AN EXAMINATION OF FACTORS THAT AFFECT TRANSVERSE PROPERTIES OF ALUMINUM-BORON COMPOSITES

by

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TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS--Continued

LIST OF ILLUSTRATIONS--Continued

LIST OF TABLES

ABSTRACT

Transverse tensile strength properties of boron-filament reinforced aluminum composites with various heat treatments and stress relief cycles were studied in an effort to determine the procedures necessary to improve these properties. Tensile specimens were fabricated by chemically etching to free the filament ends outside the reduced gage length section and by bonding of metal grips with adhesive onto the ends of the specimens. Initially a range of strain rates was used to determine the optimum strain rate to use for this experiment. The data were evaluated in terms of percent elongation, yield strength, ultimate tensile strength, modulus of elasticity, and the mode of failure. The experimental results indicated that the T6 heat treatment provided the highest transverse strength properties of the eleven different procedures evaluated.

CHAPTER I

INTRODUCTION

The transverse strength properties, of unidirectionally reinforced boron-aluminum matrix composites, has been much lower than expected, according to early investigators in 1969. This behavior has been attributed to longitudinal splitting in the boron filaments, with the cracks consequently propagating into the metal matrix causing premature tensile failure. The splits are inherent in the filaments, due to the high temperature of vapor deposition of the boron onto the 1/2 mil tungsten wire core. This is due to the thermal contraction differences between the two materials when they cool. These cracks have also developed during vapor deposition of coatings such as silicon carbide or boron nitride on the boron which are applied to increase the chemical compatibility of the filaments with the matrix at high temperature exposure.

Recent industrial programs to resolve this splitting problem have produced a 5.6 mil-diameter boron filament which is reported to have relatively few splits such that higher, transverse strength properties can be realized (Kreider,Dardi, and Prewo,1970). Kreider, et al., reported on a tensile specimen preparation technique where the metal matrix around the filament ends, of transverse tensile specimens, are chemically etched to remove the metal. This produces a reduced gage length tensile specimen with the filaments extending out the sides beyond the gage length test portion of the specimen. The result is that cracks in the filaments at the ends that developed during shearing of the specimens are removed from the test area of the specimen.

Other very recent industrial efforts on this splitting problem have resulted in development of glass core and carbon-filament core upon which the boron is vapor deposited. These types of boron filament are reported to have less thermal contraction differences and consequently fewer inherent cracks or splits.

For the research program reported herein, the only available improved filaments were the 5.6 mil diameter boron without a coating. This type filament, therefore, was used with the two most common aluminum alloys (6061 and 2024) and were fabricated into a two-filament layer composite using a diffusion method in a heated-platen press. The fabrication of the panels was performed by Harvey Aluminum Company, one of the foremost developers of filament reinforced metal composites, since fabrication was not within the scope of this research effort.

To evaluate other methods to improve transverse strength properties, assuming once again that the strength depended on the matrix and not the splitting of filaments, various thermal treatment techniques were used on the matrix. These methods used were natural and artificial aging, solution heat treatment, thermal stress relief, thermal cycling as a stress-relief procedure, and strain cycling as a stress-relief procedure.

CHAPTER 2

LITERATURE SURVEY

2.1 Critical Areas for Transverse Strength

Transverse strength of unidirectionally reinforced boron-fiber-aluminum-matrix composites has been of concern for many applications since low transverse strengths or the order of 12,000 psi to 22,000 psi have been experienced, as reported by Christian (1969) and Dolowy (1969b). These applications utilizing a composite with longitudinal tensile strengths in excess of 200 ksi in the direction of the boron fibers, also have need for transverse strengths which would be at least equal to the conventional aluminum strength of 45 to 65 ksi (6061 and 2024, respectively). Specific applications such as aircraft or missile structural members including outer skins need good transverse strength properties. Adsit and Forest (1969) reported on testing performed at Convair on aluminum-boron composites for structural stringers to reinforce and stiffen skin structures. Transverse compression tests were performed to establish design strengths to be expected from aluminum-boron composites. Christian (1969) reported on results of a Convair study program for components for the F-111 fuselage involving twelve major structural components including bulkheads, frames, longerons, door panels, shear panels, fittings, and a shear beam. In most cases, substantial weight savings, ranging from 18% to 60%, were identified by this study. In several cases, however, the low shear and transverse strength of the composite prevented a significant weight saving. In other cases, it was apparent that the weight payoff could be substantially increased, by a factor of two in some cases, if transverse properties could be increased by relatively small amounts.

The Convair Division of General Dynamics Corporation has been flight testing aluminum-boron-composite access doors on F-102, F-106, and F-111 airplanes and has been fabricating and evaluating aluminum-boron composite satellite payload adapters of conical shape 60 inches in diameter and 42 inches in length.

Another application where low transverse strength has been of concern, is for aircraft gas turbine compressor and fan blade usage. Tsareff (1969) of the Allison Division of General Motors Corporation evaluated transverse strength properties of aluminum-boron composites since the blades experience a cantilever-beam-fatigue type loading. Alloy 7178 was used for the matrix in these tests and a transverse tensile strength of 43 ksi was reported, mainly due to the high shear strength of the solution treated and aged 7178 matrix. Axial filament splitting was observed in these tests due to the inherent radial sub-surface cracks in the filaments.

Kreider, et al., (1970) of the Pratt & Whitney Aircraft Division of United Aircraft Corporation has also been evaluating aluminum-boron composite transverse strength for third-stage compressor blades that are exposed to a 600° F. operating temperature. The blades in these turbine engines also experience the cantilever-beam-fatigue-type loading. It was reported that all the filaments in the fracture plane showed splitting in the transverse tests.

Hanby (1971a) reported that NASA's planned space shuttle will help to maintain the present high interest and activity in the development of aluminum-boron composites. Hanby also reported that the Hamilton Standard Division of United Aircraft Corporation has been evaluating aluminum-boron composites for helicopter blades and propeller blades and the Bendix Corporation has been evaluating this material for landing gears.

It was concluded from these reports that transverse strength of unidirectional boron fiber-aluminum matrix composites is of utmost importance to the success of these various applications, and that much test effort is being exerted in R&D programs to improve this property.

2.2 Boron Filaments

One of the parameters of aluminum-boron composites that is being evaluated and improved is the boron filament itself. Original boron filaments consisted of boron vapor deposited from a boron trichloride (halide) and hydrogen gas mixture on to a one-half mil diameter tungsten wire substrate. This continuous filament has a tensile strength of about 450 KSI and a modulus of elasticity of about 56×10^6 psi. One problem associated with this type of filament during filament fabrication has been the thermal contraction difference between the tungsten wire core and the deposited boron. This difference has caused subsurface radial cracks in the boron that are detrimental to composite physical properties. Transverse testing almost always results in splitting of the filaments on the fracture plane, thus limiting the transverse tensile strength of the composite, as reported by Long (1969) and Hanby (1971b). Use of a silicon-carbide coating on the boron filament, to decrease chemical reaction between the aluminum matrix and the boron at high temperature, has increased the problem with additional radial cracks created during application of the coating on the filament.

Two new developments in boron filaments are the use of a glass-based core substrate and a carbon monofilament core substrate upon which the boron is vapor deposited. These combinations provide a low density for the continuous filament as well as offer a lower cost potential. It has been found with these types of filaments that radial cracks are substantially reduced. This is especially important in transverse strength where premature failure has been attributed to the propagation of the radial crack into the metal matrix thus reducing transverse strength. The average properties of these glass or carbon core filaments tend to be lower (300 KSI tensile strength) than those of the boron-on-tungsten type, but due to the lower density, the specific strength and modulus are about comparable in the boron-on-tungsten composite.

Another recent development in boron filaments is a 5.6-mil-diameter boron filament with the boron vapor deposited on a one-half-mil-diameter tungsten wire. No coating is used on this type of filament in an effort to reduce radial splits. Information concerning the fabrication processes utilized for this filament that make it have less tendency to split is not available. Usage of this type of filament, however, in aluminum matrix composites was reported by Kreider, et al., (1970), where 49 KSI transverse tensile strength was reported (2024 matrix) with no filament splitting in the test specimens.

It was concluded that full potential strength of the aluminum has not been realized during transverse testing since the filaments split with the cracks propagating into the matrix thus causing low transverse tensile strength of the matrix. Therefore, to improve composite transverse strength, the filament splitting had to be eliminated so that the transverse strength could once again be dependent upon the maximum strength that could be developed in the matrix. For this reason, the 5.6 mil diameter filaments produced by AVCO were utilized in the research program reported herein.

2.3 Processes of Composite Manufacture

There are various processes that are being used to fabricate metal-matrix composites. Experimental methods include electroplating, powder metallurgy, explosive bonding, and vapor deposition. For most small research programs, it is usually most convenient to use hot pressing, plasma spraying, or liquid infiltration, which produce higher temperature exposure for the filament with subsequent undesirable inter-metallic compounds created at the filament-matrix interface. However, Lockheed Aircraft has developed a continuous casting method where the filament (protected by a boron nitride coating) contacts molten aluminum. This process permits fabrication of composites with filament contents to 70% by volume, and reduces the overall fabrication costs. Most commercial fabrication, though, of aluminum-boron composites has been by diffusion bonding to reduce the temperature to which the filaments are exposed during fabrication.

A processing technique review was presented by Cornsweet (1971) which outlined many practical possibilities for advanced fabrication methods for aluminum-boron composites. However, they were too numerous and had too many variations to include in this literature survey.

The manufacture of composites is a complex procedure beyond the scope of this test program. So, to avoid fabricating composites that could produce questionable results, a major manufacturer of composites, Harvey Aluminum Company, was contacted and they agreed to fabricate the composite panels for this program using both 2024 and 6061 aluminum alloys with the AVCO 5.6-mil filaments. These panels were fabricated using the diffusion bonding process, details of which are not available.

2.4 Volume Percent of Filaments

Another factor that influences transverse tensile strength is the volume percent of filaments present in the composite. A study reported by Lin, Chen, and Dibenedetto (1969) developed the set of tensile curves shown in Figure 1 for annealed, as well as, aged boron-6061 aluminum composite. The modulus curves for the material are shown in Figure 2. Lenoe (1967a) showed data of modulus versus volume percent boron as shown in Figure 3. Davis (1969) of Harvey Aluminum Company also reported on transverse tensile strength influenced by volume percent filaments as shown in Table 1.

As verified by the test data from the above four sources, transverse tensile strength is greatly influenced by volume percent of filaments.

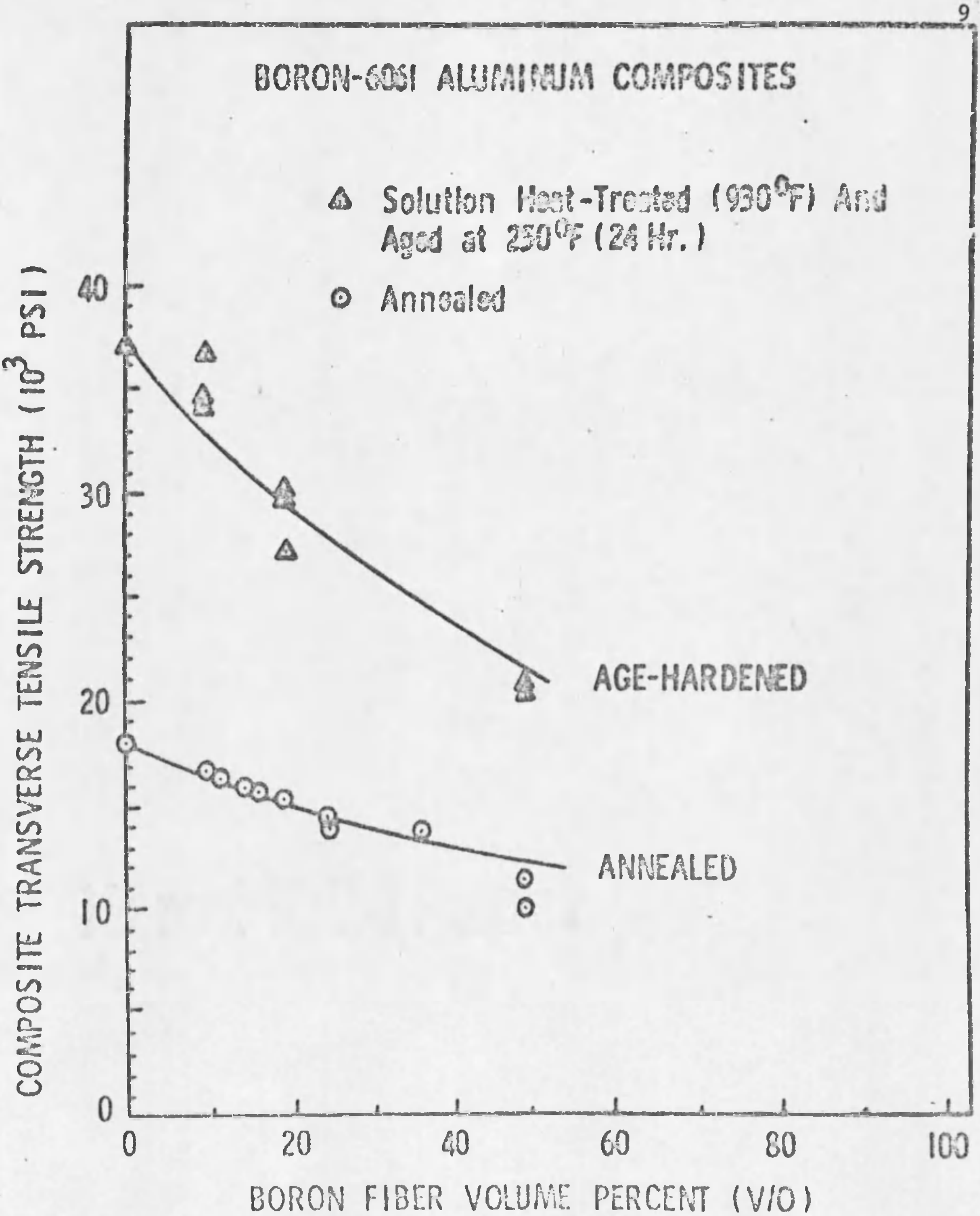


Figure 1. Boron-6061 Aluminum Composite Transverse Tensile Strength vs. Fiber Volume Percent under Different Heat Treated Conditions (Lin, et al., 1969)

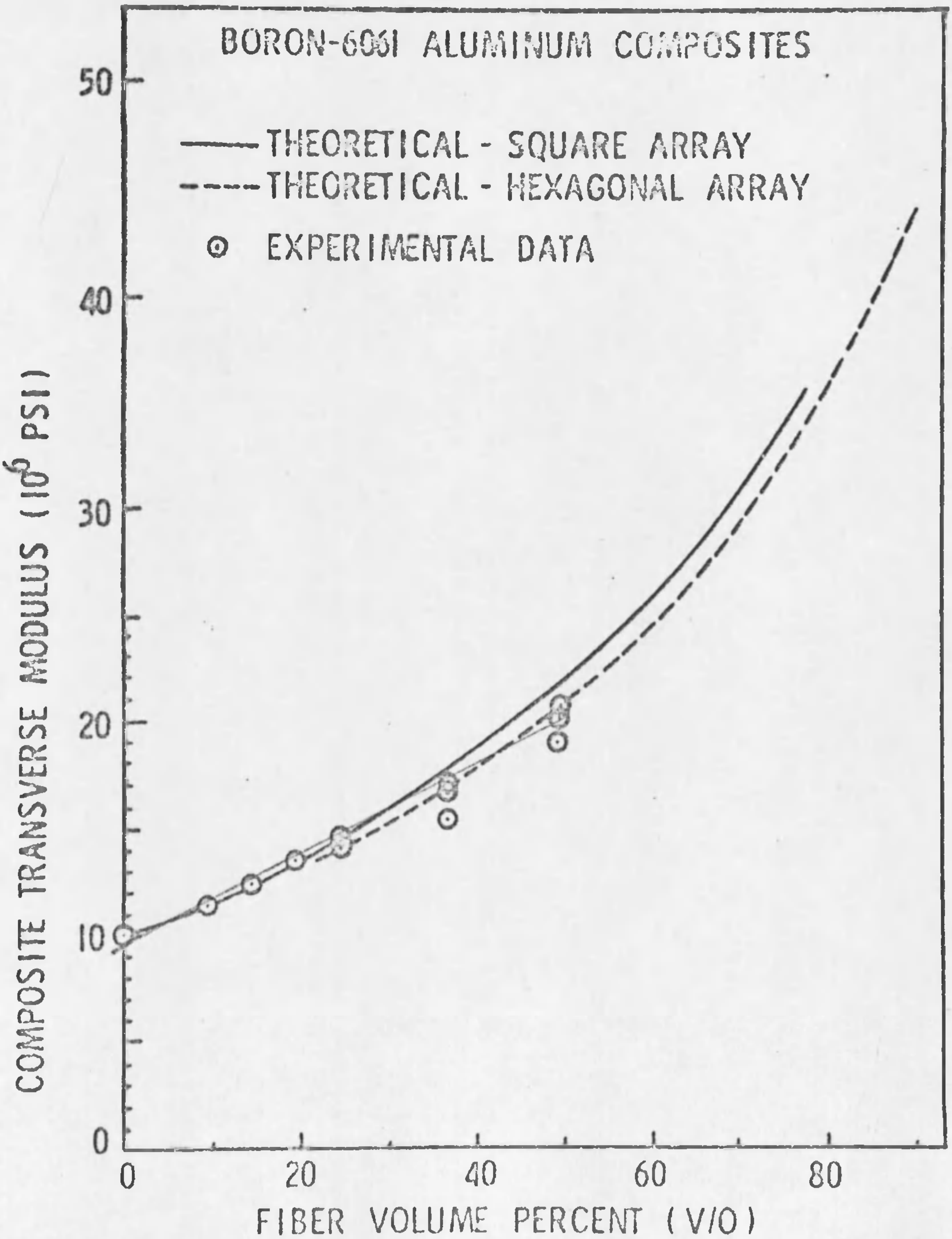


Figure 2. Boron-6061 Aluminum Composite Transverse Modulus vs. Fiber Volume Percent--Comparison Between Analytical Results and Experimental Data (Lin, et al., 1969)

