cushion the specimen from being crushed, four sheets of 400 grit wet dry emery paper was cut to match the size of the grip-face. Two pieces of the emery paper were held back to back, in effect acting as double faced emery paper. One face of the emery paper was placed against the grip and the other face was placed against the specimen. Therefore, the specimen was then tightened between the emery paper and the grips on either side. No specimen slippage was observed using this technique of gripping with any of the specimens except with the Sentalloy® preformed arches. Since these wires exhibited more slippage with the emery paper than without the emery paper, the emery paper was eliminated from the gripping technique for these runs. Because the Sentalloy® was relatively soft, there was some compression of the wire upon clamping. However, this compression did not predispose the specimens to have a failure within the grips.

The intergrip distance was set on the Instron to allow 1 3/8" between the grips before the specimen gripping procedure and testing began. The wire, and emery paper when indicated, was tightened in the

upper grip with a torque wrench to 90 to 100 ftlbs (122 to 135 Nm). The upper clamp was pinned into the multi-directional hinge that was attached to the load cell. The load meter was then re-zeroed by means of adjusting the load cell balance control. The load cell balance control was not adjusted again after this point in each test because further adjustments would throw off the zero load and introduce an error into the data. The lower grip was then installed in the bottom grip housing of the Instron machine test from and the jam-nut was secured. The wire, and emery paper when indicated, was tightened in the lower grip with a torque wrench to 90 to 100 ftlbs (122 to 135 Nm).

Great care was taken not to introduce any tension or any compression on the wire while tightening the lower grip. Slight slack or compression was taken out of the system by using the manual crosshead control at this time. The load meter was observed while doing this so no load was added to the specimen. The extensometer was then carefully placed on the specimen and the specimen was checked again for loading or slacking, if either were evident the manual crosshead adjustment was used to correct the situation. The data acquisition system was initiated via the computer just before starting the crosshead on the Instron into motion. Data was collected and stored both on the computers' hard disk and Sony Floppy disks.[101]

Frequently the wires failed partially and resembled a frayed piece of yarn. When this failure occurred there was no distinct point where the failure occurred. Wires, which failed completely, failed at the place where the wire entered the specimen grip, or occasionally, somewhere within the

gauge length. Failures at the edge of the grip would be expected due to the stress concentrations in this area arising from a dramatic change in area between the wire and the grip face. Because the primary interest of the study was with elastic and initial permanent deformation regions of the wire, the variable location of the wire failure was not of major concern since determination of the ultimate tensile strength was considered to be less important in normal clinical applications. However, ultimate yield strength data did appear to be regular.

The gauge length was slightly less than the initial distance between the grips, due to the restricted size of available straight lengths of some of the specimen taken from preformed arch wires. The extensometer, when placed on the wire specimen, was always centrally positioned between the tensile test grips, so the extensometer would consistently measure the strain near the center of the specimen. Strain may vary at different locations on a specimen.

One of the metal-alloy specimens tested was only available in preformed arch wires. The preformed arches had an approximate straight section of arch wire of 1 and 7/8" at each end (Sentalloys®). The maximum distance that the grips could be apart at the beginning of the tensile test was 1 and 3/8", and still allow for 1/4" of wire for gripping in each grip. Since only a 1" extensometer was available for use, at least 1and1/4" of wire was necessary to provide attachment of the extensometer on the wire extending between the upper and lower grip. The rectangular, 1" x 2", Instron flat type grip faces were used, however the corners had to be ground off at 45° angle to allow room for the extensometer specimen clips

to fit on the wire and not touch any part of the grips or clamps (see Figure 16). The maximal amount of specimen was clamped between the grips when possible.

A cross-head speed of 1 mm/min was selected and a data sampling at 1 second intervals provided for a sufficient amount of data points for analysis. This range is similar to that previously used by Howe et al.,1968[102]; and Asgharnia, 1983.[103] The elongation rate of the specimen would be, 0.039 in/60 sec., and a strain rate of, 6.5x103 mm/mm/sec, for a 1" gauge length assuming specimen elongation rate at the gauge length of 1mm/min (0.03g in/min) was the set cross-head speed. Dieter, 1976 considered this to be a medium strain rate for a tensile tests.[104]

The tensile modulus of elasticity was determine by means of verifying the initial linear portion of the stress-strain plots by linear regression. Linear regressions were run on Data Desk Professional® statistical analysis software. Once the raw data from the data acquisition system had been converted to stress-strain units, a plot was made using a Macintosh II computer with the Data Desk Professional®.[105] The stress-strain diagram was plotted and the initial linear portion of the curve was determined. The portion of the curve selected to represent the initial linear portion was tested for linearity by means of selecting upper and lower limits of this linear portion and examining the data points via linear regression. This was done to satisfy the statistical requirement that the adjusted coefficient of determination, the adjusted R^2 was equal to or greater than 99.6% (values tended toward 100%). The computer assisted in location of the initial linear portion as any part of the original data

curve could be magnified by the Data Desk Professional® graphical software.

The tensile modulus of elasticity is define as the slope of the linear regression line. Once this line was determined to be sufficiently linear, it was extrapolated (drawn) to its intercept with the horizontal (strain) axis. This intercept was considered to be the new (actual) origin. A new axis scale was superimposed over the old scale so that the new origin would be at this point. This procedure was necessary due to artifacts that produced a small curvilinear line at the beginning of the test due to specimen slack or slack in the gripping apparatus. Theoretically, the initial linear portion of the curve should originate at the origin.

The tensile yield strength at the 0.2% offset was found by extending a line parallel to the initial linear section starting on the horizontal (strain) axis at a strain of 0.002 in(in/in) and extending to where it intersected with the original data curve. The reading from the vertical (stress) axis at this point of intersection gave the yield strength at the 0.2% offset. The reading from the horizontal (strain) axis gave the corresponding strain at the yield strength at the 0.2% offset. For each group of wires the value for the modulus of elasticity (E) and the yield strength at the 0.2% offset and the corresponding strain at the 0.2% offset were recorded. The average and standard deviation were determined for each of these values for each test condition. The actual location of the elastic limit was not attempted in this study by these graphical means. In order to determine the exact elastic incremental loading-unloading tests[106] procedures must be done and that was beyond the scope of this protocol.

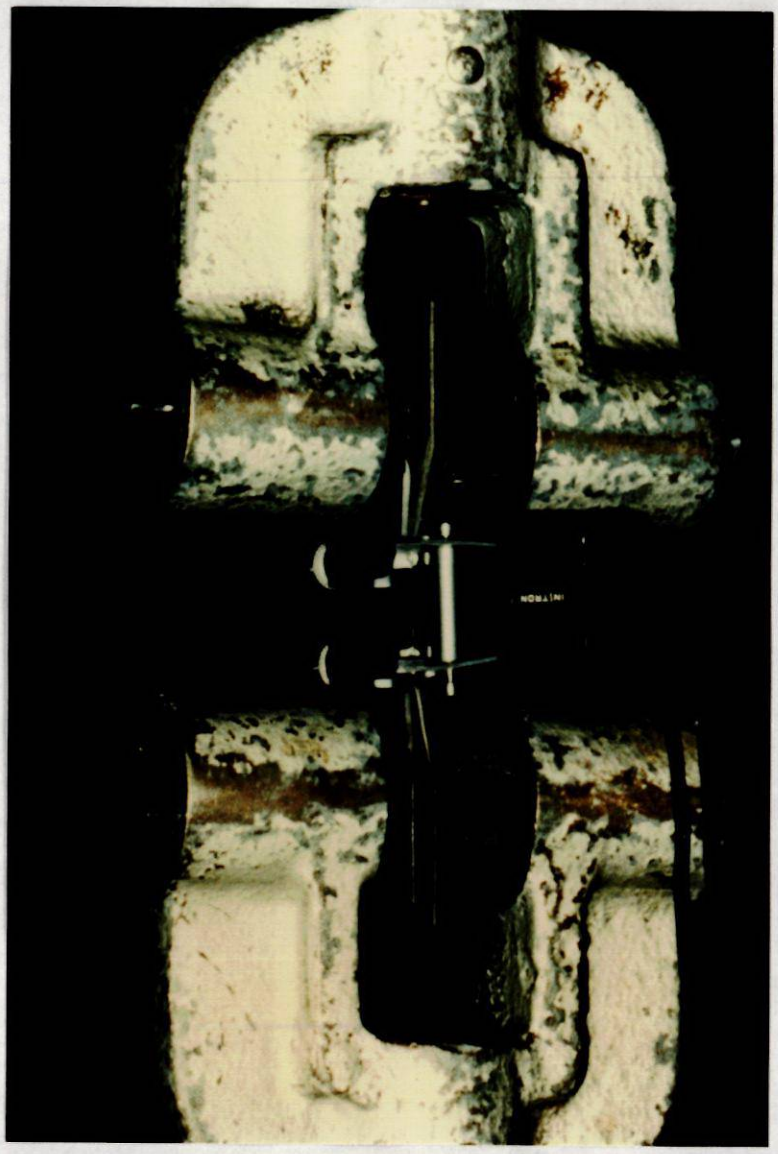


Figure 16. Close Up of Extensometer Attached To The Instrom

Protocol for the Three Point Bend Test

In addition to presenting bend test data in load-deflection diagram form, the results from the bend test were expressed in approximated flexural stress-strain diagram form. This allowed a more direct comparison with tensile test data and, as discussed earlier, it is more convenient for the wire designer to use stress-strain diagrams since there is only one curve per material and he is free to plug in parameters such as wire size and shape during new wire design. On the other hand, when selecting wires for clinical use, the clinician has wires in a limited number of sizes and shapes to choose from, it is more convenient for him to look at a load-deflection diagram of a particular wire to determine if it will respond appropriately for his intended use.

The load-deflection diagrams can be directly plotted from data taken from the three-point-bend test. The load is recorded from the load cell and the deflection is converted directly from the movement of the crosshead. Load-deflection diagrams were plotted where the abscissa (horizontal axis) was the deflection, in (mm) and the ordinate (vertical axis) was load, Lbf. The stress-strain diagrams were plotted where the abscissa was the stress, Lbf/sq in (psi) and the ordinate was given as the engineering strain, in/in .

In order to plot a load-deflection diagram, the changes in voltage provided by the load cell were converted to give load and the rate of movement of the crosshead was converted to give the deflection by using the following equations. The load, P, is given by,

$$P = c * U_p$$

where P=load, the converted ordinate data, Lbf (N)

c=data acquisition conversion factor, Lbf/volts (N/volts)

V_p= voltage from the meter detecting load, volts

and deflection, d, is given by

$$d=(t*Ch)/(60 \text{ seconds/min})$$

where d=deflection, the converted abscissa data, in (m)

t=elapsed time, seconds

Ch=rate of the crosshead movement, 1mm/min (0.0394 in/min)

In order to manipulate raw data from the three-point-bend test in to a form that could be used to plot an approximated flexural stress-strain diagram, the following standard definition that applies to the initial linear portion of the stress-strain curve will be used,

$$E=\sigma/\varepsilon$$

Where E=modulus of elasticity, psi (N/m^2)

σ=stress, psi (N/m^2)

ε=strain, in/in (mm/mm)

With this relationship, the following is true for a three-point-bend test if the conditions of linear elastic deformation and idea three-point-bending geometry are maintained. The flexural modulus of elasticity is given by the equation (Van Krevelen, 1976)[107] for the conditions of a three-point-bend test:

$$Ef=4*P*L^3/3*\pi*D^4*y$$

where Ef=the flexural modulus of elasticity, psi (N/m^2),

P=load applied to the wire, Lbf (N)

L=span length, the distance between the supports, in (mm)

D=diameter of wire, in (mm)

y=maximum wire deflection (center of the span length), in (mm)

or for convenience:

$$E_f=(4*L^3/3*\pi*D^4)*S$$

where S=slope of initial linear portion of the load-deflection curve, $\Delta P/\Delta y$, Lbf/in (N/m), and since $E_t=\sigma/\varepsilon$ and by substitution :

$$\sigma=8*P*L/p*D^3$$

and:

$$\varepsilon=6*D*y/L^2$$

The above equations are specifically for the case of round wires, rectangular wires have different equations.

The equations for stress, σ, and strain, ε, apply where the deflection, y, is maximal at the center of the test span, where load, P, is placed by the crosshead. Data from the three-point-bend test can be plugged into the above equations for stress, σ, and strain, ε, to construct an approximated flexural stress-strain diagram. Although the above equations are valid for the initial linear portion of the curve, some error will be accepted as the equation is applied through curvilinear portions of the curve to define a curve up to at least were the 0.2% offset yield point occurs. While some errors will occur in the curvilinear portions of the constructed three-point-bend test stress-strain curve, it will render a useful approximation to the very accurate tensile stress-strain curve. Since the above equations relate specifically to the initial linear part of the curve, and because the equation will be applied to some curvilinear portions of load-deflection data during the construction of flexural stress-

stress diagrams, these plots are called approximated flexural stress-strain diagrams.

Since stress-strain diagrams are presented for tensile and bending data, this allows for further comparison of characteristics using two different test techniques. The units of strain used on the tensile stress-strain diagram are presented in natural log units (in/in) or true stain. The units used in the bending (flexural) stress-strain diagram were given in in/in or the engineering strain. The stress is measured from the formulae in the two different methods. These two definitions of strain are approximately equal up to values of strain of 0.1 in/in, but after that they become progressively more unequal. Therefore, comparisons of information made between plots which use different definitions of strain should be accurate, if the data of interest does not exceed a strain of 0.1 in/in.

The bend test data originated from the origin, generally in a linear manner. Occasionally, the first few points of the bend test data were not included in the determination initial linear portion of the data plot if it was obvious they were not linear. The origin point and strain ,horizontal, scale, therefore, did not have to be adjusted for bend test data as it was with the tensile data. In the case of the bend test, since the data started at the true origin, as opposed to the tensile test that had to have the origin adjusted, the interval of the data plot that represented the initial linear portion was defined by selecting a data point to represent the upper limit of the initial linear portion that is defined as a linear segment. This segment had to meet the criterion of the minimal acceptable value for the

adjusted coefficient of determination which was the adjusted R^2 greater than or equal to 99.6%. The adjusted R^2 is the confidence interval that describes the line plotted by the linear regression. The slope of this line was later included into bend test equations that provided values for the flexural modulus of elasticity. The yield strength at the 0.2% offset and the associate strain at the 0.2% offset were established by simply drawing a parallel to the initial linear portion of the original curve at a strain of 0.002in/in (mm/mm) which equals 0.2% strain to a point were it intersected the curvilinear portion of the original data plot. Using the equation, $E=\sigma/\varepsilon$, for the flexural modulus of elasticity and understanding the potential errors in using this equations outside of the initial linear portion of the curve, back-calculations were done to approximate load and deflection on the load-deflection diagrams that would correspond to the yield strength at 0.2% offset and the associated strain on the approximated flexural stress-strain diagram. These values, the load and corresponding deflection (that is the load and deflection that corresponds to the 0.2% strain offset from the approximated flexural stress-strain diagram) represented a standardized technique for defining a clinical reference point between elastic and plastic deformation on the load-deflection diagrams.

Three wire specimens trials were run for each test condition. An Instron Model 1125 Universal Testing Machine[108] was used for all trials. The data acquisition system was the same as for the tensile test. A 2000 gram Instron Compression Load Cell[109] (See Figure 17) with full scale calibration (sensitivity) ranges of 2000, 1000, 500, 200, 100 grams was

used to detect changes in load. A full scale calibration range was selected for each specimen type so that the resulting curve would have its maximal flexural strength in the middle or upper third of the Instron chart recorder in order to maximized the sensitivity of the load cell for each specimen type. The load cell was calibrated with standard weights at zero, mid-range, and full-scale. The average error over the load range of each of the full scale calibration range used, 1000, 500, 200, and 100 g, were ± 2 g (± 0.0044 lbs), ±1 g (± 0.0022 lbs), ± 0.2 g (± 0.0004 lbs), ± 0.4 g (± 0.0009 lbs), respectively. As actual graphical interpretation of data was used from data plotted from the data acquisition system, the Instron chart recorder graph was only used so the operator could view the progression of each test and select the proper load cell sensitivity on trial runs prior to the actual recorded specimen runs. The data acquisition system sampled one data point every 1 second. A custom made three-point-bend fixture was designed to accommodate the small specimen size and small test span lengths. Since considerations had to be given to the selection of a appropriate span length do to the geometric conditions of pure bend test, the test fixture had adjustable specimen supports that allowed for appropriate span lengths for all test conditions. Test span lengths can influence the accuracy of data if it is too short in relation to the amount of deflection that will occur in the elastic range of the wire being tested. As the test span becomes shorter in relation to the amount of deflection in the elastic range, the likelihood of torsional, shear, and other none pure bending influences tends to increase. The critical question that immediately arises is at what point do these influences cause a

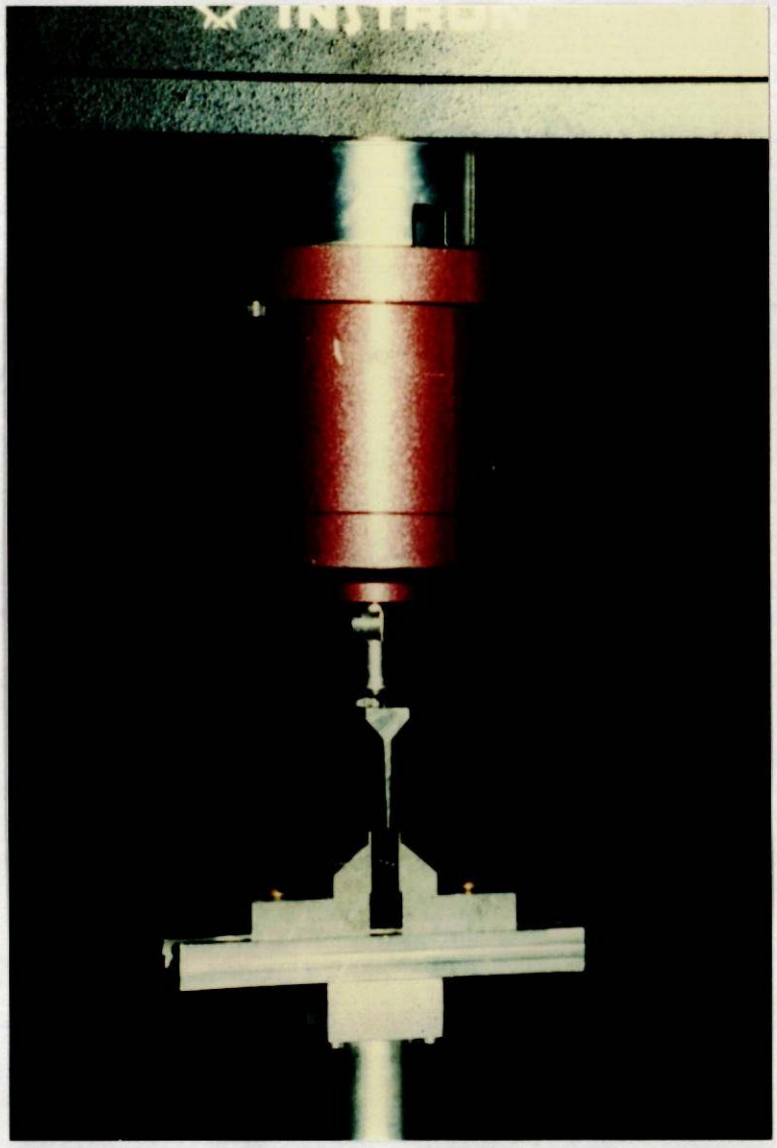


Figure 17. Load Cell And Three Point Bend Test Apparatus

significant deviation to pure bending mechanics for a given situation. The answer to this question is that the investigator must choose test parameters that provide data that is within a desired level of accuracy.

When choosing a span length for test purposes, it is necessary to take into consideration the initial assumptions made in the development of elastic bending theory so that the span is not too short as to violate assumptions made and introduce intolerable errors. It is assumed that during the bend test the change in length of the specimen, dy, will be much less than the amount of deflection, dx, or

$$dy/dx \ll 1$$

this implies for the bending angle (θ) that,

$$\tan\theta = dy/dx \sim \theta$$

When θ is measured in radians

So, with the assumption that $dy/dx = \theta$ (Byers and Synder, 1969), the derivation of the modulus of elasticity in bending equation continues. With the above assumptions it is seen that with a small bending angle, θ , $\leq 10°$ an error of only 1% will occur, with a bending angle, θ, of 20° an error of 4% will occur, and with a bending angle, $\theta_{,,}$ of 30° an error of 9% will occur, if it is assumed that $dy/dx \cong \theta$. This discussion demonstrates why the pure bending theory stipulates that the specimen be of a long length with respect to the deflection and that only deflections less than 10° occur prior to reaching the proportional limit in the bend test. Kusy and Dilley (1984) found by maintaining a test span that was 20 times the length of deflection, and for deflections of their wire specimens were between 0.04 and 0.13 cm (purposely kept with in the linear elastic range

for each particular wire tested), the maximum wire increase in length in this range was less than 0.2%.

Data from preliminary trial runs demonstrated that deflections up to the 0.2% yield strength offset rarely exceeded 0.05" (1.27 mm) when tested at a support span length of 1.0" (25.4 mm). In the light of this information and the clinical relevance of a small test span, a test span of 1.0" (25.4 mm) was selected to test all specimens. The specimens were tested at a 1" (25.4 mm) span length so the specimens would undergo the full range of elastic bending without exceeding the load limit of the 2000 g load cell. As the test span was increased, the load required to cause a given deflection decreased. Exceeding the load limit, would also damage the load cell. The small test support span was also necessary because the highly flexible wires might bow between the supports if the supports were too far apart.

Wires were cut into to 1.75" sections for the three-point-bend test at a support span length of 1.0". This length was chosen since it allowed a little extra wire for ease of placement on the test fixture, but was not excessively long because this may introduce deformations of the portion of the between the test supports, because of the excessive length.

The preformed Sentalloy® arch wires did not appear to have perfectly straight lengths when cut into the 1.75" test length. However, as consistent with bend test theory, wires that are not perfectly straight can be tolerated to a certain extent. If the wire is slightly curved, the depth of curvature must be less than 1/10th of the test span length to maintain the desired level of accuracy. Arch wires that were delivered in

preformed arch wire shape had 1 3/4" specimen length taken from the straightest portion of the wire, usually at the ends.

The crosshead was aligned so that it was dead center (within ± 0.010" of dead center) between the two test supports. Specimens were laid across the two supports so it would also be centered (± 0.025" of dead center) on each support. The crosshead was moved downward with the manual control knob until it was about 0.005" to 0.010" away from the specimen (see Figure 18). The data acquisition system was started just prior to starting the crosshead motion. A crosshead speed of 1 mm/min (0.0394 in/min) was selected since this was the same crosshead speed that was used for the tensile test. When combined with a data point selection of 1 point/second, the data acquisition system, gave an ample number of points to draw a significantly linear line through linear regions on the final data plots. The crosshead was stopped and the test completed for each specimen when the maximal flexure strength had been obtained or obvious wire slippage occurred.

The contribution of the dead weight of the wire specimen across the test span can potentially result in wire deflection that could contribute to errors in calculation of the flexural modulus of elasticity. Kusy and Dilley (1984) studied the influence of the dead weight deflections of wire during a three-point-bend test and found that as a load of 1 N (0.225 Lbf) was placed, the dead weight deflection was only 0.05% of the total wire deflection. Since the dead weight deflection does not vary with load, the dead weight deflection becomes more significant at low loads. At a load of 0.01 N (0.00225 Lbf), the dead weight deflection was 5% of the total wire

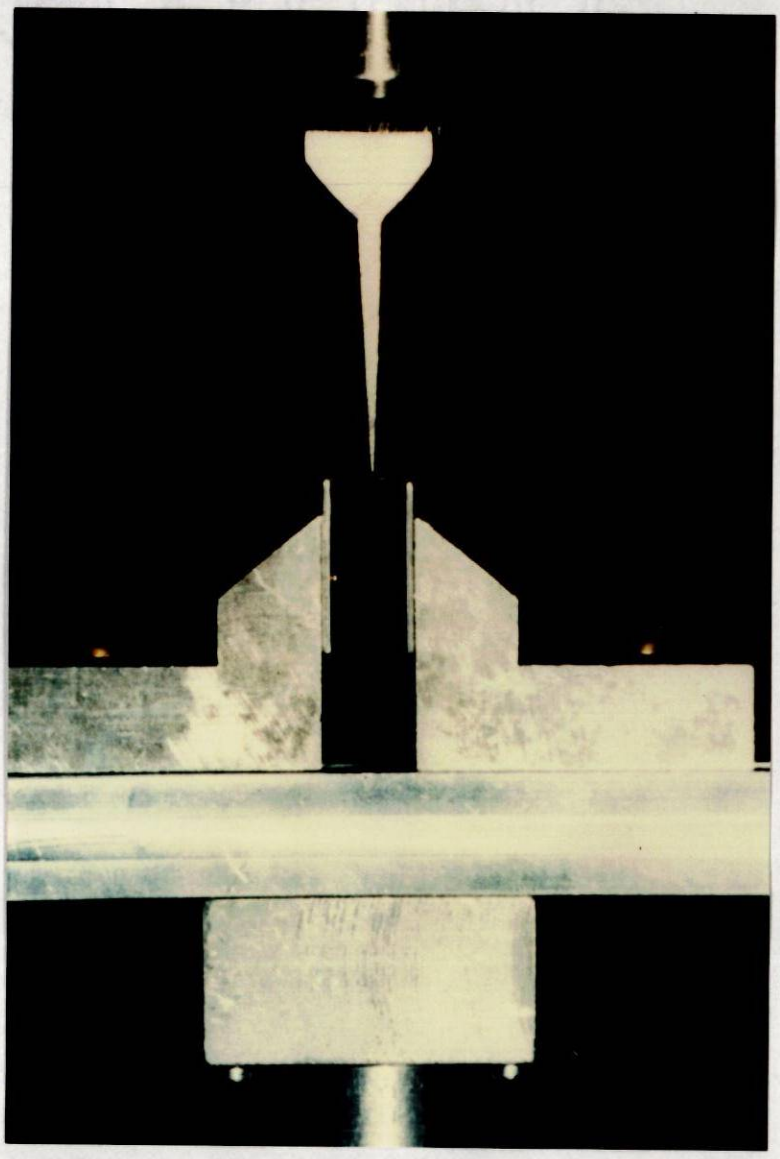


Figure 18. Close Up Of Crosshead Alignment And Specimen Placement

deflection. The load ranges encountered by the specimens tested here at the 0.2% yield strength ranged from 12.0 N (2.7 Lbf) to 0.05 N (0.012 Lbf) so the dead weight effect of the wire was considered negligible.

The machine error occurring during the three-point-bend test, that is the deflection caused by the load cell itself and other parts of the machine during testing was determined by placing a stainless steel specimen of a very large diameter 0.8764" (22.26 mm) on the test supports that would undergo no deflection when loaded throughout the full range of loads used during actual specimen testing. Great care was taken to stop the crosshead movement as soon as the full scale calibration load had been met since damage to the load cell could occur if the 2000 grams maximum limit was exceeded.

Three trials for the machine deflection were done, and average slope of the resulting load-deflection curves (the load-deflection data for the machine deflection were linear through out the entire range of loads used during all of the specimen tests) were compared to the average slope of the initial linear portions of the actual specimen load-deflection curves to see if the machine deflection was a comparatively vertical line. The three-point-bend test data of the test condition (the particular type of wire specimen) with the smallest average initial linear load-deflection slope was 0.94 ± 0.01 Lbf/in (164.6 ± 1.8 N/m) and that of the largest average initial linear load-deflection slope was 52.49 ± 0.58 Lbf/in (9,191 ± 101 N/m). The load-deflection slope of the stainless steel specimen was 1658.24 ± 7.10 Lbf/in (290,387 ± 1,244 N/m). In terms of percentages, the test conditions with the smallest and largest initial linear load-deflection

slopes were 0.06% and 3% of the linear load-deflection of the machine deflection, respectively. Since the load-deflection slope of the machine deflection was so much greater than that of the range of test conditions, it was considered to be relatively vertical and thus considered to contribute negligibly to the slopes of the test conditions and was not factored-out in subsequent calculations.

Statistical Methods of Stress and Strain Evaluation

For each test condition, the three replications were averaged and a mean was presented with the accompanying standard deviation for the group for each of the reported values of both the tensile and flexural modulus of elasticity, the yield strength at a 0.2% offset, the corresponding strain at the 0.2% offset. The portion of the curve selected to represent the initial linear portion of the curve in the tensile test was tested for linearity by means of selecting upper and lower limits of this linear portion so a linear regression of the points in this line could be done to satisfy that the adjusted coefficient of determination, the adjusted R^2, was equal to or greater than 99.6%, with values tending toward 100%, indicated that variation is explained by the linear regression model. The slope of this line then was taken as the tensile modulus of elasticity. Similarly, with the bend test data a linear portion of the stress-strain data was selected and the interval adjusted until the condition of an adjusted coefficient of determination, the adjusted R^2, was equal to or greater than 99.6%. In the case of the bend test, since the data generally started

at the true origin, as opposed to the tensile test that had to have the origin adjusted, usually only the upper limit of the initial linear portion had to be varied to meet the criterion of the minimal acceptable value for the adjusted coefficient of determination. Occasionally, the first few points of the bend test data were not included in the determination of the initial linear portion of the data plot if it was obvious they were not linear.

The average error in the loads detected in each full scale calibration range of the load cells were established by averaging the difference between actual weight of the calibration weights used and the experimental weight of each of the three calibration weights read off of the data acquisition load meter after calibration was complete and after this voltage data was converted to Lbf. Three different calibration weights were weighed and recorded that represented zero, mid-range, and full scale. Three replications of each weight were repeated and reported. The average of all these replications was the average error for determining the load at a given full scale calibration (sensitivity).

The average error for each full scale (sensitivity) strain was done similar to the average error for the load cell calibration except the measure of strain gauge movement (inches) replaced the measurement of weight. The difference between the actual length as given by the extensometer calibrator scale and the unit converted value for experimental length as read from the data acquisition strain meter was determined for each of three replications at each of three different lengths representing the zero, mid-range , and full scale lengths. These differences were averaged and this gave the average error in the

reported value of elongation that was used in further calculation to determine the true stain.

Wire Manufacturing Variation Analysis

Wire-forms were collected from each pultrusion run and each wire was measured and divided into segments approximately 14" long. These wire segments were marked at 1" away from the ends and at their midpoint. Wire diameters were measured 1" away from the ends of the wire to avoid an erroneous diameter measurement due to fraying of the composite strand when the wire-form was being cut into the segmented lengths. Measurements were made with a traveling stage light micrometer[110] that had been calibrated with a reticule accurate to ±0.0001".[111]

The measurements were analyzed by Data Desk Professional® to determine the wires average diameter, and the standard deviation of the mean diameter. Results of these analyses were then forwarded to Cricket Graph 1.3® and histograms of the wire diameters were presented in 0.010 increments. The range on individual graphs varied depending upon the data collected. Utilizing Stat View 512+®[112] a two tailed *t*-test was done to determine if the differences between the pultruded wires diameter and the inside diameter of the pultrusion die were significant. The minimum level of confidence for all two tailed *t*-tests was set at $p < 0.05$. The null hypothesis was H_θ = there is no significant difference between the diameter of the die and the final diameter size of the wire. The

hypothesis was H = there is a significant difference between the diameter of the die and the final diameter size of the wire. The degrees of freedom ranged from 3 to 13 depending upon the number of wire samples that were collected in each pultrusion run. The final comparison of the diameters was done by calculating a weighted average of the glass wires and carbon wires to create a sample population mean. This population mean was compared to the individual wire means using Stat View 512+'s two tailed *t*-test. All results are presented in tabular form in the result section of this work. Tables 17 summarize the results.

Additional two tailed *t*-tests were done to compare the significance between the variation of the wires: tensile modulus, tensile yield strength at the 0.2% offset, flexural modulus, flexural yield strength at the 0.2% offset, the flexural strain at the 0.2% offset, and the flexural load at the 0.2% offset. The null hypothesis, H_0, for all tests was; no significant difference between the non-esthetic standard wire and the esthetic wires being tested. Two degrees of freedom were used. Finally, results from these tests are presented in tabular form in the results section of this work. (Tables 18 - 24)

Results

Epoxy Curing Evaluation

Manufacture of the esthetic wire was relatively uneventful once the epoxy ratios were found. Epoxy testing revealed that a 1:1 ratio between the base resin and the catalyst was the minimum amount of catalyst that could be used to achieve an adequate rate and depth of cure. Results of the epoxy base and catalyst trials can be found in tables 15, 16, and 17.

Table 8--Initial Epoxy Curing Evaluation Ratios Single Catalyst (Resin:Catalyst)

Material	Ancamine K61.B	Ancamine 1916	Capcur 380
Epon 828	1:1 M	1:1 P	1:1 M
Epon 828	3:2 F	3:2 M	3:2 F
Epon 828	2:1 F	2:1 F	2:1 F

P = a complete cure

M= a marginal cure

F= not cured

Table 9--Initial Epoxy Curing Evaluation Ratios Dual Catalyst-Trial 1
(Resin:Catalyst)

Material	Ancamine K61.B & Ancamine 1916	Ancamine K61.B & Capcur 380	Ancamine 1916 & Capcur 380
Epon 828	1:1:1 M-	1:1:1 F	1:1:1 F
Epon 828	2:1:1 F	2:1:1 F	2:1:1 F
Epon 828	3:1:1 F	3:1:1 F	3:1:1 F

Table 10--Initial Epoxy Curing Evaluation Ratios Dual Catalyst-Trial 2
(Resin:Catalyst)

Material	Ancamine K61.B & Ancamine 1916	Ancamine K61.B & Capcur 380	Ancamine 1916 & Capcur 380
Epon 828	1:1:1 M	1:1:1 F	1:1:1 F
Epon 828	1:2:2 F	1:2:2 F	1:2:2 F
Epon 828	2:3:3 F	2:3:3 F	2:3:3 F

P = a complete cure

M= a marginal cure

F= not cured

Wire Analysis

Ancamine 1916 ® manufactured by Pacific Anchor Corporation was the catalyst that performed best under the conditions outlined previously. Nevertheless, an attempt was made to manufacture wires out of the other base resin and catalyst combinations, that were tested in the epoxy evaluation phase of this endeavor. This was done, due to the fact, that marginal results were obtained by the other two catalysts. It was felt that the results warranted at least one try with each of the filaments, that were used in this project.

Wire tensile testing was also uneventful with two exceptions. The first of which was during tensile testing all the experimental manufactured glass reinforced composite wires failed before reaching a 0.2% offset, making collection of data for calculation of the strain at the 0.2% offset impossible. The breaking strength for these wires were included in the tables. The data in the tables was annotated as to the fact that these wires failing in a brittle fashion before reaching the desired offset. Additionally, one of the carbon reinforced wires and the procured braided glass wire failed before reaching the 0.2% offset. The second problem that was encountered during the tensile testing involved the testing of the Sentalloy wire. The wire tended to slip when the sandpaper sandwich was used in the grippers. Therefore it was not used and data collection proceeded uneventfully.

The three point bend test, that was used to determine the flexural modulus of elasticity, proceeded as described in the material and methods except for the braided glass composite by Composetec Inc. The braided

wire slumped vertically more than 10% of its length making the flexural data unreliable. Furthermore, because the load deflection data was calculated from the flexural test data, results were not valid and therefore not presented. Finally, several of the glass and carbon reinforced wires failed during the bend test, however, their failures occurred outside the 0.2% offset therefore the failures did not cause a problem in collecting or interpreting the data.

Tables 11 - 24 list the mechanical testing data in tabular form. Tables 18 - 24 list the pertinent results of the significance testing from the reported data in Tables 1 -7. The general null hypothesis, that was tested by students *t*-test, was H_0= there was no significant variation of the newly manufactured esthetic wire's properties when compared to the non-esthetic standard wire's properties.

Experimental wires were manufactured out of Epon 828 and Ancamine 1916, Ancamine K61.B, and Capcur 380. A manufacturing run was discontinued when either the epoxy had gelled past the point of usefulness or the wire had undergone a tensile failure during manufacture. Sample wires for mechanical testing were collected from the pultruded composite randomly to minimize testing bias.

Table 11 is a compilation of tensile moduli of both the standard wires and the proposed esthetic wires. The glass reinforced esthetic wires that were made from Epon 828 and Ancamine K61.B, and Epon 828 and Capcur 380 were not tested due to an incomplete cure of the epoxies during the pultrusion process. The carbon reinforced laminate formulated utilizing Ancamine K61.B had the highest tensile modulus approximately

21.7 million. The Spectra 1000 composite wire had the lowest tensile modulus. Table 18 is a comparison of the Tensile moduli of the standard wires to the proposed esthetic wires. Significance testing was done using Student's t-Test.

Table 12 is a comparison the various wires tensile yield strength at the 0.2% offset. Table 19 summarize the results of significance testing by comparing the yield strength of the esthetic wires to the standard wires. The glass reinforced esthetic wires that were made from Epon 828 and Ancamine K61.B, and Epon 828 and Capcur 380 were not tested, due to the epoxies not completely curing during the pultrusion process. The glass reinforced wires universally failed before reaching the 0.2% offset. Additionally, one of the Carbon reinforced wires compounded with Epon 828 and Ancamine K61.B also failed before reaching the 0.2% offset. Finally, the braided glass composite that was supplied by Composetec also failed before reaching the 0.2% offset.