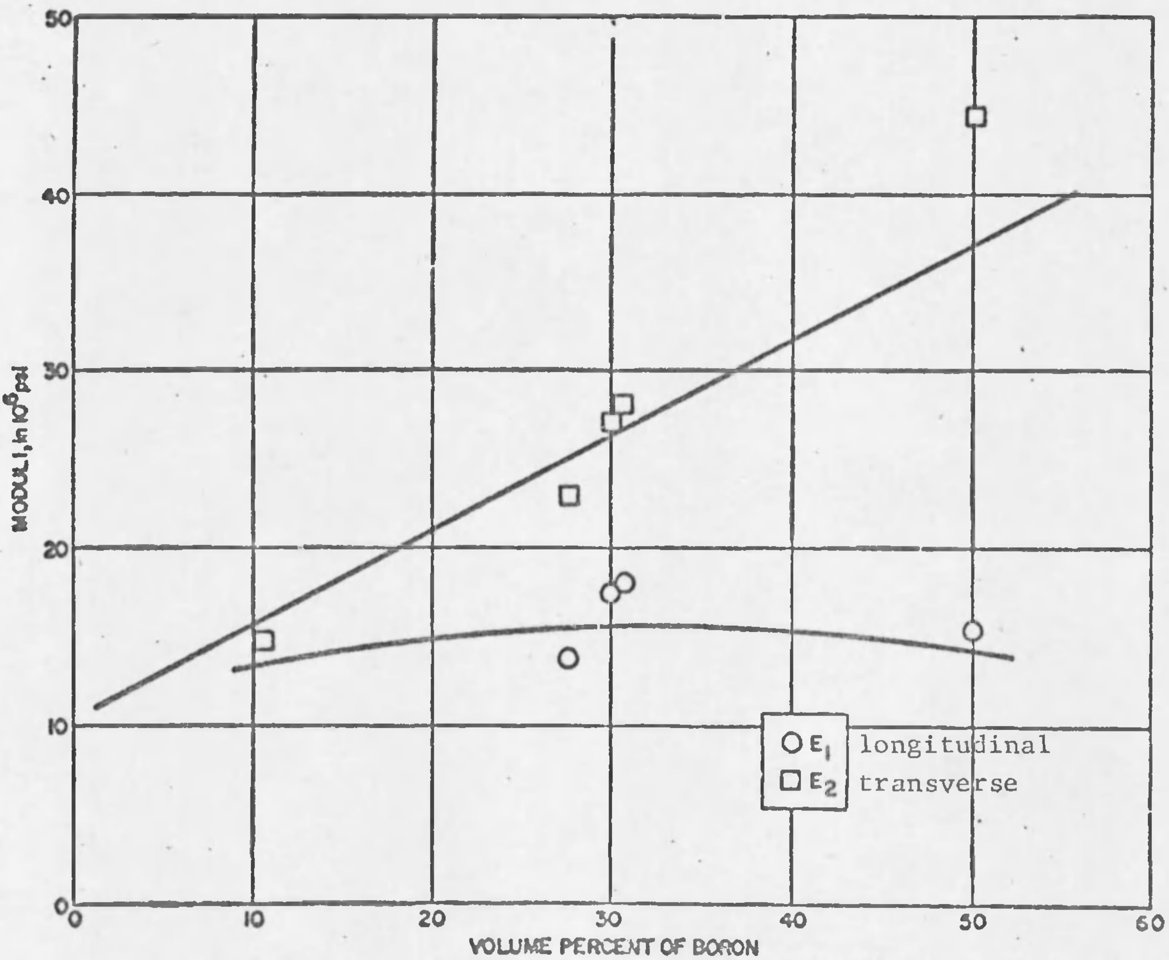


Figure 3. Longitudinal and Transverse Moduli vs. Volume-Percent Boron (Lenoe, 1967a)

Table 1. Transverse Tensile Strength (Davis, 1969)

Matrix	Average Transverse Tensile Strengths (KSI)*			
	10 v/o B	25 v/o B	40 v/o B	50 v/o B
1100	8.5	20.8	12.9	10.5
6061	16.0	7.7	13.7	14.5
2024	30.0	15.3	14.9	12.8

* All failures contained longitudinal split filaments.

The transverse tensile strength decreases as filament volume percent increases. This is most likely due to the increase of filament splitting as the percentage of filaments increases. The transverse modulus, however, increases with increase of filament addition to the composite. This increase in modulus is the result of the Law of Mixtures with the boron filaments having a higher modulus than the aluminum matrix, so that increasing the percentage of filaments increases the composite transverse modulus. For the research program for this thesis, volume percents of 25% and 50% were chosen for study.

2.5 Stress Relief by Thermal Cycling

Taylor, Shimizu and Dolowy (1969) of The Marquardt Corporation evaluated the effect of temperature cycling on relief of residual stresses in composites of Alloys 1145 and 6061 with boron filament reinforcement. The following cycles were utilized:

a. 20 cycles from 70°F. to 700°F.

b. 284°F. for 24 hours.

c. 338°F. for 24 hours.

It was concluded by Taylor, et al., however, that the thermal cycling degraded the strength of the composite. A report by Hamilton and Ebert (1969) discussed a test program to reduce or alter residual stresses. It was found that prestrain was effective in improving tensile strength by 20%. Davis (1969) evaluated a stress relief cycle on 6061 alloy matrix consisting of 200°F. for 16 hours followed by a slow cool. This produced a transverse strength of 17,000 psi (for 37 v/o B) which was much lower than the T6 condition of 31,900 psi.

It was decided to utilize stress relief cycles of 284°F. for 24 hours and 338°F. for 24 hours, as well as the 20 cycles of 70°F. to 700°F. in this thesis test program.

Residual stress measurements were made by Lenoe (1967b) by machining off one side of a composite and then measuring the amount of force required to straighten out the warped composite. The test data for four samples for various thicknesses are shown in Figure 4.

2.6 Heat Treatment and Aging

Shimizu and Dolowy (1969) of The Marquardt Corporation reported on various thermal treatments and their effect on transverse strength. The study showed that the highest transverse strength was in the range of 12 to 16 KSI for the T6 treatment; however, it was felt that the data were not representative of the true capability of the composite.

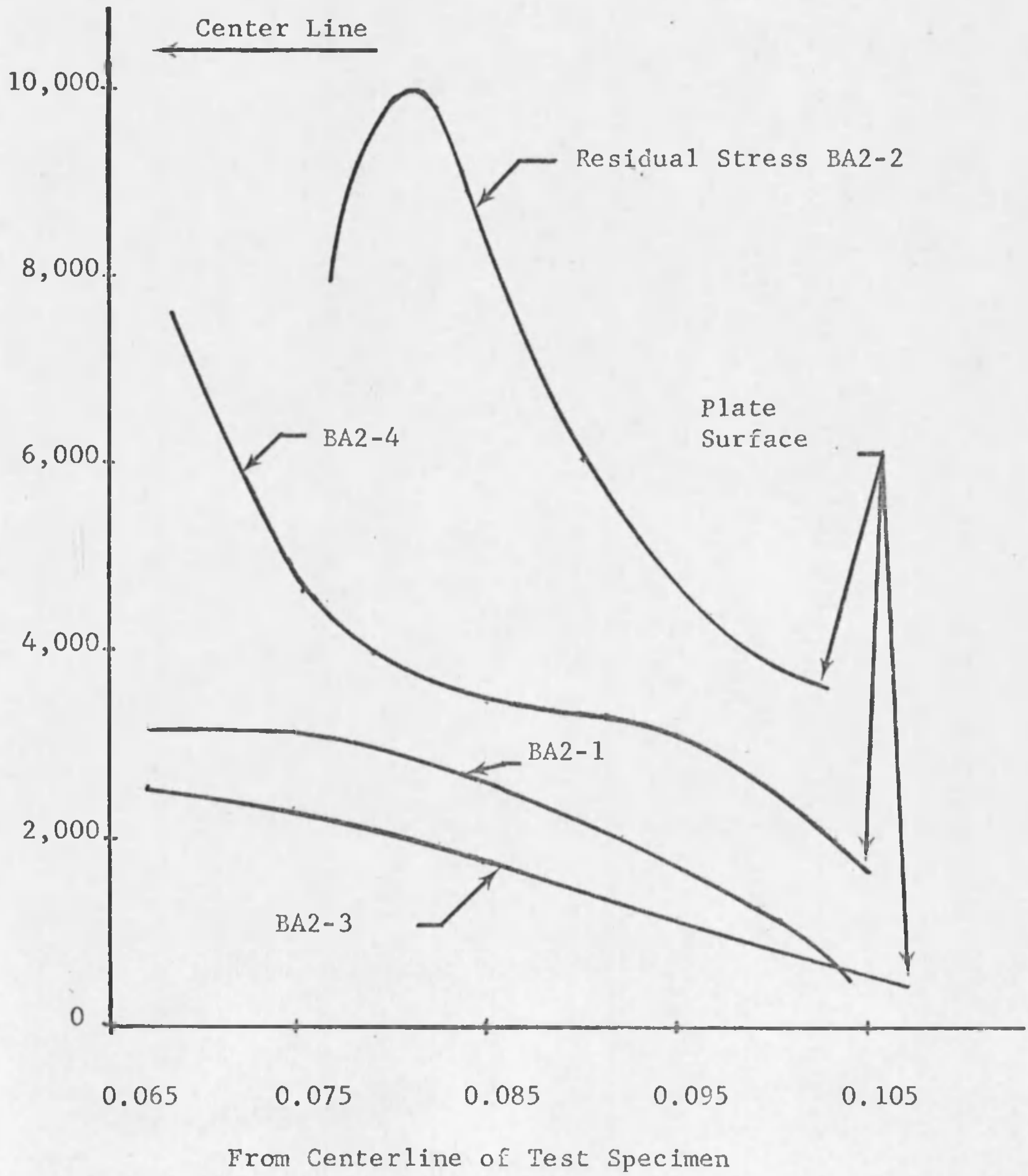


Figure 4. Residual Stress Versus Thickness (Lenoe, 1967b)

This was due to the sensitivity of transverse tests to edge effects, of splits in the fiber ends due to fabrication.

Swanson and Hancock (1971) also evaluated various heat treatments for 30 v/o boron-7075 aluminum and found that the T6 condition produced the highest UTS. The test data are shown in Figure 5; however, the transverse specimens failed by longitudinal splitting of the filaments.

Hanby (1971b) reported on some very recent research conducted at Midwest Research Institute that evaluated various heat treatments and their effect upon transverse tensile properties of 7075 aluminum matrix with 30 v/o boron filaments. These data indicated that the standard T6 treatment produced the highest strength as shown in Figure 6 although fractures contained excessive boron filament splitting, suggesting that the composite's transverse strength was limited by the properties of the filaments (splitting).

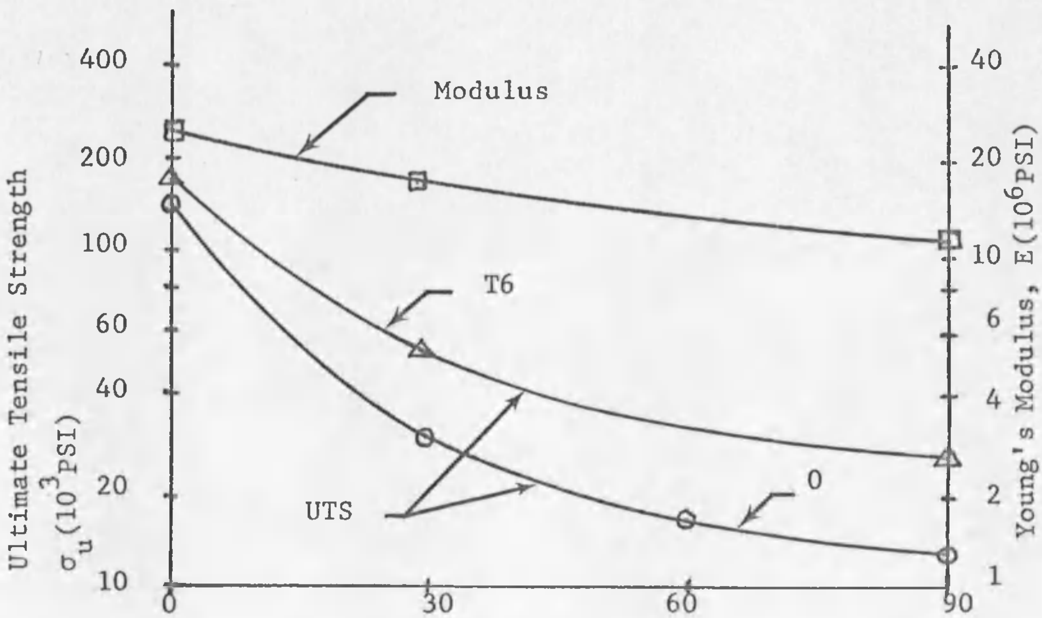


Figure 5. Filament Orientation vs. Ultimate Tensile Strength and Young's Modulus for Composite Specimens of 7075-T6 and 7075-0 Aluminum-Boron (Swanson and Hancock, 1971)