The remaining carbon reinforced wire had a tensile yield strength of 125,810. The Spectra laminate exhibited a tensile yield strength of over 370,000 psi, which is more than the yield strength of stainless steel. The data from wires, that did not fail, was analyzed by Students t-test for significant variation between the surviving test wires and the non-esthetic standards. If a wire was found to have no significant deviation from one of the standard wires a notation was made as to the fact in the table.

The modulus of elasticity was determined by the three point bend test. Results from this test are presented in table 13. Again, the glass

reinforced esthetic wires that were made from Epon 828 and Ancamine K61.B, and Epon 828 and Capcur 380 were not tested due to the epoxies not completely curing during the pultrusion process. The wires manufactured with carbon as the reinforcing material developed a flexural modulus in the range of 13 to 14 million psi. These moduli are similar to that, that were demonstrated by TMA and nickel titanium. Significance testing revealed, however, that these empirical observations were not completely correct. Only the carbon reinforced wire laminate with Epon 828 and Ancamine K61.B demonstrated a significant probability of similarity. The results from the significance testing are presented in Table 20. The braided glass wire provided by Composetec was not tested due to excessive slumping.

The flexural yield strength at the 0.2% offset was calculated for all wires that were tested. The results of these calculations are presented in table 14. The fiber optic cable reinforcement approximated the flexural yield strength of nickel titanium. The fiber optic cable reinforcement had a flexural yield strength of 81,100. Nickel titanium demonstrated a yield strength of 82,000. Significance testing verified a high degree of similarity between the esthetic wire and the non-esthetic wire. Significance testing also revealed an unexpected correlation of similarity between, Ancamine 1916 pre gelation carbon wire and Ancamine 1916 post-gelation glass, and the nickel titanium wire. The results of the significance testing are presented in table 21. Again the braided glass wire provided by Composetec was not tested due to excessive slumping.

Flexural Strain statistics are presented in table 15. Notably, all wires had undergone a 0.2% deformation at less than 0.29", 1.10 mm's. The wire reinforced with Spectra 1000 ® had the poorest offset measurement, 0.0039", 0.15 mm's. Again the fiber optic cable reinforcement performed very similarly to the nickel titanium wire tested. Significance testing results are presented in table 23. The braided glass wire provided by Composetec was not tested due to excessive slumping.

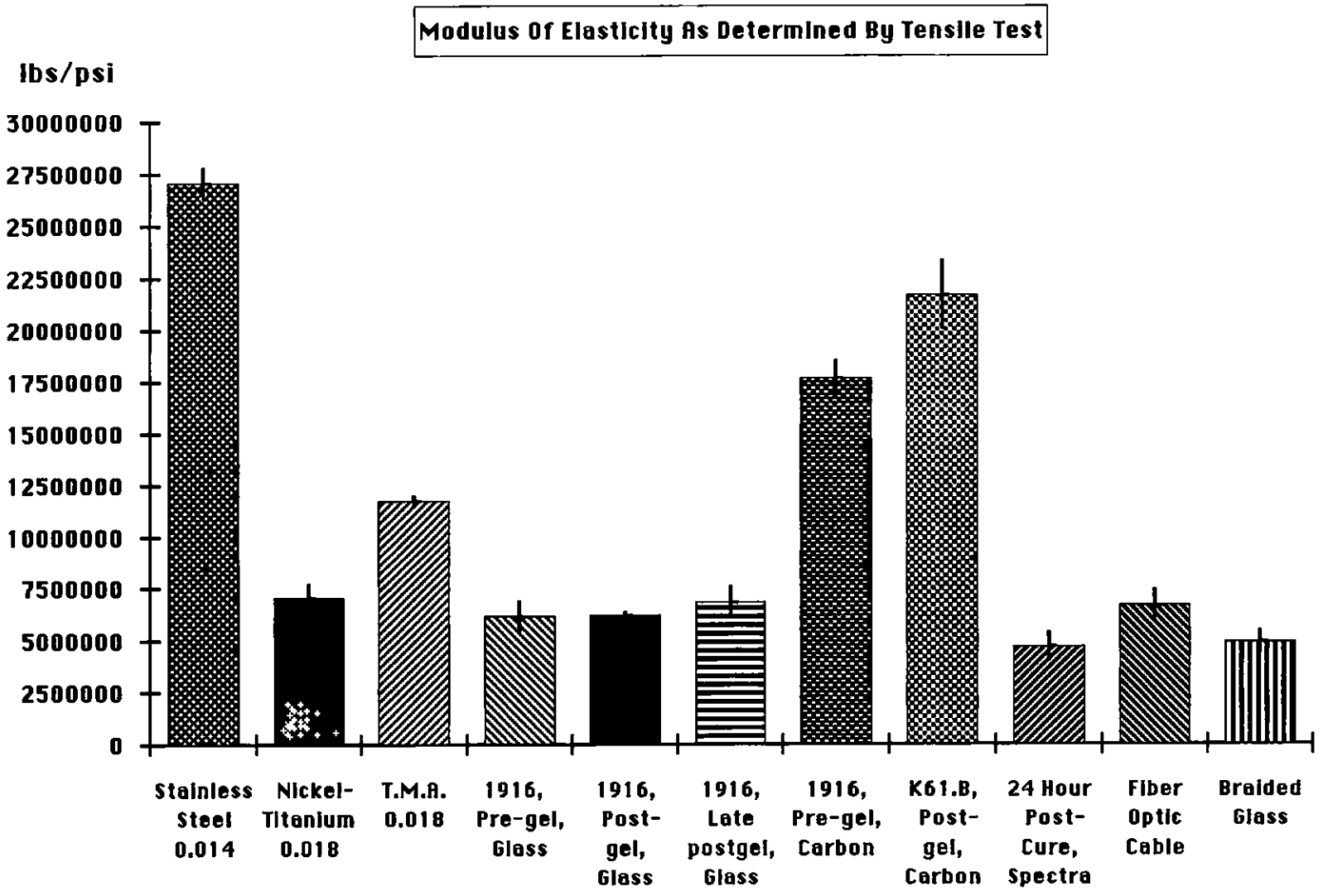
Related to the flexural strain is the flexural load. Mechanical testing data on the flexural load is depicted in table 16. There was over a thirty-five fold change in magnitude from the highest non-esthetic wire load to the lowest esthetic wire load. At the 0.2% offset, wires expressed loads ranging from 0.39 Lbf to 0.01 Lbf. The Ancamine K61.B post-gelation carbon reinforced wire had a flexural load similar to that of the Sentalloy® wire and the TMA wire, Significance testing confirmed this observation. Conclusions of the significance testing are presented in Table 22. Regrettably no wires tested positively for significant similarity to stainless steel.

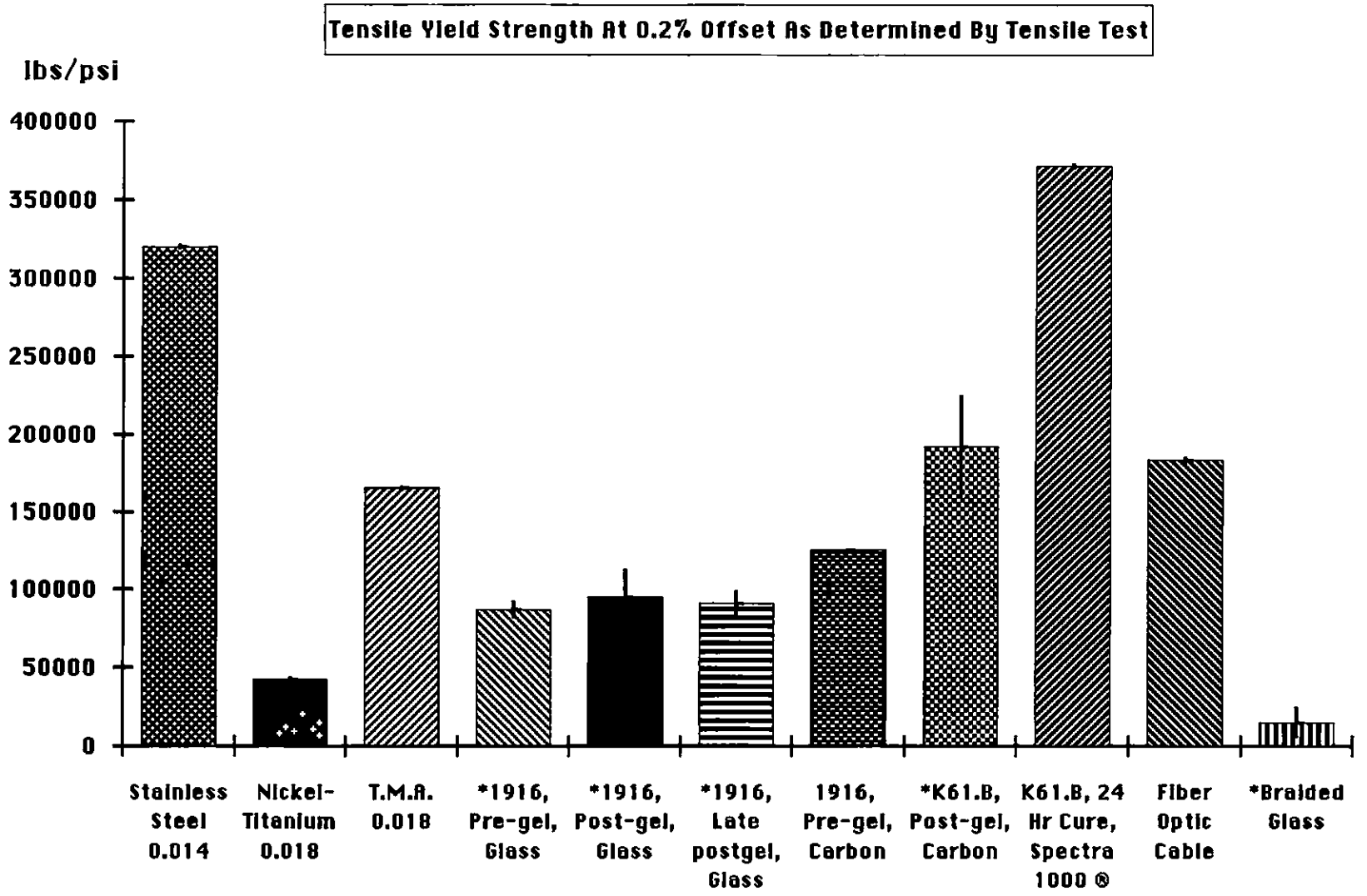
Examination of the manufacturing process was achieved by studying the variation of the wires' diameters in the manufactured wires. Data from this study is posed in Table 17. In Table 17 statistics on the die's diameter is also presented. Manufactured wires had mean wire diameters that ranged from 0.01656 to 0.02899. Individual wires had diameters that varied from 0.03147 for the largest glass fiber to 0.01331 for the smallest carbon fiber. Significance testing of the manufactured wires versus the die was carried out. The results reveal significant variation between the

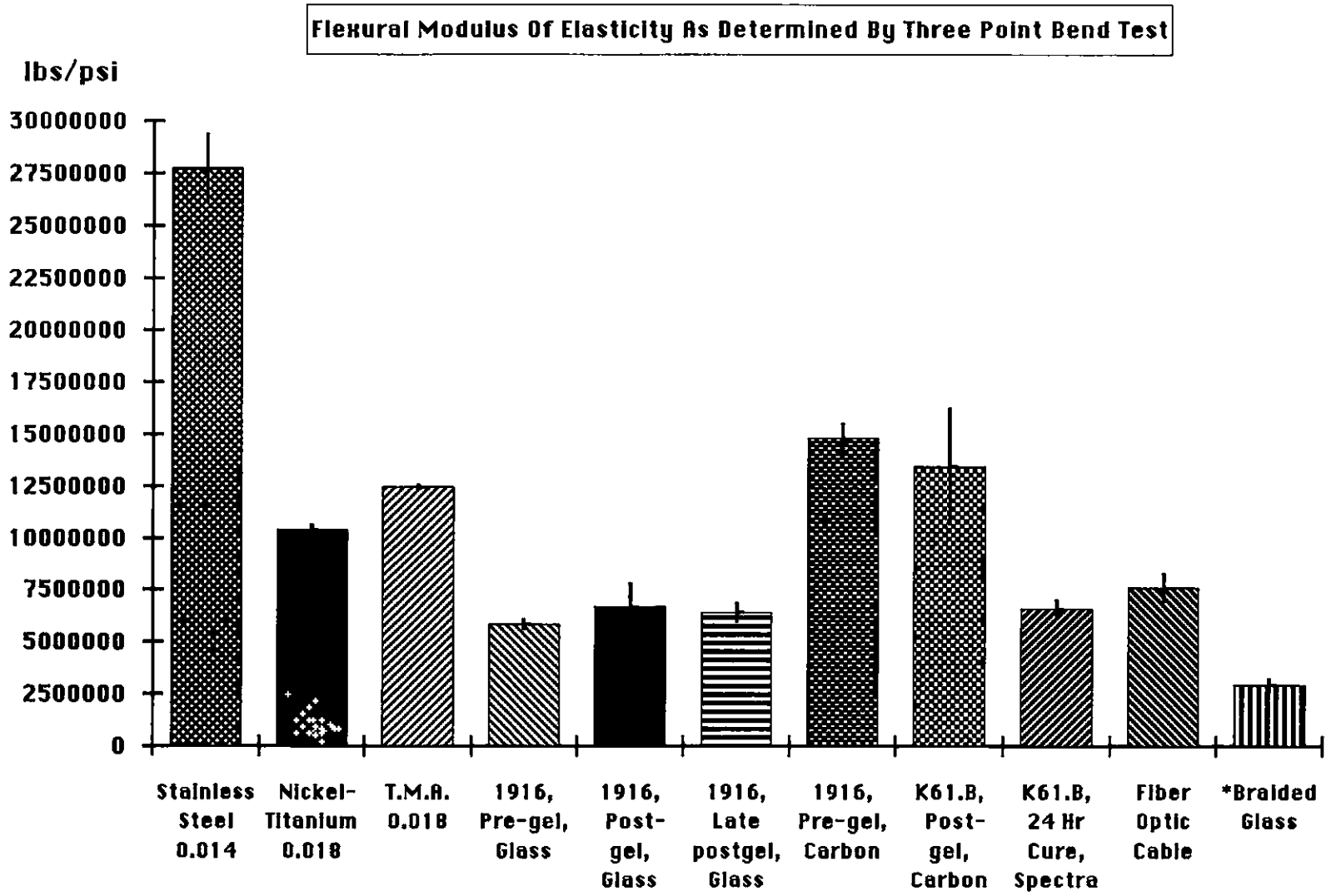
die and the wires that were created. Additionally, testing of the glass wires was carried out against a theoretical sample population that was derived from weighted means. Results of this significance testing, (table 24), revealed that all the glass wires, except for the wire made with Capcur 380, were very similar to each other in diameter. A theoretical sample population was derived for the carbon wires. However, significance testing here revealed a random relationship between the wire diameters. A graphical representation of the variation in the wire diameters for each manufacturing run are presented in Graphs 1 through 8. Units in the graphs on the ordinate axis are in inches. The abscissa is a simple count of the number of wires that fall into that specific range.

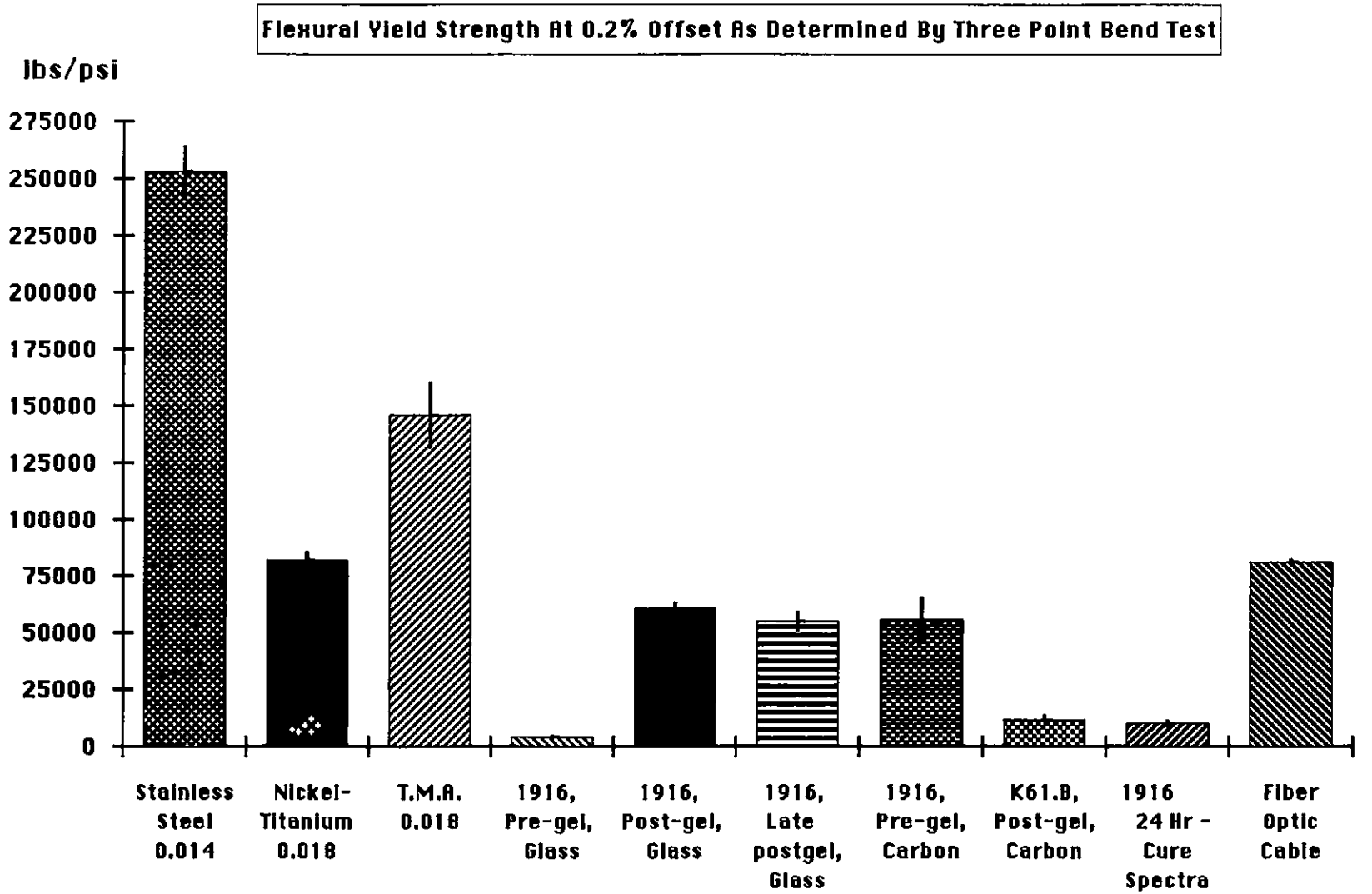
Three manufacturing runs were controlled in such a way as to allow determination of the effect of gelation upon the composite wire form, However, due to excessive variation in wire diameter this comparison was not possible to perform. The latter quarter of Table 24 lists the results of the significance testing for the three manufacturing runs. A mean sample population wire diameter was developed for only the three isolated manufacturing runs whereas the mean sample population for the comparisons detailed in Table 14 included all 5 manufacturing runs. It can be seen that the Epon 828 Ancamine 1916 pre-gelation wire has a finished wire diameter significantly different from the other two wires. Since this wire would be used as the standard for comparison, and significance testing reveled that this wire has a different diameter from other wires it is to be compared to, the only conclusion that can be reached, is that no meaningful comparisons can be done.

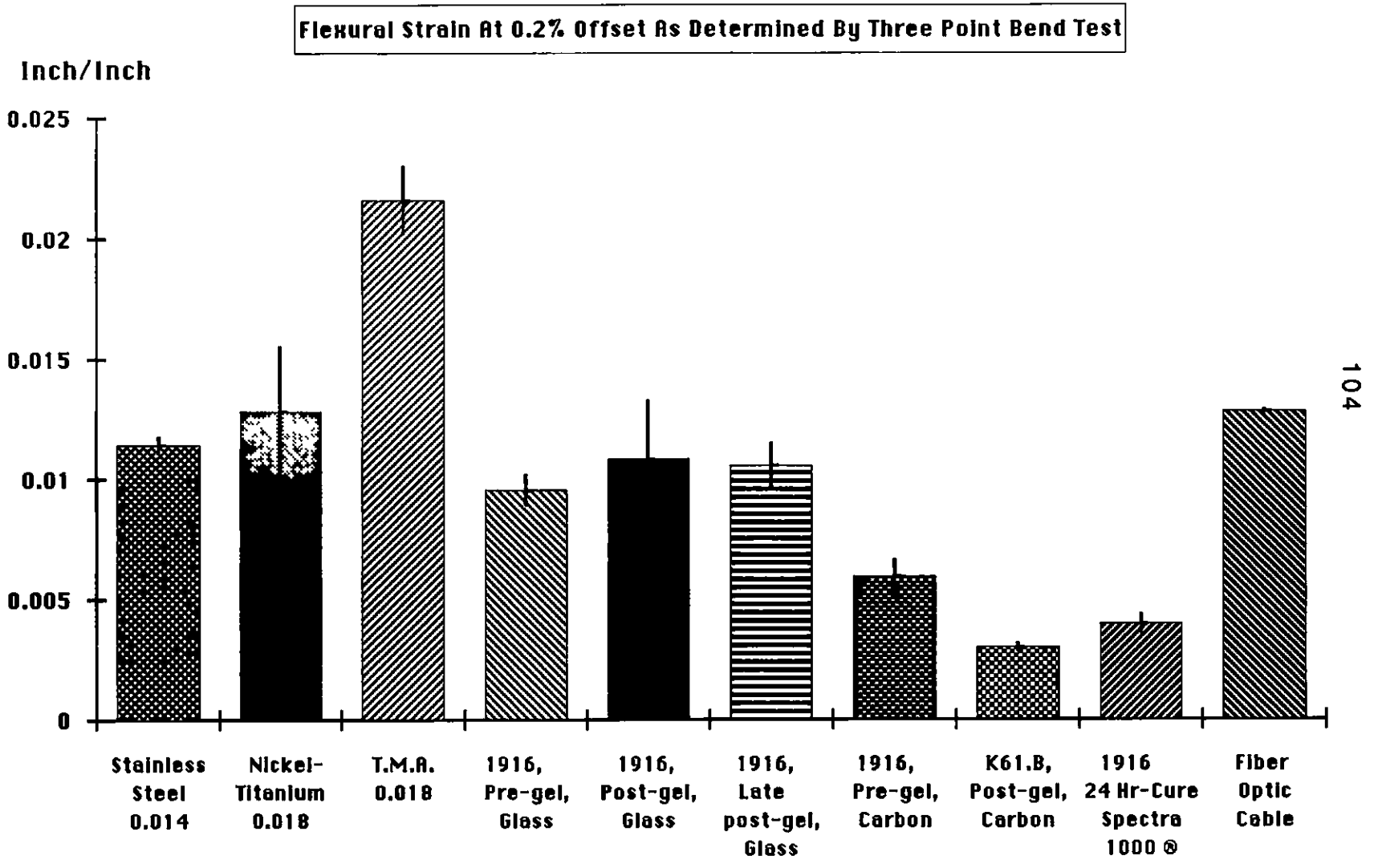
The following section is a graphical depiction of representative sample of the raw data for each wire representing the wires: tensile stress strain plot, flexural stress strain plot, and the flexural load deflection plot. Finally, to facilitate a simultaneous comparison the various wires properties for tensile modulus, tensile yield strength at the 0.2% offset, flexural modulus, flexural yield strength, flexural strain, and flexural load at the 0.2% offset, Histograms were developed. The Histograms depict the wire's properties and the standard deviations of the sample groups. Wires annotated with an * are wires that failed during testing before testing was completed therefore, the figures are the values demonstrated by the wire prior to failure.

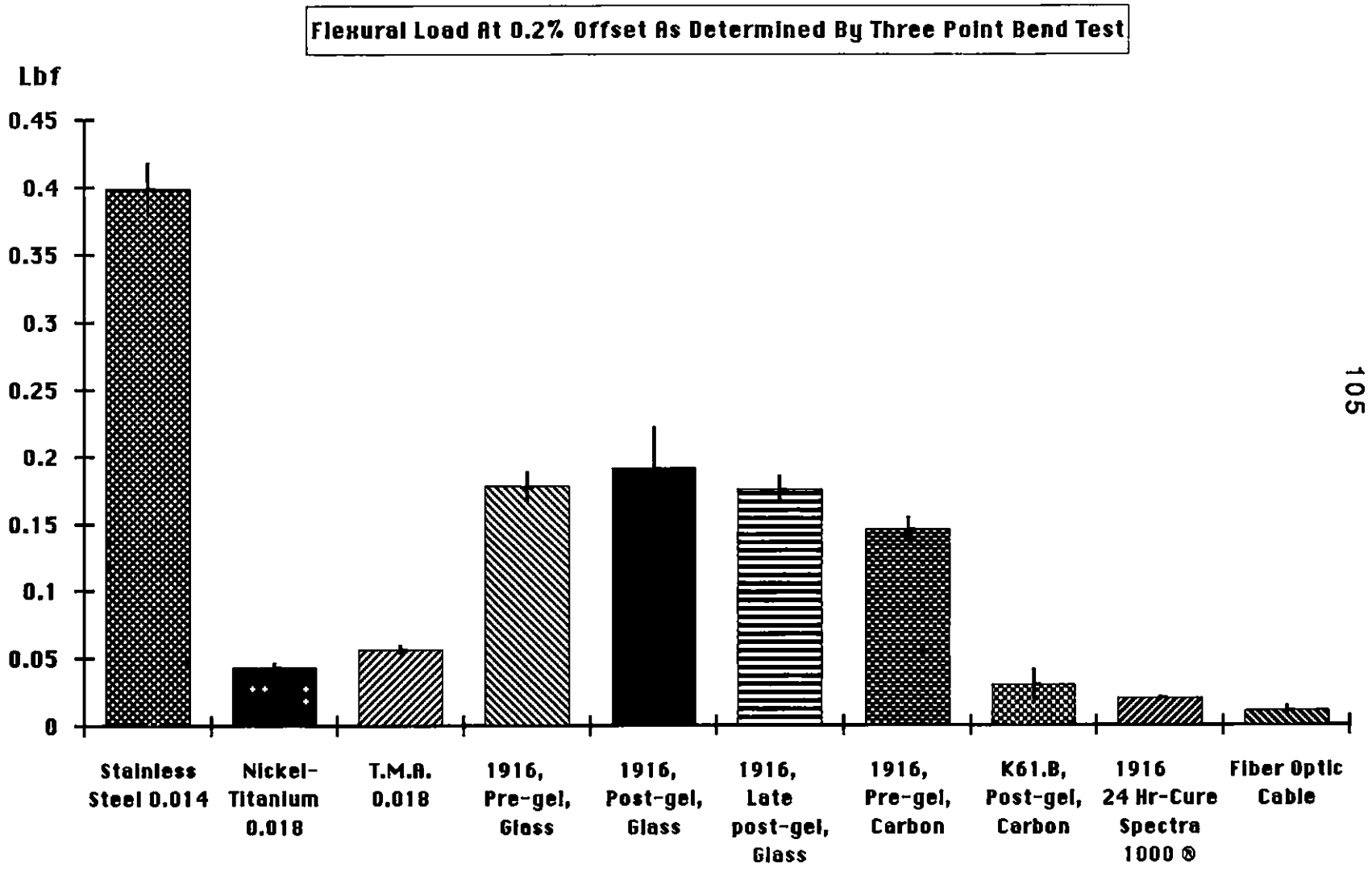

Modulus Of Elasticity As Determined By Tensile Test
lbs/psi
30000000
27500000
25000000
22500000
20000000
17500000
15000000
12500000
10000000
7500000
5000000
2500000
0
Stainless Steel 0.014
Nickel-Titanium 0.018
T.M.A. 0.018
1916, Pre-gel, Glass
1916, Post-gel, Glass
1916, Late postgel, Glass
1916, Pre-gel, Carbon
K61.B, Post-gel, Carbon
24 Hour Post-Cure, Spectra
Fiber Optic Cable
Braided Glass


Tensile Yield Strength At 0.2% Offset As Determined By Tensile Test
lbs/psi
400000
350000
300000
250000
200000
150000
100000
50000
0
Stainless Steel 0.014
Nickel-Titanium 0.018
T.M.A. 0.018
*1916, Pre-gel, Glass
*1916, Post-gel, Glass
*1916, Late postgel, Glass
1916, Pre-gel, Carbon
*K61.B, Post-gel, Carbon
K61.B, 24 Hr Cure, Spectra 1000 ®
Fiber Optic Cable
*Braided Glass


Flexural Modulus Of Elasticity As Determined By Three Point Bend Test
lbs/psi
30000000
27500000
25000000
22500000
20000000
17500000
15000000
12500000
10000000
7500000
5000000
2500000
0
Stainless Steel 0.014
Nickel-Titanium 0.018
T.M.A. 0.018
1916, Pre-gel, Glass
1916, Post-gel, Glass
1916, Late postgel, Glass
1916, Pre-gel, Carbon
K61.B, Post-gel, Carbon
K61.B, 24 Hr Cure, Spectra
Fiber Optic Cable
*Braided Glass


Flexural Yield Strength At 0.2% Offset As Determined By Three Point Bend Test
lbs/psi
275000
250000
225000
200000
175000
150000
125000
100000
75000
50000
25000
0
Stainless Steel 0.014
Nickel-Titanium 0.018
T.M.A. 0.018
1916, Pre-gel, Glass
1916, Post-gel, Glass
1916, Late postgel, Glass
1916, Pre-gel, Carbon
K61.B, Post-gel, Carbon
1916 24 Hr - Cure Spectra
Fiber Optic Cable


Flexural Strain At 0.2% Offset As Determined By Three Point Bend Test
Inch/Inch
0.025
0.02
0.015
0.01
0.005
0
Stainless Steel 0.014
Nickel-Titanium 0.018
T.M.A. 0.018
1916, Pre-gel, Glass
1916, Post-gel, Glass
1916, Late post-gel, Glass
1916, Pre-gel, Carbon
K61.B, Post-gel, Carbon
1916 24 Hr-Cure Spectra 1000 ®
Fiber Optic Cable


Flexural Load At 0.2% Offset As Determined By Three Point Bend Test
Lbf
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Stainless Steel 0.014
Nickel-Titanium 0.018
T.M.A. 0.018
1916, Pre-gel, Glass
1916, Post-gel, Glass
1916, Late post-gel, Glass
1916, Pre-gel, Carbon
K61.B, Post-gel, Carbon
1916 24 Hr-Cure Spectra 1000 ®
Fiber Optic Cable

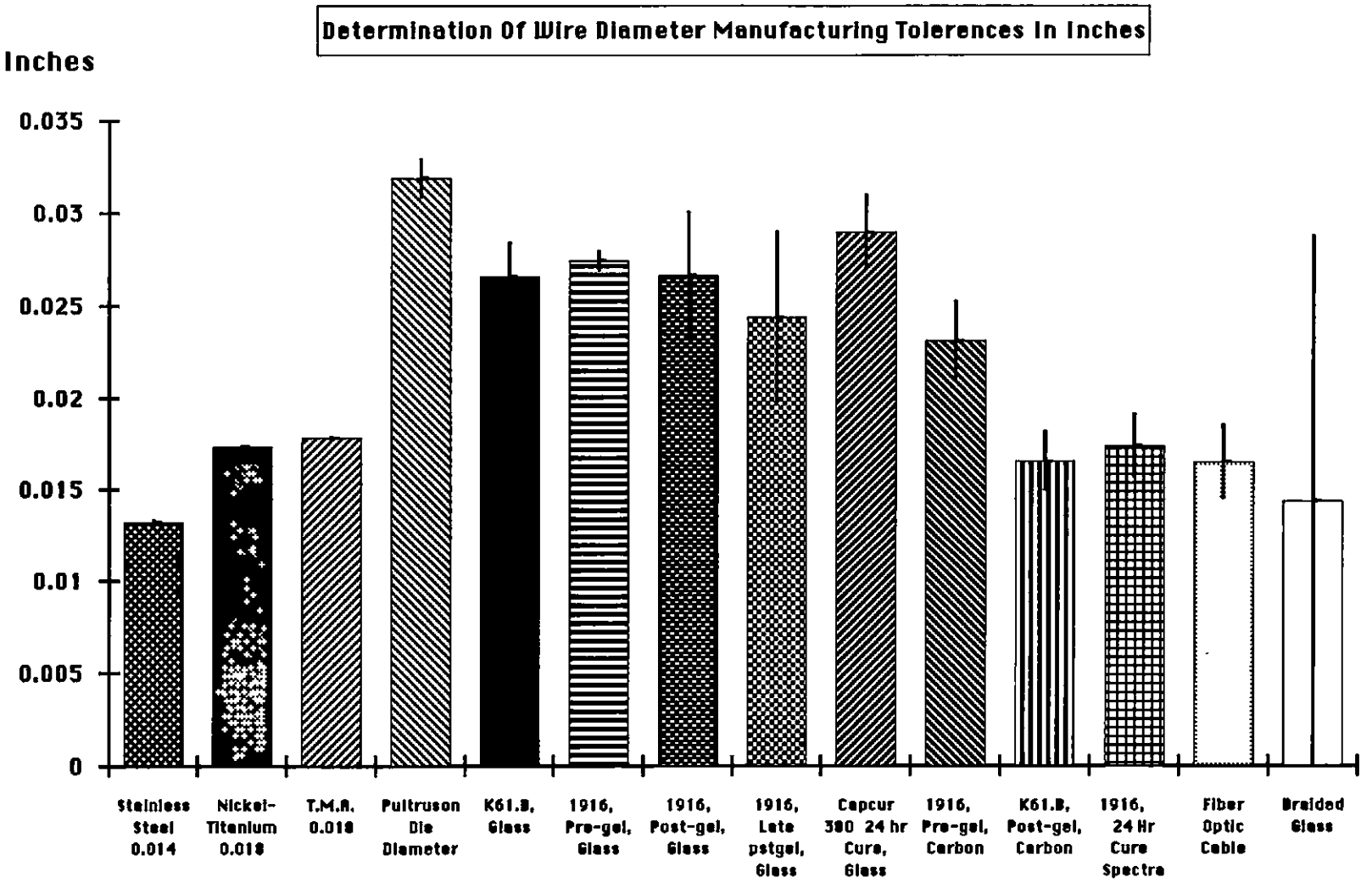

Determination Of Wire Diameter Manufacturing Tolerences In Inches
Inches
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Stainless Steel 0.014
Nickel-Titanium 0.018
T.M.A. 0.018
Pultruson Die Diameter
K61.B, Glass
1916, Pre-gel, Glass
1916, Post-gel, Glass
1916, Late pstgel, Glass
Capcur 380 24 hr Cure, Glass
1916, Pre-gel, Carbon
K61.B, Post-gel, Carbon
1916, 24 Hr Cure Spectra
Fiber Optic Cable
Braided Glass

Table 11

Modulus of Elasticity as Determined by the Tensile Test

Variable Metal Wires	Sample Number	Mean Wire Diameter	Mean Modulus of Elasticity x 10^6 psi	Standard Deviation x 10^6 psi
Tru-Chrome	3	0.01325	27.06	0.71
Sentalloy, medium	3	0.01733	7.05	0.62
TMA	3	0.01783	11.75	0.21
Composite Wires - Glass				
Epon 828, Ancamine K61.B*	3	0.02660	Not Tested	Not Tested
Epon 828, Ancamine 1916, Pre-gelation	3	0.02744	6.18	0.64
Epon 828, Ancamine 1916, Post-gelation	3	0.02666	6.22	0.10
Epon 828, Ancamine 1916, Late Post-gelation	3	0.02441	6.83	0.71
Epon 828, Capcur 380, 24 hour Post Cure *	3	0.02899	Not Tested	Not Tested
Composite Wires - Carbon				
Epon 828, Ancamine 1916, Pre-gelation	3	0.01533	17.7	0.79
Epon 828, Ancamine K61.B, Post-gelation	3	0.01656	21.7	1.61
Composite Wires - Spectra 1000				
Epon 828, Ancamine 1916, 24 Hour Post Cure	3	0.01740	4.7	0.64
Composite Wires - Glass, Procured				
Fiber Optic Cable Reinforcement	3	0.01651	6.68	0.69
Composetec Braided Glass	3	0.01438	4.94	0.48

Table 12

Tensile Yield Strength at 0.2% Offset

Variables Metal Wires	Sample Number	Average Wire Diameter	Tensile Yield Strength x 10^3 psi	Standard Deviation x 10^3 psi
Tru-Chrome	3	0.01325	320.15	0.68
Sentalloy, medium	3	0.01733	42.60	0.24
TMR	3	0.01783	165.53	0.22
Composite Wires - Glass				
Epon 828, Ancamine K61.B *	3	0.02660	Not Tested	Not Tested
Epon 828, Ancamine 1916, Pre-gelation **	3	0.02744	87.08**	4.52**
Epon 828, Ancamine 1916, Post-gelation**	3	0.02666	95.27**	16.41**
Epon 828, Ancamine 1916, Late Post-gelation**	3	0.02441	91.31**	6.61**
Epon 828, Capcur 380, 24 hour Post Cure*	3	0.02899	Not Tested	Not Tested
Composite Wires - Carbon				
Epon 828, Ancamine 1916, Pre-gelation	3	0.01533	125.81	0.17
Epon 828, Ancamine K61.B, Post-gelation**	3	0.01656	192.45**	31.66**
Composite Wires - Spectra 1000				
Epon 828, Ancamine 1916, 24 Hour Post Cure	3	0.01740	371.66	0.78
Composite Wires - Glass, Procured				
Fiber Optic Cable Reinforcement	3	0.01651	183.66	0.83
Composetec Braided Glass**	3	0.01438	15.18**	8.69**

* Not tested due to incomplete cure, material was tacky and had no body.

** The sample failed before a 0.02% offset occurred, the fibers were either broken or pulled from the matrix, numbers presented for reference only, data was not included in statistical analysis.

Table 13

Modulus of Elasticity as Determined By Three Point Bend Test

Variable Metal Wires	Sample Number	Mean Wire Diameter	Mean Modulus of Elasticity x 10^6 psi	Standard Deviation x 10^6 psi
Tru-Chrome	3	0.01325	27.76	1.58
Sentalloy, medium	3	0.01733	10.40	0.19
TMA	3	0.01783	12.46	0.05
Composite Wires - Glass				
Epon 828, Ancamine K61.B *	3	0.02660	Not Tested	Not Tested
Epon 828, Ancamine 1916, Pre-gelation	3	0.02744	5.83	0.19
Epon 828, Ancamine 1916, Post-gelation	3	0.02666	6.69	1.05
Epon 828, Ancamine 1916, Late Post-gelation	3	0.02441	6.40	0.38
Epon 828, Capcur 380, 24 hour Post Cure*	3	0.02899	Not Tested	Not Tested
Composite Wires - Carbon				
Epon 828, Ancamine 1916, Pre-gelation	3	0.01533	14.80	0.65
Epon 828, Ancamine K61.B, Post-gelation	3	0.01656	13.46	2.74
Composite Wires - Spectra 1000				
Epon 828, Ancamine 1916, 24 Hour Post Cure	3	0.01740	6.57	0.38
Composite Wires - Glass, Procured				
Fiber Optic Cable Reinforcement	3	0.01651	7.59	0.62
Composetec Braided Glass**	3	0.01438	2.93	0.24

* Not tested due to incomplete cure, material was tacky and had no body.

** Because the wire slumped more than 10% between the 1" test span the results are only an estimate of the materials modulus of elasticity.

Table 14

Flexural Yield Strength at 0.2% Offset

Variables Metal Wires	Sample Number	Average Wire Diameter	Yield Strength at 0.2% x 10^3 psi	Standard Deviation x 10^3psi
Tru-Chrome	3	0.01325	253	10.32
Sentalloy, medium	3	0.01733	82	3.37
TMA	3	0.01783	146	13.69
Composite Wires - Glass				
Epon 828, Ancamine K61.B *	3	0.02660	Not Tested	Not Tested
Epon 828, Ancamine 1916, Pre-gelation	3	0.02744	4.2	0.14
Epon 828, Ancamine 1916, Post-gelation	3	0.02666	60.7	1.76
Epon 828, Ancamine 1916, Late Post-gelation	3	0.02441	55.0	3.53
Epon 828, Capcur 380, 24 hour Post Cure*	3	0.02899	Not Tested	Not Tested
Composite Wires - Carbon				
Epon 828, Ancamine 1916, Pre-gelation	3	0.01533	55.7	9.04
Epon 828, Ancamine K61.B, Post-gelation	3	0.01656	11.8	1.38
Composite Wires - Spectra 1000				
Epon 828, Ancamine 1916, 24 Hour Post Cure	3	0.01740	10.1	0.67
Composite Wires - Glass, Procured				
Fiber Optic Cable Reinforcement	3	0.01651	81.1	7.6
Composetec Braided Glass**	3	0.01438	Failed	Failed

* Not tested due to incomplete cure, material was tacky and had no body.

** Wire slumped more than 10% between the 1" test span making the test results false.

Table 15

Flexural Strain Statistics at 0.2% Offset

Variables				
Metal Wires	Sample Number	Average Wire Diameter	strain at 0.2% Offset (in/in)	Standard Deviation (in/in)
Tru-Chrome	3	0.01325	0.01144	0.00030
Sentalloy, medium	3	0.01733	0.01284	0.00265
TMA	3	0.01783	0.01260	0.00136
Composite Wires - Glass				
Epon 828, Ancamine K61.B *	3	0.02660	Not Tested	Not Tested
Epon 828, Ancamine 1916, Pre-gelation	3	0.02744	0.00955	0.00059
Epon 828, Ancamine 1916, Post-gelation	3	0.02666	0.01085	0.00239
Epon 828, Ancamine 1916, Late Post-gelation	3	0.02441	0.01057	0.00089
Epon 828, Capcur 380, 24 hour Post Cure *	3	0.02899	Not Tested	Not Tested
Composite Wires - Carbon				
Epon 828, Ancamine 1916, Pre-gelation	3	0.01533	0.00594	0.00063
Epon 828, Ancamine K61.B, Post-gelation	3	0.01656	0.00300	0.00013
Composite Wires - Spectra 1000				
Epon 828, Ancamine 1916, 24 Hour Post Cure	3	0.01740	0.00398	0.00036
Composite Wires - Glass, Procured				
Fiber Optic Cable Reinforcement	3	0.01651	0.01283	0.00005
Composetec Braided Glass**	3	0.01438	Failed	Failed

* Not tested due to incomplete cure, material was tacky and had no body.

** Wire slumped more than 10% between the 1" test span making the test results false.

Table 16

Flexural - Load at the 0.2% Offset

Variables Metal Wires	Sample Number	Average Wire Diameter	Load at 0.2%Offset (Lbf)	Standard Deviation (Lbf)
Tru-Chrome	3	0.01325	0.39875	0.01838
Sentalloy, medium	3	0.01733	0.04322	0.00241
TMA	3	0.01783	0.05645	0.00209
Composite Wires - Glass				
Epon 828, Ancamine K61.B *	3	0.02660	Not Tested	Not Tested
Epon 828, Ancamine 1916, Pre-gelation	3	0.02744	0.17778	0.00967
Epon 828, Ancamine 1916, Post-gelation	3	0.02666	0.19127	0.02962
Epon 828, Ancamine 1916, Late Post-gelation	3	0.02441	0.17536	0.00914
Epon 828, Capcur 380, 24 hour Post Cure*	3	0.02899	Not Tested	Not Tested
Composite Wires - Carbon				
Epon 828, Ancamine 1916, Pre-gelation	3	0.01533	0.14577	0.00826
Epon 828, Ancamine K61.B, Post-gelation	3	0.01656	0.03035	0.01039
Composite Wires - Spectra 1000				
Epon 828, Ancamine 1916, 24 Hour Post Cure	3	0.01740	0.02011	0.0006
Composite Wires - Glass, Procured				
Fiber Optic Cable Reinforcement	3	0.01651	0.0109	0.00251
Composetec Braided Glass **	3	0.01438	Failed	Failed

---

* Not tested due to incomplete cure, material was tacky and had no body.

** Wire slumped more than 10% between the 1" test span making the test results false.

Table 17

Determination of Wire Diameter and Manufacturing Tolerances in Inches

Variable Metal Wires	Sample Number	Mean Wire Diameter	Standard Deviation
Tru-Chrome	6	0.01325	0.00006
Sentalloy, medium	6	0.01733	0.00003
TMA	6	0.01783	0.00002
Composite Wires - Glass			
Epon 828, Ancamine K61.B	10	0.02660	0.00176
Epon 828, Ancamine 1916, Pre-gelation	3	0.02744	0.00049
Epon 828, Ancamine 1916, Post-gelation	6	0.02666	0.00336
Epon 828, Ancamine 1916, Late Post-gelation	9	0.02441	0.00455
Epon 828, Capcur 380, 24 hour Post Cure	8	0.02899	0.00195
Composite Wires - Carbon			
Epon 828, Ancamine 1916, Pre-gelation	7	0.02312	0.00209
Epon 828, Ancamine K61.B, Post-gelation	13	0.01656	0.00157
Composite Wires - Spectra 1000			
Epon 828, Ancamine 1916, 24 Hour Post Cure	9	0.01740	0.00166
Composite Wires - Glass, Procured			
Fiber Optic Cable Reinforcement	8	0.01651	0.00196
Composetec Braided Glass *	8	0.01438	0.05761
Die Diameter Statistics			
Die Diameter	15	0.03190	0.00100

* Measurements of this wire are approximate due to the variability in diameter caused by the braiding effect.

Table 18

t-Test to Evaluate Differences in the Tensile Modulus as Determined by the Tensile Test

(m,n=3 for all Wires Tested)

t-Test For 0.018 TMA vs:

Wire	Probability	Level of Significance
Fiber Optic Cable Reinforcement	0.003	**
Epon 828, Ancamine 1916, Late Post-gelation, Glass	0.0034	**
Epon 828, Ancamine K61.B, Post-gelation, Carbon	0.0001	***

t-Test For 0.014 Stainless Steel vs:

Wire	Probability	Level of Significance
Epon 828, Ancamine K61.B, Post-gelation, Carbon	0.0093	**
Epon 828, Ancamine 1916, Pre-gelation, Carbon	0.0001	***
Epon 828, Ancamine 1916, Late Post-gelation, Glass	0.0001	***

m,n = Number of measurements

** $p \leq 0.01$

*** $p \leq 0.001$

Table 18 continued

t-Test to Evaluate Differences in the Tensile Modulus as Determined by the Tensile Test

(m,n=3 for all Wires Tested)

t-Test For 0.018 Sentalloy®, medium Nickel Titanium vs:

Wire	Probability	Level of Significance
Epon 828, Ancamine 1916, Pre-gelation, Glass	0.1097	No
Epon 828, Ancamine 1916, Late Post-gelation, Glass	0.05158	No
Fiber Optic Cable Reinforcement	0.06731	No
Epon 828, Ancamine 1916, Post-gelation, Glass	0.0002	***

m,n = Number of measurements

*** $p \leq 0.001$

Table 19

t-Test to Evaluate Differences in the Tensile Yield Strength at the 0.2% Offset

(m,n=3 for all Wires Tested)

t-Test For 0.018 TMA vs:

Wire	Probability	Level of Significance
Epon 828, Ancamine 1916, 24 hour post cure, Spectra 1000 ®	0.0043	**
Epon 828, Ancamine 1916, Pre-gelation, Carbon	0.0121	*
Fiber Optic Cable Reinforcement	0.0654	No

t-Test For 0.014 Stainless Steel vs:

Wire	Probability	Level of Significance
Fiber Optic Cable Reinforcement	0.0039	**
Epon 828, Ancamine 1916, 24 hour post cure, Spectra 1000 ®	0.001	***
Epon 828, Ancamine 1916, Pre-gelation, Carbon	0.0004	***

m,n = Number of measurements

** $p \leq 0.01$

* $p \leq 0.05$

*** $p \leq 0.001$

Table 19 continued

t-Test to Evaluate Differences in the Tensile Yield Strength

at the 0.2% Offset

(m,n=3 for all Wires Tested)

t-Test For 0.018 Sentalloy®, medium Nickel Titanium vs:

Wire	Probability	Level of Significance
Fiber Optic Cable Reinforcement	0.005	* *
Epon 828, Ancamine 1916, 24 hour post cure, Spectra 1000 ®	0.0011	**
Epon 828, Ancamine 1916, Pre-gelation, Carbon	0.0019	**

m,n = Number of measurements

** $p \leq 0.01$

Table 20

t-Test to Evaluate Differences in the Flexural Elastic Modulus as Determined by The Three Point Bend Test

(m,n=3 for all Wires Tested)

t-Test For 0.018 TMA vs:

Wire	Probability	Level of Significance
Fiber Optic Cable Reinforcement	0.0062	**
Epon 828, Ancamine 1916, Pre-gelation, Carbon	0.0289	*
Epon 828, Ancamine K61.B, Post-gelation, Carbon	0.5998	No

t-Test For 0.014 Stainless Steel vs:

Wire	Probability	Level of Significance
Fiber Optic Cable Reinforcement	0.0039	**
Epon 828, Ancamine 1916, Pre-gelation, Carbon	0.0057	* *
Epon 828, Ancamine K61.B, Post-gelation, Carbon	0.0226	*

m,n = Number of measurements

---

* $p \leq 0.05$

** $p \leq 0.01$

Table 20 continued

t-Test to Evaluate Differences in the Flexural Elastic Modulus

as Determined by The Three Point Bend Test

(m,n=3 for all Wires Tested)

t-Test For 0.018 Sentalloy®, medium Nickel Titanium vs:

Wire	Probability	Level of Significance
Fiber Optic Cable Reinforcement	0.0178	*
Epon 828, Ancamine 1916, Post-gelation, Glass	0.0196	*
Epon 828, Ancamine K61.B, Post-gelation, Carbon	0.0285	*

m,n = Number of measurements

* $p \leq 0.05$

Table 21

t-Test to Evaluate Differences in the Flexural Yield Strength at the 0.2% Offset

(m,n=3 for all Wires Tested)

t-Test For 0.018 TMA vs:

Wire	Probability	Level of Significance
Epon 828, Ancamine 1916, Late Post-gelation, Glass	0.0055	**
Epon 828, Ancamine 1916, Pre-gelation, Glass	0.0032	**
Fiber Optic Cable Reinforcement	0.0654	**

t-Test For 0.014 Stainless Steel vs:

Wire	Probability	Level of Significance
Epon 828, Ancamine 1916, Pre-gelation, Carbon	0.0027	**
Fiber Optic Cable Reinforcement	0.0182	*
Epon 828, Ancamine 1916, Pre-gelation, Glass	0.0266	*

m,n = Number of measurements

** $p \leq 0.01$

* $p \leq 0.05$

Table 21 continued

t-Test to Evaluate Differences in the Flexural Yield Strength

at the 0.2% Offset

(m,n=3 for all Wires Tested)

t-Test For 0.018 Sentalloy®, medium Nickel Titanium vs:

Wire	Probability	Level of Significance
Epon 828, Ancamine 1916, Pre-gelation, Glass	0.0264	*
Epon 828, Ancamine 1916, Post-gelation, Glass	0.0019	**
Epon 828, Ancamine 1916, Pre-gelation, Carbon	0.0151	*
Fiber Optic Cable Reinforcement	0.09058	No

m,n = Number of measurements

* $p \leq 0.05$

** $p \leq 0.01$

Table 22

t-Test to Evaluate Differences in the Flexural Load at the 0.2% Offset

(m,n=3 for all Wires Tested)

t-Test For 0.018 TMA vs:

Wire	Probability	Level of Significance
Epon 828, Ancamine 1916, 24 Hour Post Cure, Spectra 1000	0.0042	**
Epon 828, Ancamine 1916, Post-gelation, Glass	0.0136	*
Epon 828, Ancamine K61.B, Post-gelation, Carbon	0.062	No

t-Test For 0.014 Stainless Steel vs:

Wire	Probability	Level of Significance
Epon 828, Ancamine 1916, Post-gelation, Glass	0.001	***
Epon 828, Ancamine 1916, Pre-gelation, Glass	0.0005	***
Epon 828, Ancamine 1916, Late Post-gelation, Glass	0.0006	***

m,n = Number of measurements

** $p \leq 0.01$

* $p \leq 0.05$

*** $p \leq 0.001$

Table 22 Continued

t-Test to Evaluate Differences in the Flexural Load at the 0.2% Offset

(m,n=3 for all Wires Tested)

t-Test For 0.018 Sentalloy®, medium Nickel Titanium vs:

Wire	Probability	Level of Significance
Epon 828, Ancamine 1916, 24 Hour Post Cure, Spectra 1000	0.0087	**
Epon 828, Ancamine 1916, Post-gelation, Glass	0.0111	*
Epon 828, Ancamine K61.B, Post-gelation, Carbon	0.1919	No

m,n = Number of meesurements

** $p \leq 0.01$

* $p \leq 0.05$

Table 23

t-Test to Evaluate Differences in the Flexural Strain at the 0.2% Offset

(m,n=3 for all Wires Tested)

t-Test For 0.018 TMA vs:

Wire	Probability	Level of Significance
Epon 828, Ancamine 1916, Pre-gelation, Glass	0.0206	*
Epon 828, Ancamine 1916, Late Post-gelation, Glass	0.0448	*
Epon 828, Ancamine 1916, Post-gelation, Glass	0.0987	No
Fiber Optic Cable Reinforcement	0.7898	No

t-Test For 0.014 Stainless Steel vs:

Wire	Probability	Level of Significance
Fiber Optic Cable Reinforcement	0.010	*
Epon 828, Ancamine 1916, Late Post-gelation, Glass	0.0209	*
Epon 828, Ancamine 1916, Post-gelation, Glass	0.6932	No

m,n = Number of measurements

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* $p \leq 0.05$

Table 23 continued

t-Test to Evaluate Differences in the Flexural Strain

at the 0.2% Offset

(m,n=3 for all Wires Tested)

t-Test For 0.018 Sentalloy®, medium Nickel Titamium vs:

Wire	Probability	Level of Significance
Epon 828, Ancamine 1916, Post-gelation, Glass	0.0001	* * *
Epon 828, Ancamine 1916, Pre-gelation, Carbon	0.0001	***
Epon 828, Ancamine 1916, Late Post-gelation, Glass	0.2645	No
Fiber Optic Cable Reinforcement	0.9953	No

m,n = Number of measurements

* $p \leq 0.05$

Table 24

t-Test to Evaluate Differences in the Finished Wire Diameter

Statistical Evaluation

Die Diameter Variation (n=15) **vs:**

Wire	m =	Probability	Level of Significance
Epon 828, Ancamine K61.B, Glass	10	0.0001	* * *
Epon 828, Ancamine 1916, Pre-gelation, Glass	3	0.0001	* * *
Epon 828, Ancamine 1916, Post-gelation, Glass	6	0.0001	* * *
Epon 828, Ancamine 1916, Late Post-gelation, Glass	9	0.0001	* * *
Epon 828, Capcur 380, 24 hour Post Cure, Glass	8	0.0001	* * *
Epon 828, Ancamine 1916, Pre-gelation, Carbon	7	0.0001	* * *
Epon 828, Ancamine K61.B, Post-gelation, Carbon	13	0.0001	* * *
Epon 828, Ancamine 1916, 24 Hour Post Cure, Spectra 1000 ®	9	0.0001	* * *

m,n = Number of measurements

*** $p \leq 0.001$

Table 24 continued

t-Test to Evaluate Differences in the Finished Wire Diameter

Statistical Evaluation

Sample Population Mean Glass Reinforced Wire Diameter vs:
(n=36 for all Wires Tested)

Wire	m=	Probability	Level of Significance
Epon 828, Capcur 380, 24 hour Post Cure, Glass	8	0.0154	*
Epon 828, Ancamine 1916, Late Post-gelation, Glass	9	0.1888	No
Epon 828, Ancamine K61.B, Glass	10	0.623	No
Epon 828, Ancamine 1916, Pre-gelation, Glass	3	0.6342	No
Epon 828, Ancamine 1916, Post-gelation, Glass	6	0.7955	No

Sample Population Mean Carbon Reinforced Wire Diameter vs:
(n=20 for all Wires Tested)

Wire	m=	Probability	Level of Significance
Epon 828, Ancamine 1916, Pre-gelation, Carbon	7	0.0001	***
Epon 828, Ancamine K61.B, Post-gelation, Carbon	13	0.0199	*

m,n = Number of measurements

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* $p \leq 0.05$

*** $p \leq 0.001$

Table 24 continued

t-Test to Evaluate Differences in the Finished Wire Diameter

Statistical Evaluation

(n=18 for all Wires Tested)

Sample Population Mean Glass Reinforced Wire Diameter for the Controlled Manufacturing Run vs:

Wire	m=	Probability	Level of Significance
Epon 828, Ancamine 1916, Pre-gelation, Glass	3	0.0014	**
Epon 828, Ancamine 1916, Late Post-gelation, Glass	9	0.0542	No
Epon 828, Ancamine 1916, Post-gelation, Glass	6	0.5425	No

m,n = Number of measurements

** $p \leq 0.01$

Discussion

Overview

Using a modification of the pultrusion process experimental continuous fiber reinforced composite wires were manufactured. The epoxy component of the wires was selected to be easily approved by the Federal Food and Drug Administration, should the results from this research warrant further investigation. All reinforcing materials that were used have not been approved for Class 2 or 3 usage by the FDA (see Literature Review). Currently there is no continuous fiber reinforcement that has been approved by the FDA for the purposes proposed herein. However, some manufactures have had the FDA approve proprietary resin-glass composite pellets. These pellets are suitable for injection moulding and extrusion moulding. Basic data was collected to evaluate the manufacturing process. Wire diameter was compared to the pultrusion die's diameter and to a weighted mean sample population wire diameter for both the glass and carbon fiber reinforced materials.

The mechanical properties of newly manufactured esthetic archwires, and two procured esthetic wire candidates, and three commonly used metal alloy orthodontic arch wires were determined by means of a uniaxial tensile test and a three-point-bend test. By comparing results from the tensile and bend tests, the unique mechanical characteristics of the materials were identified. On the basis of comparison of the mechanical properties of the various types of metal alloy wires, which have known clinical efficacy when used for specific

treatment purposes, with the experimental esthetic wires,judgments whether the esthetic materials tested have potential in clinical use can were made.

Charts 1 thru 7 are a graphical representation of the mean values of the wire's physical properties, standard deviations are also included. Tables 11 thru 18 are a numerical description of the data presented in Charts 1 thru 7. Tables 19 thru 25 are the results of significance testing presented in tabular form. Graphs 1 thru 41 are graphical representations of the physical properties of the wires. The data that was used to create Graphs 1 thru 41, was also used to develop the values listed in Tables 11 thru 18 and Charts 1 thru 7.

Manufacture of Experimental Continuous Fiber Reinforced Wire-forms

The pultrusion process was chosen for manufacture of these wire-forms because it is the only manufacturing technology that allows the continuous production of a product of a fixed cross-sectional area. While wire coating may be considered as a competitor for producing products such as the continuous wire-form it requires the core material, that is to be coated, to be in its final form. Since the continuous filaments are not bound together as received from the manufacturer clearly wire-coating would not work in the production of continuous fiber reinforced wire-forms.

The pultrusion process itself is relatively straight forward, however, there are numerous factors that can influence the products outcome. The

two most critical variables to be controlled are the matrix and the number of fibers in the product. Controlling the epoxy is relatively easy provided that the ratios of base to catalyst and the temperature it will be cured at are known and controlled.

After epoxy evaluation testing was completed the challenge of controlling the epoxy was minimized. The curing temperature and the pulling speed were therefore the most problematic aspects of the manufacture process. Because of the difficulty of threading fibers through the pultrusion die a short die was used. Due to this arrangement the wire-form was cured in a hollow portion of the die. Curing the epoxy in this manner relied upon air transfer of the heat from the die to the wire-form. This is a highly inefficient way of transferring heat energy. Even though the die was heated to its maximum output 180 ^{o}C many of the runs were failures due to insufficient cure of the matrix which resulted in the wire-form not having enough body to resist slumping once tension was released. The pultruder was slowed to its slowest speed in an effort to yield an increase in effective heating time of the wire-forms. However, stalling problems began to occur. This was remedied by increasing the puller speed to approximately 10" per minute. This solution worked well for the glass and carbon reinforcement, however, the Spectra 1000 ® was unstable at this temperature. Spectra thermally degrades at 147 ^{o}C. Therefore the die was cooled to 135 ^{o}C and an attempt was made to produce wire forms. Only one run had enough body to maintain its round shape during the post cure process.

Material Properties of the Manufactured and Procured Esthetic Wires and The Likelihood of Their Efficacy as Esthetic Orthodontic Arches

As the search for esthetic materials began, it became obvious that epoxies and polymers were being used to produce common place items such as fishing line, broom bristles, filament winding rovings, and many other products. These products resembled the dimensions and shapes of orthodontic arch wires. The flexibility and esthetic quality found in some of these common products encouraged investigation of the mechanical properties of various polymers and epoxies. References on the mechanical properties of polymers immediately demonstrated that unreinforced polymers or epoxies could not provide a modulus of elasticity in the range of stainless steel. Therefore, reinforcements were investigated. It was felt that if a composite could be created that had the strengths of the reinforcement and the flexibility of the polymer a suitable substitute for non-esthetic wires might be found. However, it was found that polymers and epoxies generally lacked the property of formability, which is important for wires that would be used later in orthodontic treatment.

Polymers, as a broad class, usually have a flexural modulus of elasticity of approximately 5,000 to 650,000 psi in their unfilled state (The Modern Plastics Encyclopedia, 1990). Furthermore, these values generally do not consider the dramatic increase in the modulus of elasticity resulting from increasing the molecular orientation of the polymer during some formation processes.

Furthermore, when considering fillers, the addition of 30% or more volume percent of glass particles the flexural modulus of elasticity of the composite can be boosted to over 1,000,000 psi, however the composites become brittle. With the addition of 40% volume percent randomly orientated PAN carbon fibers in composites, the moduli can approach 5,000,000 psi but again they become brittle. Furthermore some fillers may be of limited use due to their color. Composites with high volumes of filler may be too brittle for use in producing effective initial leveling arch wires. If the goal was to develop a wire that has the stiffness of steel and could be substituted for stainless steel, the epoxy orientated fiber composite wires could be investigated as a viable alternative. However, if the goal was to develop an initial aligning wire the epoxy composite would be a poor choice due to their brittleness.

The obvious advantage of using fiber glass as a reinforcing filler is that it is clear and provides good esthetics. Also the addition of fillers improves the creep properties of the polymer matrix, so the wire may be protected from losing some of its flexural properties while sustaining a load over a period of long time intervals.[113] However, because of the nature of the fiber glass in the esthetic wires, some breakage of fibers maybe expected if they are deformed under certain conditions that may arise in clinical use. Thus if the wire is broken or a substantial portion of the fibers that are present in the composite wire have failed the fiber composite wire will not be capable of exerting the desired force in the manner that was intended by the clinician.

Choice of Materials Used

The materials that were tested here represent three categories of fiber reinforcements, glass, carbon and polymer. The three different categories of fibers were chosen as such for the following reasons. Glass fibers are the easiest to handle from a manufacturing perspective and it was felt that the glass fibers would provide valuable training knowledge as the pultrusion process was being refined. Furthermore, the sizing systems for glass provide access to a wide spectrum of epoxies, again simplifying the manufacturing process. Finally glass has been thoroughly investigated and the properties and characteristics have been well documented. While carbon itself is not esthetic, carbon fiber properties are in general superior to those of glass. The problem of esthetics with carbon could be resolved by using a colored epoxy or by applying a thin opaquing layer of epoxy to the final wire-form. Finally polymer reinforcements have the greatest potential from a theoretical bases. Polymer fibers have moduli greater than glass or carbon and when polymer fibers fail they do so only after undergoing significant plastic deformation, and this property would help eliminate the shattering problems observed when glass or carbon composite laminates fail. Furthermore when these fibers fail due to excessive flexure the fiber retains some of its properties. Fiber failure due to transverse loading results in a kinking of the fibrils and not actual breakage of the fibers therefore, the fibers are still physically connected on either side of the transverse failure and thus the wire is still capable of transmitting some force to the teeth.

The tensile modulus of elasticity of orientated high modulus fibers with a low modulus matrix is determined primarily by the longitudinal elastic modulus of the continuous high modulus glass fibers. The longitudinal modulus of elasticity could be calculated from the equation (Weeton, Peters, and Thomas, 1987) for specimens in elastic deformation by the following equation where: the Elastic modulus of the composite longitudinally (EMCL)

EMCL = kfiber * Efiber + kmatrix * Ematrix

where

K = the respective volume fraction of filler or composite, ie. volume fraction,

and

E = the respective longitudinal elastic modulus of the filler or the continuous fiber reinforcement, PSI.

This equation is only valid if voids are not present, other wise corrections for voids must be made. (Weeton, Peters, and Thomas, 1987[114].)

An example of the application of this equation can be demonstrated by taking the fiber glass filler, in the proposed esthetic wires, as S-glass with a longitudinal modulus of 12.73 million psi and the modulus of the epoxy matrix of 400,000 to 1.2 million psi, the longitudinal modulus of elasticity can be calculated for an esthetic glass fiber reinforced wire of a given volume percent without having to manufacture it. Equations are also available to estimate the transverse modulus of elasticity of the composite. This is important to know since it is this direction in which longitudinal fibers would be primarily stressed during orthodontic

procedures. Glass fibers are unique as reinforcing materials because it's longitudinal modulus of elasticity is reported as equal to its transverse modulus of elasticity. Most fibers have a dramatic difference between the two. Therefore, many longitudinally oriented fibers while adding greatly to the longitudinal modulus may not add very significantly to the transverse modulus. For example, in the case of Kevlar ® fibers the transverse modulus is only 3% of longitudinal moduli. The difference between the longitudinal and transverse moduli of elasticity of certain materials is a manifestation of their unique molecular structure, ie. polymers fillers like Spectra 1000®. Polymers have high longitudinal moduli of elasticity because of their longitudinally oriented molecular chain structure, but because of this longitudinal orientation they have a low transverse moduli. Therefore the orientation of the filler fibers is critical when designing a composite system. Finally, when considering how the transverse strength of the laminate is effected by the reinforcement, one last possibility needs to be considered in future research; that is, mixing fibers. Because the continuous filaments vary substantially in their transverse properties it may be desirable to use combinations of different fibers to achieve a wire that has particular transverse and longitudinal properties.

Comparison of The Tensile Test and Bending Test

Since an ideal tensile test involves the uniaxial, centroidal loading throughout the cross sectional area of the specimen, tensile

characteristics of the material can be isolated. Because it involves stressing of all elements of the wire in a homogeneous manner, the tensile test tends to separate various characteristics of deformation phenomenon. On the other hand when considering the case of the bend test, both compression and tensile behavior occurs simultaneously in a non-homogeneous manner throughout the cross section of the specimen. Thus the deformation phenomenon as observed on the bend diagrams tends to present an obscured blending of characteristics. This is particularly true at higher stresses where yielding may occur on the compressive side of the specimen.

In the case of the bending test, the loading of the specimen results in a blend of compression and tensile characteristics because stresses are more variable throughout the specimen cross section. On the basis of this fact, information derived from the bend test is more difficult to interpret. The calculations using the data from the tensile test and the actual theoretical modeling of pure tensile deformation is simpler than the of the bend test. However, the experimental technique of the tensile test is more complicated than the bend test due to the testing apparatus involved. The inherent mechanical complexity of the test grips, clamps, the universal joint connecting the load cell to the upper grip, and the extensometer with its specimen clips makes the tensile test a physically more complicated procedure, as opposed to the simplicity of the three-point-bend test. Due to these complicating factors the exact repeatability of test conditions during the tensile test may be difficult to obtain. Additionally, in orthodontic applications wires are not subject to pure

tensile stress but, are subjected to bending and torsion type stresses. Consequently, bending tests have particular salience to orthodontics. Torsional tests were not done.

The results of the tensile test for the metal alloy wires tested in this protocol are in agreement with values reported in other orthodontic investigations for the tensile modulus of elasticity, and the yield strength at the 0.2% offset. There is, however, more variability in yield strength than the modulus of elasticity as reported by various authors. The method of determination of the yield strength involves the selection of an arbitrary offset or actually determining the linear limit of the initial linear portion of the stress-strain curve, which has not been standardized among the investigators.

The bending load-deflection diagram is transformed in to an approximated flexural stress-strain diagram by using the definition of the modulus of elasticity, $E=\sigma/\varepsilon$, and values of load and deflection are plugged in to the respective stress, σ, and strain, ε, coefficients (see Methods section for equations used), the curves plotted on this approximated flexural stress-strain diagram tend to be independent of wire sizes. Potentially, the constructed approximated flexural stress-strain curves from the bend test offer the wire designer the ability to enter variable parameters such as wire size into calculations and determine load deflection, stress-strain behavior for an arbitrary wire size. This can be done without requiring a separated load-deflection diagram for specific wire size that is to be considered. The orthodontic clinician may find it convenient to look at load-deflection diagram, since only four

standardized wire sizes are usually offered for orthodontic arch wires. However, this approach requires that wires of different sizes can be produced with uniform properties.

During the literature review it was noticed that there was variation in selecting a value for the amount of yield strength offset. Values of yield strength at 0.01% (Goiberg et al., 1977), 0.1% (Goiberg et al., 1977; Drake, et al., 1982; Asgharnia and Brantley, 1986), 0.2% (Burstone and Goiberg, 1983) offsets and at the proportional limit (Asgharnia, 1983) have been reported by the various orthodontic researchers. The decision where to select the yield strength offset should be carried out on the basis of whether or not it has clinical significance. Therefore, the offset should provide useful information, rather than accepting offsets, which were selected by other investigator with interests other than orthodontics. For example, the standard 0.2% yield strength offset used in general engineering purposes was selected specifically as it related to specific parameters of importance to engineering design applications. These parameters may not have the same significance when trying to define useful deformation parameters of orthodontic arch wire.

Several values for the arbitrary yield point offset were investigated before choosing the 0.2% offset in this study, which itself was initially selected to be consistent with engineering and other orthodontic reference values. It was noticed while trying to determine yield strengths at exactly where the proportional limit occurred there was great variation in determination of the corresponding yield strengths due to subtle differences in curve shapes between replications of the same test

conditions. The proportional limit is were a line drawn on the initial linear portion of the data curve of stress-strain diagrams becomes tangential to the initial curvilinear portions. Therefore, it was difficult to determine were this line became tangential, thus the assignment of a corresponding yield strength was difficult and subject to large variation. Since the proportional limit indicates where plastic deformation begins to occur it could have clinical relevance if the yield strength was chosen coincident with this point. Additionally the proportional limit could be of significance in the long term serviceability of an appliance because the effects of fatigue and creep increase the closer stress levels approach the proportional limit. The proportional limit is a difficult parameter to determine experimentally. On the other hand a 0.2% yield can be readily observed and may have clinical relevance when deforming the wires in clinical practice.

It was seen by observing the data from the materials presented here, that when the yield strength offset was chosen at a 0.2% strain, a significant amount of deflection had occurred which would be clinically visible. The approximated flexural yield strength strain at the 0.2% offset for all the materials studied here fell in the range between 0.0039", 0.15 mm's and 0.29", 1.10 mm's. The majority of trials fell around 0.010 ± 0.002 inches. This demonstrates that with the selection of a 0.2% strain offset, the clinician can approximate the 0.2% yield offset with visual detection of the actual deflection of the wire, and still not dramatically underestimate were the proportional limit of the wire occurs. However, this is a generalization and the previous observation does depend on were

the particular wire type in question falls in the above mentioned ranges of difference between the proportional limit and the approximated flexural yield strength at the 0.2% offset in terms of deflection ie. a clinically noticeable deflection.

Evaluation of Results

Burstone and Goiberg reported the yield strength at a 0.1% offset. It is expected that their yield strength value of 239,000 psi should be lower than the value of yield strength reported here at the 0.2% offset which was 320,000 psi. However, a lower value for the yield strength at the 0.2% offset was found. Considering this source of variation, the yield strength at a 0.2% offset reported here is slightly lower but within the ranges reported for the various metal alloy wires by other investigators.

The results presented here for the tensile modulus of elasticity of the wires used as experimental standards are in agreement with the work of Burstone and Goiberg[115] who reported for stainless steel a tensile yield strength of 239,000 psi and Asgharina and Brantley.[116] who reported for stainless steel a tensile modulus of 250000 psi. Drake et al.[117] reported for nickel titanium a tensile modulus of 4.3×10^6 psi. and Miura et al.[118] reported for nickel titanium a tensile modulus of 8.5×10^6 psi. These values are similar to the work presented here. Additionally, Burstone and Goiberg used tensile test instrumentation that is very similar to the one used by this author. By comparing the tensile test results of the other studies to the values presented for the steel wire in Table I, it is obvious

that the test protocol used here is accurate. It can isolate the mechanical properties of the tensile modulus of elasticity and yield strength for a given material.

The values reported here for the flexural modulus of elasticity and the flexural yield strength at the 0.2% offset were higher than for the corresponding values reported for the tensile test. The values for the flexural modulus of the wires can be found in Table 13 and Chart 1. That observation is consistent with the findings of other investigators (Ashgarnia and Brantley, 1986[116]).

The "superelastic" properties of the nickel-titanium wires as reflected in the discontinuous yielding region on the tensile test stress-strain were not seen with any of the experimental manufactured esthetic wires nor with the procured wires.

A material characteristic that was demonstrated on the tensile test was the amount of elongation a specimen would tolerate before it failed. The area under the curve from the onset of the load to the point of failure indicates the toughness of the materials. A relative comparison of material toughness can be done by examining Chart 7. Furthermore, it can be seen in Graphs 11 and 14 that the stainless steel specimen failed at an approximate strain of 0.022" or 2.2%, Sentalloy® medium, nickel-titanium failed at an approximate strain of 0.08" or 8%. Many of the esthetic specimens did exhibit failure during the bend test because they were too brittle.