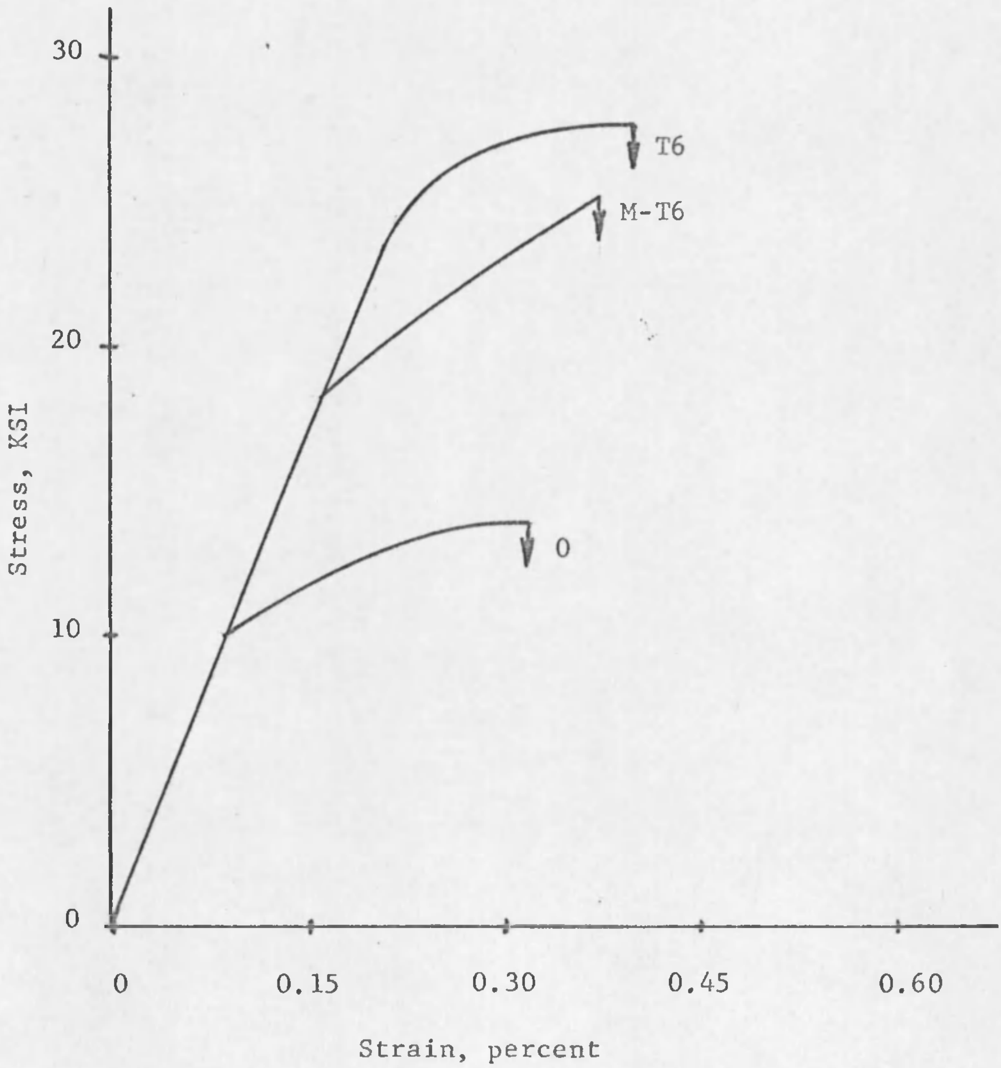


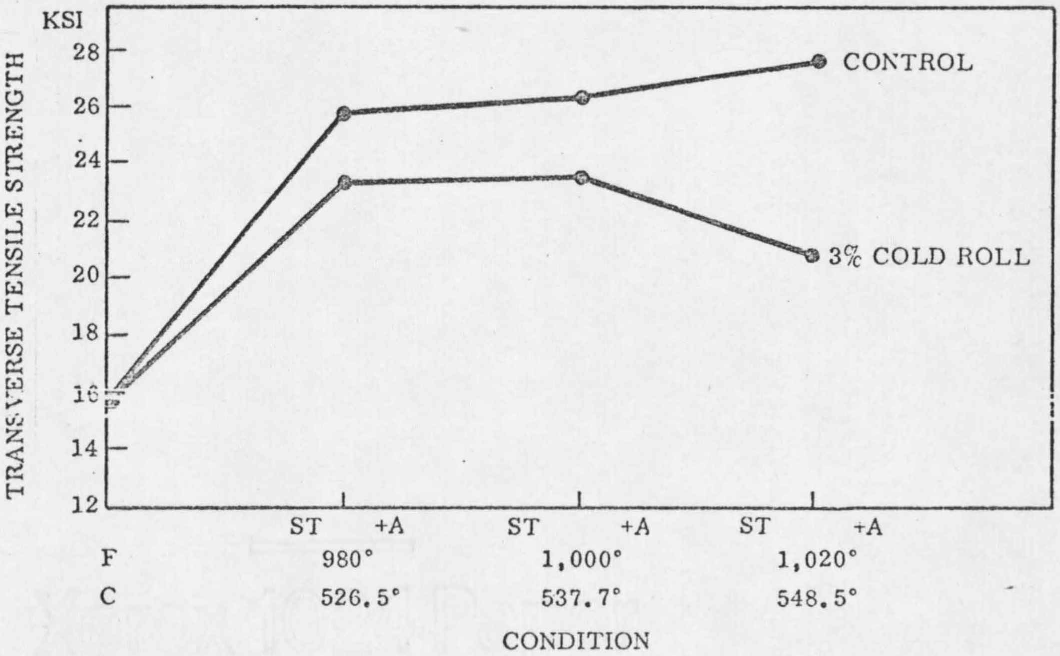
Figure 6. Effect of Heat Treatment on Representative Stress-Strain Curves for 7075 Aluminum/30 Vol % Boron Composite Tested Transversely to the Fiber Direction (Hanby, 1971b)

Many of the other reports in the literature survey reported herein evaluated the effect of T4 and T6 heat treatment and aging procedures on the transverse tensile strength. In all cases, the T4 and T6 conditions were reported to be beneficial, so that these treatments were included in this experiment.

2.7 Cold Rolling

A 10% reduction by cold rolling transverse to the filaments was reported by Taylor, et al. (1969) to show an increase in transverse strength. Christian (1969) reported on test data where 3% transverse cold rolling decreased transverse tensile strength of 6061 alloy composite as shown in Figure 7. Christian also reported that 5-6% of cold working on this composite structure resulted in matrix crazing. Dolowy and Taylor (1969) described transverse 10% cold rolling of 6061 matrix-boron composite that increased the longitudinal tensile strength by 30 KSI; however, the effect upon transverse strength was not described. Another report of the effect of transverse cold rolling upon longitudinal tensile strength was reported by Getten and Ebert (1969) with the test results plotted as shown in Figure 8.

Dolowy (1969a) reported that although transverse 10% cold rolling increased longitudinal ultimate tensile strength by 10%, the transverse ultimate tensile strength was reduced for the 6061 matrix composite. Forest (1968) of Convair reported that composites obtained from both Marquardt and Harvey Aluminum Corporation showed cold working was actually deleterious to transverse strength.



ST = Solution heat treating at the subscript temperature (i.e. 980°F, 1000°F, or 1020°F; 526.5°C, 537.7°C, 548.5°C) for 30 minutes Aging (350°F, 176.7°C) for 8 hours).

Figure 7. Effect of Cold Working on Transverse Tensile Strength

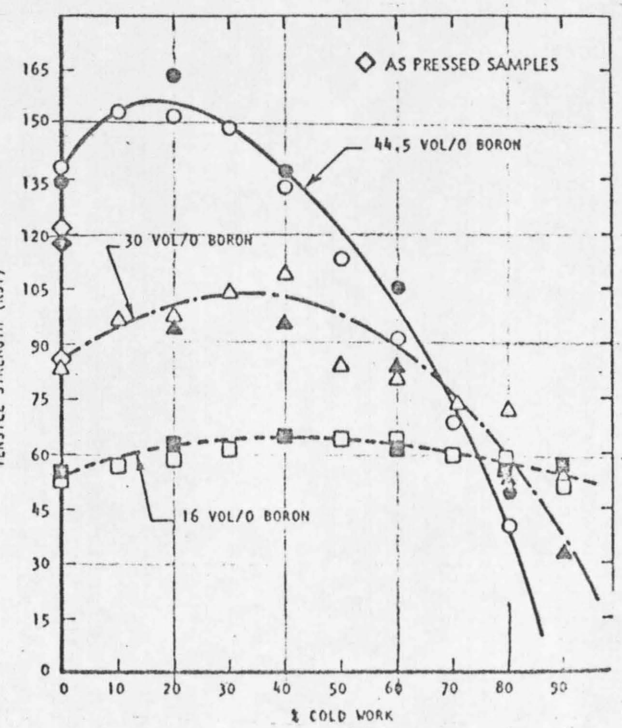


Figure 8. The Effect of Transverse Rolling on the Tensile Strength of Aluminum-Boron Composites (Open Points: 10% Reduction per Pass--Closed Points: 20% Reduction per Pass)

A review of the available data of the effect of transverse tensile strength of transverse cold rolling seemed to indicate that this thesis test program should evaluate at least 5% and 10% transverse cold rolling.

2.8 Pre-stretching of Filaments

A review of the literature in regard to research in pre-stretching the filaments during composite fabrication indicated that no effort has been exerted to evaluate this variable. Since the pre-stretching is a common procedure used in pre-stressed concrete, it would seem logical that the same pre-stretching would be beneficial to aluminum matrix composites. However, although this technique is within the realm of fabrication of composites, it was not considered for this test program since only post-fabrication variables were to be evaluated in this program.

2.9 Stress Relief by Stress Cycling

No reference could be found in the literature for metal matrix composites where stress cycling had been evaluated as a method for stress relief. This method, however, has been used for metals and it was felt that this method may be beneficial to transverse tensile strength of the aluminum-boron composite materials to be tested in this thesis. A stress cycling of 10% of the ultimate tensile strength (transverse) was used in this thesis with ten cycles applied from no load to 10% of the UTS, prior to the specimens being tested to failure.

2.10 Matrix-to-Fiber Bond

No reference could be found in the literature where matrix-to-fiber bond was evaluated in relation to transverse strength properties. Failure mode up to this time has been splitting of the fibers where the splits propagated into the aluminum matrix causing premature failure of the matrix. However, with the new glass core and carbon monofilament core filaments, as well as the new 5.6-mil-diameter filaments, relatively few splits of the boron is experienced. Therefore, higher transverse strengths have been obtained from the matrix. Even with the higher strengths, no mention has been found of bond failures between the matrix and the filaments.

There have been several reports in the literature evaluating the chemical reaction between the aluminum matrix and the boron filaments associated with high-temperature exposure. The inter-metallic compounds found at the matrix-fiber interface, degrade the bond strength of the matrix to the filament. These reports have attempted to identify the intermetallic compounds, degree of boron attack or decomposition, and use of coatings such as silicon carbide on the boron filament to decrease the filament-matrix reaction. However, there were no data found in the literature search relating transverse tensile strength to bond strength of the matrix to the filament.

It was decided that this bond factor was not to be within the scope of this thesis program unless the bond factor became a prominent mode of failure in the tests to be performed.

2.11 Addition of Transverse Fibers

The literature search disclosed that several programs had evaluated the effect of adding a small percentage (5%) of stainless steel filaments in the transverse direction to increase transverse tensile strength. Christian (1969) discussed the usage of 5% by volume of AM-355 stainless steel wire (cross-plied) in 6061 aluminum matrix. These composites produced data as shown below in Table 2, with the transverse strength approximately twice that reported by Christian (1969).

Dolowy (1969b) reported also about double the transverse tensile strength to 30-43 KSI with the addition of 5% stainless steel transverse wire.

Again, this factor of adding transverse filaments or wire to increase transverse tensile strength is a factor involved in fabrication of the composites and therefore was not considered to be within the scope of this thesis. This thesis evaluated only post-fabrication variables that affect transverse properties.

2.12 Summary of Literature Search

The foregoing literature survey was developed in some detail in an effort to take in the wide scope of experimental work carried out in the area of transverse properties of boron-filament-reinforced-aluminum composites. In the course of sorting out the many approaches used by the investigators, it became evident that there was no common agreement about which approaches produce the best results.

Table 2. Mechanical Properties of Al-B-SS Composites

Condition	Long. Tensile		Trans. Tensile			Shear
	F_{tu}(KSI)	E(MSI)	F_{tu}(KSI	F_{ty}(KSI)	E(MSI)	F_{su}(KSI)
Al-35B-5SS:						
F	115(80.8)	22.5(15,820)	42.7(30.0)	19.1(13.5)	11.5(8,080)	24.2(17.0)
ST&A	124(87.1)	23.3(16,380)	41.3(29.0)	29.3(20.6)	13.9(9,770)	22.6(15.9)
Al-45B-5SS:						
F	175(123)	29.7(20,880)	36.2(25.4)	15.0(10.5)	14.2(9,980)	18.4(12.9)
ST&A	159(112)	31.3(22,000)	32.1(22.5)	23.0(16.2)	15.8(1,110)	19.2(13.5)

NOTE: All figures in parentheses are kgf/mm^2.

This was particularly true since some test results contradict results from other investigators. Thus, at this juncture, it appears that all the post-fabrication approaches should be investigated in this thesis within the limits of the material available. There were several analytical studies made of composites and transverse strength properties such as that by Chen and Lin (1968) and Ebert (1970). However, an analytical study of composites was not within the scope of this test effort and no analysis was made of the analytical studies.

CHAPTER 3

OBJECTIVES OF THIS INVESTIGATION

The general purpose of this investigation was to study the transverse physical properties possessed by boron-filament-unidirectionally-reinforced-aluminum-matrix composites with various post-fabrication treatments to determine the nature of the relationship between the post-treatments and the behavior resulting from these treatments.

The detailed objectives of this study were:

1. To determine the effectiveness of a new transverse tensile specimen preparation technique first reported by Kreider,et al.,(1970) improving transverse strength. This technique involves the freeing of the filament ends at the edges of the specimen by chemically etching the aluminum away from the machined edges. This technique reduces the possibility of cracks at the ends of the filaments (created during specimen machining) propagating into the reduced gage length section of the specimen.

2. To evaluate observed behavior of the transverse strength properties with the post-treatments of solution heat treatment, natural and artificial aging, cold-rolling, thermal stress relief cycles, and strain cycling for stress relief. These processes were evaluated in an effort to improve the transverse strength properties of the composites.

3. To evaluate the new 5.6-mil-diameter boron filaments reported to produce transverse tensile specimens that do not fail prematurely from filament splitting.

CHAPTER 4

THEORETICAL CONSIDERATIONS RELATED TO TRANSVERSE STRENGTH IMPROVEMENT

The two most commonly used aluminum alloys are 6061 and 2024; therefore, these alloys were evaluated in this thesis. These alloys have nominal compositions as indicated in Table 3.

Table 3. Alloy Compositions

Alloy	Si	Cu	Mn	Mg	Cr	Al
6061	0.6%	0.25%	--	1.0%	0.25%	97.9%
2024	0.5%	4.5%	0.6%	1.5%	0.1%	92.8%

The 6061 alloy is popular since it is characterized by excellent corrosion resistance and is more workable than other heat-treatable alloys. The 2024 alloy develops the highest strengths of any naturally aged aluminum-copper alloy.

4.1 Precipitation Hardening Process

The general principle of precipitation hardening is to make use of the supersaturation condition that exists when a solid solution is preserved by a rapid cooling process. This is prominently encountered with low carbon steel, beryllium copper, precipitation hardening steels, and most prominently with many of the aluminum alloys. Supersaturation can only be induced when the phase diagram has a solid solubility line that has a significantly positive slope, that is, solubility increases with increasing temperature. The solid solubility line separates the single-phase (α) region from the two-phase region of the phase diagram.

Since the matrix materials in this thesis are two precipitation hardening aluminum alloys, the precipitation hardening process will be defined specifically for these materials. The precipitation hardening process is divided into three basic steps as follows:

a. Solution heat treatment step--In this process, it is necessary to heat the alloy into the solid solution temperature range for a time long enough to permit solid state diffusion processes to occur and produce a completely homogeneous solid solution. It is imperative that the solution heat treatment temperature never exceeds the eutectic temperature to prevent melting of the eutectic that may be present along the grain boundaries. This is known in industrial heat treating as "burning the alloy." The solution heat treatment temperature for 6061 alloy is 985°F. and for 2024 alloy is 920°F. Times required for this process are a function of the thickness of the material, and the inherent diffusion coefficients of the alloying elements.

b. Preservation of a homogeneous solid solution--The state of supersaturation is produced by rapidly cooling (water quench) the solid solution alloy to prevent precipitation of the now-excess insoluble phase.

c. Aging to enhance mechanical properties--Aging may be defined as a heat treatment of the supersaturated alloy that utilizes a temperature/time combination sufficient to precipitate the critical size sub-microscopic particles that produce optimum properties of strength and ductility. Currently accepted theory explains this hardening and strengthening phenomenon as a result of the formation of Guinier-Preston Zones along the $\{100\}$ planes (two-dimensional platelets one atom thick and 30 to 50 Angstroms in diameter for GP [1] zones and several atoms thick for three-dimensional GP [2] zones), (Van Horn, 1967). Dislocation theory accepts the Guinier-Preston theory and explains the optimization of strength and hardness by the impeding of dislocation movement when the limiting radius of the dislocation loop is equal to the distance between zones (approximately 100 Ångstroms). In order for the dislocation to progress through the aluminum lattice, it is necessary for the dislocation to shear the zone, that is, to overcome the elastic strain energy produced in the aluminum lattice by the coherent platelets of foreign atoms (precipitate as a Guinier-Preston Zone); or, it is necessary to glide by overcoming the interaction energy of the zone.

In the case of the 2024 alloy, ordinary room temperature (70°-90°F.) is high enough to permit precipitation to occur at a significant rate. This condition is described as 2024-T4 and is representative of the "natural aging" process. In the 2024 alloy, the magnesium addition accelerates and intensifies the natural aging and the precipitation zones are believed to consist of groups of magnesium and copper atoms. The apparent acceleration of the natural aging by the addition of magnesium may result from complex interactions between vacancies and the two solutes.

In the case of the 6061 alloy, it is necessary to "artificially age" the alloy at elevated temperature in order to achieve optimum precipitation conditions. In artificial aging (heat treatment) of the 6061 alloy to obtain the T-6 condition, a temperature cycle of 320^{o}F. for 18 hours is utilized. In artificial aging of the 2024 alloy to obtain the T-6 condition, a temperature cycle of 375^{o}F. for 9 hours is utilized.

4.2 Cold Rolling Process

Metals and alloys can be strengthened by cold working (strain hardening) below the recrystallization temperature. Certain precipitation-hardenable alloys can be further strengthened by aging after cold working.

Work hardening causes the generation and multiplication of dislocations and the subsequent locking (impeding of movement) of these dislocations due to elastic interaction of the dislocation strain fields. Several of the locking mechanisms are as follows:

a. There can be both interactions with strain fields of dislocations parallel to each other as well as interactions of the strain field of a dislocation with forest dislocations.

b. There can be elastic interaction with stress fields of piled-up groups of dislocations creating Cottrell-Lomer sessile dislocations.

c. There can be elastic interaction with stress fields of high energy dislocation networks and tangles.

d. There can be elastic interaction with "debris" produced by dislocation movement. Debris consists of edge dislocation dipoles and loops.

e. There can be energy required to form a jog at a dislocation intersection.

f. There can be energy required to form vacancies and interstitial atoms by non-conservation motion of jogs on screw dislocations.