Data collection was stopped at an arbitrary and variable point for the esthetic specimens; when the specimen appear to slip through the

supports, or an obvious maximal bending load had been found, or the material had failed. Some specimens obtained obvious maximal loads and then would show a decreased load as the test progressed beyond this point, and still before any slippage behavior was noticed. In these cases the test was stopped here before slippage was seen, but after the maximal bending load was obtained, see Graph 30.

In Chart 1 the standard wires describe clinically useful range, for the tensile modulus of elasticity, that extends from approximately 7×10^6 to 27×10^6 psi. Three of the experimentally manufactured fiber-reinforced wires, specifically Epon 828 Ancamine 1916 late post-gelation glass, Epon 828 Ancamine 1916 pre-gelation carbon, Epon 828 Ancamine K 61.B post -gelation carbon, were included in this range. The conventionally manufactured fiber optic cable reinforcement is also included this range.

Chart 2 describes the tensile yield strength at the 0.2% offset. All of the experimental manufactured fiber reinforced wires and the fiber optic cable reinforcement had tensile yield strengths at least as great as Nickel Titanium. The only wire that did not exhibit a yield strength at least as great as Nickel Titanium, was the braided glass fiber from Composetec.

The flexural moduli of elasticity, as determined by the Three Point Bend Test, for the standard and experimental wires is depicted in Chart 3. In the range that is described by Nickel Titanium and Stainless Steel, only the two carbon wires can be included. The glass fiber and Spectra 1000® wires, had moduli that were significantly less than that of Nickel Titanium. However, in certain clinical situations, the flexural moduli that these wires demonstrated could be useful.

When evaluating the flexural yield at the 0.2% offset, (Chart 4) only the fiber optic cable reinforcement fell into the range described by Stainless Steel and Nickel Titanium. All other wires showed a significantly less flexural yield strength. A low flexural yield strength will result in a wire with a very small working range. Thus, the poor flexural yield strength of these wires will be a significant problem that must be overcome before the fiber reinforced wires will be useful in common place orthodontic applications. This poor yield strength may be improved by better coupling agents or by using a different matrix, such as a polymer.

When evaluating the flexural strain at the 0.2% offset, (Chart 5) the range that is described is done so by TMA and Stainless Steel. Most of the experimentally manufactured wires fell short of being included in this range. However, the fiber optic cable reinforcement did demonstrate a flexural strain similar to that of Nickel Titanium.

When evaluating the flexural load at the 0.2% offset in Chart 6, all of the experimentally glass reinforced wires and the pre-gelation carbon wire demonstrated flexural loads that were greater than the flexural load demonstrated by TMA, but was less than the flexural load demonstrated by Stainless Steel. The flexural load of the post-gelation carbon reinforced wire and the Spectra 1000® wire, was approximately half of the Nickel Titanium wire. Again under certain clinical circumstances, these wires may useful. Which demonstrates that potentially similar properties can be obtained from composite wires with improved methods of fabrication.

Chart 7 is a graphical representation of all wires examined. The standard wires all had very small standard deviations indicating very good

manufacturing controls. The pultrusion die had little variability in die diameter dimensions as compared to the high degree of variability in wire dimensions demonstrated by the experimentally manufactured wires. This supports the hypothesis that the finished wire diameter is dependent upon several factors which include the number and size of fibrils in the roving, the viscosity of the matrix, the line tension during manufacture, and the diameter of the die.

The number and size of fibrils in the roving influence wire diameter by affecting the volume percent content of fibers in the wire form. A larger number of small diameter fibers can achieve a higher density of packing as compared to a small number of large diameter fibers. A high density of fibers, in the wire form, allows the composite to demonstrate properties more closely related to the fiber rather than the matrix. As discussed in the literature review, it is advantageous to construct a composite with a high number of fibers due to the higher probability of the composite containing flawless fibers, in a given cross section. The flawless fibers will demonstrate ideal properties and allow the composite to exhibit superior physical characteristics.

The viscosity of the matrix influences the wire diameter by effecting the hexagonal packing of the fibrils in the wire form. A more viscous matrix, hinders the packing process during wire manufacture, Thus, a low fiber density composite is produced and ,as discussed previously, a composite with a low fiber content will have poor properties when compared to a composite that has a high fiber content.

Line tension, during pultrusion, influences the wire form in two different manors. The first, is its influence on the hexagonal packing of the wire form. Higher tension, tends to promote a higher packing of the fibers and exclusion of the matrix. However, if line tensions are too high, the fibers can be damaged or the composite may be manufactured with a residual stress. Thus, resulting in a composite with poor properties.

The diameter of the die provides the wire form with its initial shape. Furthermore, the die initiates the packing process by removing excess matrix and collimating the fibrils. This, in conjunction with, the factors mentioned previously, determine the fiber density in the composite.

Evaluation of Individual Composite Wire-forms

Evaluation of Epon 828, Ancamine 1916 pre-gelation - glass wire-form demonstrated a tensile modulus of elasticity of approximately 6.18 million psi. When its tensile modulus is compared to that of Sentalloy®, medium ® (7.05 million psi) a significant degree of similarity is noted. However, when evaluating the yield strength of Epon 828, Ancamine 1916 pre-gelation - glass wire-forms useful comparisons cannot be done because the material failed before reaching a 0.2% offset. The experimental material's ultimate yield strength is 87,080 psi. The large standard deviation in determining the ultimate yield strength is due to inconsistent modes of failure in the experimental wire-form. In one of the testing runs, the material appeared to undergo fiber failure. This mode of failure resulted in a relatively high ultimate yield strength,

However, the remaining two (2) runs demonstrated matrix failure which resulted in a relatively low ultimate yield strength. When the results of these three runs were compiled a relatively large standard deviation resulted.

Referring to Table 13 when comparing the approximate flexural modulus of Epon 828, Ancamine 1916 pre-gelation, glass wire-form to that of the standard wires yielded non significant results. The experimental manufactured wire's flexural modulus of 5.83 million psi was significantly different from the flexural modulus of stainless steel, NiTi, and TMR standards. This observation also holds true for the flexural yield strength, flexural load, and the flexural strain at the 0.2% offset.

The experimental wire form manufactured with Epon 828, Ancamine 1916 post-gelation, glass demonstrated consistent loading when tested for tensile properties. The standard deviation for the tensile modulus of the experimental manufactured wire was 0.1 x 10^6 psi. This was the smallest standard deviation of all wires tested. However, when evaluating the ultimate yield strength of the composite, the experimental composite demonstrated one of the highest standard deviations, 16.41 x 10^6 psi for tensile yield strength. Data describing these findings can be found in Table 11. This large standard deviation is a result of two different failure modes. The composite demonstrated fiber failure in the first two runs, and in the last run it demonstrated matrix failure. This combination of failure modes resulted in a large standard deviation.

The experimental wire's flexural modulus of elasticity (6.69 million psi) tested significantly different from the standard wires. This was also

true for the flexural load (0.19127 ± 0.02962 Lbf), and the flexural yield strength (6,700 ± 1,760 psi) at the 0.2% offset. However, the flexural strain (0.0185 ± 0.00239 in/in) at the 0.2% offset is significantly similar to the flexural strain of the 0.014 Tru-Chrome stainless steel wire (0.01144 ± 0.0003 in/in) and to the flexural strain of the TMA standard wire (0.0126 ± 0.000136 in/in). The similarity of the experimental wire's flexural strain to TMA may be spurious. It should not be interpreted as indicating similar function in an orthodontic application. This relationship is due to the relatively large standard deviation of the TMA standard. A larger sample of the TMA standard wires might allow clarification of the relationship between the experimental wire and the TMA wire through a more accurate determination of the standard deviation. Finally, functional similarity is dependent upon similarity between wires from both the yield strength and flexural strain.

The late post -gelation version of Epon 828, Ancamine 1916, glass, reinforced composite wire-form had the highest tensile modulus of elasticity 6.83 ± 0.71 x 10^6 psi of all the glass reinforced wires. Significance testing using the Students *t*-Test revealed a significant degree of similarity to Sentalloy®, medium (7.05 ± 0.62 x 10^6 psi). Due to pre-mature failure of the experimental wire form, tensile yield strength at the 0.2% offset was not determined. The ultimate strength was 91,310 ± 6,610 psi. Again the relatively large standard deviation is a result of the material undergoing two different types of failure. The first experimental run resulted in the wire form undergoing matrix failure. In the following two runs, the wire form underwent fiber failure. The flexural modulus of

elasticity for the experimental manufactured wire was 6.4 ± 0.38 x 10^6 psi. and as such, it tested significantly different from the standard wires when evaluating the flexural modulus of elasticity, and the flexural yield strength and flexural load at the 0.2% offset. Significance testing evaluating the flexural strain at the 0.2% offset (0.01057 ± 0.00089 in/in) was significantly similar to the flexural strain of the Tru-Chrome® stainless steel (0.01144 ± 0.0003 in/in), Sentalloy, medium® (0.01284 ± 0.00265 in/in) and TMA (0.0126 ± 0.00136 in/in). Therefore, with respect to strain characteristics,, Epon 828, Ancamine 1916, late post -gelation, glass wire-forms are very similar to materials currently used in orthodontics.

The experimental manufactured wires fabricated with carbon as the reinforcing material had many interesting features. Frequently, these wires had properties that were intermediate between stainless steel and TMA when compared to the standard wires. However, their properties were significantly different as to constitute a nonsignificant result when evaluated by Students *t*-test. An example of this can be seen with the experimental wire formed from Epon 828, Ancamine 1916, pre- gelation, carbon. (See Chart # 1) Epon 828, Ancamine 1916, pre- gelation, carbon wire-forms had a tensile modulus of 17.7 ±0.79 million psi. Significance testing revealed this wire was not similar to the standard wires $p \leq 0.001$. The stainless steel evaluated here which had a tensile modulus of 27.06 ±0.71 million psi. and the TMA tested here which had a tensile modulus of 11.75 ± 0.21 million psi. Therefore, this experimentally manufactured wire has a tensile modulus that is within the range that is currently used in the orthodontic field. When evaluating the tensile yield strength at the 0.2%

offset for Epon 828, Ancamine 1916, pre- gelation, carbon wire-forms again these wires have intermediary properties that bridges the gap between stainless steel wires and TMA or NiTi. If these wires could by manufactured with a consistent cross-sectional diameter these wires might be useful in certain situations with the provision that they could by rendered esthetic. Epon 828, Ancamine 1916, pre- gelation, carbon wires have a tensile yield strength at the 0.2% offset of 125.81 ± 0.17 x 10^3 psi. The nickel titanium wire had an offset strength of 42.6 ± 0.24 x 10^3 psi. and the TMA wire demonstrated an offset yield strength of 165.53 ±0.22 x 10^3 psi. Again the empirical conclusion is that the experimental wire is different from both of the standards but the wire does demonstrate an offset yield strength that is within the range that is used clinically.

Flexurally, Epon 828, Ancamine 1916, pre- gelation, carbon again falls into the not significantly similar to the standards category, Epon 828, Ancamine 1916, pre- gelation, carbon wires demonstrate a flexural modulus of 14.8 ± 0.65 million which places the wire between TMA with a flexural modulus of 12.46 ± 0.05 million psi. and the stainless steel standard with a flexural modulus of 27.76 ± 1.58 million psi. Significance testing confirms that the wire is different from the standards at $p \leq 0.001$ level of confidence. This result, however, does not mean that the wire is clinically useless, as demonstrated by the experimental wires intermediate status when compared to the standards. With respect to the flexural yield strength (55.7 ± 3.53 x 103 psi.) and flexural strain at the 0.2% offset (0.00594 ±0.00063 in/in) the experimental wire manufactured from Epon 828, Ancamine 1916, pre- gelation, carbon was statistically

different from the standards and it revealed inferior properties when evaluated. Epon 828, Ancamine 1916, pre- gelation, carbon wire-form when evaluated for flexural load at the 0.2% offset characteristics (0.14577 ± 0.00826 Lbf) revealed a significant difference from the standard wires, however the load range that the experimental wire demonstrated appears to be in a useful range clinically. That range would be described as the range defined by TMA and stainless steel. If the problem of a low flexural yield strength and flexural load could be resolved this epoxy fiber combination would appear to have significant potential for practical clinical applications.

The wire-form manufactured from Epon 828, Ancamine K61.B, post-gelation, carbon had a tensile modulus of 21.7 ± 1.61 million psi. While this is an impressive tensile modulus for a composite it is 5.36 million psi. less than the tensile modulus for stainless steel (27.06 ± 0.71 million psi). Students t-test confirmed this as a significant difference. This composite failed before reaching the 0.2% offset. Its ultimate yield strength is 192.45 ± 31.66 x 10^3 psi. This wire-form, like the glass reinforced wire-forms, failed by two different methods. The first and third run the wire-form appeared to fail due to fiber failure. The second run appeared to exhibit matrix failure and as with the glass fibers when the data was compiled to determine the materials ultimate strength a large standard deviation resulted.

Evaluation of the flexural modulus of this composite yielded significant similarity to only one of the standard wires. The flexural modulus of the Epon 828, Ancamine K61.B, post- gelation, carbon wire-

form was 13.46 ± 2.74 million psi. The one standard wire that most closely resembled the composites flexural modulus was the 0.018 TMA. TMA had a Flexural modulus of 12.46 ± 0.05 million psi. Significance testing confirmed this observation. The flexural yield strength (11.8 ±1.38 x 10^3 psi.) and the flexural strain (0.003 ±.00013 in/in) at the 0.2% offset were found not to be significant nor were they in a clinically useful range as described by the standard wires. The flexural load at the 0.2 % offset was found to be similar to the Sentalloy®, medium nickel titanium wire whose flexural load was 0.04322 ±0.00209 Lbf. Considering this wires short comings in several areas it is the authors opinion that this particular combination of epoxy and fiber will not have a potential for clinical use unless substantial changes are incorporated into the composite.

The composite wire-form manufactured from Spectral 1000® and Epon 828, Ancamine 1916, with a 24 hour post cure behaved in a somewhat unpredictable manner with respect to its physical properties. It's Tensile modulus was the lowest of all material tested (4.7 ±0.64 x 10^6 psi). However, its tensile strength at the 0.2% offset was the highest of all materials tested with a tensile yield strength at the 0.2% offset of 371.66 ± 0.78 x 10^3 psi. This figure is below the published value of 435 x 10^3 psi.[119] The discrepancy between the published and actual testing values is most probably due to problems with the epoxy matrix or low fiber volume percent. However, when the flexural properties of this composite are evaluated the properties are similar to published values indicating that the fiber volume percent are similar and therefore the problem is most likely with the epoxy matrix. During the manufacture of the spectra

revealed no significant similarities to any of the standard wires, with respect to flexural modulus, flexural yield strength, flexural load nor flexural strain at the 0.2% offset. While theoretically this reinforcement has the best potential as an esthetic archwire, until a better FDA approved matrix system is developed this reinforcement material is a very poor candidate for an esthetic archwire.

The fiber optic cable reinforcement demonstrated consistent desirable results. Its tensile modulus of elasticity was 6.68 ± 0.69 million psi and this wire was statistically similar to the tensile modulus of elasticity for Sentalloy, medium®. The cable's tensile yield strength (183,660 ± 830 psi) at the 0.2% offset was similar to the tensile yield strength of 0.018 TMA.

The Cable's flexural modulus 7.59 ± 0.62 million psi was not similar to any of the standard wires. However the Flexural yield strength at the 0.2% offset (81,100 ± 7,600 psi) was very closely related to the Flexural yield strength at the 0.2% offset of Sentalloy Medium ® (82,000 ± 3,370 psi). Furthermore the flexural strain at the 0.2% offset (0.01283 ± 0.00005 in/in) was similar the flexural strain of both Sentalloy®, medium (0.01284 ± 0.00265 in/in) and TMA (0.01260 ± 0.00136 in/in). Conversely the flexural load at the 0.2% offset (0.0109 ±0.00251 Lbf) was out side of the range of any of the standard wires therefore, the load that the cable produced at the 0.2%b offset was below a clinically useful range.

Finally the last wire-form evaluated was the braided glass fiber from Composetec. This wire form demonstrated poor properties in all categories. All properties were below those of any of the standard wires

The variability of the final diameter of the wire-forms was probably due to the relatively low fiber loading of the die, volume percentage. Low fiber loading of the die allowed large variation in the amount of epoxy that surrounded the fibers. This variation, in turn, resulted in a large variation in finished diameters of the wires. Future testing should include manufacturing runs that have different numbers of fibers of the same reinforcement in the same matrix to allow testing of this hypothesis. Another variation of this experiment would be to have the same number of fibers in the same matrix and vary the diameter of the die. This would allow evaluation of the effect of matrix upon the composite and it would also provide information as to what extent die diameter and percent fiber loading can be varied and still produce a clinically useful product. Additionally, wires produced from runs with differing fiber numbers within the same matrix would allow testing to determine the clinical effect, of varying the number of fibers in a composite, on the tensile and flexural moduli and the finished wire diameter.

of the polymers increases the creep resistant properties in composite materials.[6] On the other hand static creep could be readily investigated for these wires when subject to a static load in flexure.

Because these wires are brittle, alternative matrixes need to be investigated. Polymer resin matrixes are the most likely candidate due to the fact that most of the polymers undergo significant plastic deformation before they fail unlike the epoxies which tend to fracture or shatter. The other advantage of a resinous matrix would be the materials cohesive property. Even if the wire-form failed completely these wire-forms should be resistant to the shattering that is seen with an epoxy matrix. The only significant drawback to utilizing a polymer matrix is the general lack of sizing for the rovings. Without the use of sizing on the rovings there is no direct method of coupling the fibers to the matrix, therefore load sharing by the fibers is diminished. The factor that needs to be evaluated here is to what extent the sizing agents actually contribute to the composites final properties and to what extent sizing agents inhibit or increase creep problems. From the manufacturing side of things polymer resins are much more difficult to work with, for several reasons. Polymer resins have very high viscosities and as discussed earlier, high viscosities are detrimental to achieving volume high percent loading. Additionally, polymer resins tend to be sensitive to high temperatures which further complicates achieving good fiber wet-out.

The final consideration that needs to be accounted for is the effect of moisture on these wires. Glass and carbon filaments are subject to wicking, Water that is wicked into the composite may effect the bonds

between the sizing and or the epoxy itself. Therefore, all mechanical tests should eventually be carried out in a water saturated environment to determine the precise effect that water, and/or saliva, has on the wire-forms physical characteristics. However , if the proposed methodology turns out to be impractical the wire may by stored in a water environment and tested while moist in a dry environment.

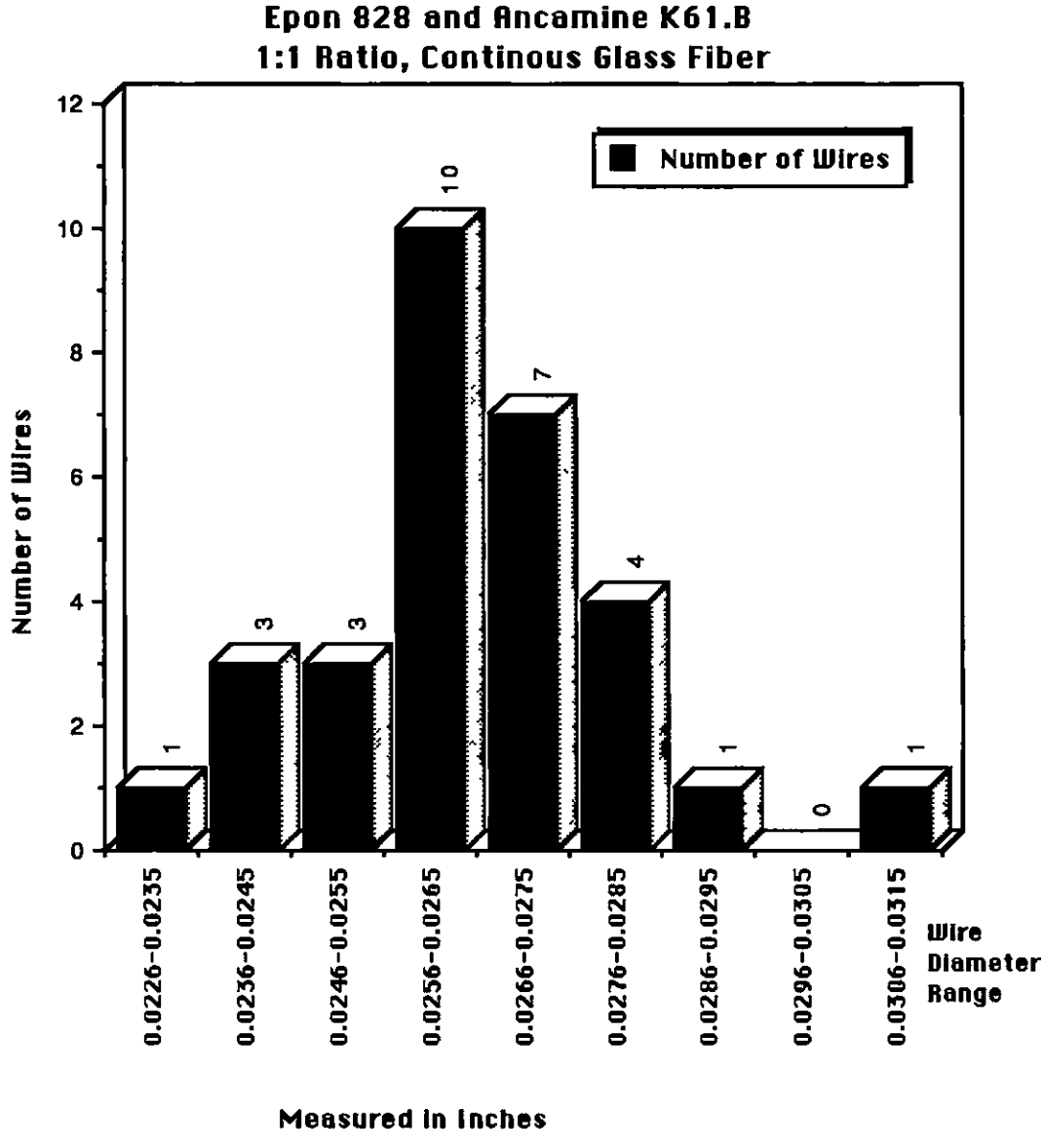
Summary and Conclusions

Continuous reinforced wire-form products have the potential to replace some non-esthetic orthodontic wires in a properly controlled environment. As was demonstrated in Charts 1 through 7 many of the fiber reinforced wires have properties that are in the spectrum that is currently used clinically. The glass reinforced wires have a stiffness close to steel when the wire-forms are cured properly. The carbon reinforced wires have the potential to be stronger than steel, however, their brittleness is a problem. Perhaps the most promising material in this study was the extended chain polyethylene. Though its properties were less than that of the standards with the exception of tensile modulus this material is not as brittle as the other materials. When this material failed during flexure it did not shatter as did some of the glass and carbon reinforced wires did. Thus in the proper matrix this material may prove to be ideal.

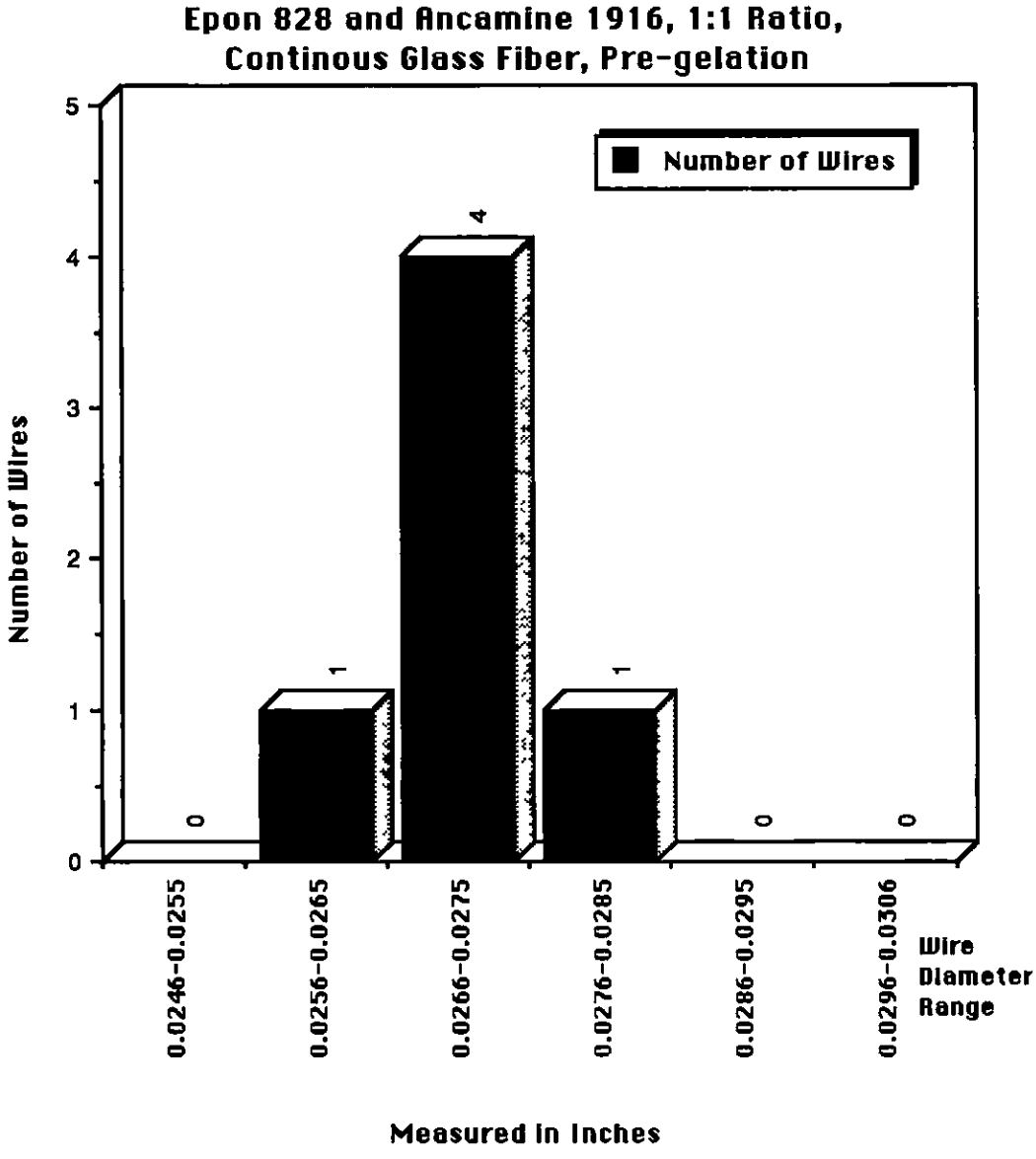
The primary manufacturing difficulties that must be overcome are controlling the epoxy depth of cure and achieving good fiber wet-out. This may be done by achieving slower pulling speeds, longer effective curing times, or by utilizing a multi catalyst system that can be initiated at lower temperatures. Achieving good fiber wet-out is simply a matter or developing an effective method for coating the rovings with the epoxy. Nevertheless, until these problems are dealt with in an effective manner the true potential of these wires will not be known. With two stage epoxies on the horizon and thermoplastic matrices as possibilities for wire-form matrices, post-forming of the wires will be a reality in the near

future. This will allow the use of these proposed esthetic wires in all types of orthodontic mechanics. This research endeavor has pointed the way to several possible new esthetic advances and it is the author's hope that follow-up studies are conducted to develop a realistic esthetic orthodontic archwire.

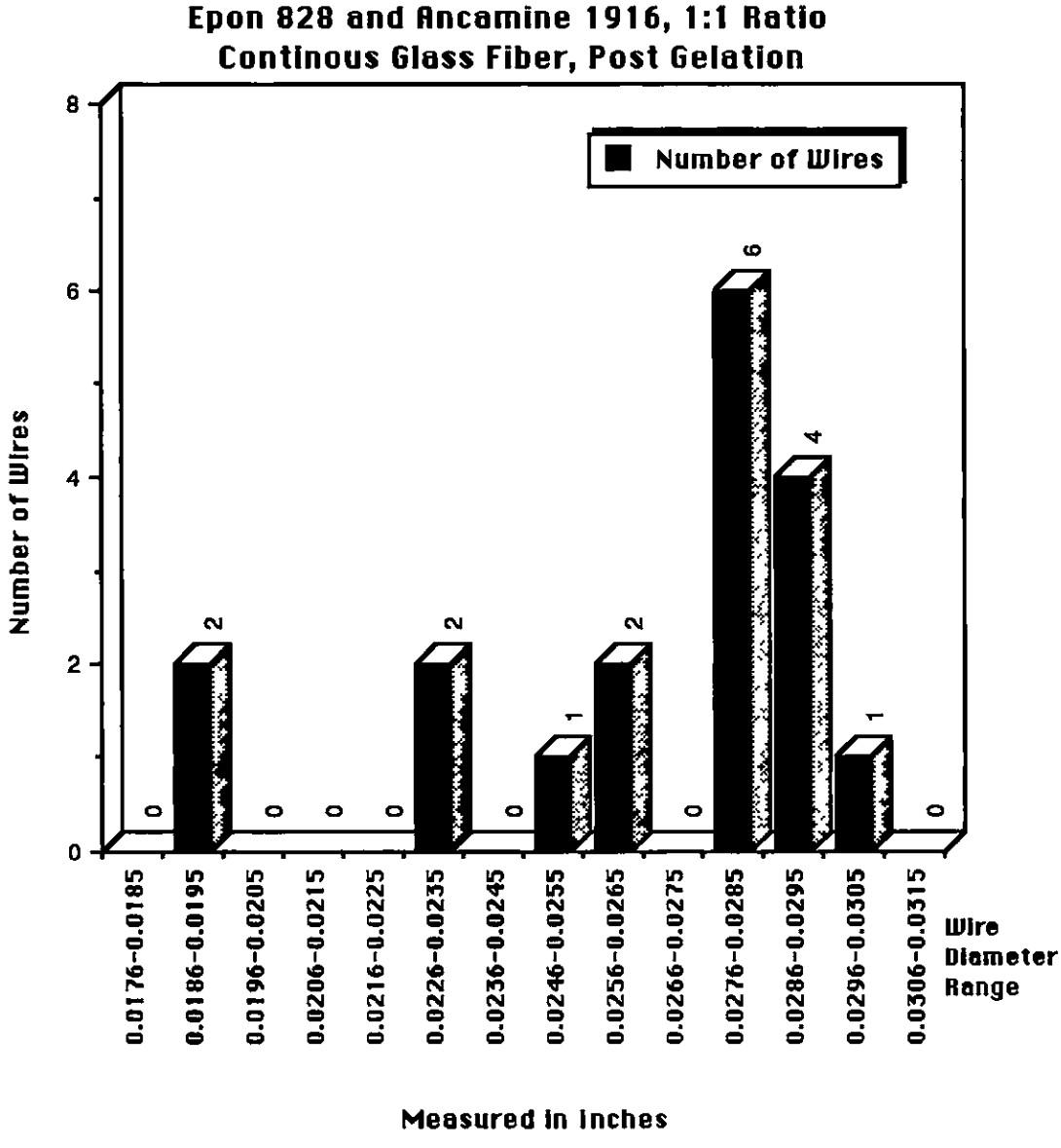
Graph 1


Epon 828 and Ancamine K61.B
1:1 Ratio, Continous Glass Fiber
Number of Wires
Number of Wires
0
2
4
6
8
10
12
1
3
3
10
7
4
1
0
1
0.0226-0.0235
0.0236-0.0245
0.0246-0.0255
0.0256-0.0265
0.0266-0.0275
0.0276-0.0285
0.0286-0.0295
0.0296-0.0305
0.0306-0.0315
Wire Diameter Range
Measured in Inches

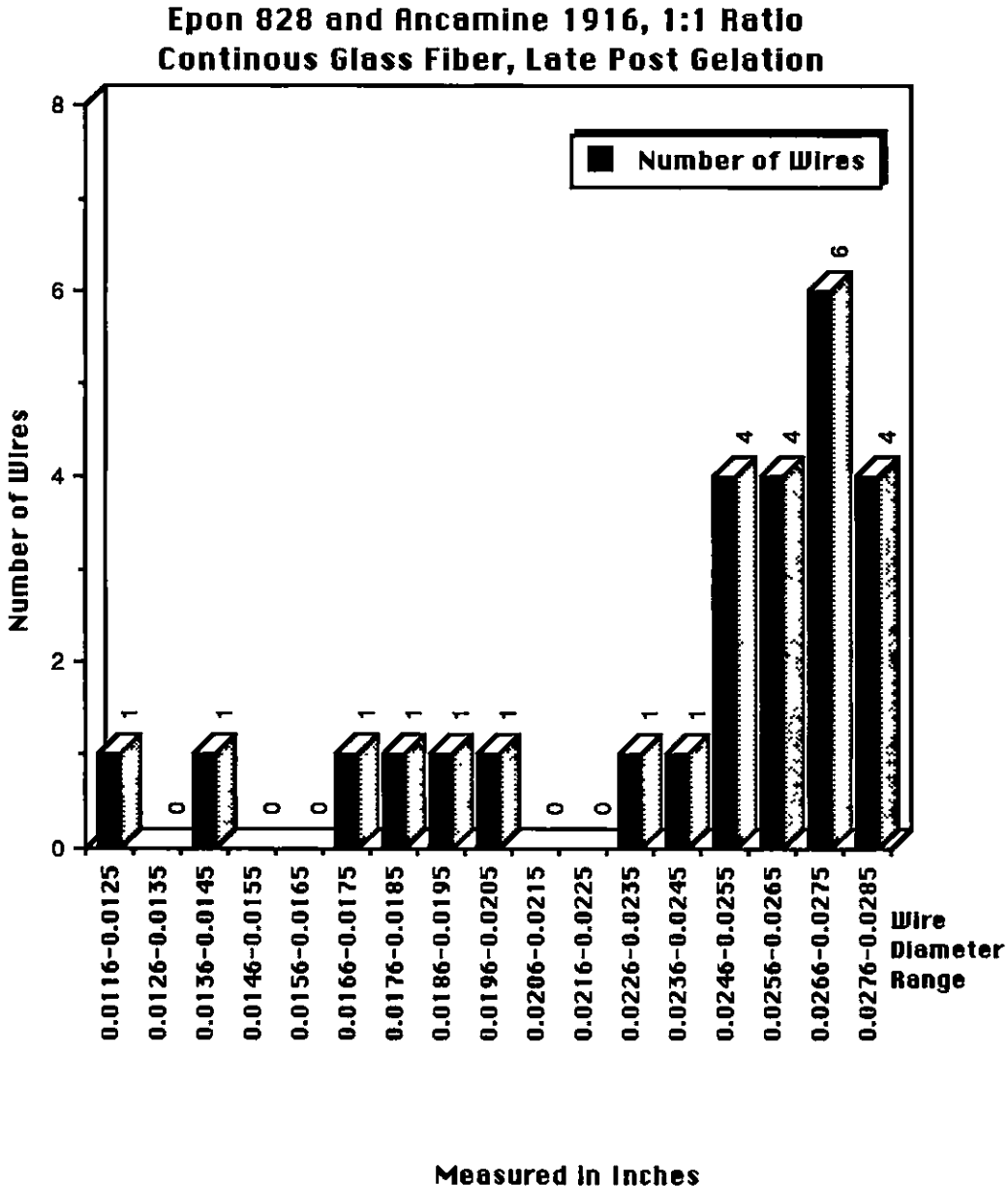
Graph 2


Epon 828 and Ancamine 1916, 1:1 Ratio,
Continous Glass Fiber, Pre-gelation
Number of Wires
Number of Wires
5
4
3
2
1
0
0
1
4
1
0
0
0.0246-0.0255
0.0256-0.0265
0.0266-0.0275
0.0276-0.0285
0.0286-0.0295
0.0296-0.0306
Wire Diameter Range
Measured in Inches

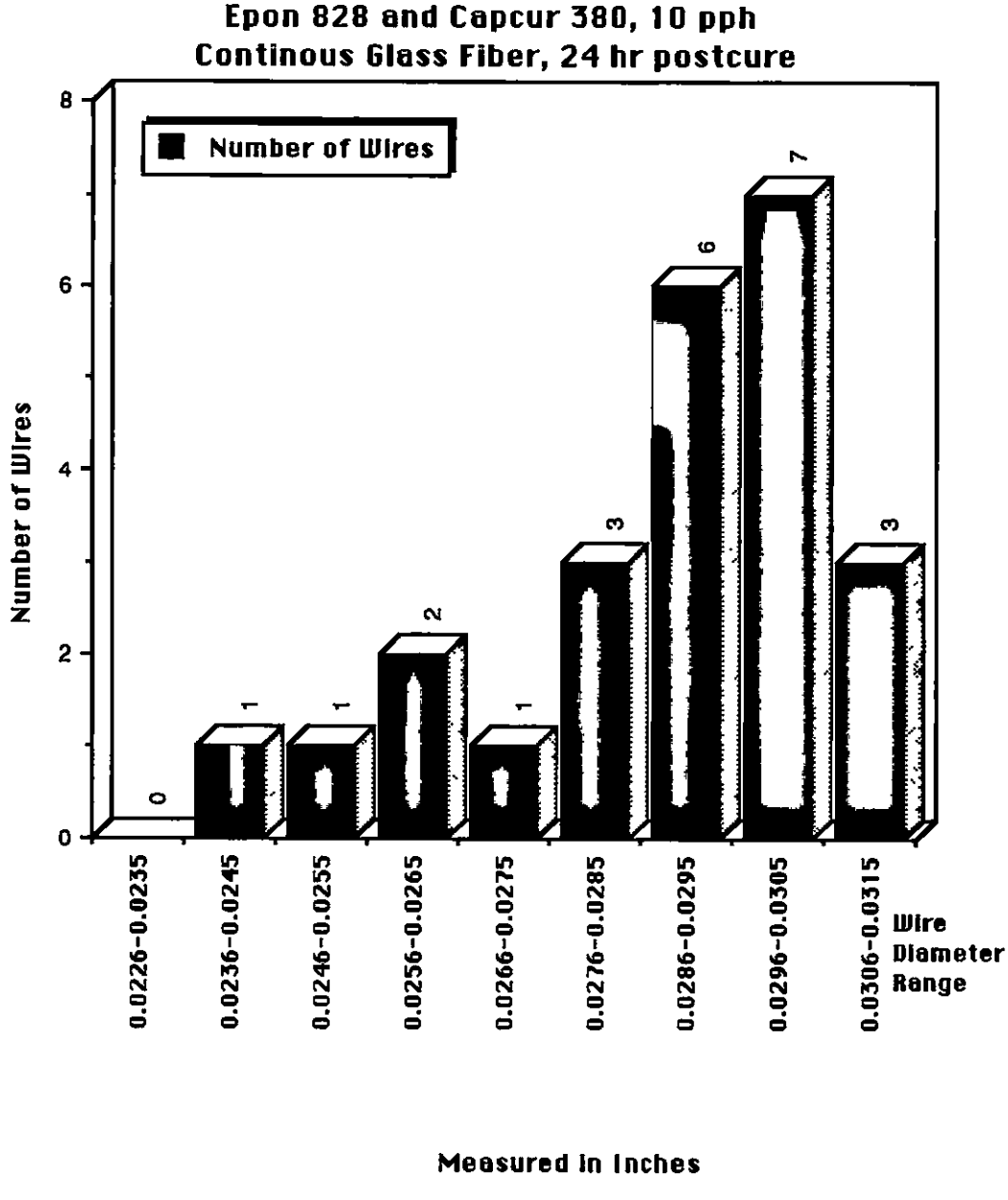
Graph 3


Epon 828 and Ancamine 1916, 1:1 Ratio
Continous Glass Fiber, Post Gelation
Number of Wires
Number of Wires
0
2
4
6
8
0
2
0
0
0
2
0
1
2
0
6
4
1
0
0.0176-0.0185
0.0186-0.0195
0.0196-0.0205
0.0206-0.0215
0.0216-0.0225
0.0226-0.0235
0.0236-0.0245
0.0246-0.0255
0.0256-0.0265
0.0266-0.0275
0.0276-0.0285
0.0286-0.0295
0.0296-0.0305
0.0306-0.0315
Wire Diameter Range
Measured in Inches

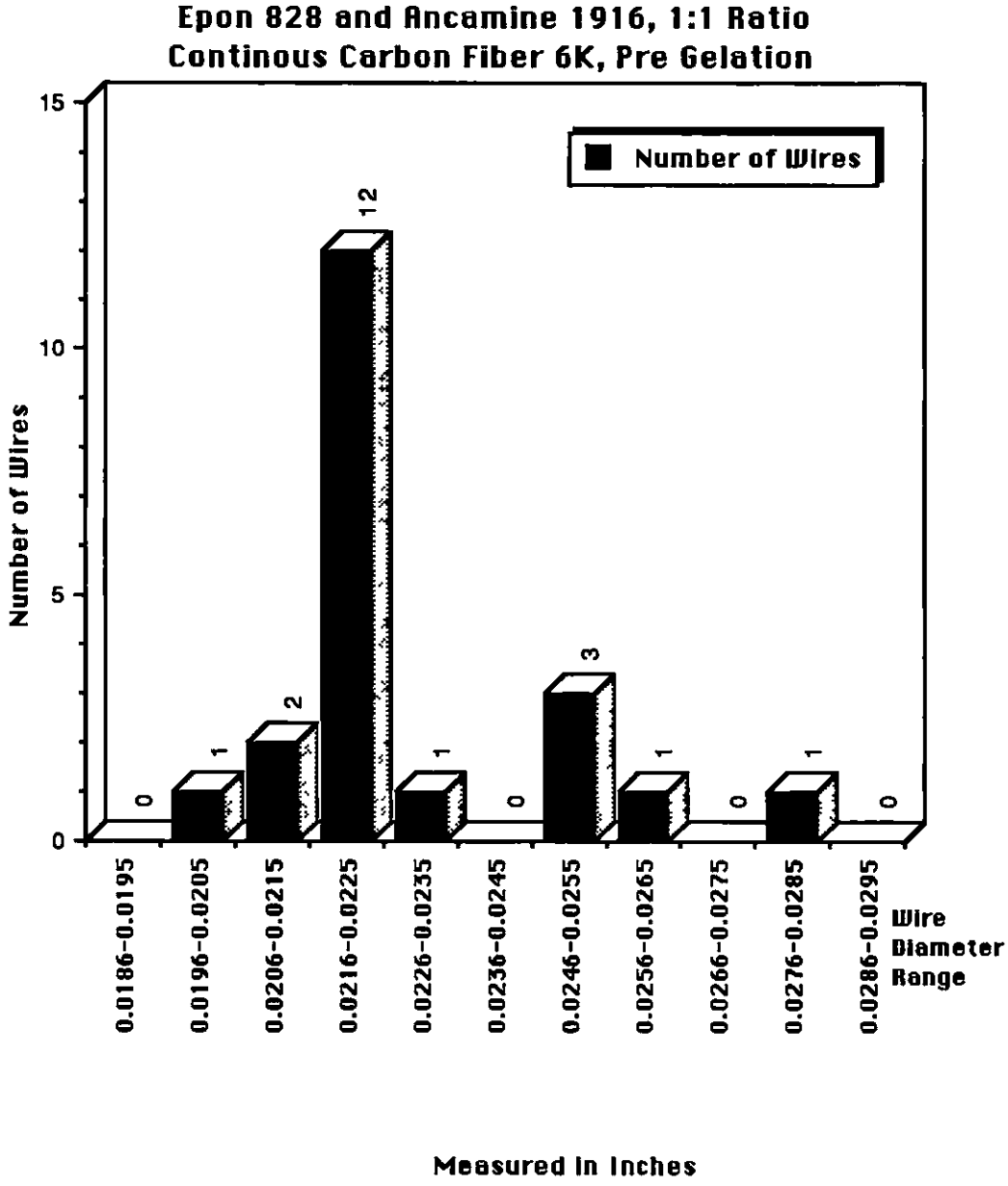
Graph 4


Epon 828 and Ancamine 1916, 1:1 Ratio
Continous Glass Fiber, Late Post Gelation
Number of Wires
Number of Wires
0
2
4
6
8
1
0
1
0
0
1
1
1
1
0
0
1
1
4
4
6
4
0.0116-0.0125
0.0126-0.0135
0.0136-0.0145
0.0146-0.0155
0.0156-0.0165
0.0166-0.0175
0.0176-0.0185
0.0186-0.0195
0.0196-0.0205
0.0206-0.0215
0.0216-0.0225
0.0226-0.0235
0.0236-0.0245
0.0246-0.0255
0.0256-0.0265
0.0266-0.0275
0.0276-0.0285
Wire Diameter Range
Measured in Inches

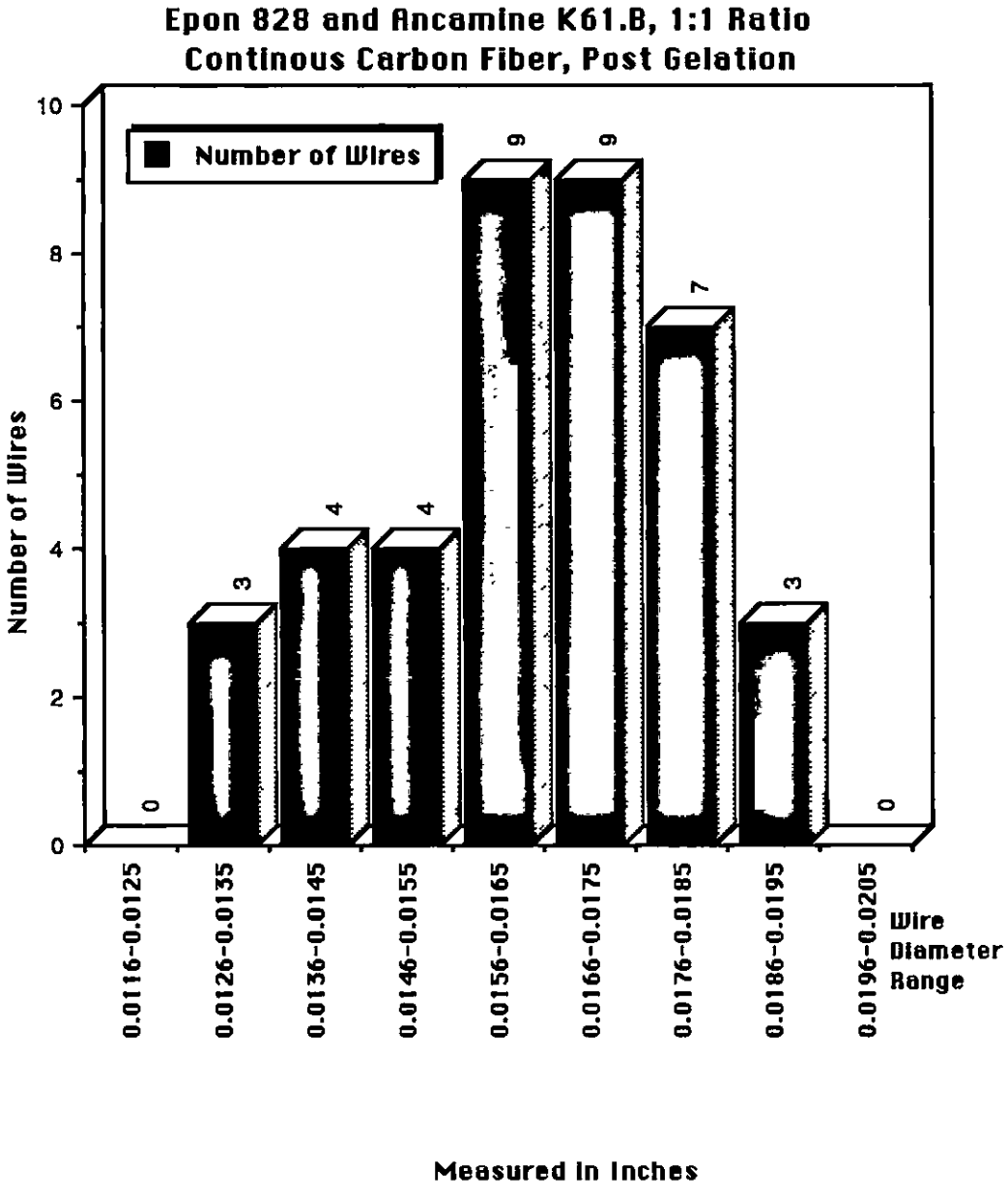
Graph 5


Epon 828 and Capcur 380, 10 pph
Continous Glass Fiber, 24 hr postcure
Number of Wires
Number of Wires
0
2
4
6
8
0
1
1
2
1
3
6
7
3
0.0226-0.0235
0.0236-0.0245
0.0246-0.0255
0.0256-0.0265
0.0266-0.0275
0.0276-0.0285
0.0286-0.0295
0.0296-0.0305
0.0306-0.0315
Wire Diameter Range
Measured in Inches

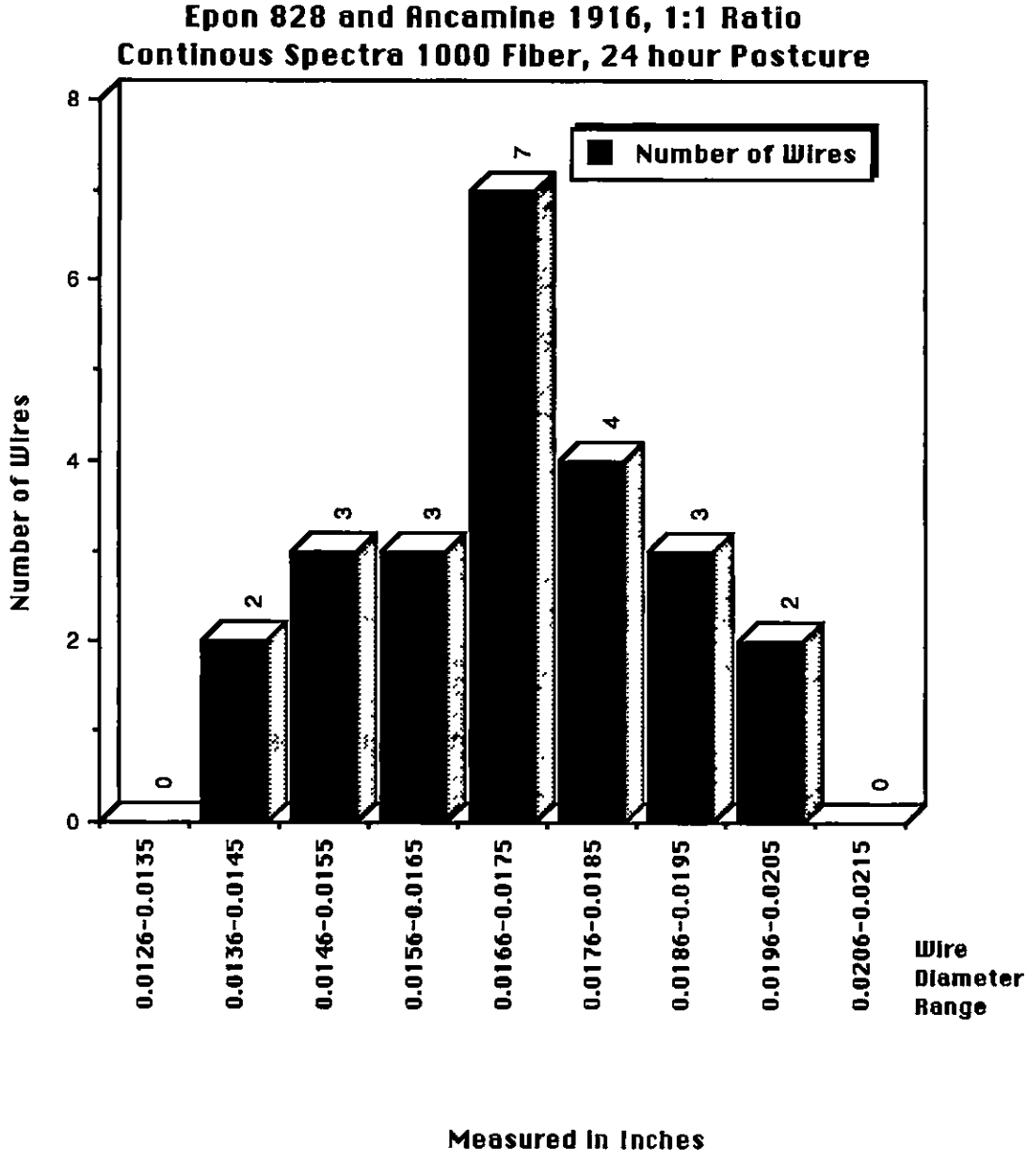
Graph 6


Epon 828 and Ancamine 1916, 1:1 Ratio
Continous Carbon Fiber 6K, Pre Gelation
Number of Wires
15
10
5
0
0
1
2
12
1
0
3
1
0
1
0
0.0186-0.0195
0.0196-0.0205
0.0206-0.0215
0.0216-0.0225
0.0226-0.0235
0.0236-0.0245
0.0246-0.0255
0.0256-0.0265
0.0266-0.0275
0.0276-0.0285
0.0286-0.0295
Wire Diameter Range
Measured In Inches

Graph 7


Epon 828 and Ancamine K61.B, 1:1 Ratio
Continous Carbon Fiber, Post Gelation
Number of Wires
Number of Wires
10
8
6
4
2
0
0
3
4
4
9
9
7
3
0
0.0116-0.0125
0.0126-0.0135
0.0136-0.0145
0.0146-0.0155
0.0156-0.0165
0.0166-0.0175
0.0176-0.0185
0.0186-0.0195
0.0196-0.0205
Wire Diameter Range
Measured In Inches

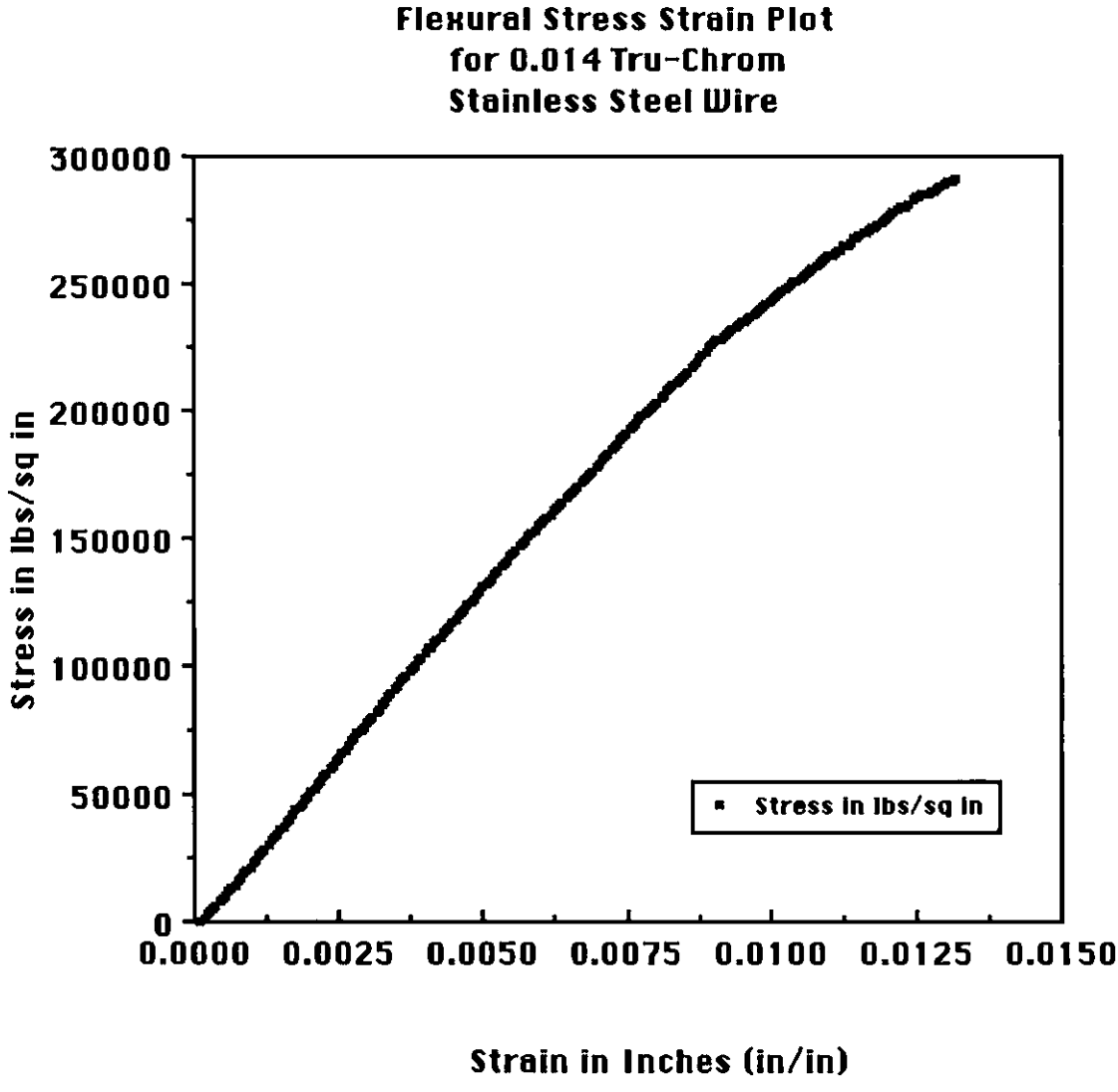
Graph 8


Epon 828 and Ancamine 1916, 1:1 Ratio
Continous Spectra 1000 Fiber, 24 hour Postcure
Number of Wires
Number of Wires
0
2
4
6
8
0
2
3
3
7
4
3
2
0
0.0126-0.0135
0.0136-0.0145
0.0146-0.0155
0.0156-0.0165
0.0166-0.0175
0.0176-0.0185
0.0186-0.0195
0.0196-0.0205
0.0206-0.0215
Wire Diameter Range
Measured in Inches

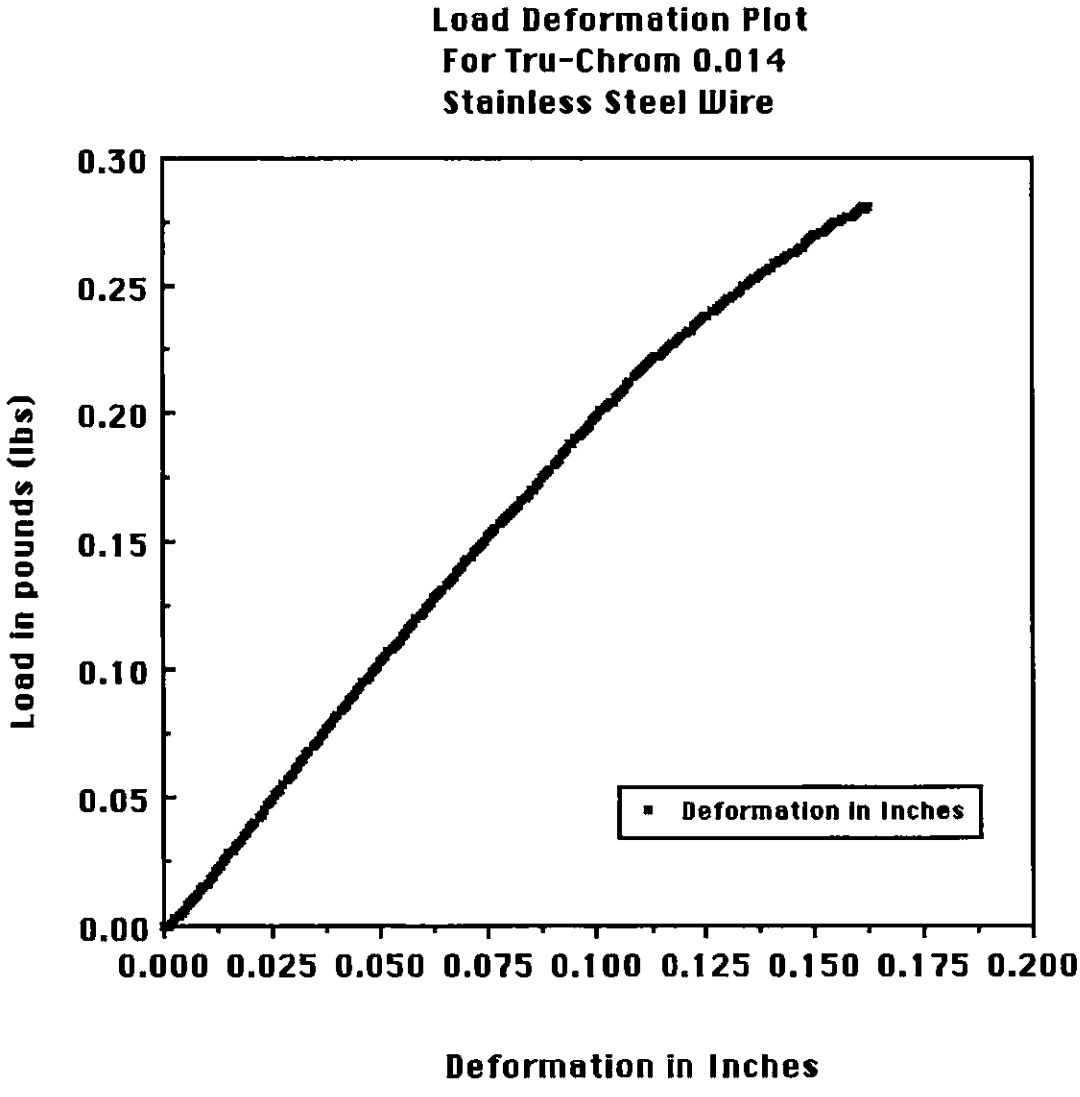
Appendix 2

Stress Strain Curves of Tested Materials

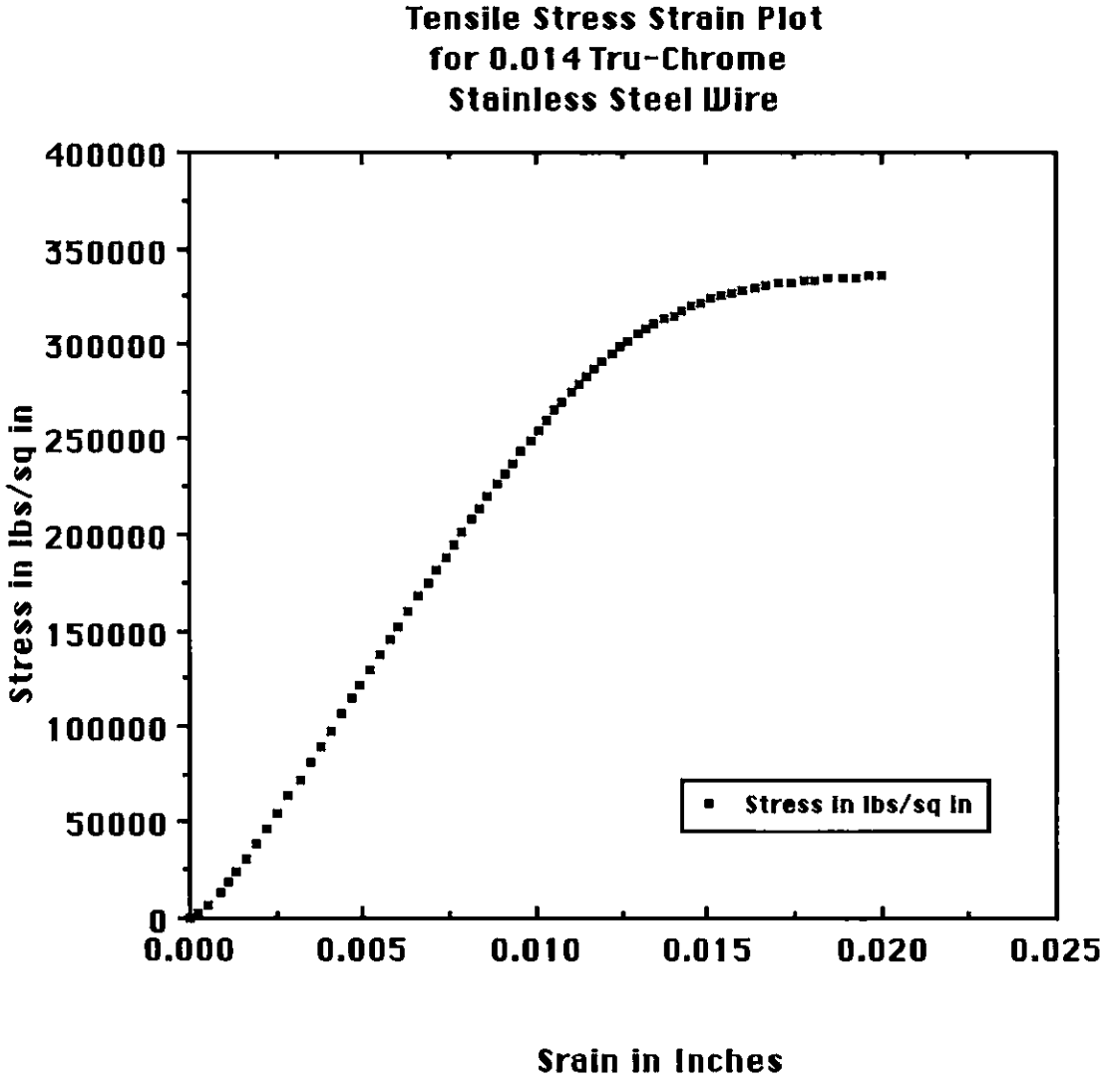
Graph 9


Flexural Stress Strain Plot
for 0.014 Tru-Chrom
Stainless Steel Wire
300000
250000
200000
150000
100000
50000
0
Stress in lbs/sq in
0.0000
0.0025
0.0050
0.0075
0.0100
0.0125
0.0150
Strain in Inches (in/in)
Stress in lbs/sq in

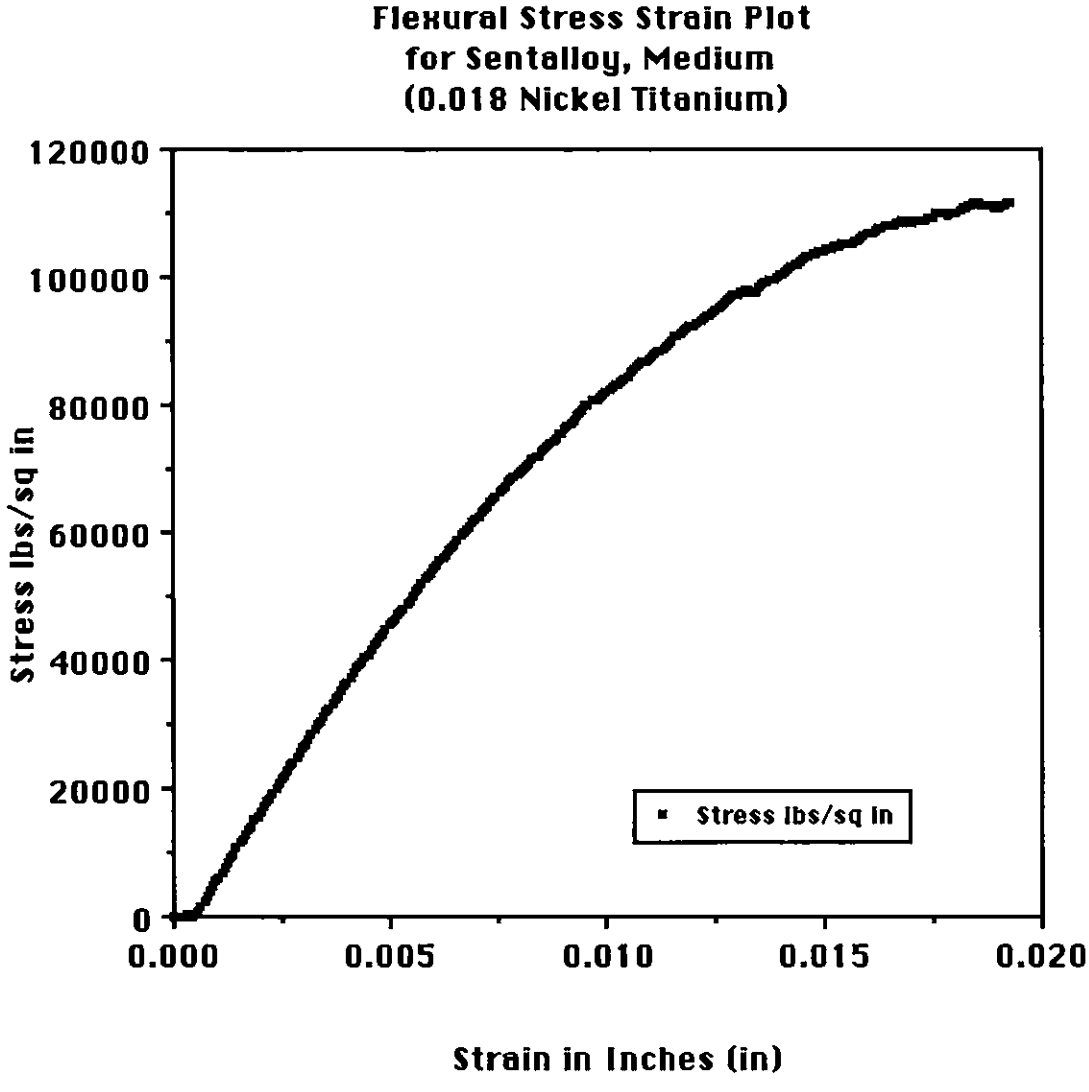
Graph 10


Load Deformation Plot
For Tru-Chrom 0.014
Stainless Steel Wire
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Load in pounds (lbs)
0.000 0.025 0.050 0.075 0.100 0.125 0.150 0.175 0.200
Deformation in Inches
Deformation in Inches

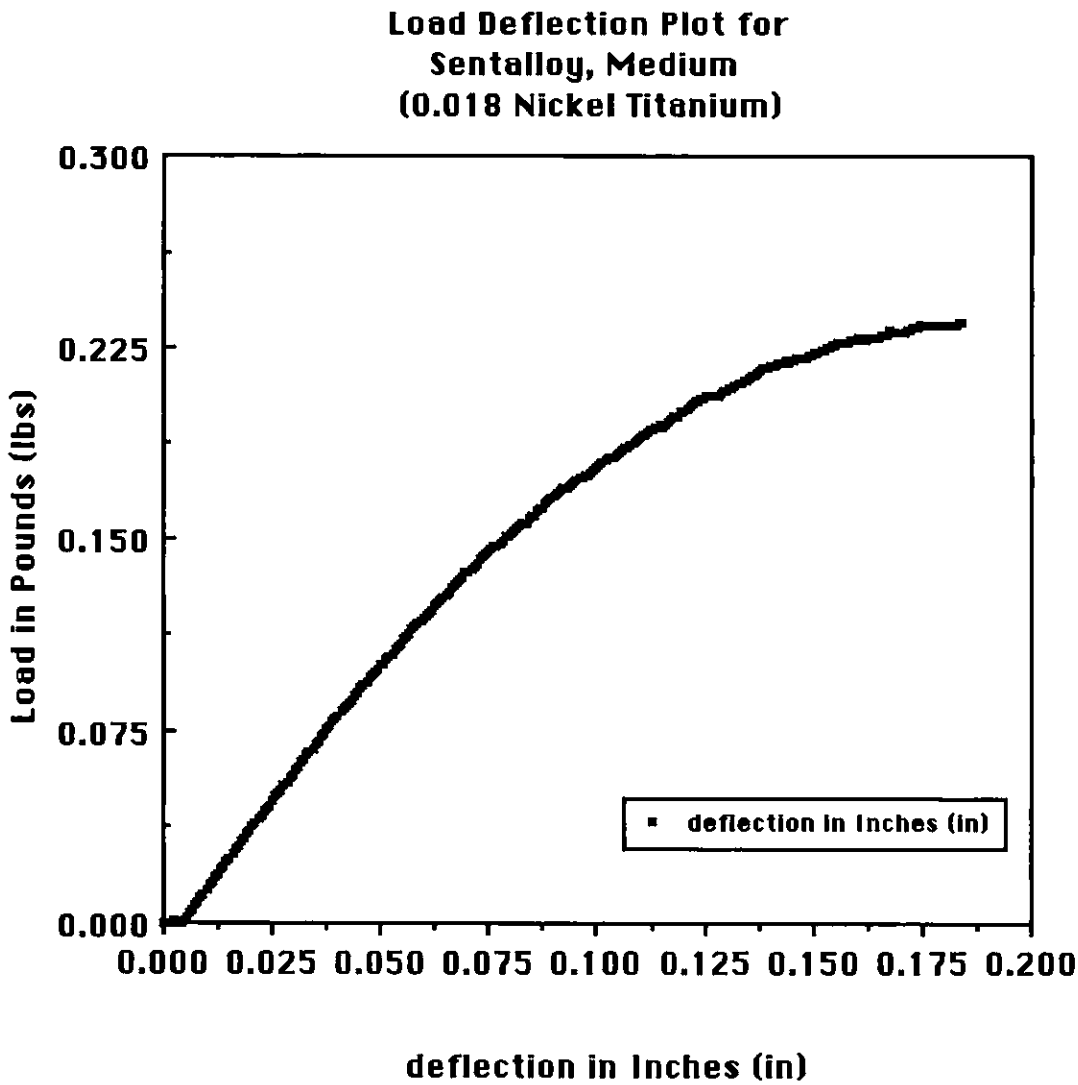
Graph 11


Tensile Stress Strain Plot
for 0.014 Tru-Chrome
Stainless Steel Wire
400000
350000
300000
250000
200000
150000
100000
50000
0
Stress in lbs/sq in
0.000
0.005
0.010
0.015
0.020
0.025
Srain in Inches
Stress in lbs/sq in