The additional energy required to produce dislocation movement, as described above, is the major contributing factor for the increase of strength realized in strain hardening.

4.3 Thermal Stress Relief

Thermal stress relief is a heat treatment that tends to uniformly redistribute the stress fields thereby preventing premature failure that could occur if highly stressed local conditions existed. This is accomplished because the higher temperature permits localized movement of individual dislocations (movement starts and is most active at high stress centers). During the movement and migration of the dislocations, annihilation of dislocations, glide, movement along low angle grain boundaries, and relief of violent tangles (stress concentrations) is realized.

The basic cause of these high stress concentrations is due to the difference in the thermal contraction rates between the boron filaments and the aluminum matrix when the composite is cooled from the fusion temperature. The aluminum tries to contract more than the boron, and therefore, stress concentrations are established at the interface. The thermal stress relief therefore has a tendency to relieve these high stress centers at the bond interface between the boron filament and the aluminum matrix as well as at other points within the matrix.

4.4 Strain Cycling

The strain cycling process accomplishes the same stress relief as does the thermal stress relief process. However, instead of using elevated temperature to provide the energy to allow dislocation movement, this process uses small tensile strain cycling applications (10% of UTS) within the elastic range to provide the energy for the dislocation movement.

CHAPTER 5

EXPERIMENTAL PROCEDURE

In this investigation, tensile specimens of the aluminum-boron composites were prepared by shearing, cold-rolling or thermally treating, masking, chemical etching, and adhesive bonding. Eleven (11) different treatment conditions were chosen to provide the experimental data, and tests were performed on three specimens for each condition for both 25% and 50% boron in 6061 and 2024 aluminum alloy matrixes. The treatment conditions consisted of 5% and 10% cold rolling (T3) with and without additional heat treatment (T36), natural age hardening (T4), artificial age hardening (T6), two thermal stress relief procedures, one thermal-cycling-stress-relief procedure, and one strain-cycling-stress-relief procedure. The test conditions are tabulated in Table 4.

Tensile specimens of one-inch gage length were used throughout, thereby making the term "pulling speed" equivalent in magnitude to strain rate. Aluminum pads were epoxy adhesive bonded on each side of each end of the specimens so that grip areas were provided for the Instron serrated jaws.

5.1 Material

One panel 0.022 inch thick of each 6061 and 2024 aluminum alloy containing 25% by volume of boron filaments was obtained from Harvey Engineering Laboratories for Research and Development,

Table 4. Aluminum 6061-F Composite Test Results

Condition	Heat Treatment	Stress Relief	Percent Boron (Vol.)	Elongation at Break %	Ave	Yield Strength PSI	Ave	Ultimate Tensile Strength PSI	Ave	Modulus of Elasticity x 10^6 PSI	Ave	Comments of Fracture Appearance
Annealed (T-0)	None	None	25%	2.0		11,730		19,050		8.9		
				1.45	1.52	12,400	12,190	17,900	17,950	10.75	11.1	
				1.1		12,450		16,850		12.7		
			50%	0.45		9,800		11,200		15.25		
				0.32	0.46	5,680	9,090	6,300	10,200	11.55	13.0	
				0.60		11,800		13,000		12.25		
Annealed Soln. Treat	Age at R.T. for 4 days (T-4)	None	25%	1.4		23,600		28,800		12.90		
				1.33	1.42	25,600	23,980	30,500	29,600	14.70	13.6	
				1.52		22,750		29,500		13.10		
			50%	0.69		23,400		25,500		20.35		
				0.57	0.70	21,000	21,800	21,000	24,400	19.6	20.0	
				0.84		20,900		26,700		20.15		
Annealed Soln. Treat	320°F. 18 hrs. (T-6)	None	25%	1.45		40,800		40,800		14.9		
				1.40	1.42	39,600	37,300	39,600	37,300	15.0	14.0	
				1.37		31,500		31,500		12.2		One fiber split 100%.
			50%	0.92		33,400		33,400		19.25		
				0.48	0.65	15,800	22,700	15,800	22,700	17.50	18.3	One fiber split 90%.
				0.55		18,900		18,900		18.20		One fiber split 60%.
Annealed Soln. Treat	320°F. 18 hrs. (T-6)	284°F. 24 hrs.	25%	0.89		23,000		23,000		13.7		One fiber split 40%.
				0.90	1.04	22,300	25,700	22,300	25,700	13.15	13.2	
				1.32		31,700		31,700		12.7		
			50%	0.88		29,000		29,000		17.5		
				0.88	0.84	29,700	28,400	29,700	28,400	19.2	18.2	
				0.76		26,500		26,500		17.8		
Annealed Soln. Treat	320°F 18 hrs. (T-6)	338°F. 24 hrs.	25%	1.20		33,400		33,400		14.7		
				1.30	1.27	32,800	34,100	32,800	34,100	13.35	14.2	
				1.30		36,100		36,100		14.7		
			50%	0.68		21,500		21,500		16.8		One fiber split 100%.
				0.81	0.71	29,600	24,300	29,600	24,300	19.4	18.2	No fiber splits.
				0.63		21,700		21,700		18.3		One fiber split 60%.

Table 4 (continued)

Annealed Soln. Treat	320°F. 18 hrs. (T-6)	20 cycles 70°F. to 700°F.	25%	1.50 1.29 1.70	1.52	12,300 13,500 12,800	12,900	18,200 18,900 20,200	19,100	10.85 11.9 11.65	11.5	
			50%	0.69 0.69	0.69	7,250 8,160	7,705	10,550 11,400	10,980	12.0 11.8	11.9	
Anneal Soln. Treat Cold Roll 5% (T-3)	None	None	25%	1.42 1.11 1.70	1.41	28,000 21,600 26,600	25,400	32,200 26,200 34,300	30,900	12.55 12.7 12.8	12.7	One fiber split 15%. One fiber split 80%. No fiber splits.
			50%	0.71 0.79 1.05	0.85	23,900 27,400 24,500	25,300	25,000 31,000 32,700	29,600	18.9 23.4 18.5	20.3	One fiber split 25%. No fiber splits. No fiber splits.
Anneal Soln. Treat Cold Roll 5%	320°F. 18 hrs. (T-36)	None	25%	1.67 1.10 1.41	1.39	44,300 30,800 39,900	38,300	44,300 30,800 39,900	38,300	14.05 15.3 15.0	14.8	One fiber split 15%. No fiber splits.
			50%	0.50 0.88	0.88	14,300 29,200	29,200	14,300 29,200	29,200	15.15 17.5	17.5	One fiber split 50%. No fiber splits.
Anneal Soln. Treat Cold Roll 10% (T-3)	None	None	25%	1.22 0.90 1.02	1.05	26,300 16,950 23,000	22,100	28,900 18,400 24,700	24,000	13.05 11.5 13.4	12.7	No fiber splits. No fiber splits. No fiber splits.
			50%	0.70 0.65 0.65	0.67	16,200 17,700 18,900	17,600	16,200 17,700 18,900	17,600	12.3 14.4 15.4	14.0	No fiber splits. One fiber split 30%. No fiber splits.
Anneal Soln. Treat Cold Roll 10%	320°F. 18 hrs. (T-36)	None	25%	0.98 1.07 0.98	1.01	24,350 24,400 24,600	24,450	24,350 24,400 24,600	24,450	13.2 12.1 13.3	12.9	
			50%	0.60 0.80	0.70	17,800 21,900	19,800	17.800 21.900	19,800	15.7 14.5	15.1	No fiber splits. One fiber split 40%.

a division of Harvey Aluminum, Inc. Sections 1-1/2 inches by 4 inches were sheared from these panels with the filaments in the 1-1/2-inch direction. These sections then were processed by solution treating, cold-rolling, age hardening, or stress relief as required.

5.2 Tensile Specimen Fabrication

Test specimens 1/2 inch by 4 inches were sheared from each of the conditioned sections. For specimens to contain 50% by volume filaments, the thickness of the material was chemically etched from the original 0.022-inch thickness to approximately a 0.013-inch thickness, only in the necked down portion of the specimen (the grip areas were masked with Scotch No. 56 Mylar Masking Tape). Difficulty was experienced with this etching operation since some of the specimens (particularly the 2024 specimens) had a tendency to pit and etch unevenly. The original etchant was composed of four volumes HCl, one volume HF, and twelve volumes of water. The etchant was changed to a 0.1 normal NAOH solution. However, the aluminum pitted just as badly with this alternate etchant. For this reason, much of the 50%-boron-composite strength data are lower than expected.

The next specimen operation in fabrication consisted of masking the reduced-width section of the specimens. It was found that a Teflon pressure-sensitive tape was adequate for masking specimens which were not heat treated. However, the hardened aluminum alloys required longer etching times and this increased the tape exposure time in the etchant. The tape adhesive could not resist these longer etching times. An Eastman-Kodak photo-sensitive maskant, Photo-Resist

Type 3, was utilized to provide adequate masking for the long etching times (as long as 45 minutes). The panels which contained 50 volume percent boron (where the surfaces were etched to the 0.0135-inch thickness) were so rough that two coats of the Photo Resist were required for protection. The steps in the fabrication are described in Figure 9. The completed test specimen is shown in Figure 10.

5.3 Metallographic Examination

During various phases of the fabrication of test specimens and after tensile tests, sample pieces were taken from the composite material and from tensile specimens for microscopic examination and evaluation of microstructures. These sample cross-sections are shown in Figure 11. There was no visual indication of deterioration of the boron filaments with long heat exposures. There was some difficulty in grinding and polishing these metallographic samples due to the relative softness of the aluminum compared to the hardness of the boron. The aluminum had a tendency to be undercut from the surface of the boron, and the boron had a tendency to propagate cracks or create new cracks during the grinding and polishing. One sample was ground down 1/4 inch from the initial polished surface but the cracking tendency persisted.

5.4 Measurement of Tensile Strength

The tensile testing was performed with an Instron Table Model No. 1130 Universal Testing Machine, using a 1000 pound load cell. Initially to determine what strain rate should be used, tensile tests