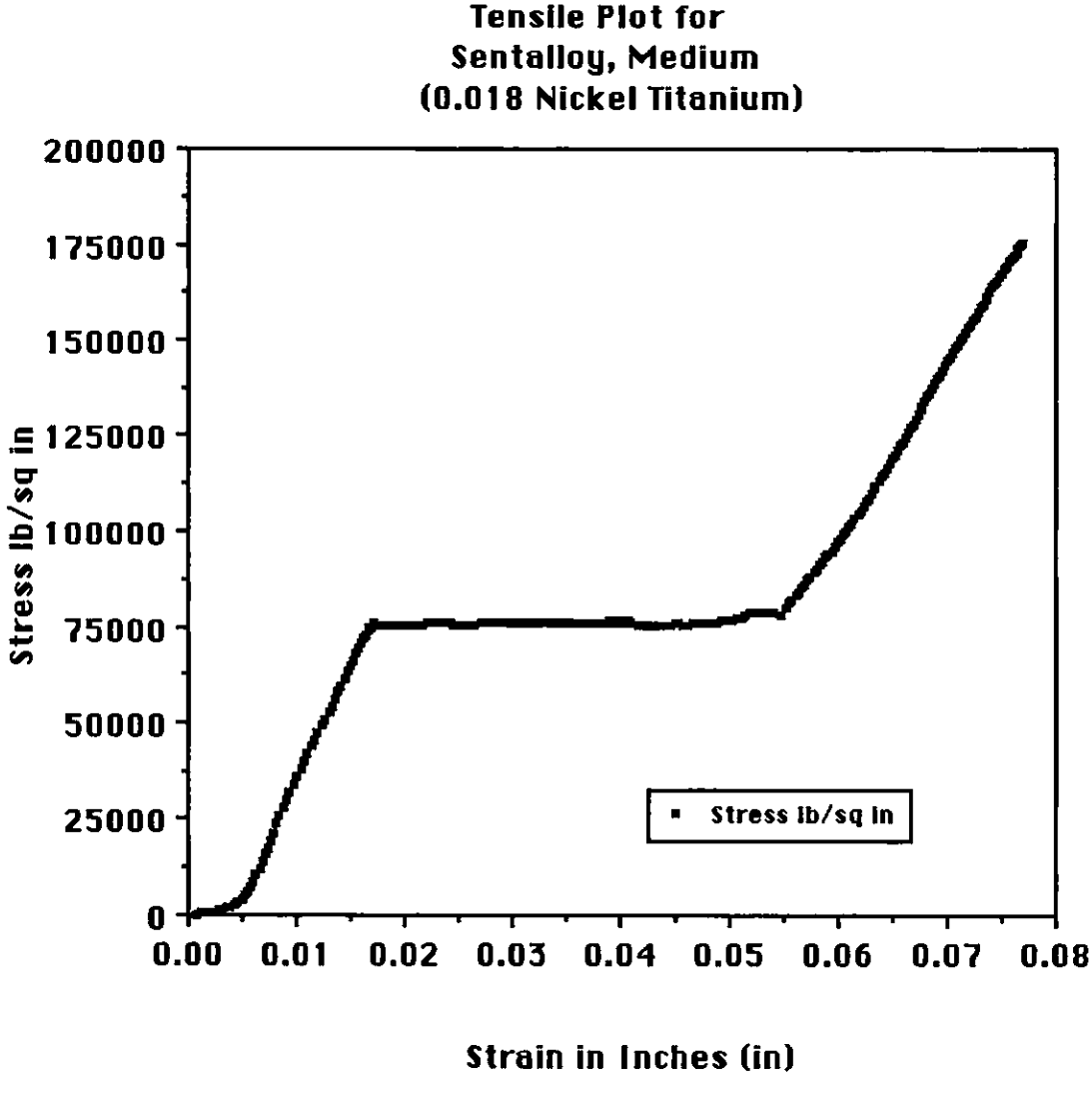
Graph 12


Flexural Stress Strain Plot
for Sentalloy, Medium
(0.018 Nickel Titanium)
120000
100000
80000
60000
40000
20000
0
Stress lbs/sq in
0.000
0.005
0.010
0.015
0.020
Stress lbs/sq in
Strain in Inches (in)

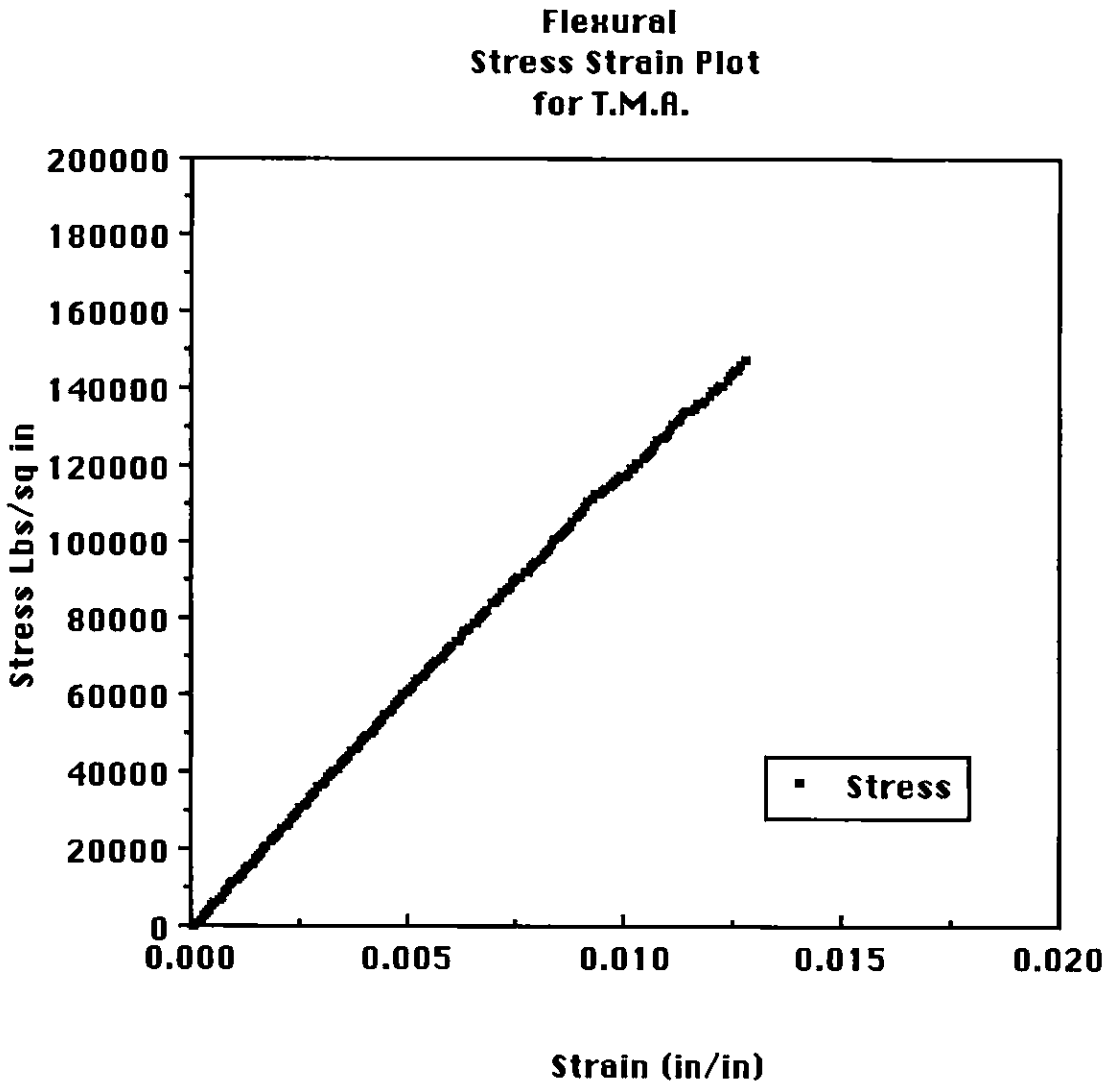
Graph 13


Load Deflection Plot for
Sentalloy, Medium
(0.018 Nickel Titanium)
0.300
0.225
0.150
0.075
0.000
Load in Pounds (lbs)
deflection in Inches (in)
0.000 0.025 0.050 0.075 0.100 0.125 0.150 0.175 0.200
deflection in Inches (in)

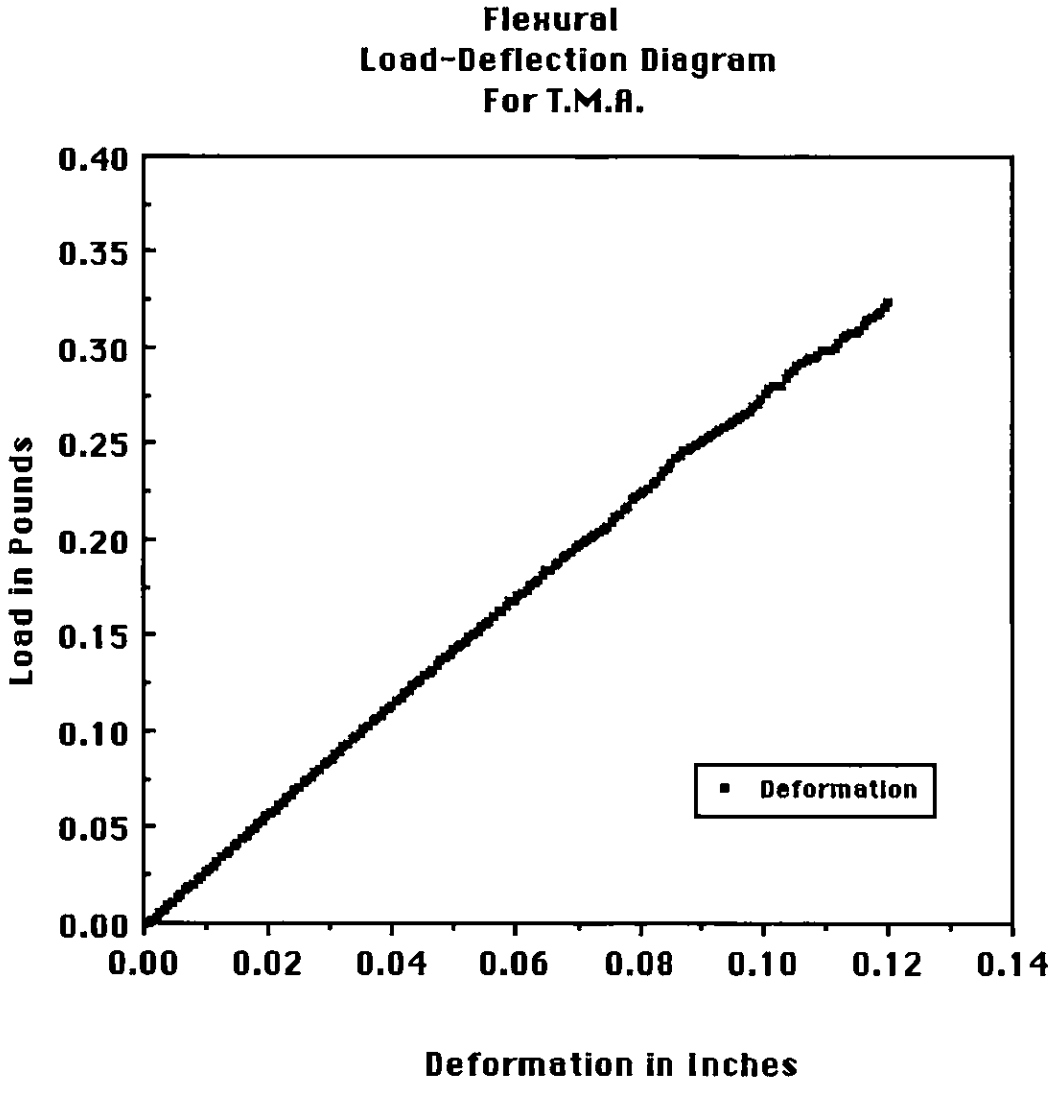
Graph 14


Tensile Plot for
Sentalloy, Medium
(0.018 Nickel Titanium)
200000
175000
150000
125000
100000
75000
50000
25000
0
Stress lb/sq in
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Stress lb/sq in
Strain in Inches (in)

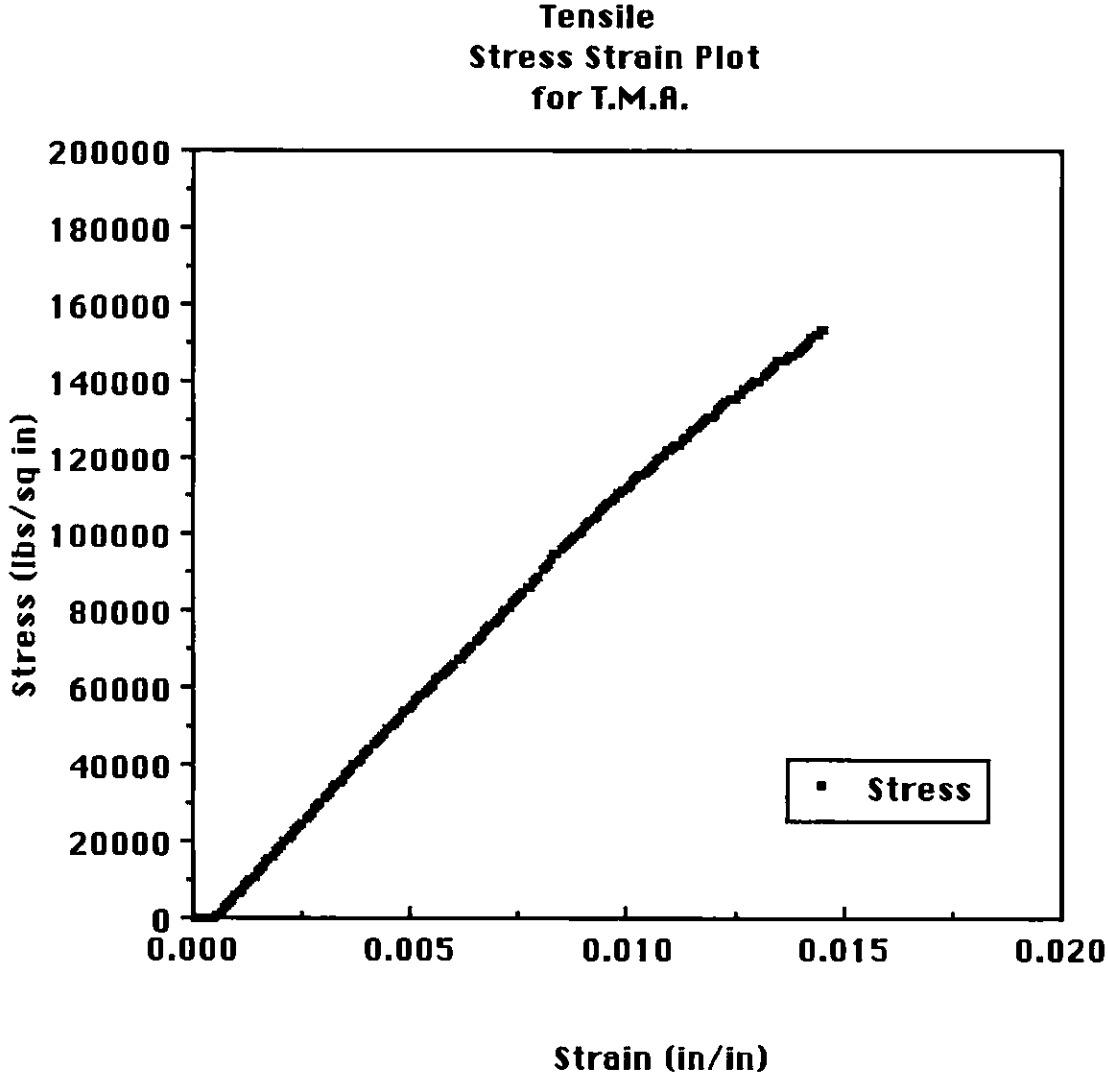
Graph 15


Flexural
Stress Strain Plot
for T.M.A.
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
Stress Lbs/sq in
0.000
0.005
0.010
0.015
0.020
Stress
Strain (in/in)

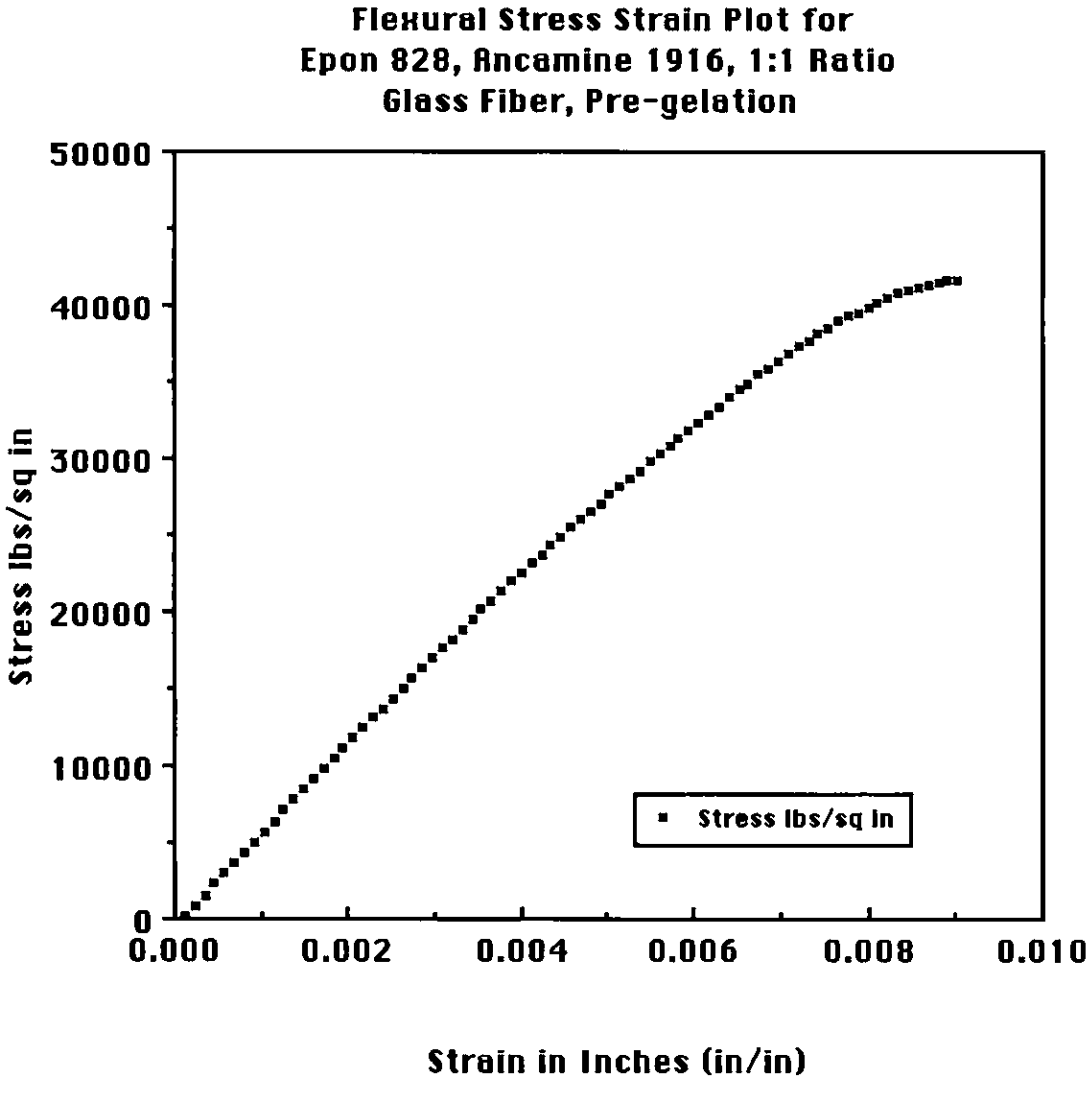
Graph 16


Flexural
Load-Deflection Diagram
For T.M.A.
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Load in Pounds
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Deformation in Inches
Deformation

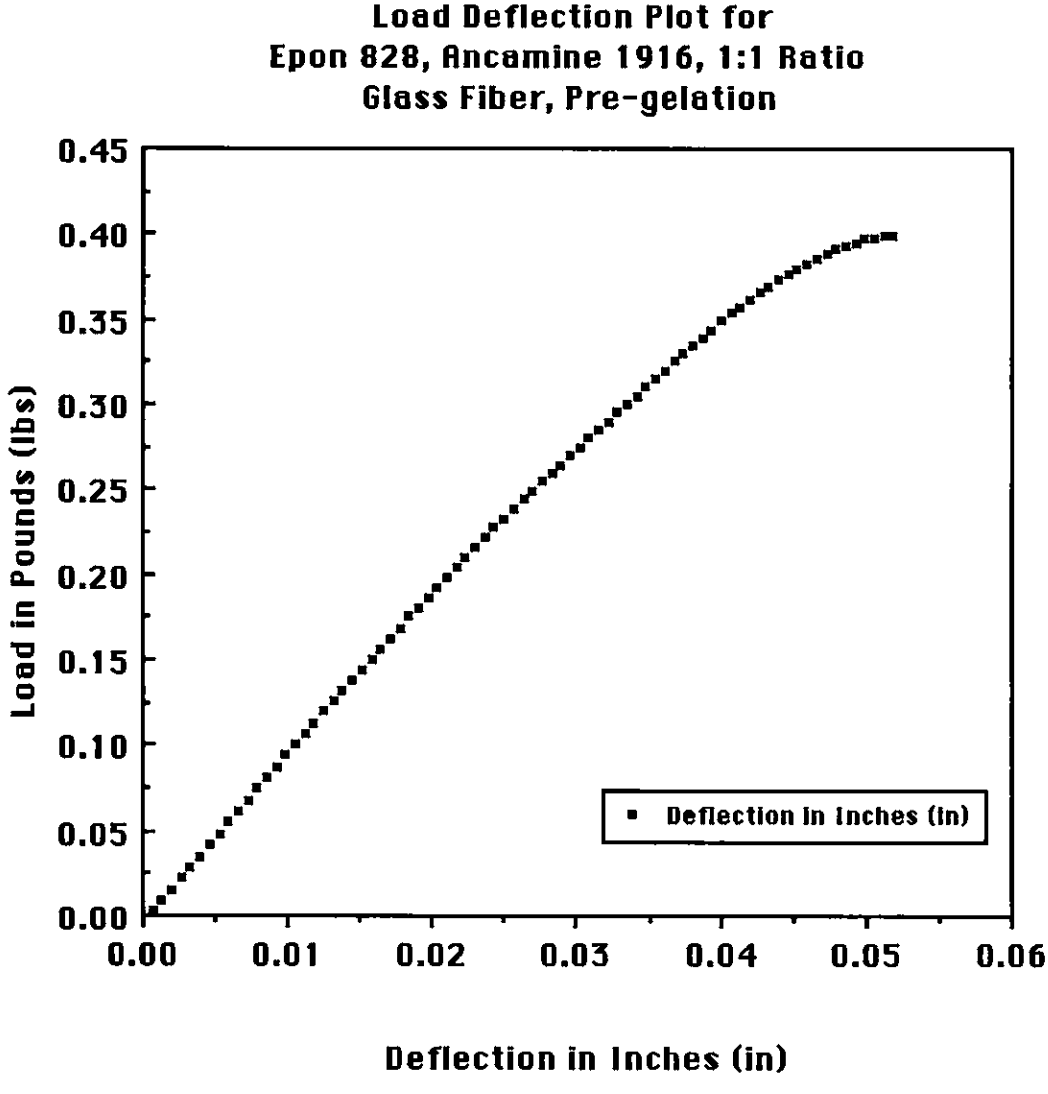
Graph 17


Tensile
Stress Strain Plot
for T.M.A.
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
Stress (lbs/sq in)
0.000
0.005
0.010
0.015
0.020
Strain (in/in)
Stress

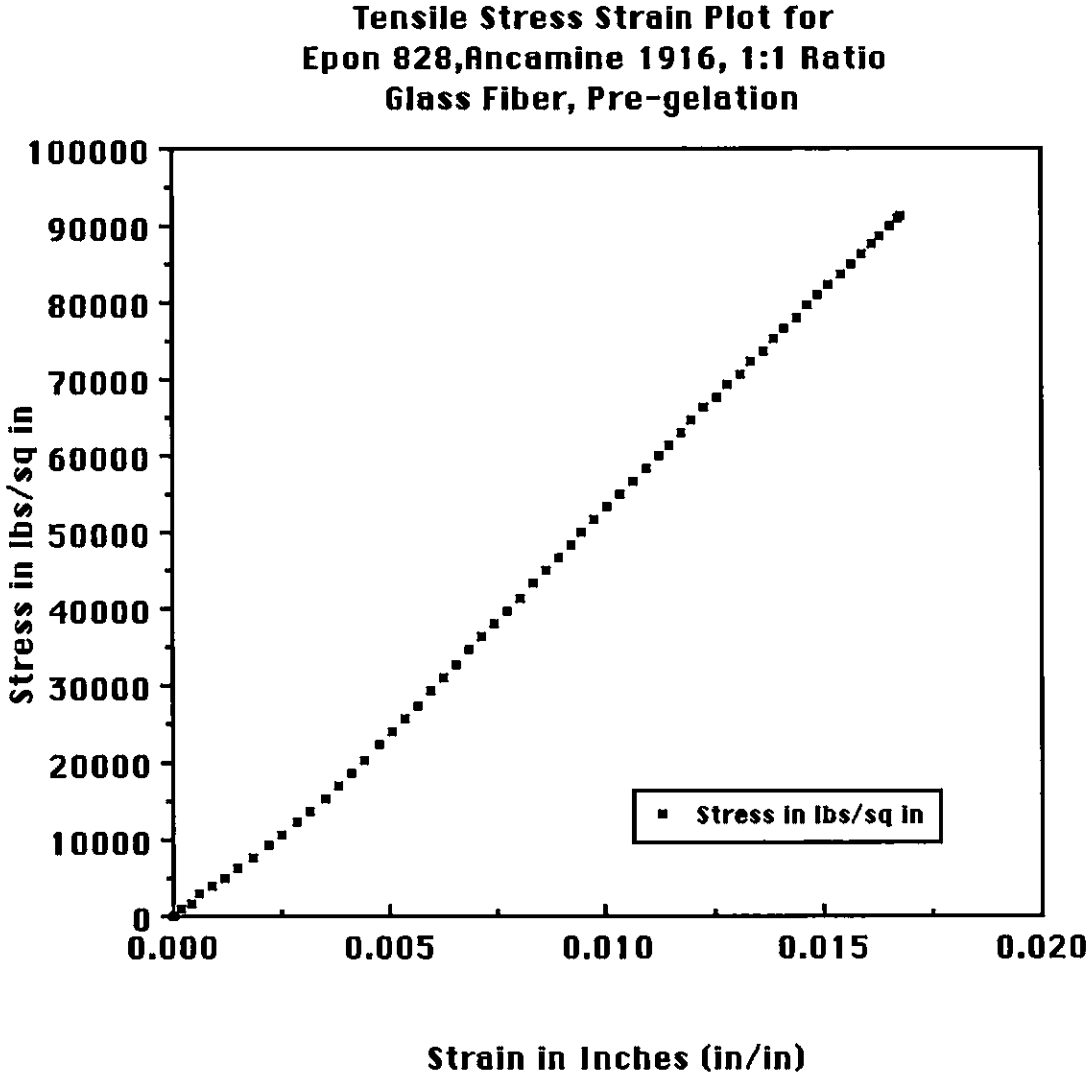
Graph 18


Flexural Stress Strain Plot for
Epon 828, Ancamine 1916, 1:1 Ratio
Glass Fiber, Pre-gelation
50000
40000
30000
20000
10000
0
Stress lbs/sq in
0.000
0.002
0.004
0.006
0.008
0.010
Stress lbs/sq in
Strain in Inches (in/in)

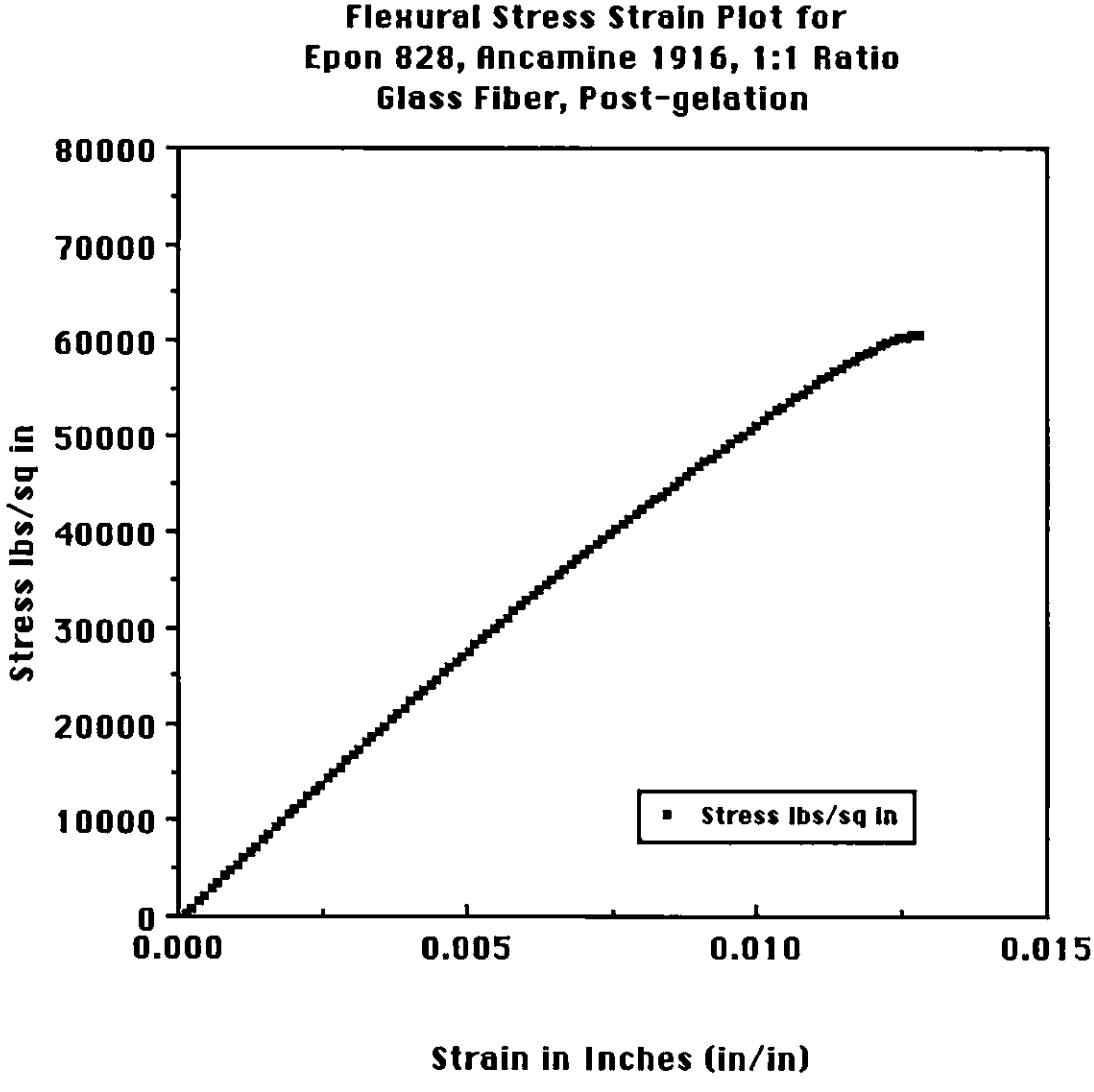
Graph 19


Load Deflection Plot for
Epon 828, Ancamine 1916, 1:1 Ratio
Glass Fiber, Pre-gelation
Load in Pounds (lbs)
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.00
0.01
0.02
0.03
0.04
0.05
0.06
Deflection in Inches (in)
Deflection in Inches (in)

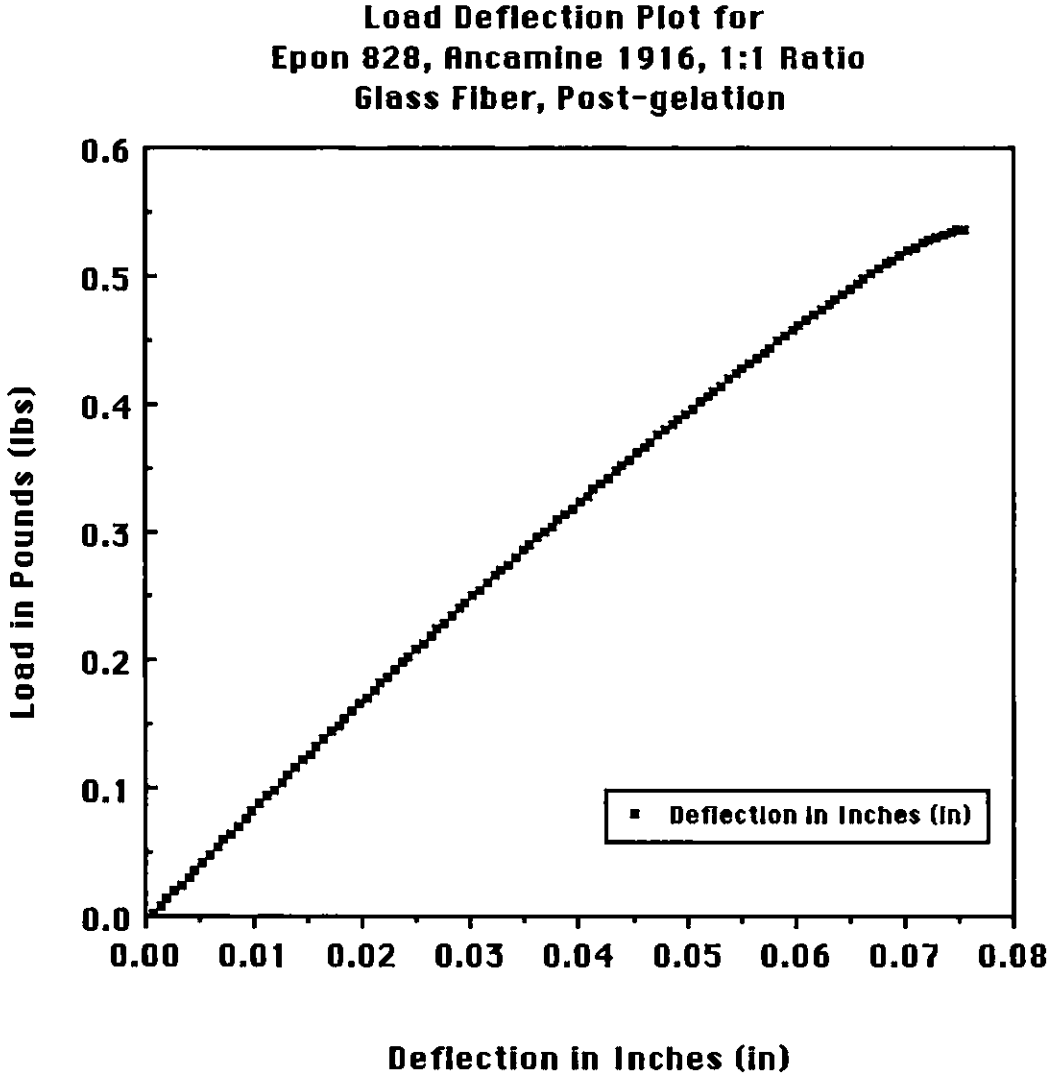
Graph 20


Tensile Stress Strain Plot for
Epon 828,Ancamine 1916, 1:1 Ratio
Glass Fiber, Pre-gelation
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Stress in lbs/sq in
0.000
0.005
0.010
0.015
0.020
Stress in lbs/sq in
Strain in Inches (in/in)

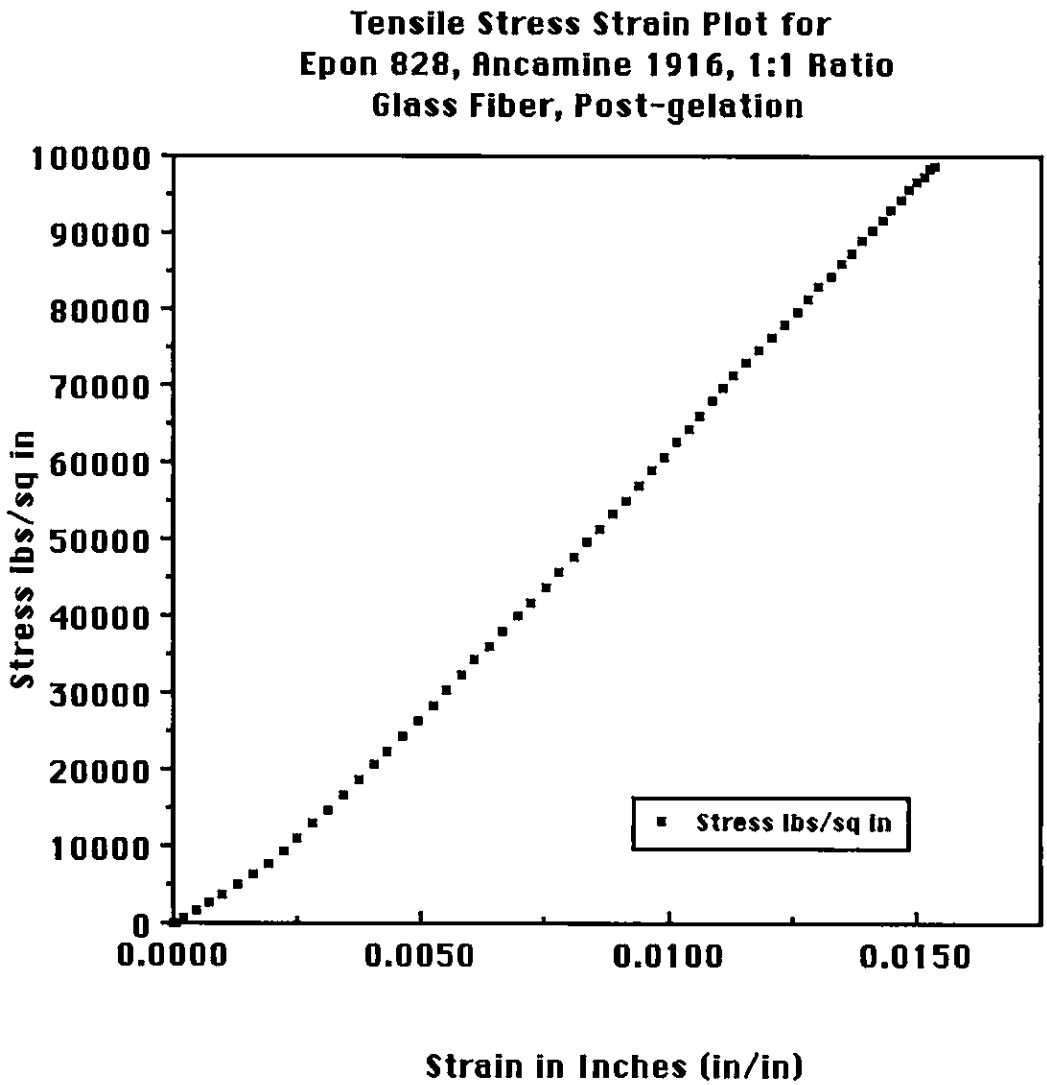
Graph 21


Flexural Stress Strain Plot for
Epon 828, Ancamine 1916, 1:1 Ratio
Glass Fiber, Post-gelation
80000
70000
60000
50000
40000
30000
20000
10000
0
Stress lbs/sq in
0.000
0.005
0.010
0.015
Stress lbs/sq in
Strain in Inches (in/in)