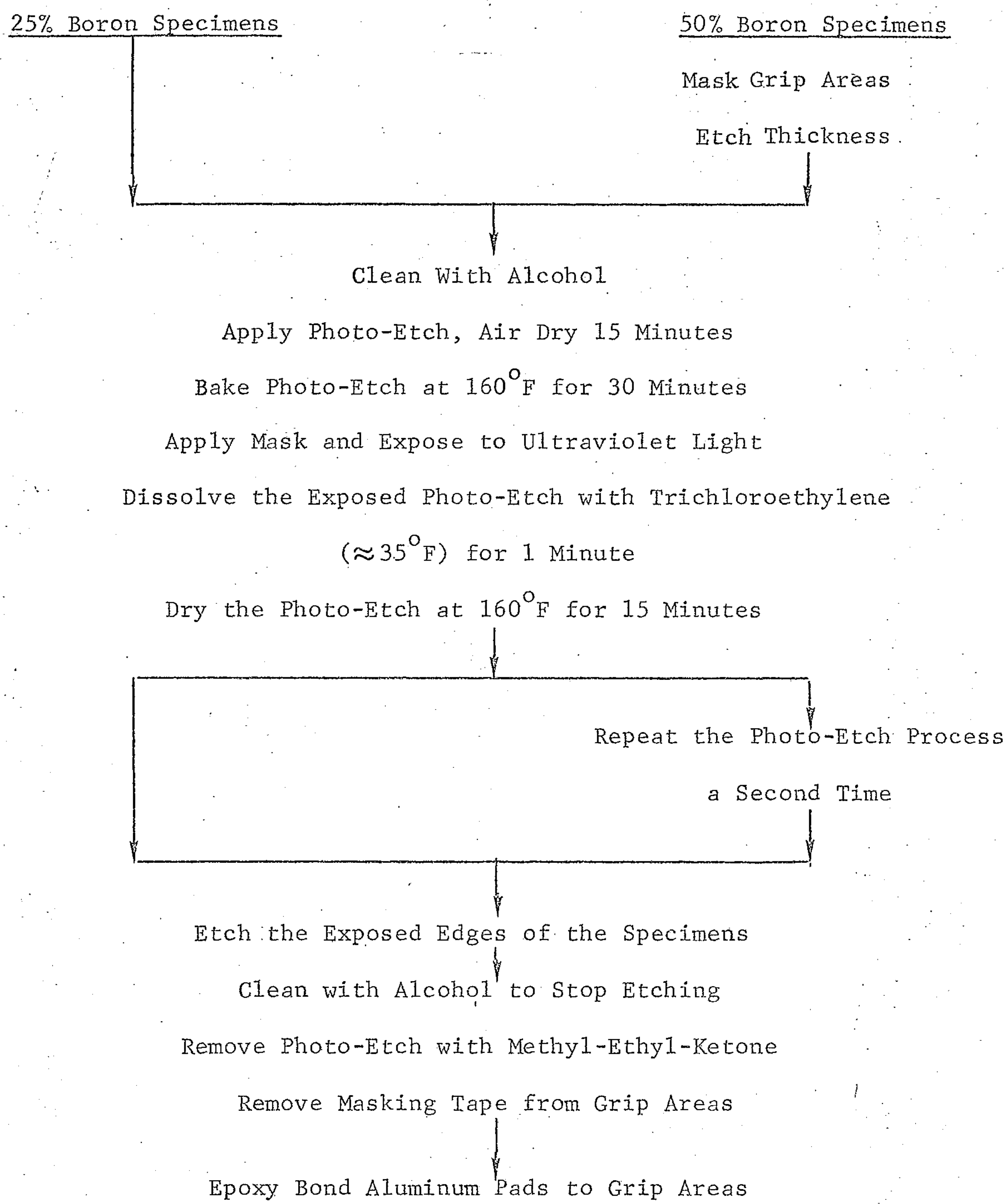


Figure 9. Flow Chart of Processes Performed to Fabricate Tensile Test Specimens

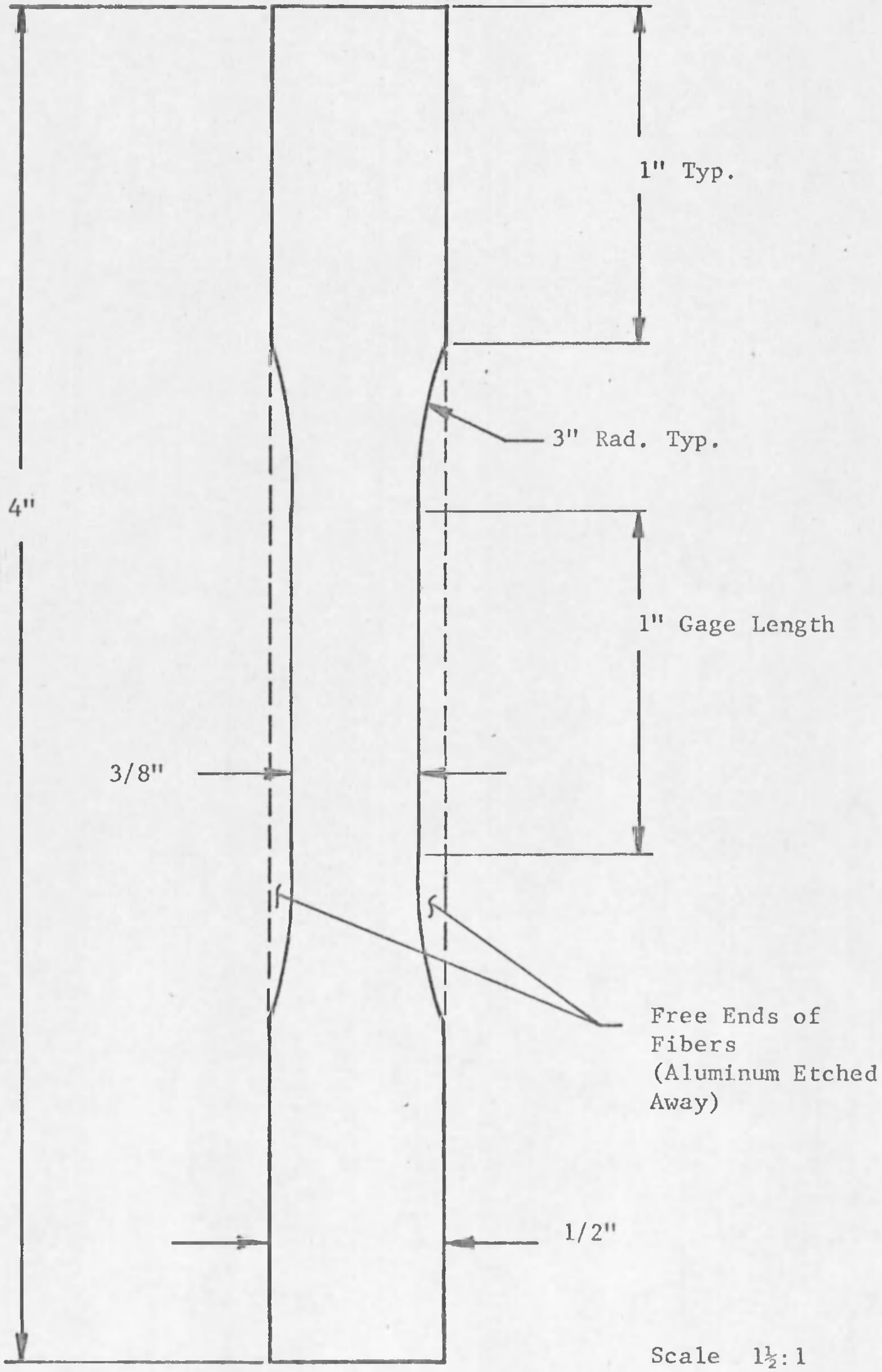
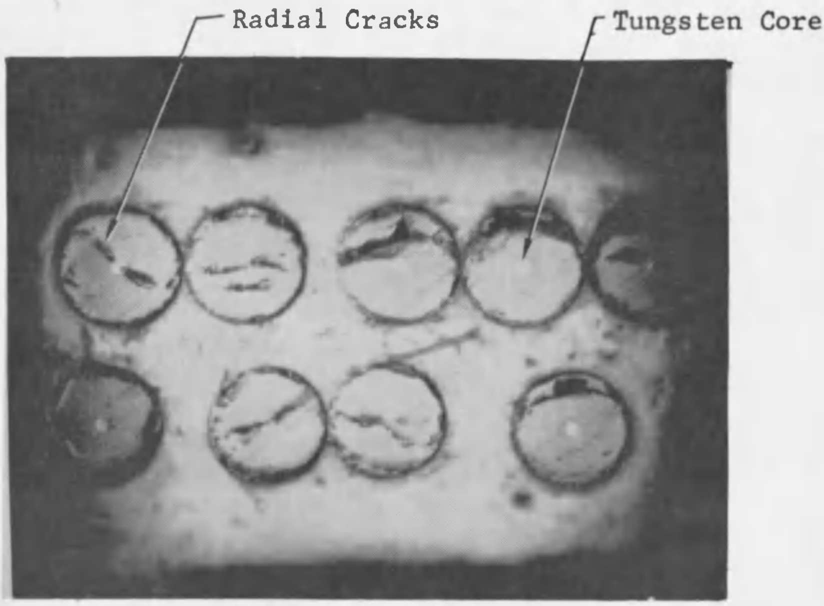
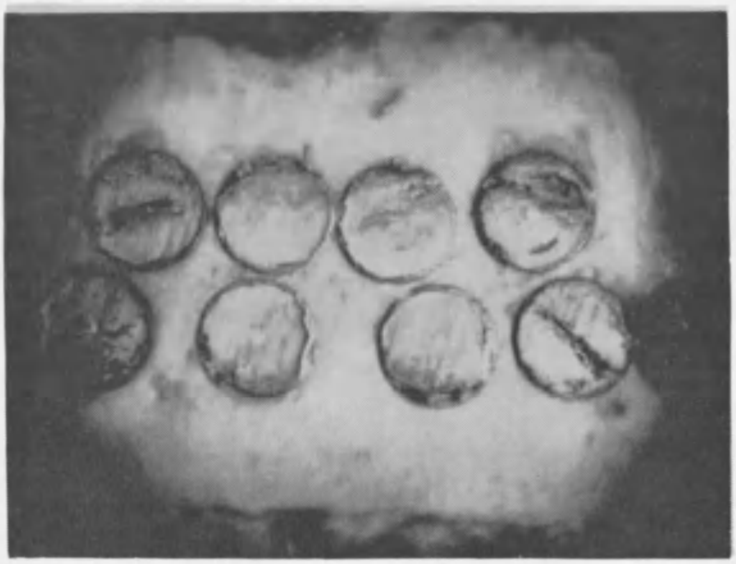


Figure 10. Configuration of Typical Tensile Specimen



2024 Composite



6061 Composite

Figure 11. Photomicrographs of Composite Cross-sections $\approx$ 100X.

were performed on both 6061-F and 2024-0 test specimens (all 25% boron in the as-received condition) using strain rates of 2, 0.2, 0.05, 0.02, 0.01, and 0.005 using an Instron Model No. TT-C Universal Testing Machine. The percent elongation did not essentially change regardless of which strain rate was used. A strain rate of 0.2 in/min. was selected since this was the slowest rate that could be performed with the Model 1130 Instron. The test data for this initial strain-rate investigation are tabulated in Table 5.

Table 5. Strain Rate Evaluation

Strain Rate In/Min	Yield Strength, KSI		Ultimate Strength, KSI		Percent Elongation,%	
	6061-F	2024-0	6061-F	2024-0	6061-F	2024-0
2.0	11.80	-	11.80	-	1.50	-
0.2	12.70	15.15	16.70	23.40	1.44	2.00
0.05	13.35	20.00	14.95	21.65	1.25	0.95
0.02	13.25	21.40	14.90	24.90	1.38	1.12
0.01	12.50	15.15	16.95	22.05	1.48	1.09
0.005	11.70	13.35	16.00	23.80	1.25	1.40

All further testing was performed on the Model 1130 Instron, using 0.2 inches/minute loading rate and 20 inches/minute chart speed, with the 1000 pound load cell set for 500 pounds full scale. Elongation was measured by the distance measured on the chart times the ratio of the cross-head travel speed divided by the chart speed which then produced elongation in terms of in/min since the specimen gage length was one inch.

CHAPTER 6

RESULTS AND DISCUSSION

The results obtained in this investigation are presented and discussed in the following order:

First, the directly-observed values of percent elongation, yield strength, ultimate tensile strength, and modulus of elasticity are presented.

Second, visual observation of the fractures is described, since several modes of failure can be present, such as filament splitting, unbonding at filament-matrix interface, and matrix failure.

Third, a correlation is then made of the test results and the treatment conditioning used on the various specimens.

6.1 Test Data Results

For each test specimen, the percent elongation at fracture, the yield strength, the ultimate tensile strength, and the modulus of elasticity were calculated. The calculated results were then tabulated and are shown in Table 4 for the 6061 composite and in Table 6 for the 2024 composite.

The modulus data were found to be below the expected range by a factor of about five, due probably to the elongation of the epoxy adhesive used to bond the aluminum pads in the grip areas of the specimens.

Table 6. Aluminum 2024-0 Composite Test Results

Condition	Heat Treatment	Stress Relief	Percent Boron (Vol.)	Elongation at Break		Yield Strength		Ultimate Tensile Strength		Modulus of Elasticity x 10^6		Comments of Fracture Appearance
				%	Ave	PSI	Ave	PSI	Ave	PSI	Ave	
Annealed (T-0)	None	None	25%	1.55 1.35 1.02	1.31	18,600 19,900 17,200	18,600	29,000 33,500 23,400	28,600	12.5 12.9 14.5	13.3	
			50%	1.05 0.71 0.78	0.85	21,700 20,800 19,800	20,800	28,200 22,100 22,100	24,100	16.4 17.0 16.1	16.5	One fiber split 80%.
Soln. Treat	Age 4 days at RT. (T-4)	None	25%	1.55 1.62 1.60	1.59	48,900 47,700 45,500	47,400	48,900 47,700 45,500	47,400	16.7 15.6 15.1	15.8	
			50%	0.90 1.09 1.15	1.05	33,300 32,400 41,300	35,700	33,300 32,400 41,300	35,700	19.6 15.7 19.1	18.1	
Soln. Treat	375°F. 9 hrs. (T-6)	None	25%	1.92 1.57 1.88	1.79	53,500 44,400 49,900	49,300	53,500 44,400 49,900	49,300	14.7 15.0 14.0	14.6	One fiber split 50%.
			50%	0.77 0.97 0.81	0.85	27,200 36,300 29,400	31,000	27,200 36,300 29,400	31,000	18.8 19.9 19.3	19.3	One fiber split 90%. One fiber split 100%.*
Soln. Treat	375°F. 9 hrs. (T-6)	284°F. 24 hrs.	25%	1.40 1.48 1.60	1.49	41,800 47,000 53,000	47,300	41,800 47,000 53,000	47,300	15.9 16.9 17.7	16.8	
			50%	0.98 0.80 0.89	0.89	35,500 32,800 36,100	34,800	35,500 32,800 36,100	34,800	19.3 21.7 21.4	20.8	
Soln. Treat	375°F. 9 hrs. (T-6)	338°F. 24 hrs.	25%	1.22 1.17 1.20	1.19	40,600 38,200 36,100	38,300	40,600 38,200 36,100	38,300	17.6 17.3 16.1	17.0	
			50%	0.93 1.19 1.05	1.06	35,100 44,100 41,000	40,100	35,100 44,100 41,000	40,100	20.0 19.7 20.8	20.2	

* Fiber split in neckdown section but not in etched areas at ends, indicating no end splits were present before tensile test.

Table 6 (continued)

Soln. Treat	375°F. 9 hrs. (T-6)	20 cycles 70°F. to 700°F.	25%	1.88 1.50 1.90	1.76	15,200 16,500 14,500	15,400	24,800 24,800 25,100	24,900	14.4 13.5 12.8	13.6	
			50%	1.14 0.88 1.35	1.12	14,500 15,700 15,700	15,300	23,950 21,600 24,100	23,200	14.0 16.7 14.6	15.1	
Soln. Treat Cold Roll 5% (T-3)	None	None	25%	1.67 1.42 1.38	1.49	23,400 25,800 27,400	25,500	31,200 30,600 29,700	30,500	11.5 12.0 11.6	11.7	
			50%	0.88 0.63 0.84	0.78	20,600 16,850 20,600	26,000	24,200 16,850 22,700	21,300	15.6 14.2 15.4	15.1	No fiber splits. One fiber split 100%. No fiber splits.
Soln. Treat Cold Roll 5%	375°F. 12 hrs. (T-81)	None	25%	1.64 1.53 1.70	1.62	38,400 39,000 44,500	40,600	42,000 39,000 46,000	42,300	14.4 14.3 14.7	14.5	
			50%	0.70 0.85 0.71	0.75	20,200 25,700 22,600	22,800	20,200 25,700 22,600	22,800	15.3 16.1 16.9	16.1	
Soln. Treat Cold Roll 10% (T-3)	None	None	25%	1.50 1.52 1.62	1.55	35,000 39,900 40,400	38,400	35,000 39,900 40,400	38,400	12.3 13.9 13.2	13.1	
			50%	0.57 0.72	0.64	15,600 19,100	17,300	15,600 19,100	17,300	14.5 14.1	14.3	
Soln. Treat Cold Roll 10%	375°F. 12 hrs. (T-81)	None	25%	1.38 1.38 1.38	1.38	35,200 33,300 32,300	33,600	35,200 33,300 32,300	33,600	13.5 12.8 12.4	12.9	
			50%	**								
Soln. Treat	375°F. 12 hrs.	Stretch Cycle Ten Cycles 10% UTS	25% (Stretch 350 lbs.)	1.63 1.41 1.42	1.49	50,500 38,600 27,600	38,900	50,500 40,000 34,000	41,500	16.4 15.6 13.6	15.2	Both fibers split 50% & 100%.
			50% (Stretch 15 lbs.)	1.08 0.83 0.75	0.89	40,400 32,800 29,000	34,100	40,400 32,800 29,000	34,100	19.8 21.0 20.5	20.4	One fiber split 100%. Both fibers split 50%. One fiber split 100%.

** All specimens were ruined due to severe pitting during chemical etching of thickness.

To support this hypothesis, aluminum specimens were machined from 6061-T4 (.025 mil thick) and 2024-T3 (.032 mil thick) and aluminum pads were epoxy adhesive bonded to them in the same manner used for the composite test specimens. Tensile tests performed using identical procedures as those used for testing the composite specimens, produced the data shown in Table 7.

Table 7. Modulus of Elasticity of Aluminum Specimens with Epoxy Bonded Grips

Material	Modulus of Elasticity	Average Modulus of Elasticity
6061 (.025" thick)	1.9×10^6	1.92×10^6
	1.94×10^6	
2024 (.032" thick)	1.88×10^6	1.86×10^6
	1.83×10^6	

Comparing the modulus measured on the aluminum specimens to the known modulus of 10.0×10^6 psi, it is shown that a ratio of 5.3 is needed to correct the modulus values determined for the composite specimens, because of the elongation in the epoxy. The modulus values in the graphs are corrected by this ratio. It was unfortunate that an extensometer was not available to attach directly to the specimens.

Photographs of the tensile test specimens are shown in Figure 12. The top photograph shows a completed test specimen with the aluminum

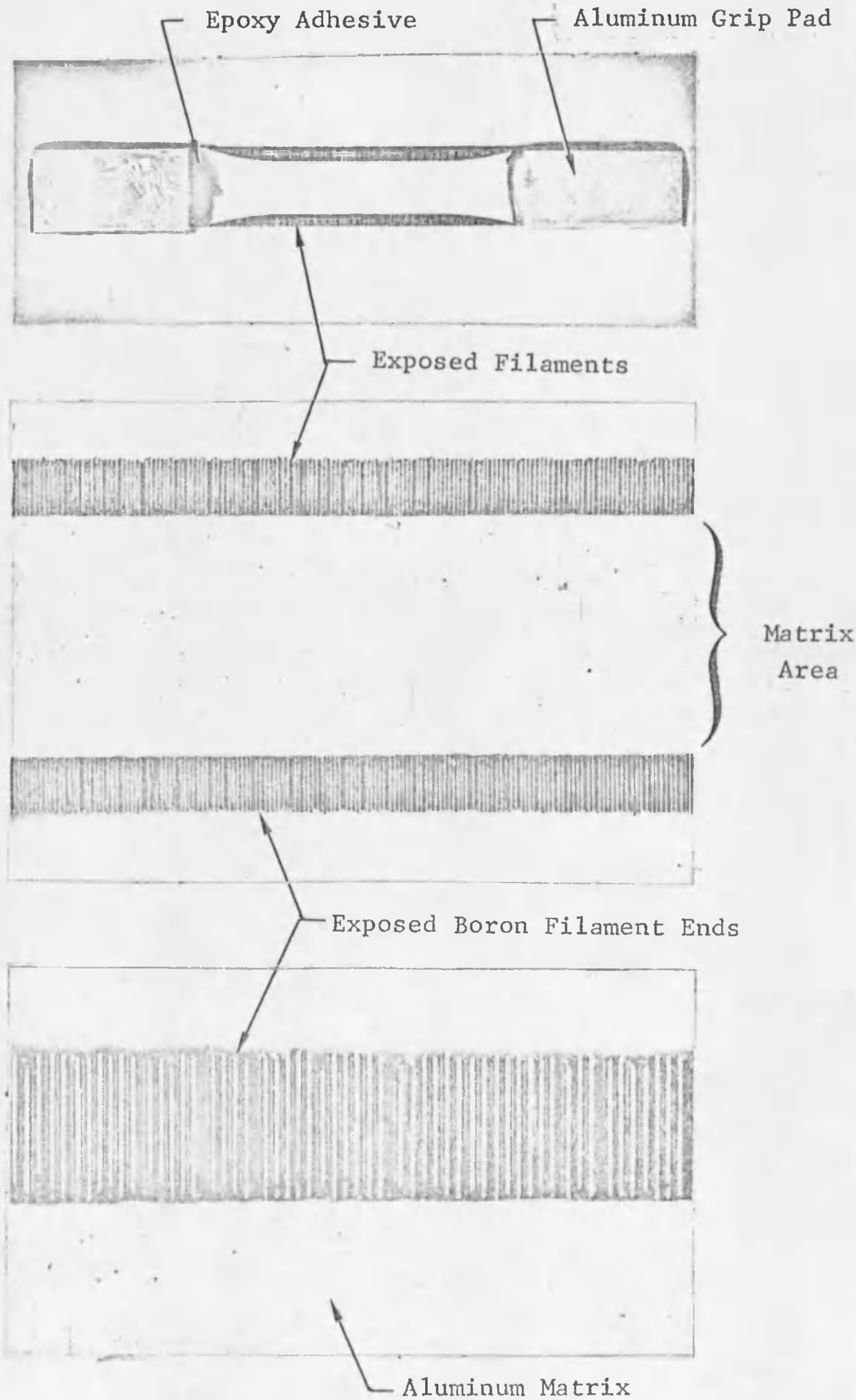


Figure 12. Photographs of Tensile Test Specimen

matrix etched away from the boron filament ends in the area of the gage length. The top photograph also shows the epoxy bonded aluminum pads used for the serrated test jaws of the Instron test machine that prevented jaw teeth damage to the composite. The other two photographs in Figure 12 show enlarged views of the test specimen.

6.2 Effect of Thermal Conditioning

The effects of the various aging, heat treatment, and thermal stress relief procedures on the boron reinforced aluminum composites, are shown in Figure 13 for yield strength and in Figure 14 for ultimate tensile strength for 2024 matrix. In both the yield strength as well as the ultimate tensile strength, the standard T6 treatment of the 25%-filament alloy produced the highest strengths, with the thermal cycling of 70°F. to 700°F. producing the lowest strengths. The lower T6 strengths shown by the 50% boron specimens are believed due to the pitting problem experienced during chemical etching of the specimen thickness. Figure 15 shows the yield strength for 6061 matrix and Figure 16 shows the ultimate tensile strength for 6061 matrix, and again the standard T6 treatment produced the highest strengths of all the treatments tested.

A plot of the transverse yield strength and tensile ultimate strength versus percent filament reinforcement for 2024-T6 aluminum matrix is shown in Figure 17. A similar plot for 2024-T4 is shown in Figure 18. For the aluminum matrix of 6061-T6, a plot of the transverse yield strength and tensile ultimate strength versus percent

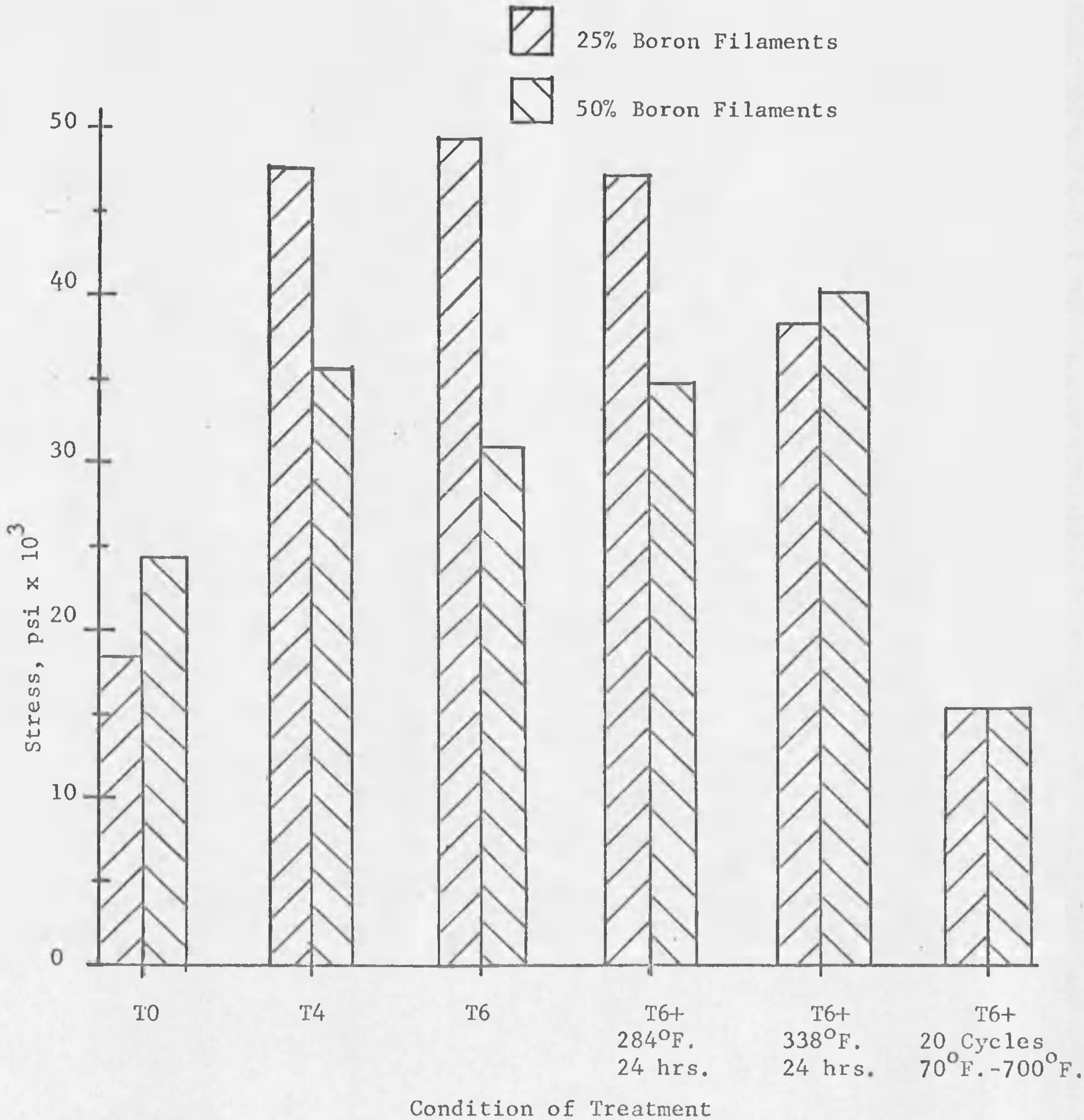


Figure 13. Transverse Tensile Yield Strength Versus Heat Treatment or Stress Relief (2024 Alloy)

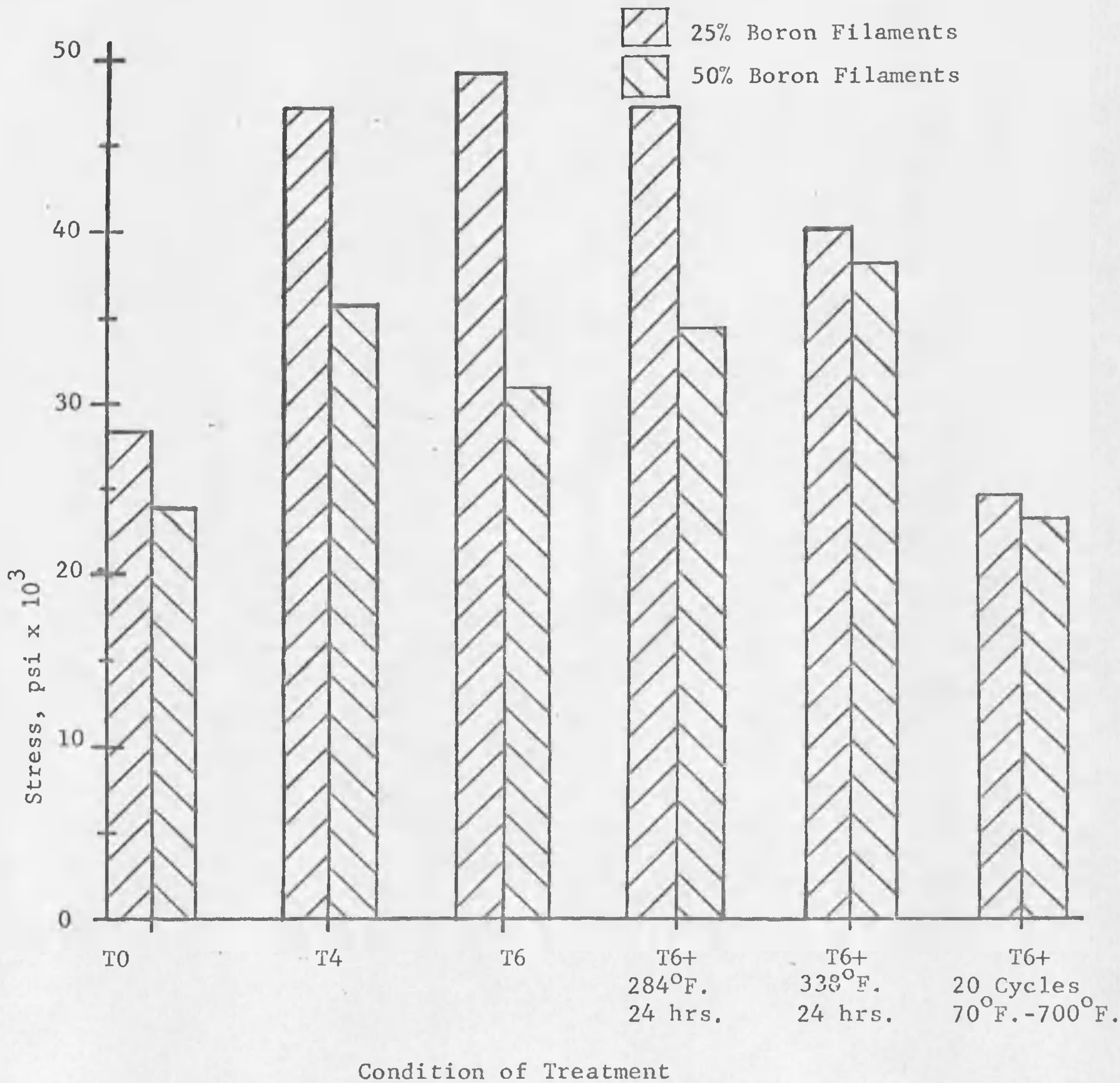


Figure 14. Transverse Ultimate Tensile Strength Versus Heat Treatment or Stress Relief (2024 Alloy)

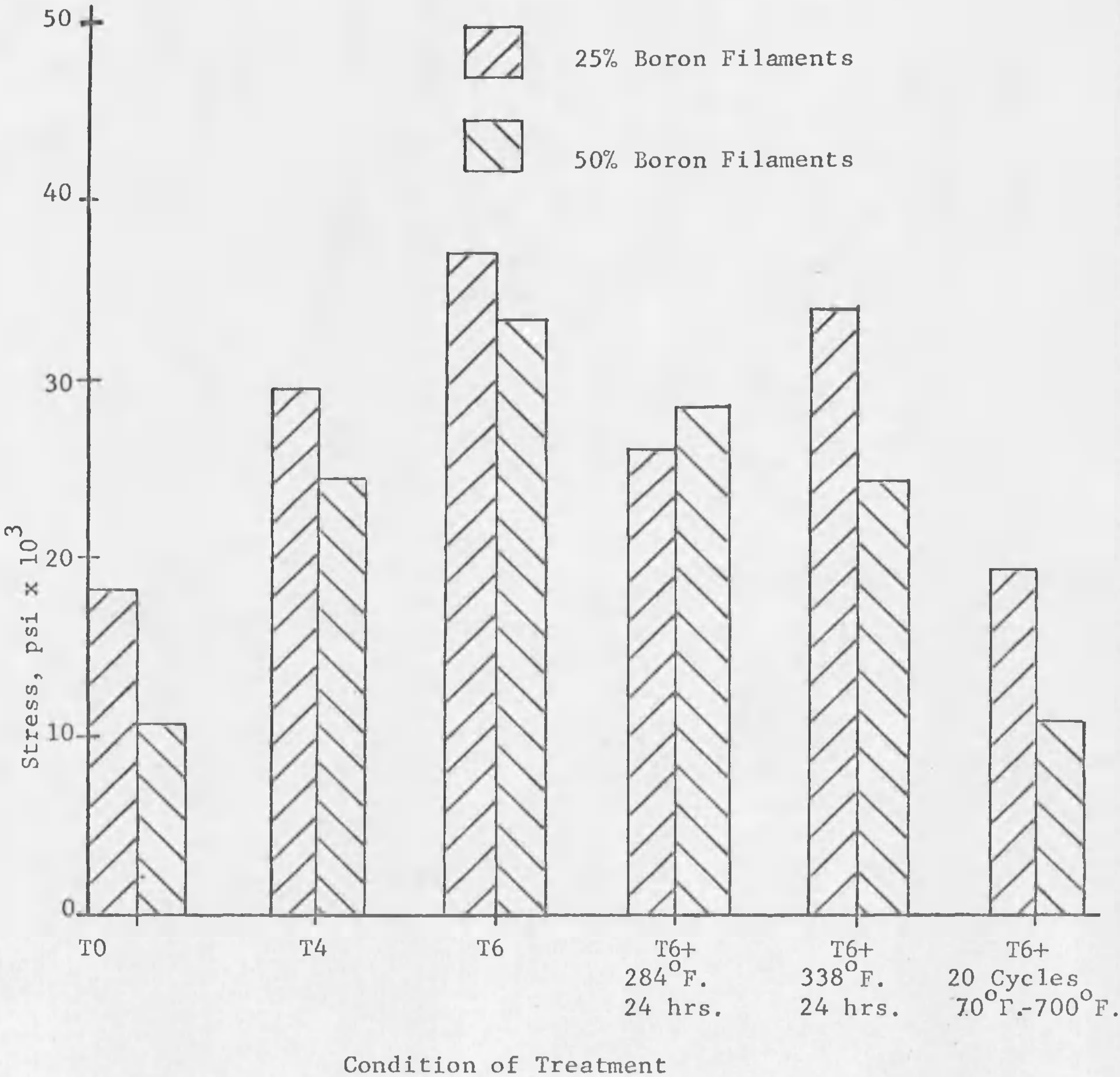


Figure 15. Transverse Tensile Yield Strength Versus Heat Treatment or Stress Relief (6061 Alloy)

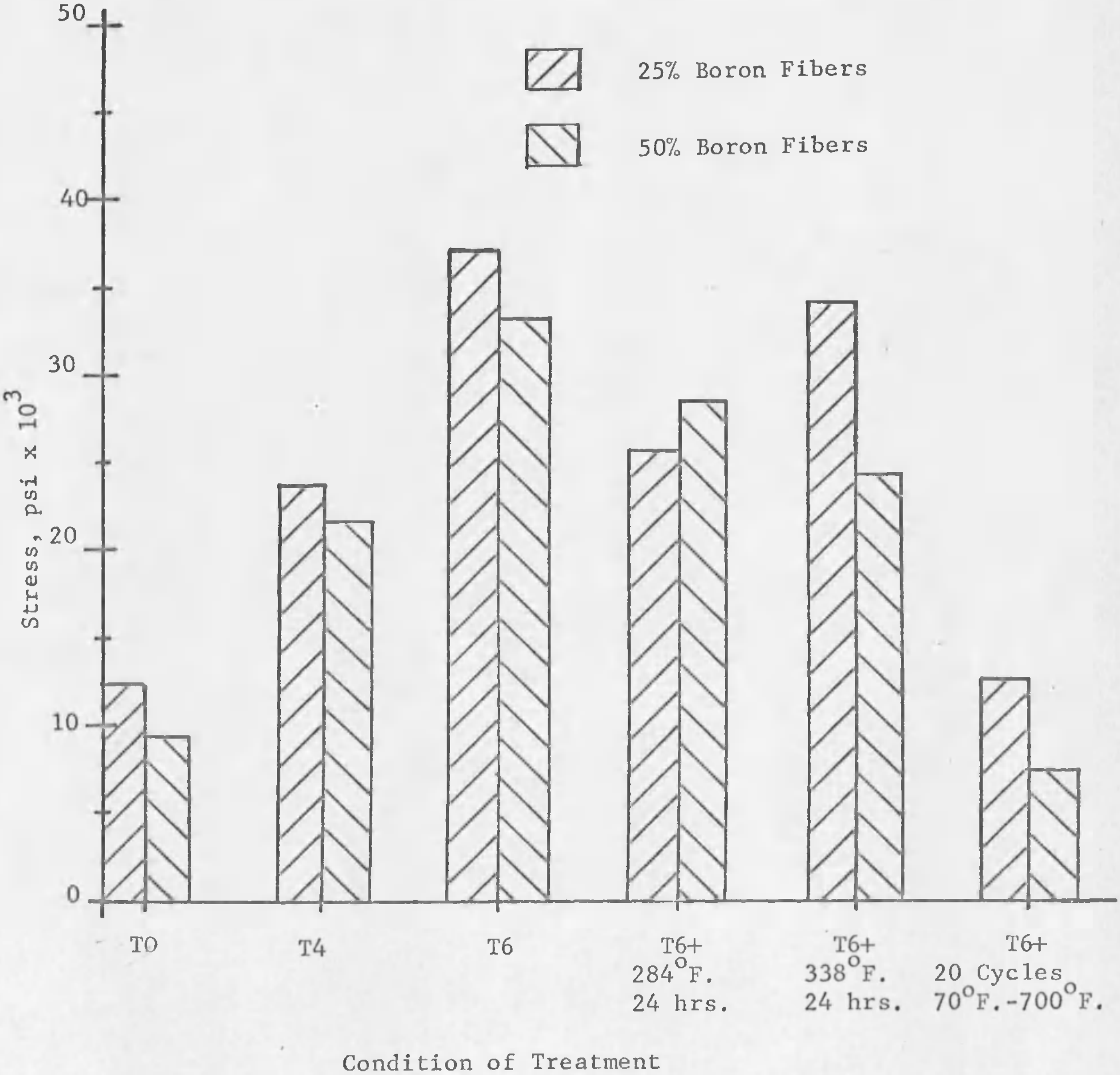


Figure 16. Transverse Ultimate Tensile Strength Versus Heat Treatment or Stress Relief (6061 Alloy)