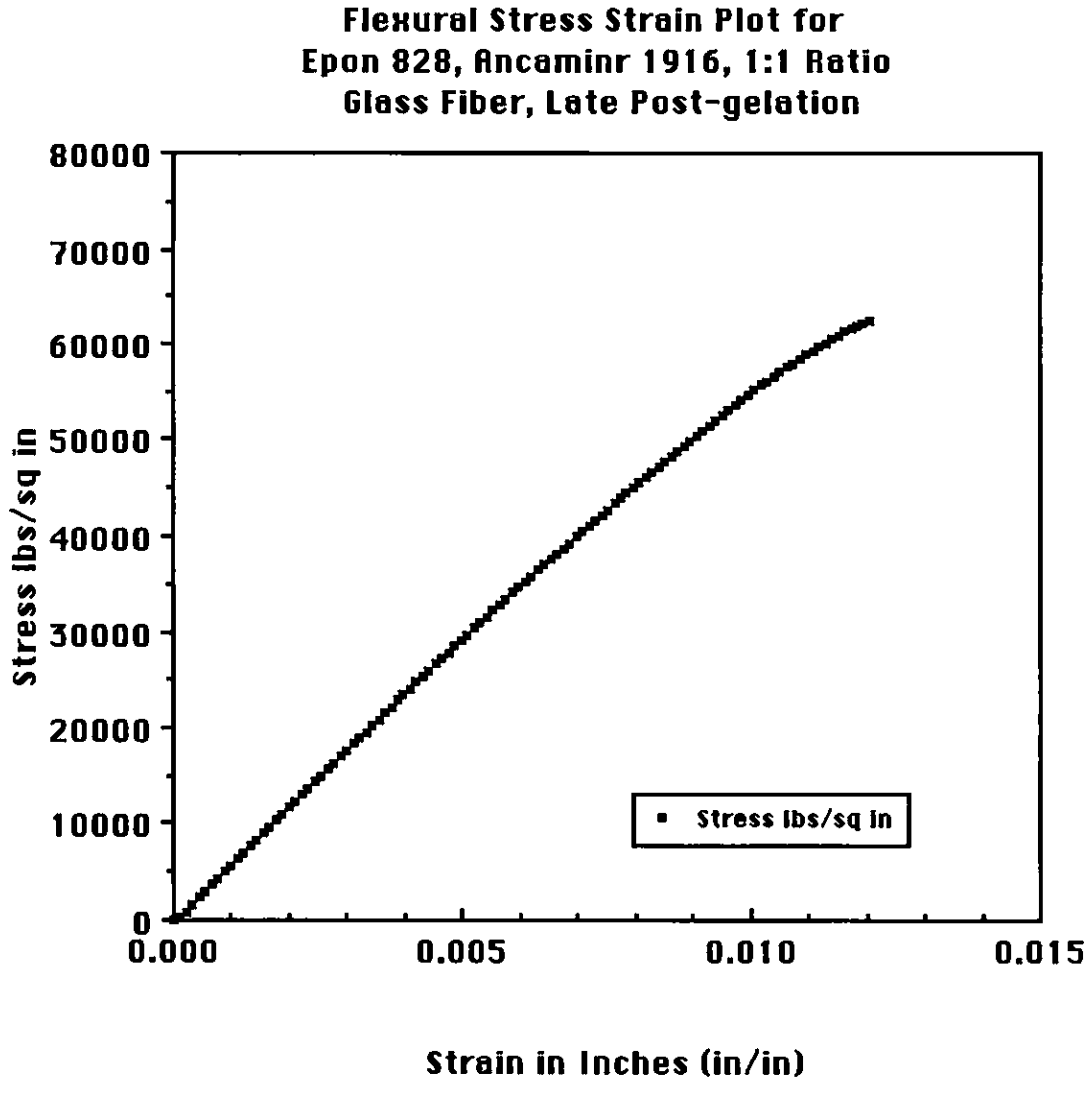
Graph 22


Load Deflection Plot for
Epon 828, Ancamine 1916, 1:1 Ratio
Glass Fiber, Post-gelation
Load in Pounds (lbs)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Deflection in Inches (in)
Deflection in Inches (in)

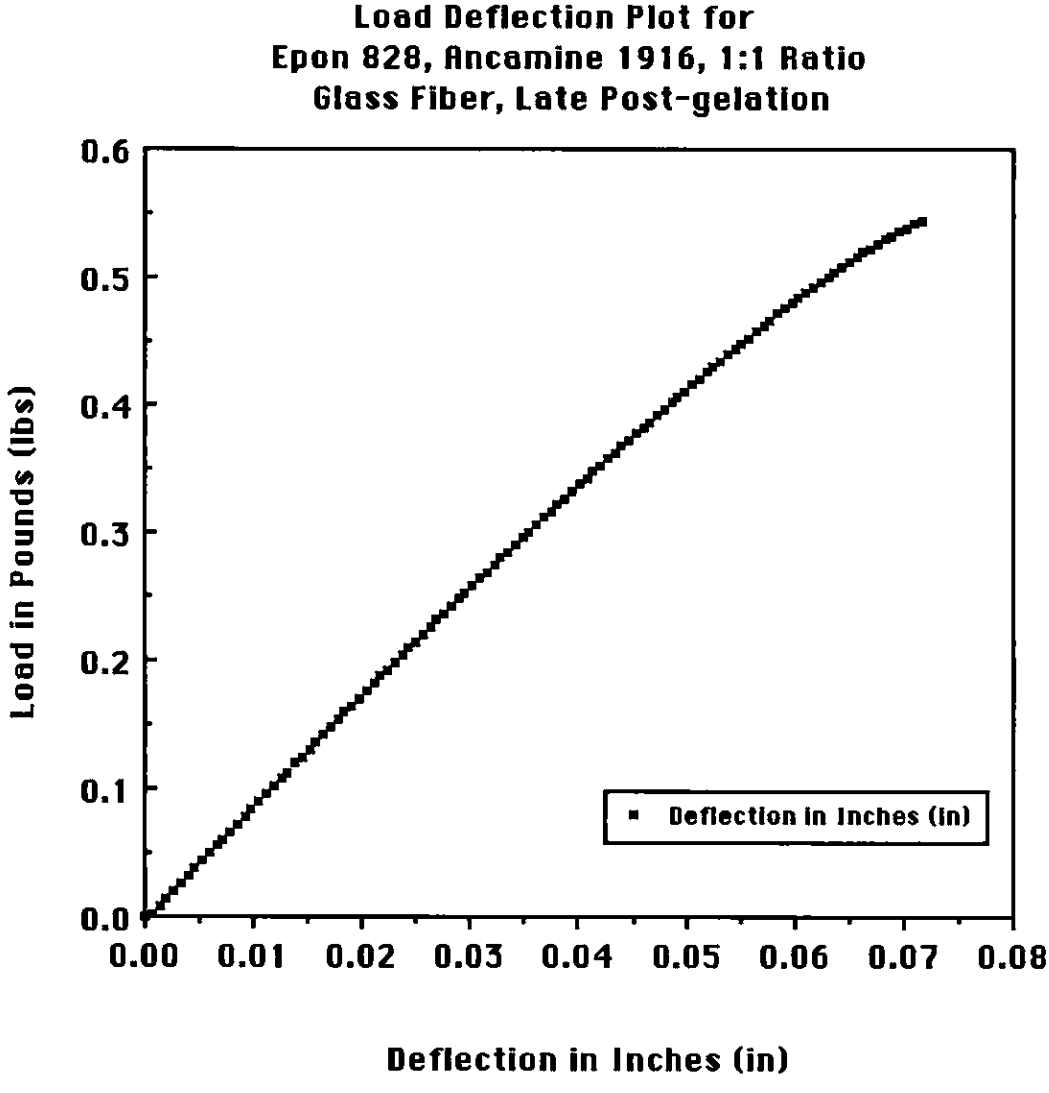
Graph 23


Tensile Stress Strain Plot for
Epon 828, Ancamine 1916, 1:1 Ratio
Glass Fiber, Post-gelation
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Stress lbs/sq in
0.0000
0.0050
0.0100
0.0150
Stress lbs/sq in
Strain in Inches (in/in)

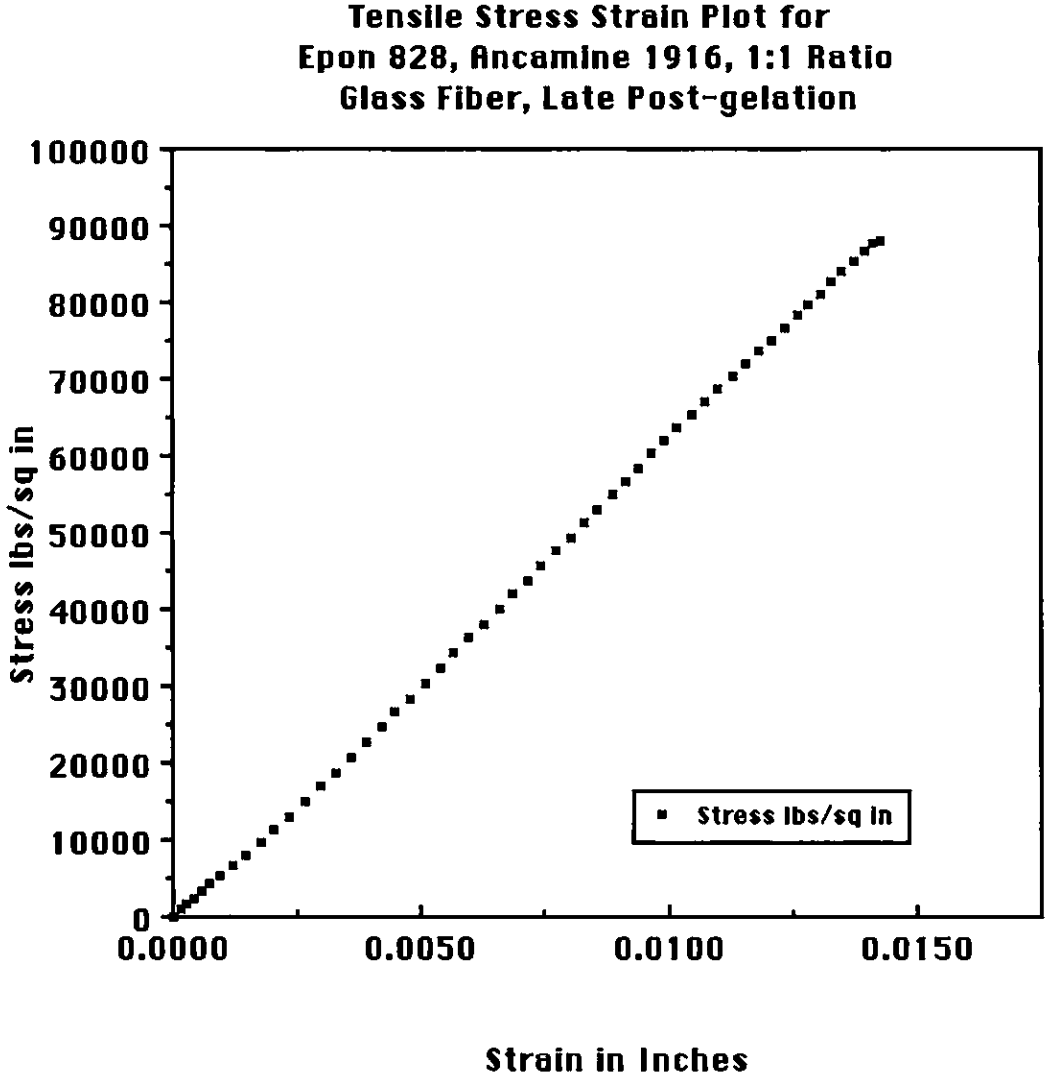
Graph 24


Flexural Stress Strain Plot for
Epon 828, Ancaminr 1916, 1:1 Ratio
Glass Fiber, Late Post-gelation
80000
70000
60000
50000
40000
30000
20000
10000
0
Stress lbs/sq in
0.000
0.005
0.010
0.015
Stress lbs/sq in
Strain in Inches (in/in)

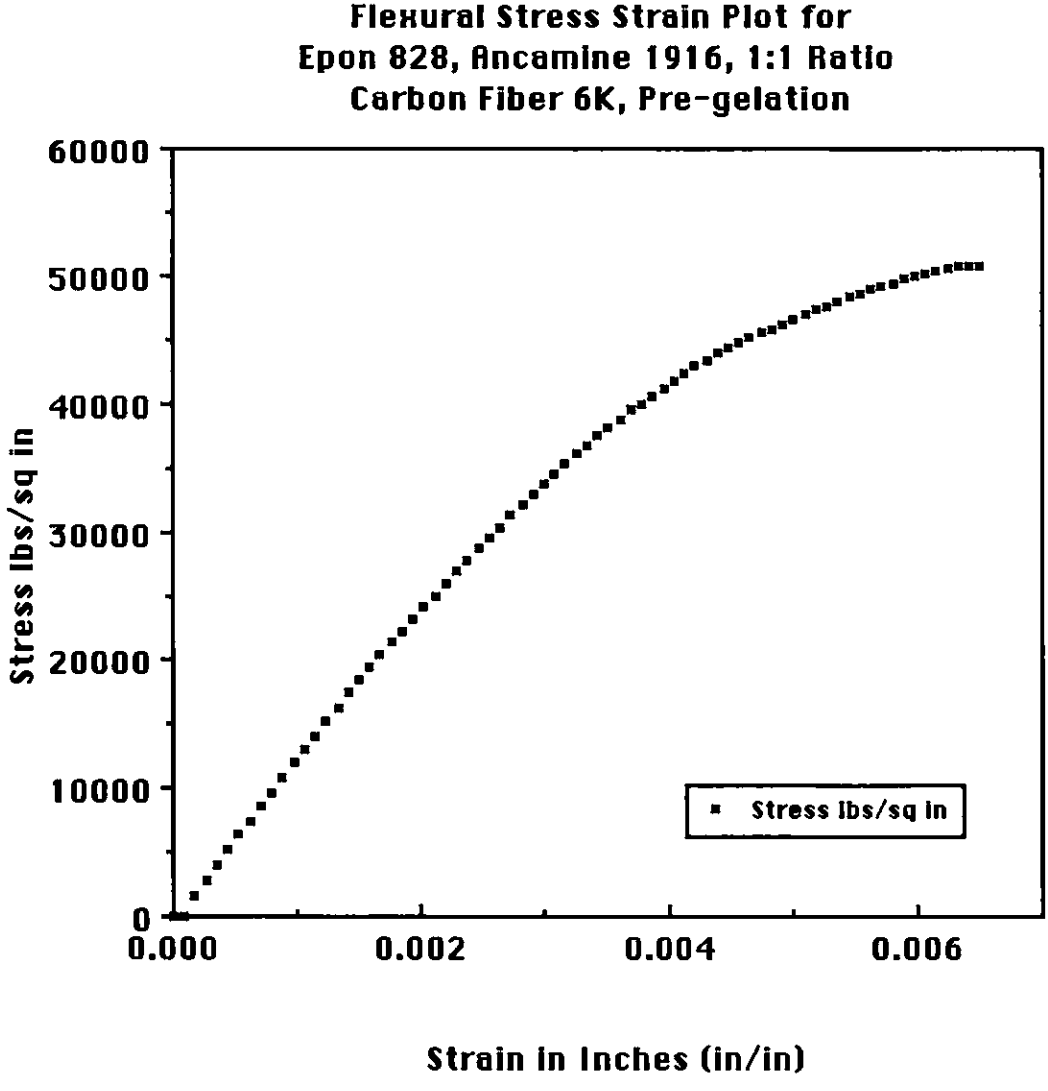
Graph 25


Load Deflection Plot for
Epon 828, Ancamine 1916, 1:1 Ratio
Glass Fiber, Late Post-gelation
Load in Pounds (lbs)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Deflection in Inches (in)
Deflection in Inches (in)

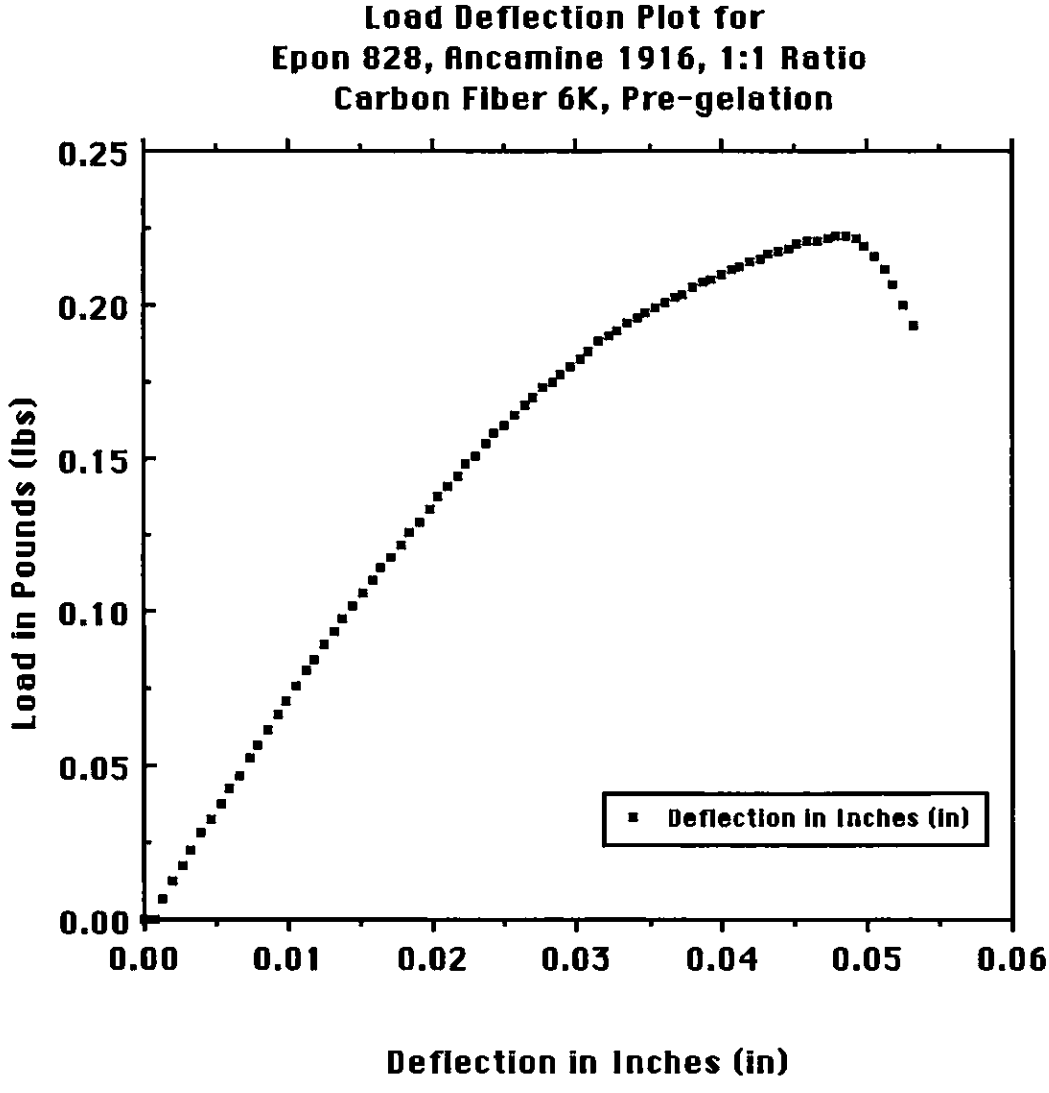
Graph 26


Tensile Stress Strain Plot for
Epon 828, Ancamine 1916, 1:1 Ratio
Glass Fiber, Late Post-gelation
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Stress lbs/sq in
0.0000
0.0050
0.0100
0.0150
Stress lbs/sq in
Strain in Inches

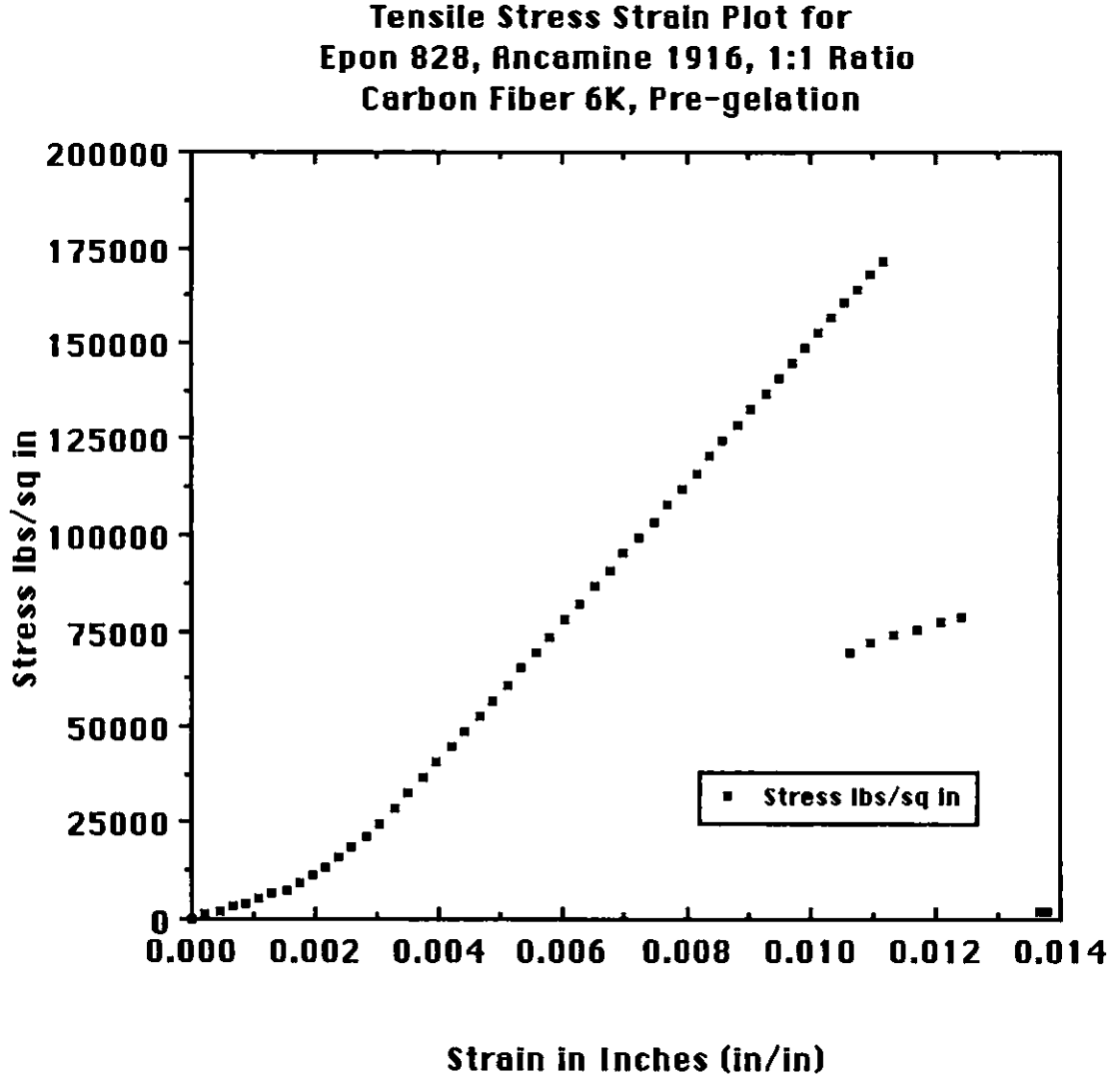
Graph 27


Flexural Stress Strain Plot for
Epon 828, Ancamine 1916, 1:1 Ratio
Carbon Fiber 6K, Pre-gelation
60000
50000
40000
30000
20000
10000
0
Stress lbs/sq in
0.000
0.002
0.004
0.006
Stress lbs/sq in
Strain in Inches (in/in)

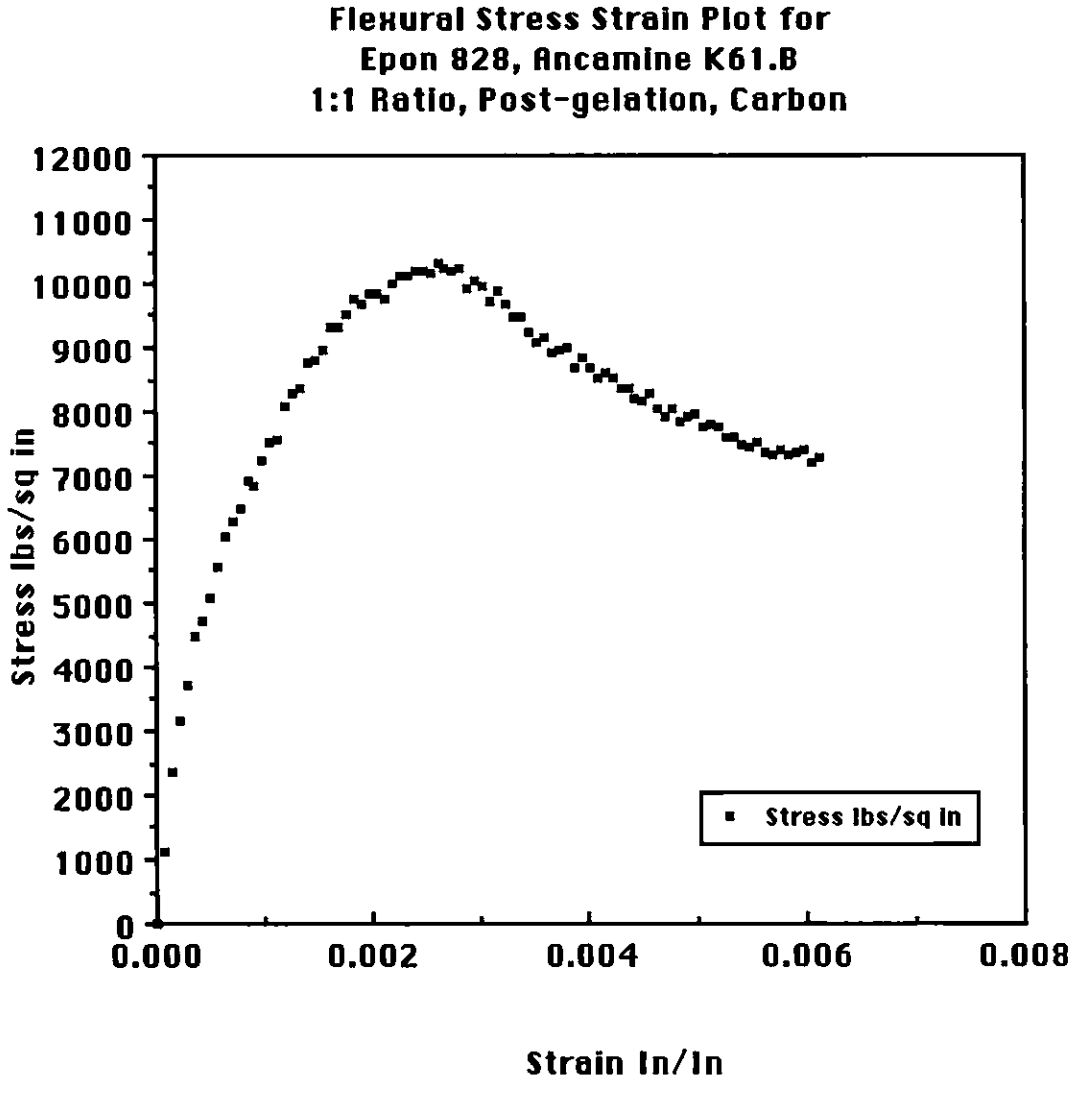
Graph 28


Load Deflection Plot for
Epon 828, Ancamine 1916, 1:1 Ratio
Carbon Fiber 6K, Pre-gelation
Load in Pounds (lbs)
0.25
0.20
0.15
0.10
0.05
0.00
0.00
0.01
0.02
0.03
0.04
0.05
0.06
Deflection in Inches (in)
Deflection in Inches (in)

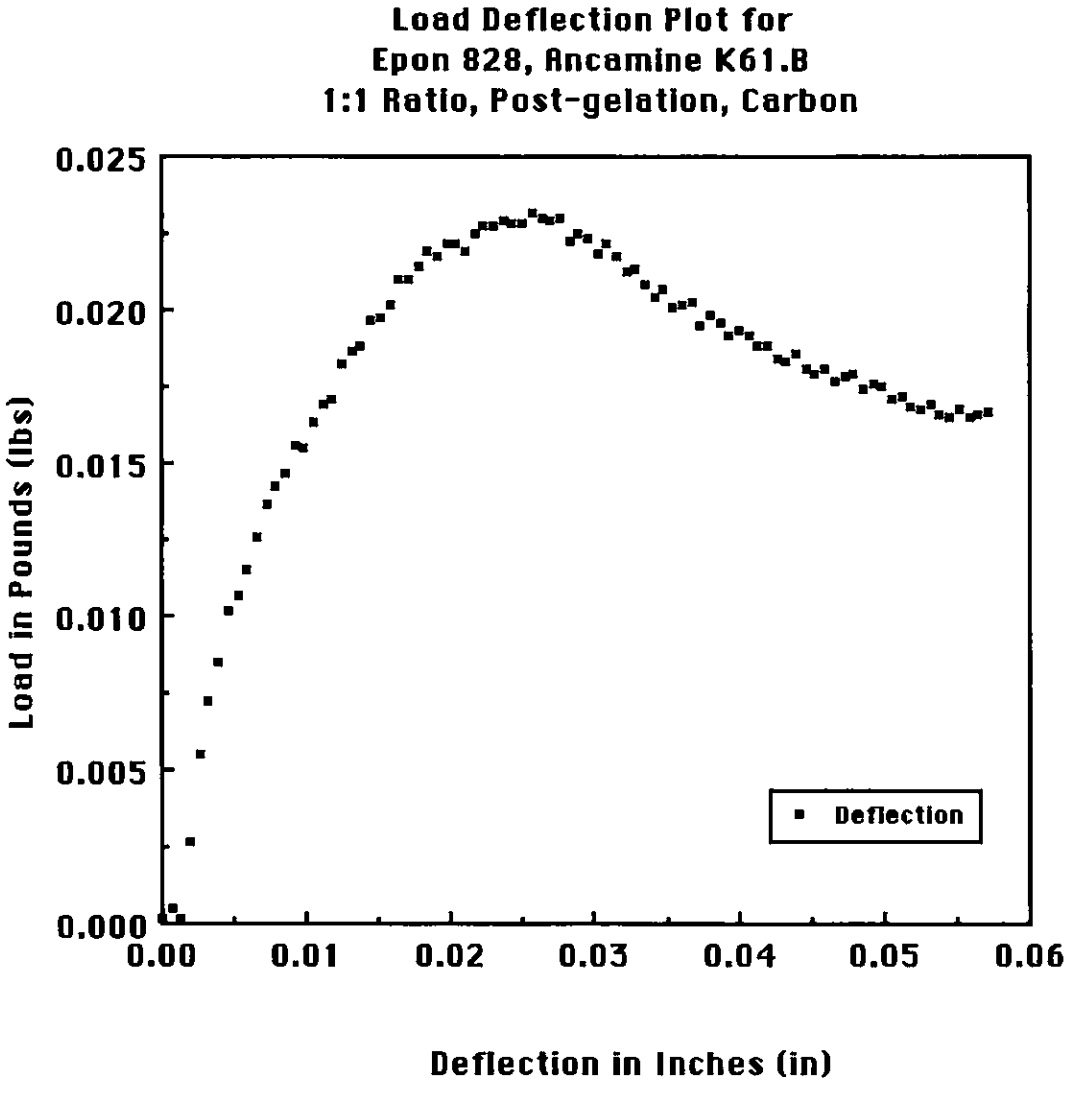
Graph 29


Tensile Stress Strain Plot for
Epon 828, Ancamine 1916, 1:1 Ratio
Carbon Fiber 6K, Pre-gelation
200000
175000
150000
125000
100000
75000
50000
25000
0
Stress lbs/sq in
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
Stress lbs/sq in
Strain in Inches (in/in)

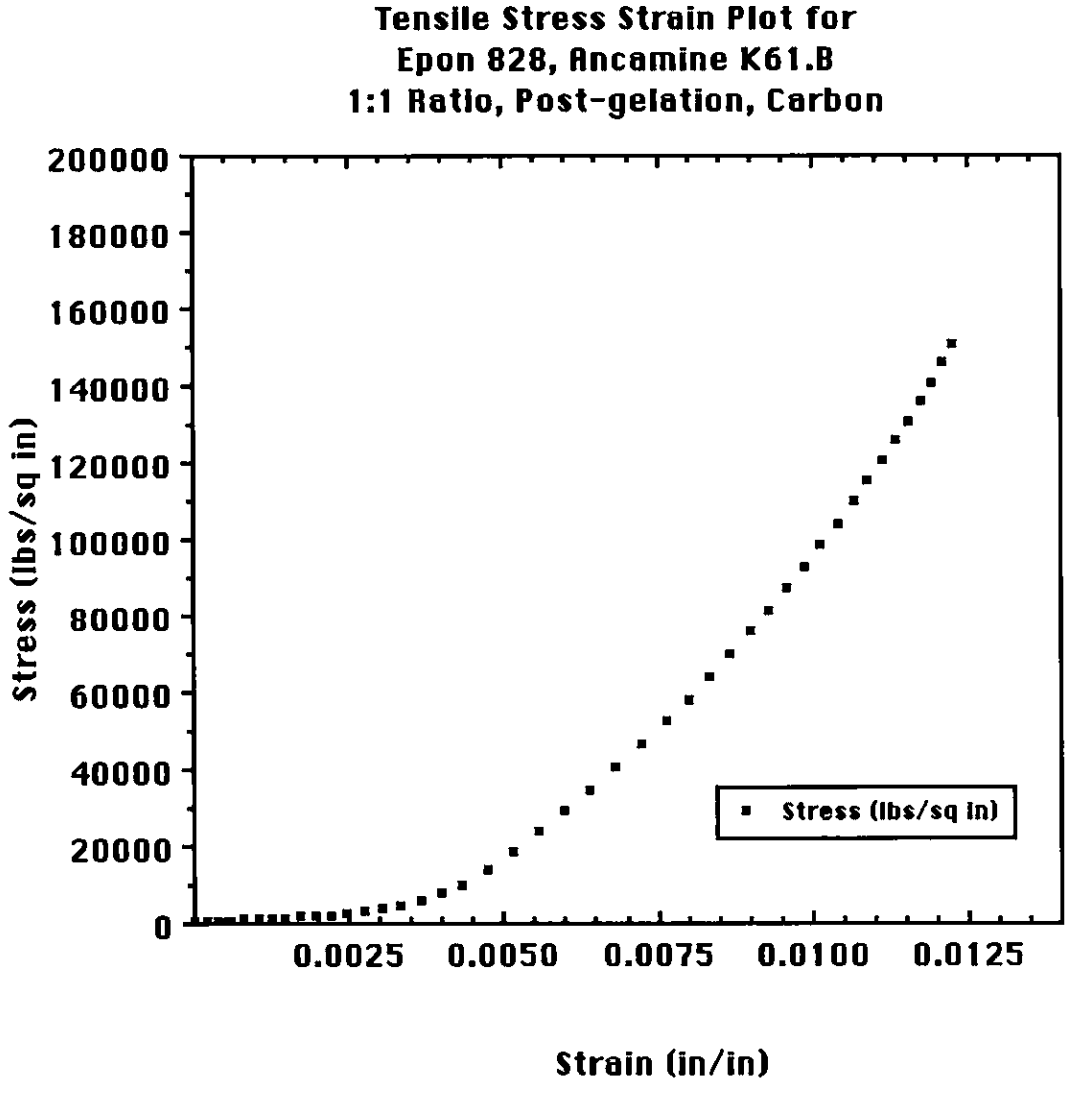
Graph 30


Flexural Stress Strain Plot for
Epon 828, Ancamine K61.B
1:1 Ratio, Post-gelation, Carbon
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Stress lbs/sq in
0.000
0.002
0.004
0.006
0.008
Strain In/In
Stress lbs/sq in