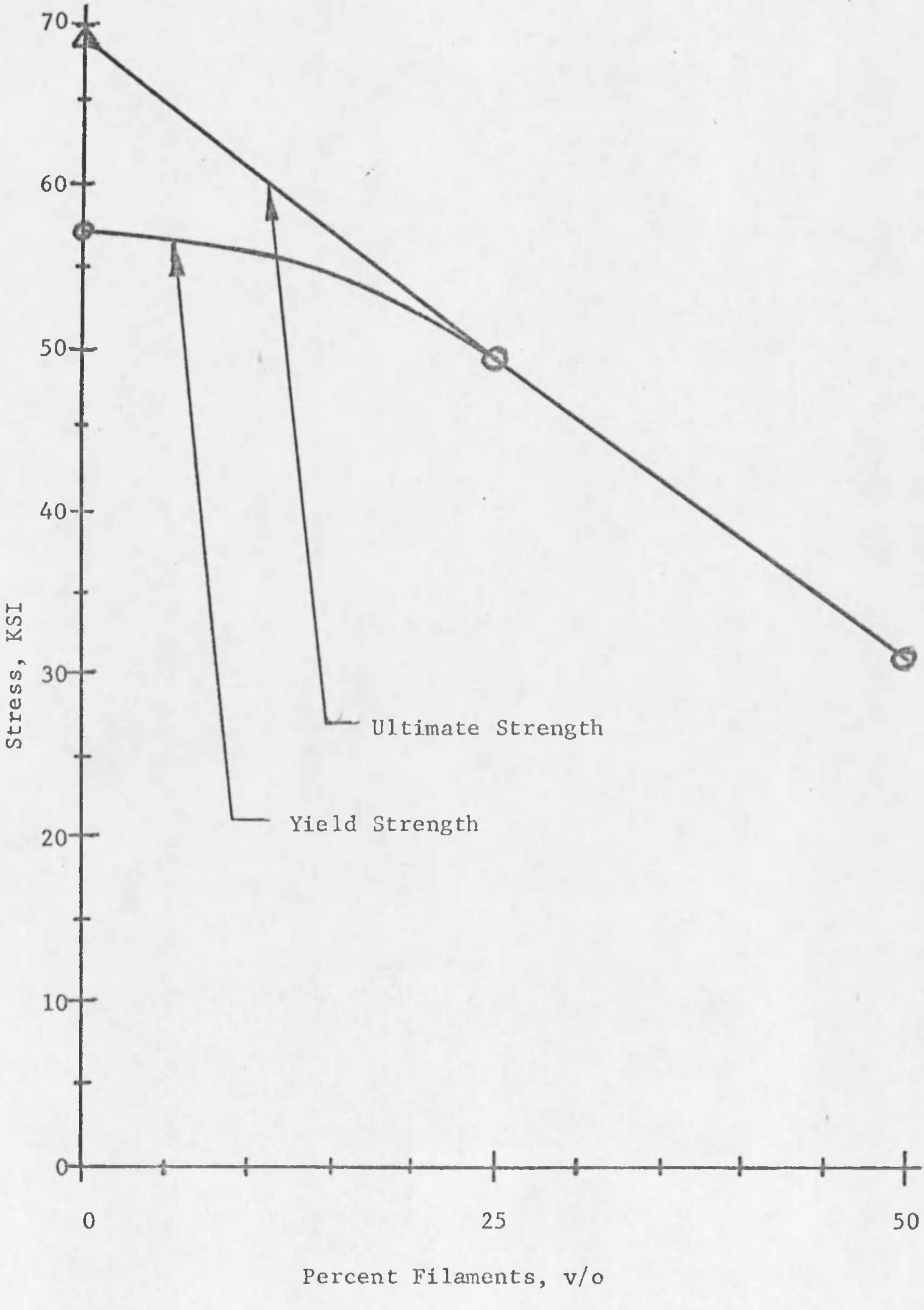


Figure 17. Transverse Tensile Strength Versus Percent Reinforcement (Material: 2024-T6 Matrix)

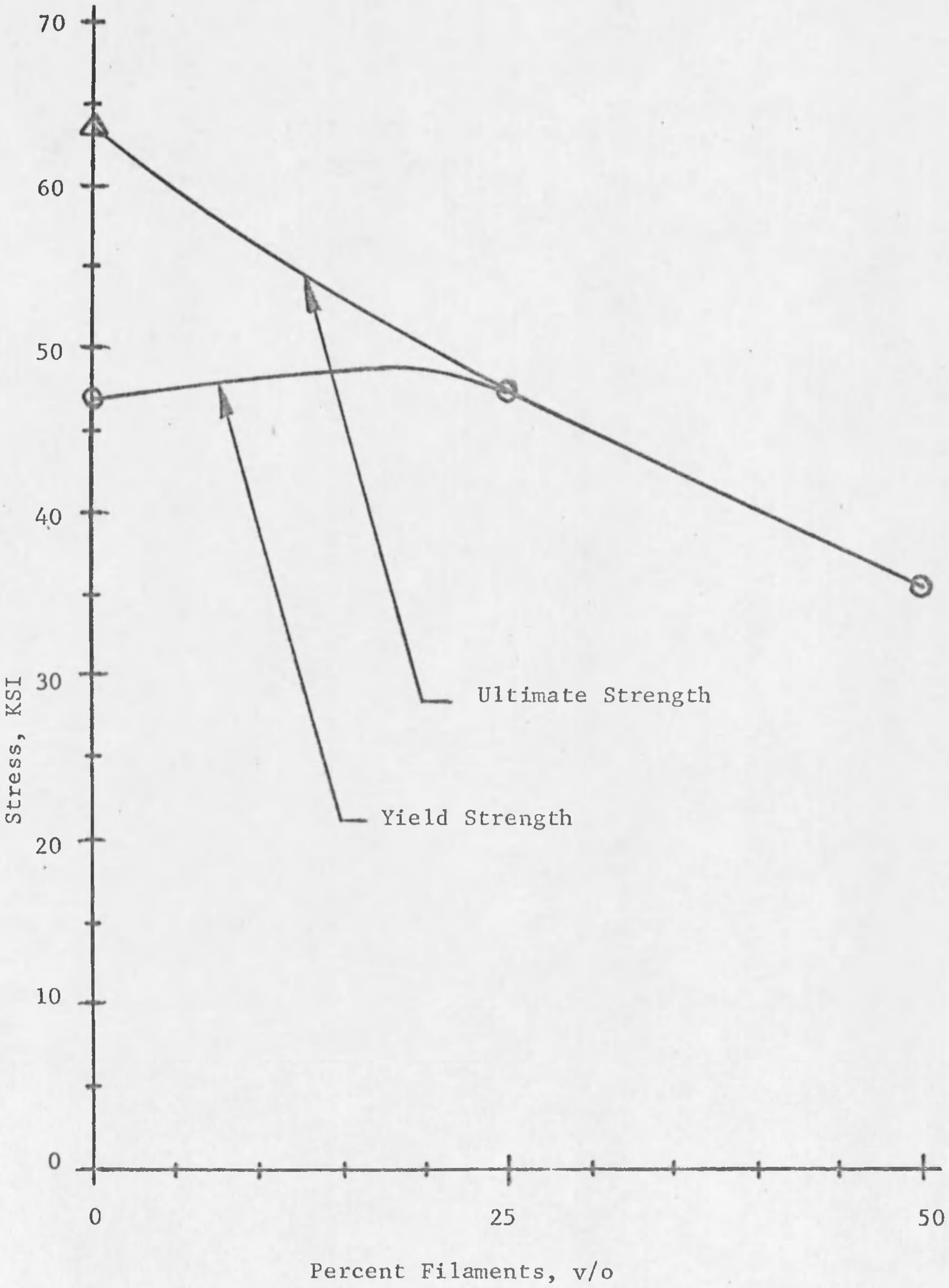


Figure 18. Transverse Tensile Strength Versus Percent Reinforcement (Material: 2024-T4 Matrix)

filament reinforcement, is shown in Figure 19. The matrix 6061-T4 plot is shown in Figure 20.

The change of transverse modulus of elasticity due to percent filament reinforcement for both 2024 and 6061 aluminum composites is shown in Figure 21. As expected from the rule of mixtures, the high modulus of the boron increases the composite transverse modulus as the percent boron increases.

6.3 Effect of Cold Rolling

The effect of cold rolling of the aluminum composite to the T3 condition using 5% and 10% cold rolling (decrease in thickness), and also heat treating after cold rolling to the T36 condition is shown in Figures 22 through 27. For alloy 6061 with 25% boron filaments, the effect upon yield strength due to cold rolling is shown in Figure 22. For this same 6061 alloy with 25% boron, the effect upon ultimate tensile stress due to cold rolling, is shown in Figure 23. In both cases, it is noted that 5% cold rolling indicates that it increases these mechanical properties somewhat ($\approx$ 6%).

Cold rolling of 6061 alloy composite with 50% boron filaments, using the 5% and 10% cold rolling (T3) as well as the added heat treatment (T36), has the effect upon transverse yield strength as shown in Figure 24. The effect upon transverse ultimate tensile strength is shown in Figure 25. As noted for the 25% boron composites, the 5% cold rolling procedure appears to produce the highest strengths for the 50% boron composites as well.

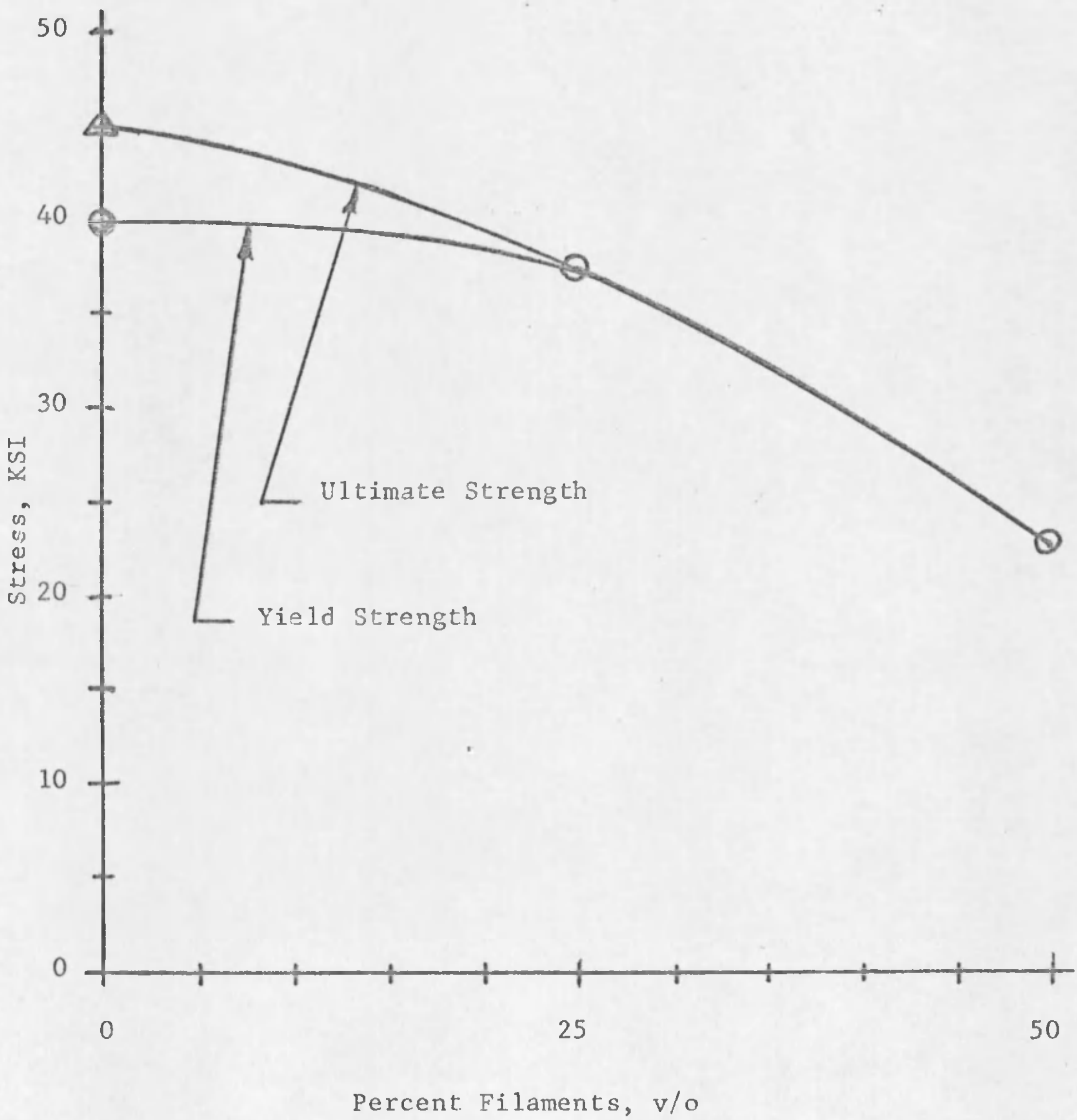


Figure 19. Transverse Tensile Strength Versus Percent Reinforcement (Material: 6061-T6 Matrix)

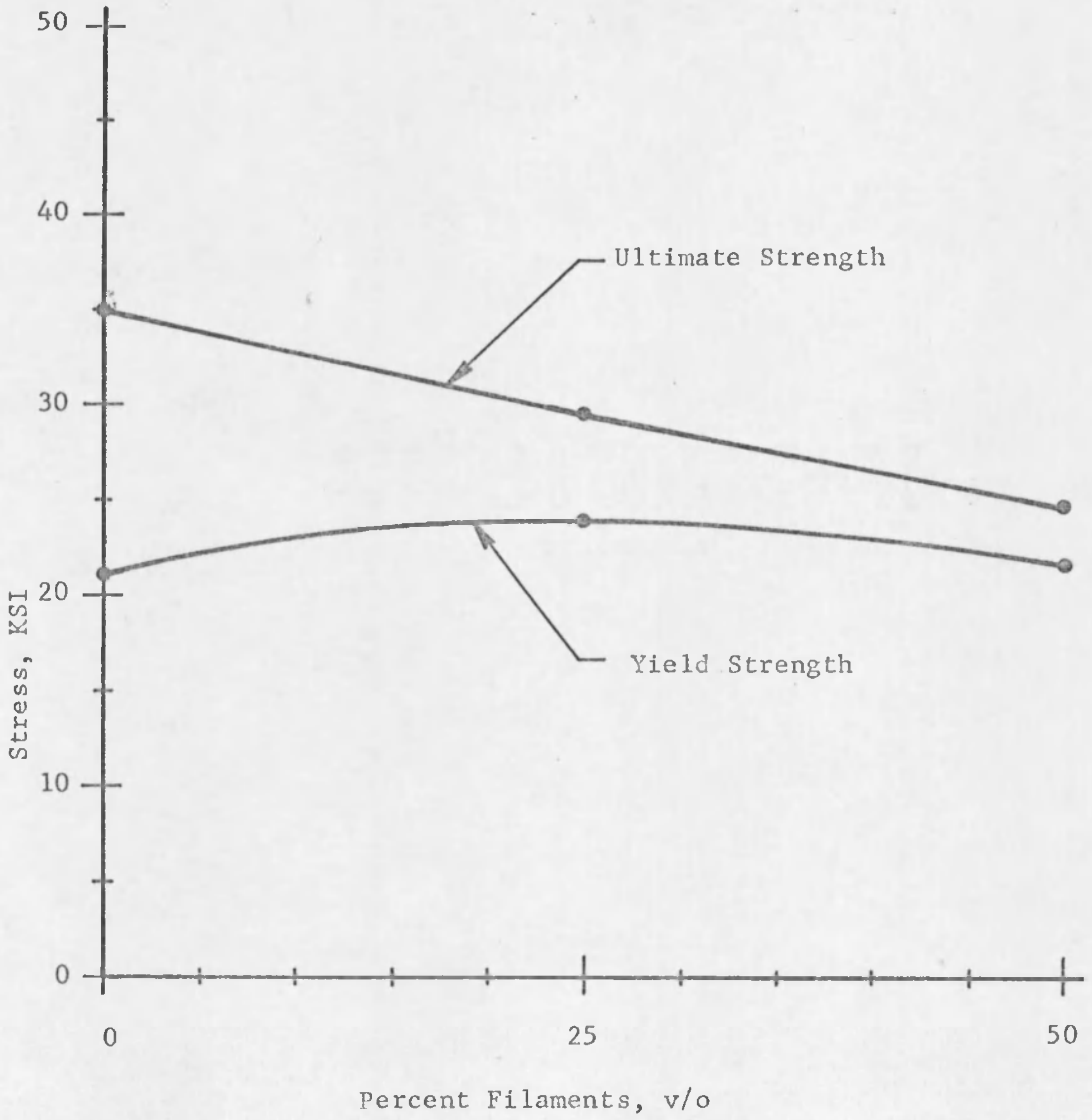


Figure 20. Transverse Tensile Strength Versus Percent Reinforcement (Material: 6061-T4 Matrix)