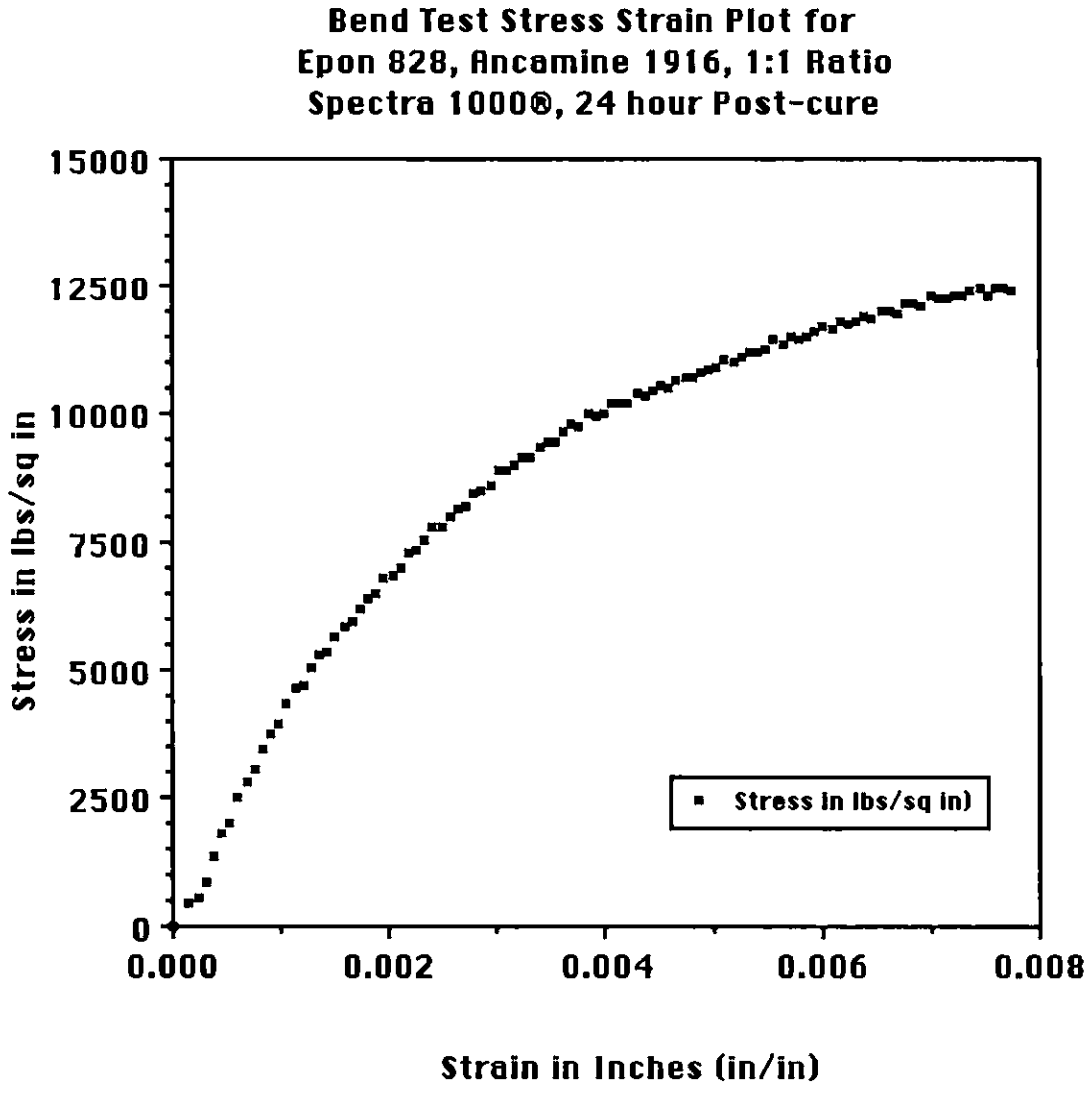
Graph 31


Load Deflection Plot for
Epon 828, Ancamine K61.B
1:1 Ratio, Post-gelation, Carbon
0.025
0.020
0.015
0.010
0.005
0.000
Load in Pounds (lbs)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
Deflection
Deflection in Inches (in)

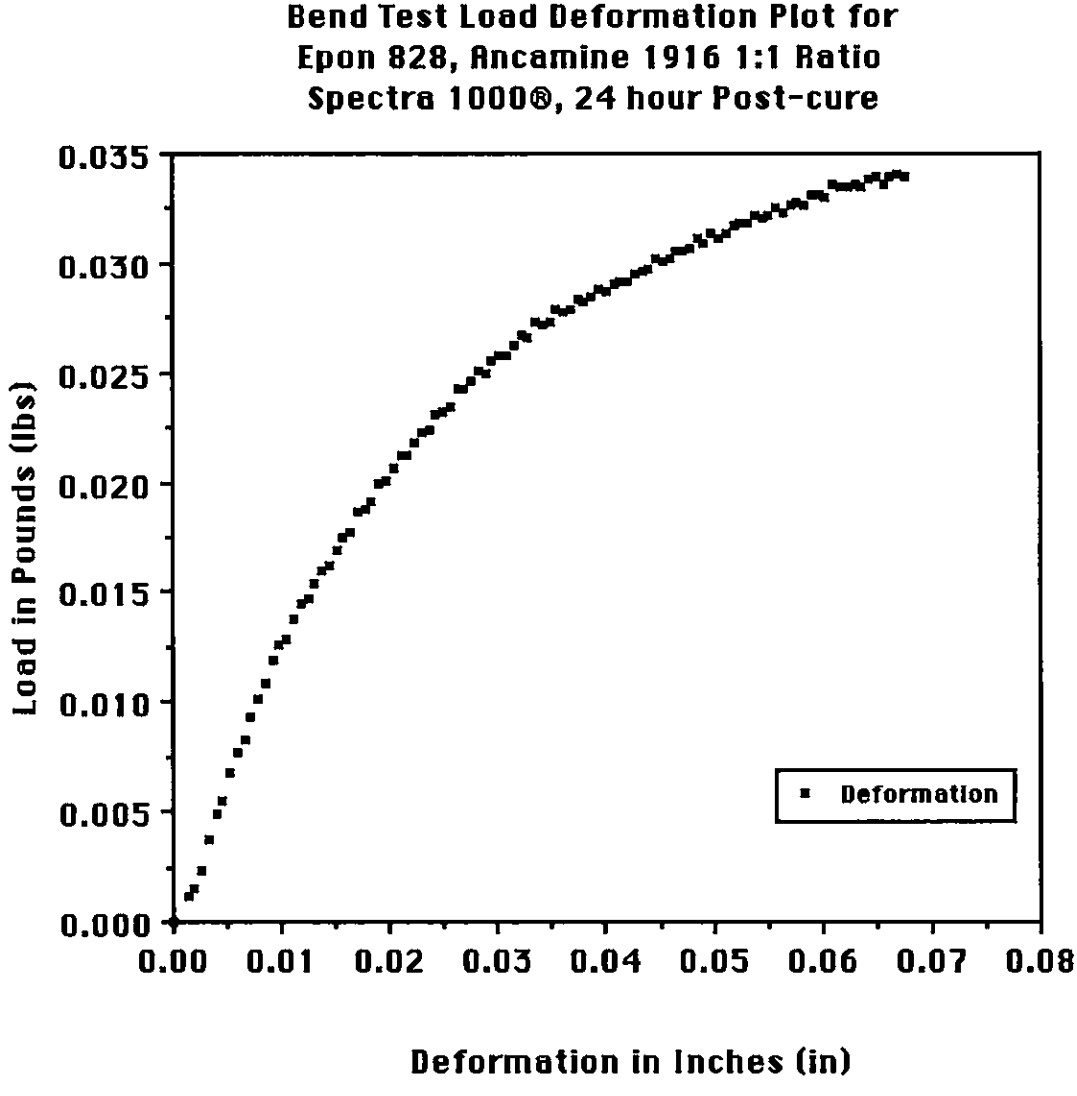
Graph 32


Tensile Stress Strain Plot for
Epon 828, Ancamine K61.B
1:1 Ratio, Post-gelation, Carbon
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
Stress (lbs/sq in)
0.0025
0.0050
0.0075
0.0100
0.0125
Strain (in/in)
Stress (lbs/sq in)

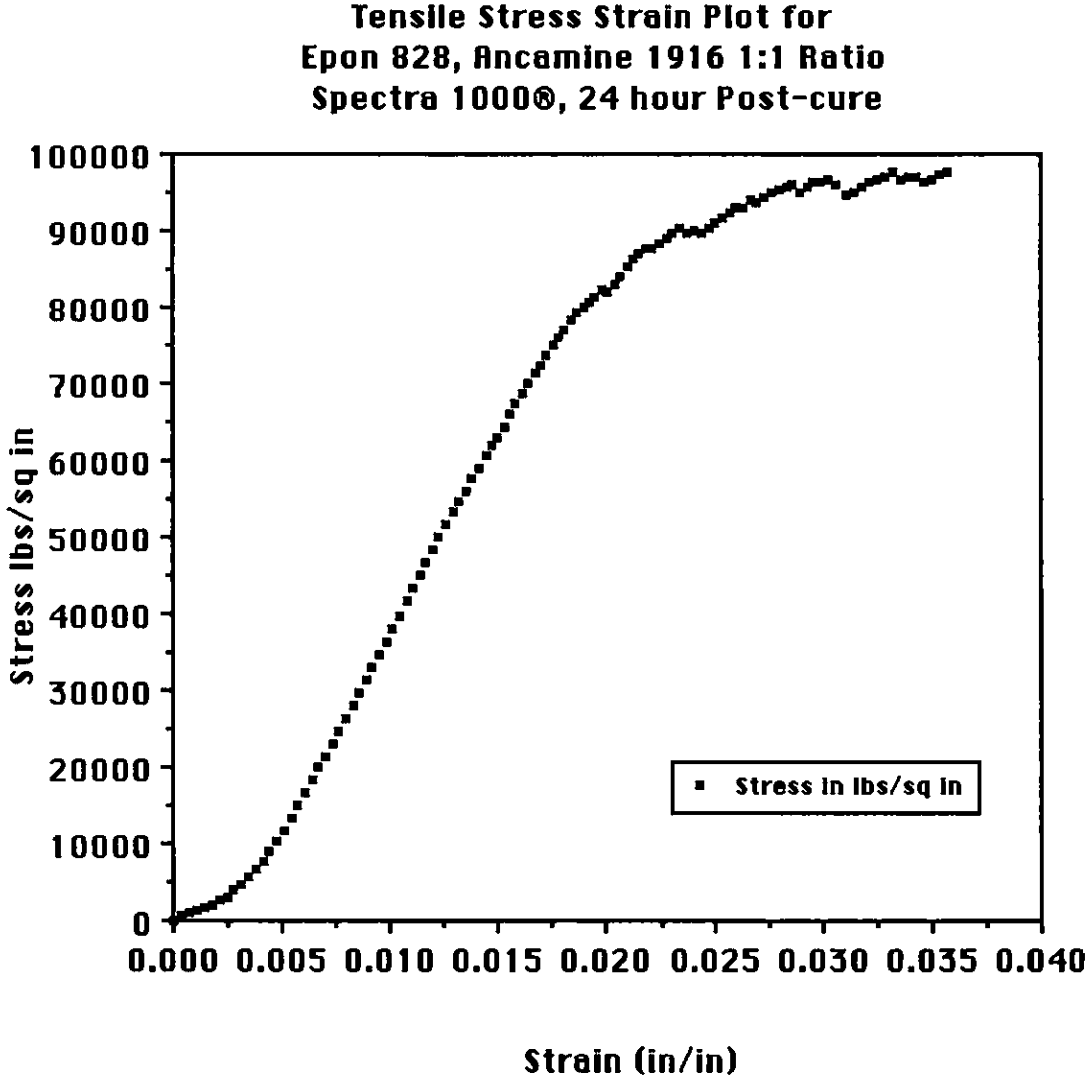
Graph 33


Bend Test Stress Strain Plot for
Epon 828, Ancamine 1916, 1:1 Ratio
Spectra 1000®, 24 hour Post-cure
15000
12500
10000
7500
5000
2500
0
Stress in lbs/sq in
0.000
0.002
0.004
0.006
0.008
Strain in Inches (in/in)
Stress in lbs/sq in)

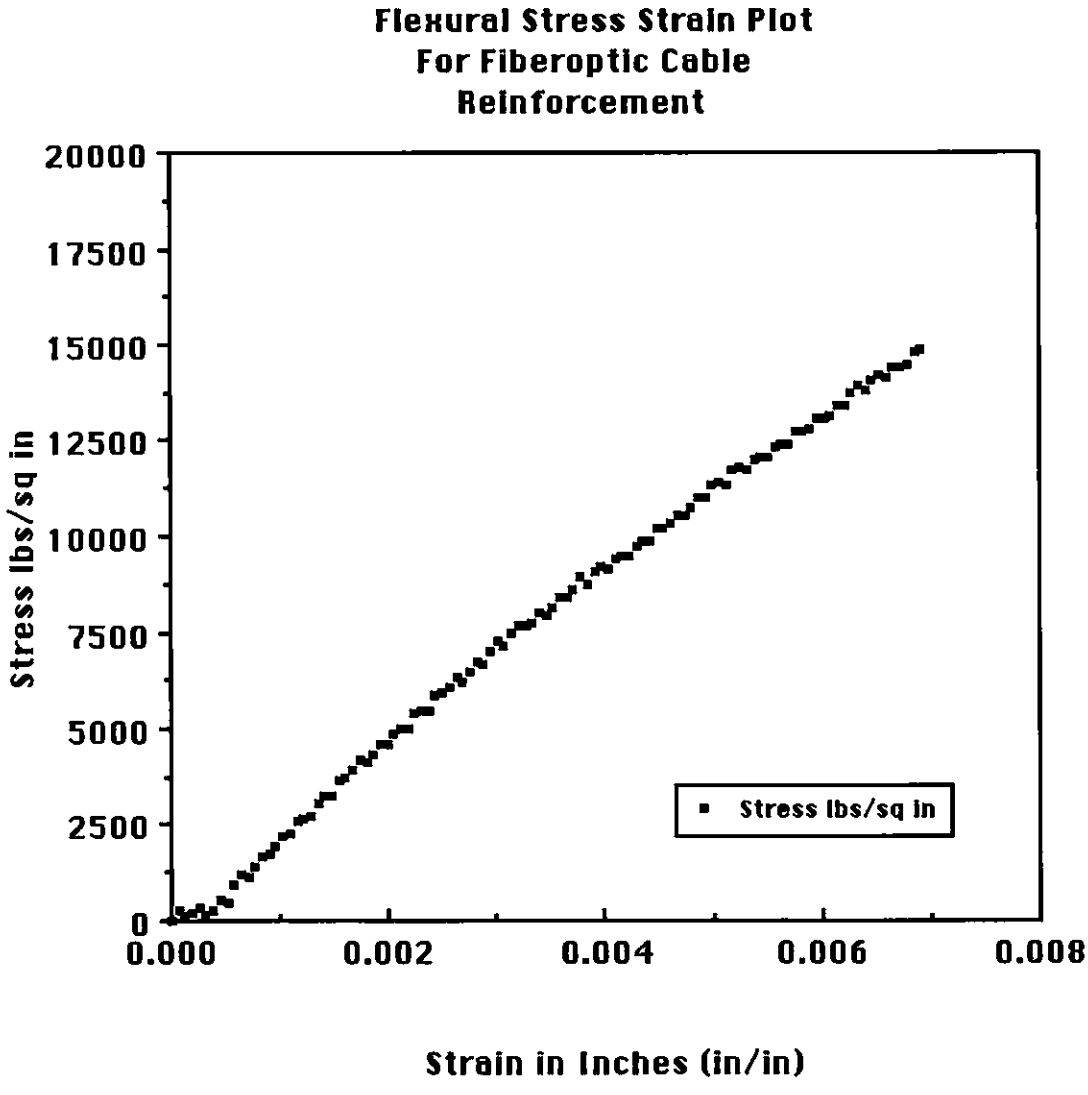
Graph 34


Bend Test Load Deformation Plot for
Epon 828, Ancamine 1916 1:1 Ratio
Spectra 1000®, 24 hour Post-cure
Load in Pounds (lbs)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Deformation
Deformation in Inches (in)

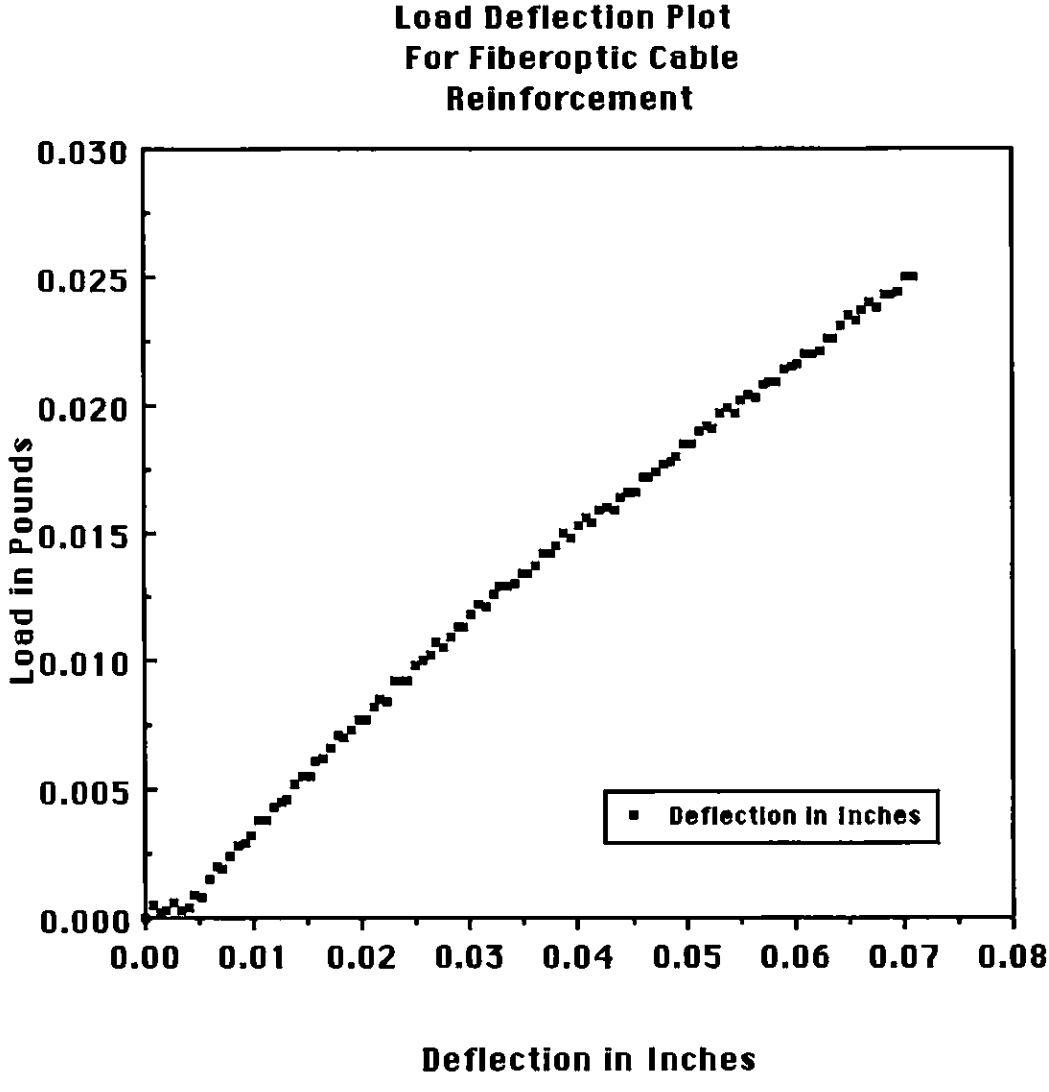
Graph 35


Tensile Stress Strain Plot for
Epon 828, Ancamine 1916 1:1 Ratio
Spectra 1000®, 24 hour Post-cure
Stress lbs/sq in
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
0.000 0.005 0.010 0.015 0.020 0.025 0.030 0.035 0.040
Strain (in/in)
Stress in lbs/sq in

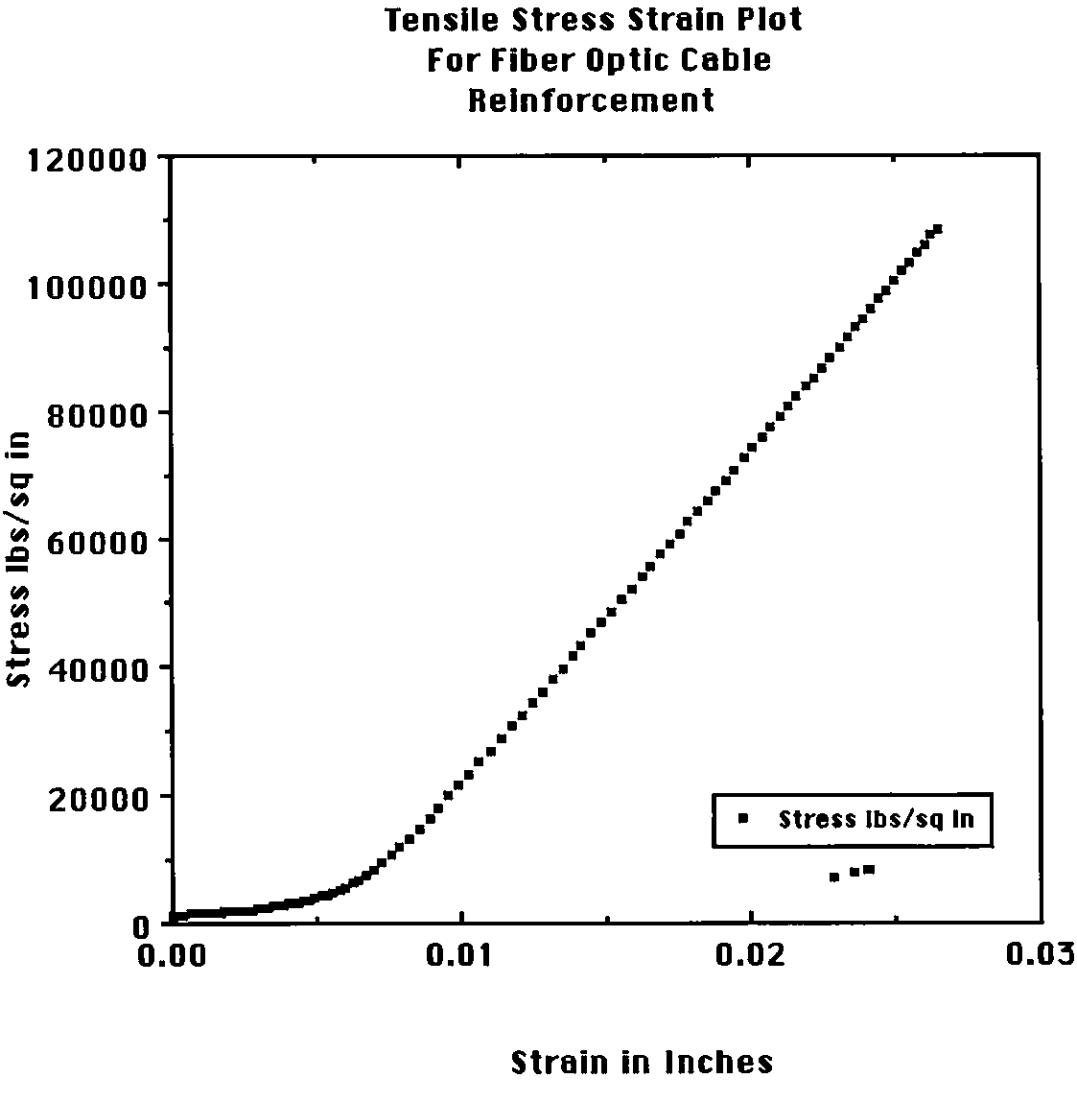
Graph 36


Flexural Stress Strain Plot
For Fiberoptic Cable
Reinforcement
20000
17500
15000
12500
10000
7500
5000
2500
0
Stress lbs/sq in
0.000
0.002
0.004
0.006
0.008
Stress lbs/sq in
Strain in Inches (in/in)

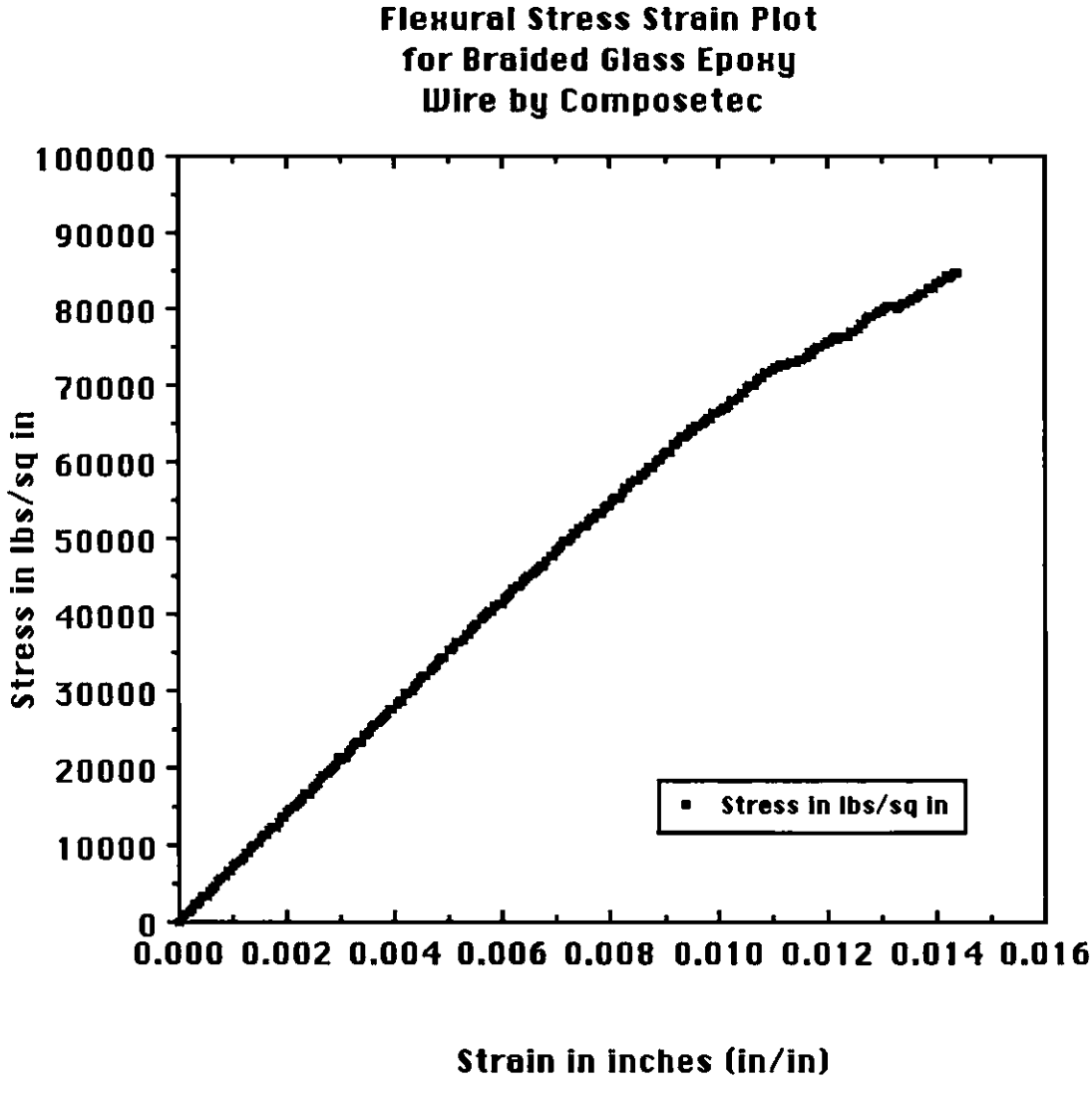
Graph 37


Load Deflection Plot
For Fiberoptic Cable
Reinforcement
0.030
0.025
0.020
0.015
0.010
0.005
0.000
Load in Pounds
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Deflection in Inches
Deflection in Inches

Graph 38

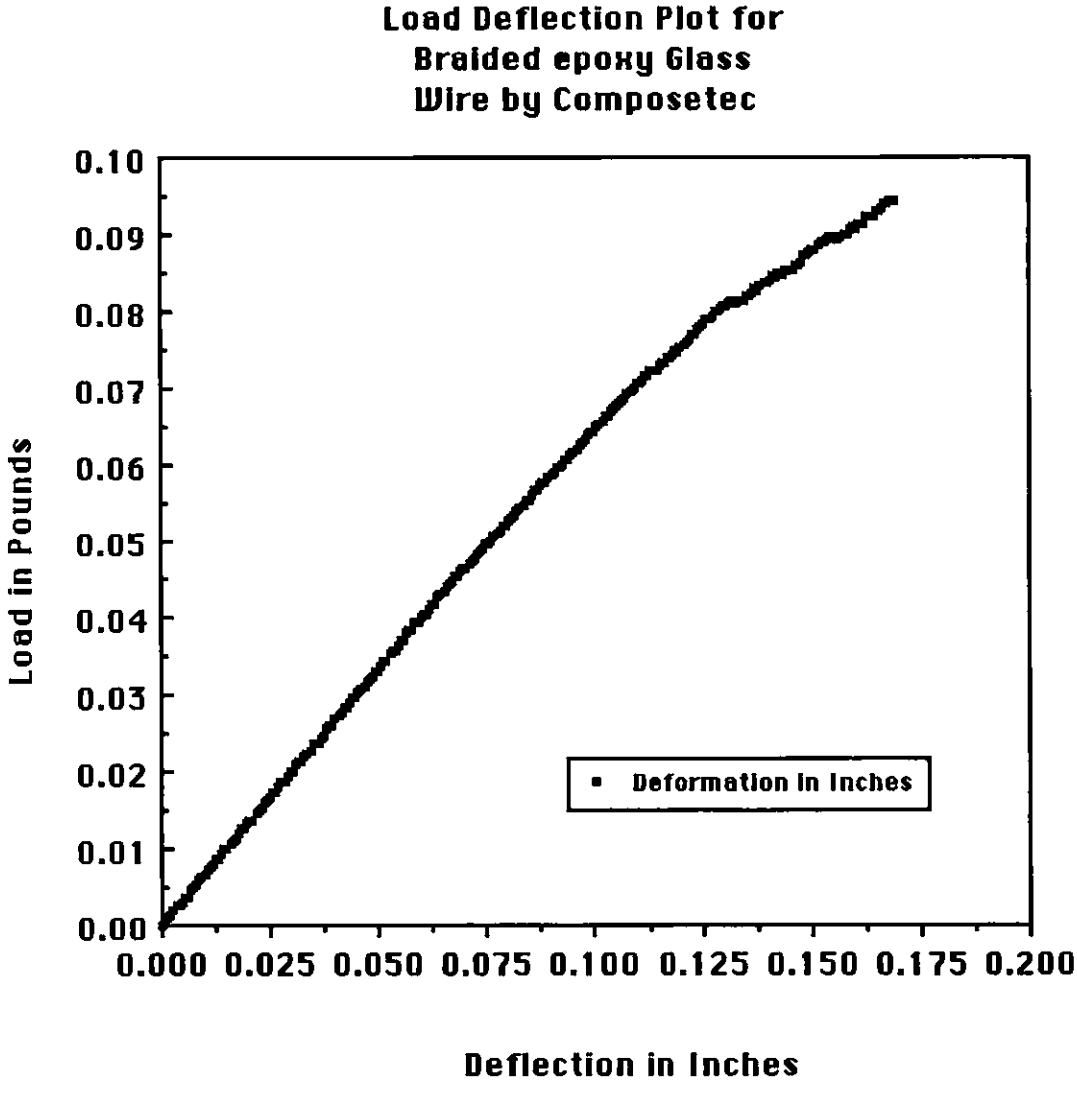

Tensile Stress Strain Plot
For Fiber Optic Cable
Reinforcement
120000
100000
80000
60000
40000
20000
0
Stress lbs/sq in
0.00
0.01
0.02
0.03
Strain in Inches
Stress lbs/sq in

Graph 39



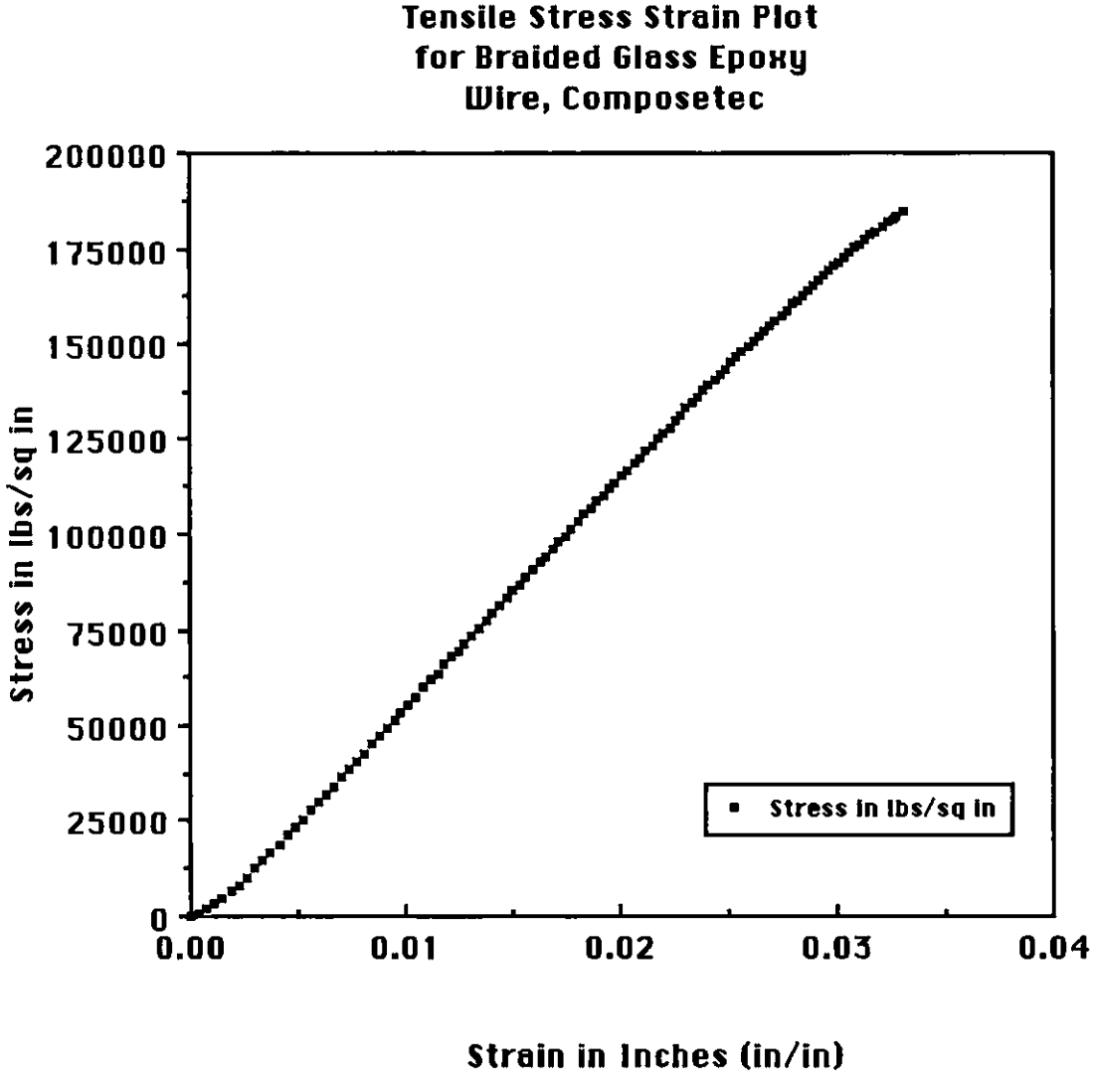
* Graph is an approximation of the materials true properties, the sample slumped more than 10% of the 1" test span making the data unreliable.

Graph 40



* Graph is an approximation of the materials true properties, the sample slumped more than 10% of the 1" test span making the data unreliable.

Graph 41


Tensile Stress Strain Plot
for Braided Glass Epoxy
Wire, Composetec
200000
175000
150000
125000
100000
75000
50000
25000
0
Stress in lbs/sq in
0.00
0.01
0.02
0.03
0.04
Stress in lbs/sq in
Strain in Inches (in/in)

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