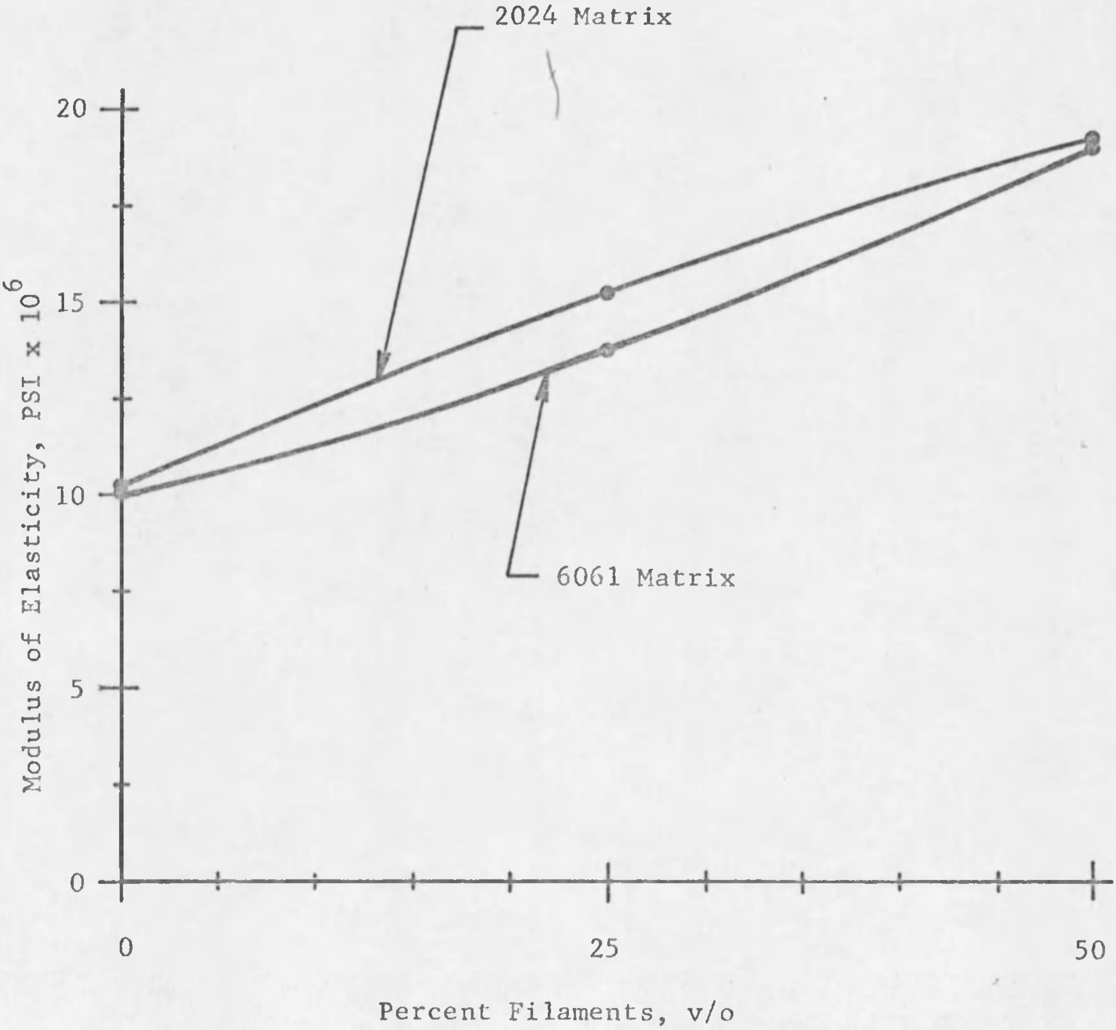


Figure 21. Transverse Modulus of Elasticity Versus Percent Reinforcement

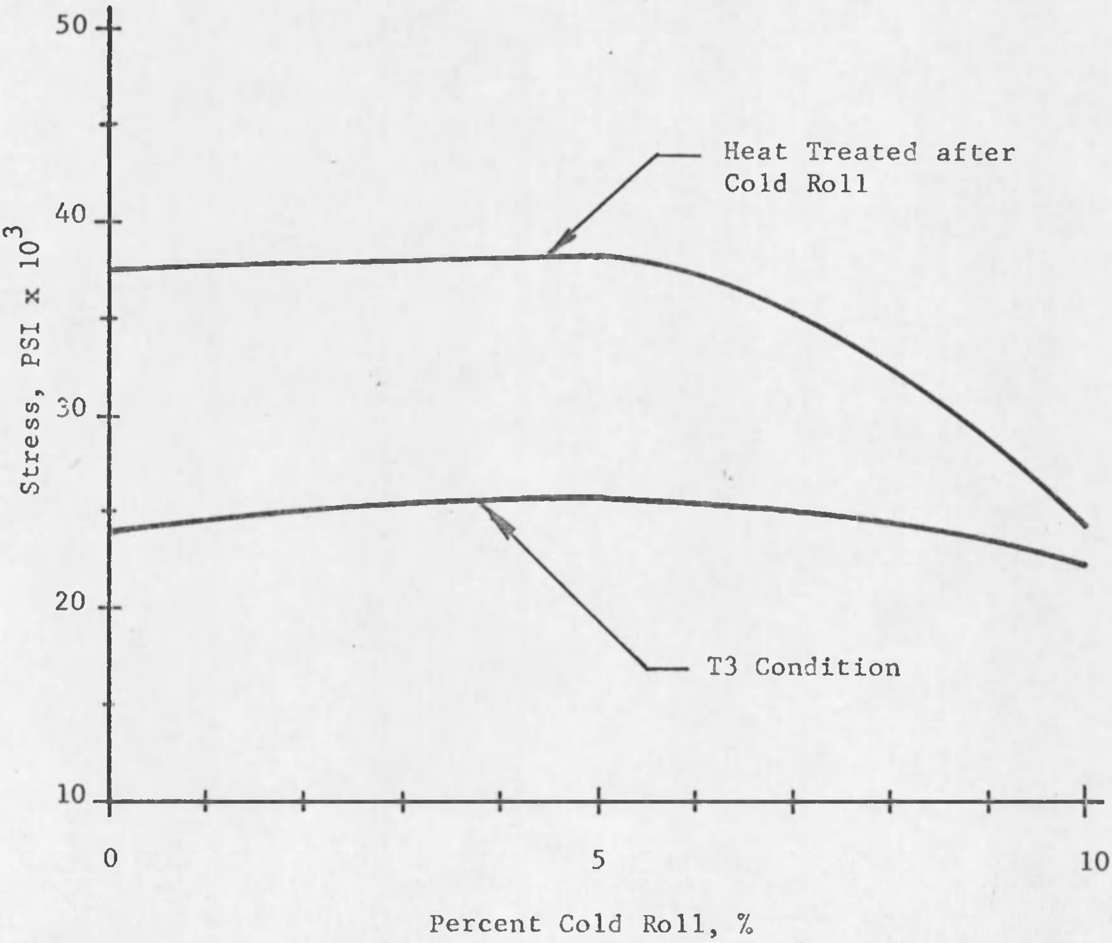


Figure 22. Effect of Cold Rolling on Transverse Yield Strength (6061 Alloy--25% Boron Filaments)

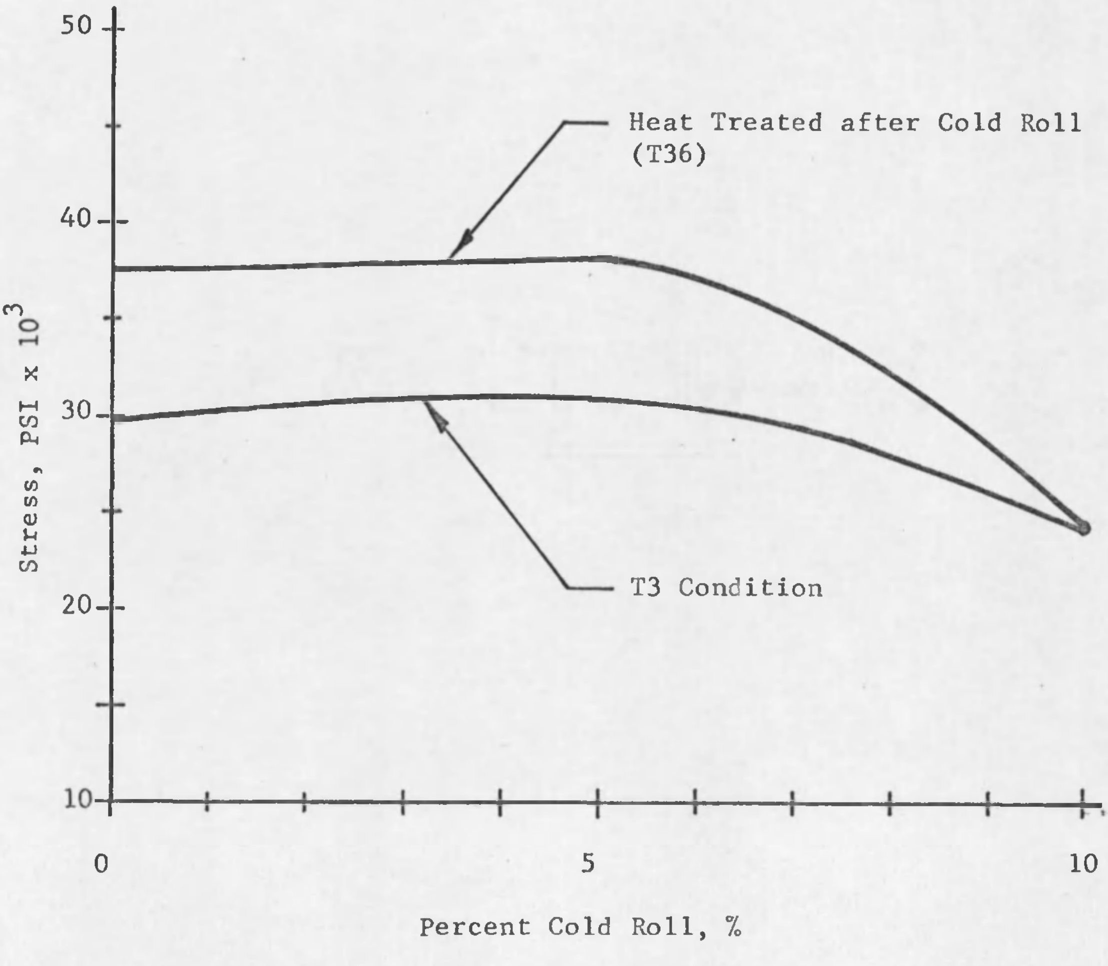


Figure 23. Effect of Cold Rolling on Transverse Ultimate Strength (6061 Alloy--25% Boron Filaments)

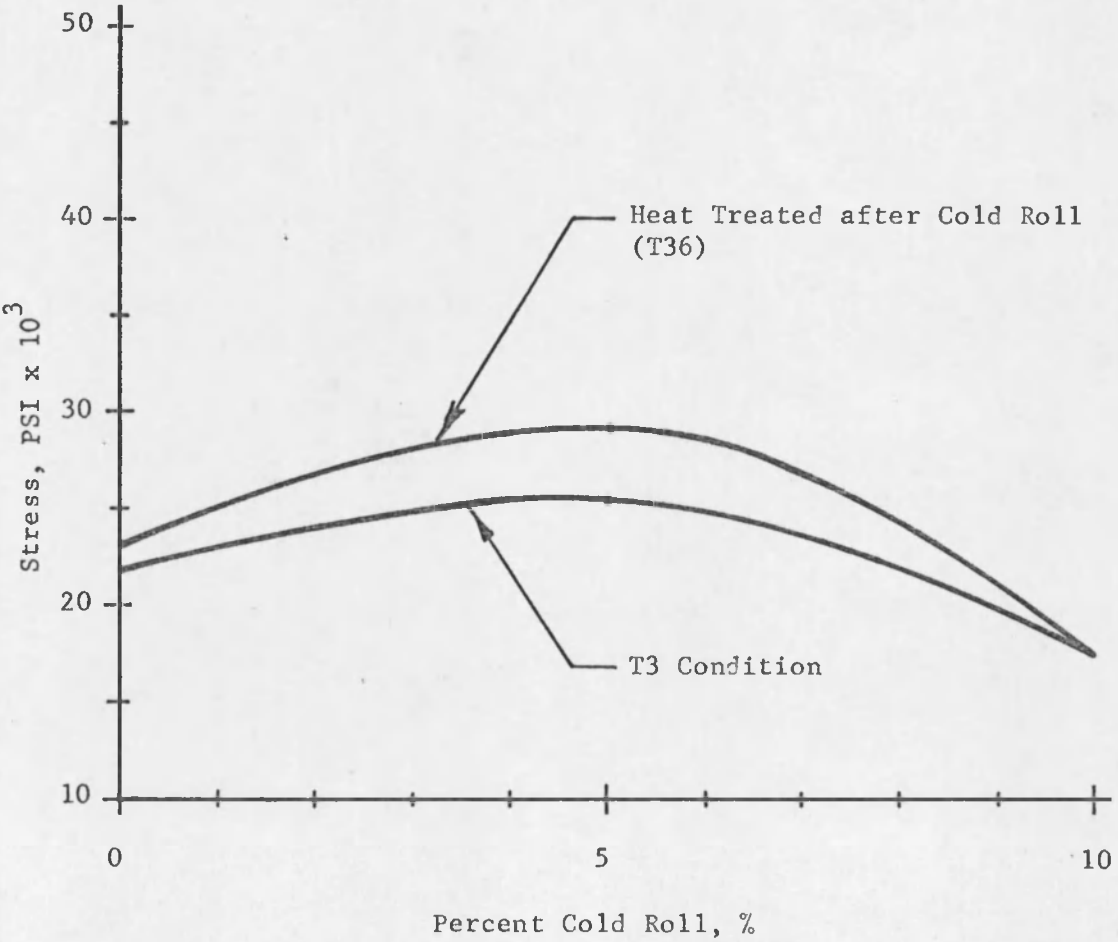


Figure 24. Effect of Cold Rolling on Transverse Yield Strength (6061 Alloy--50% Boron Filaments)

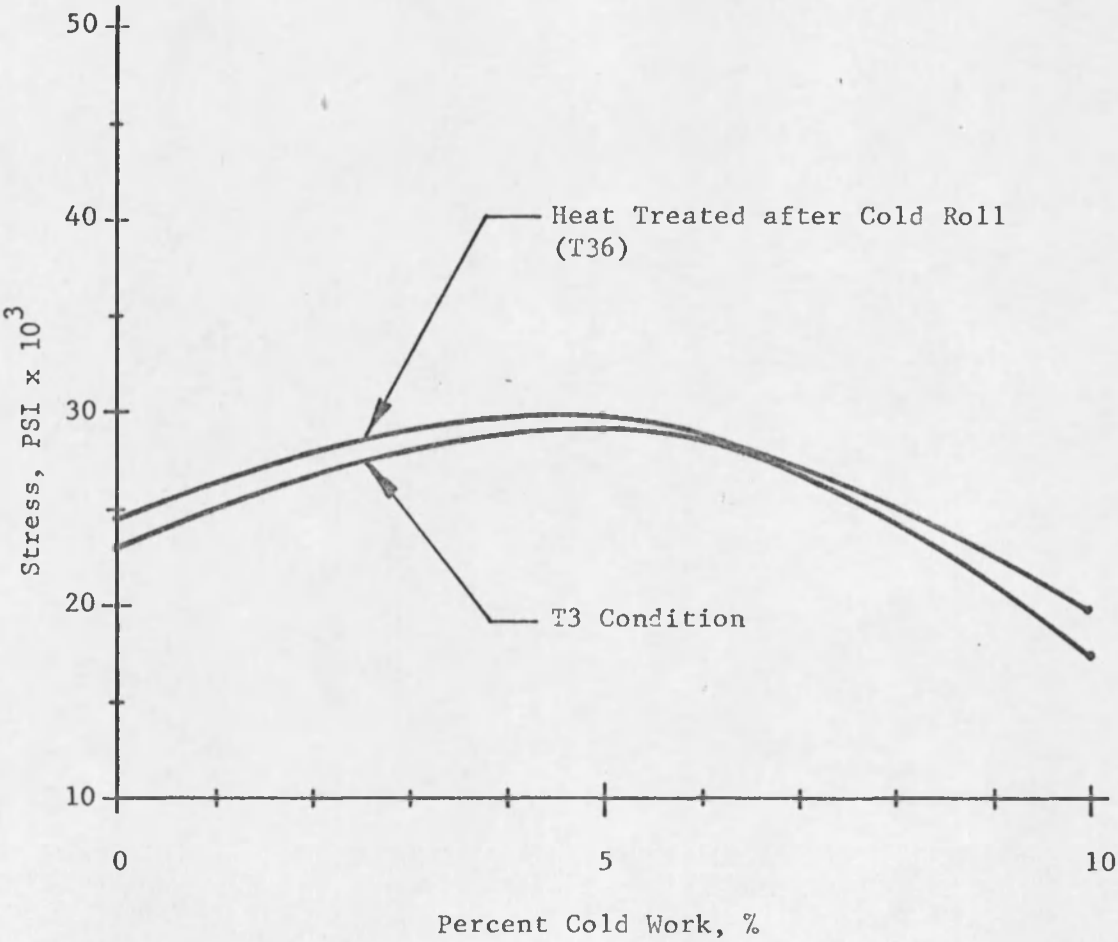


Figure 25. Effect of Cold Rolling on Transverse Ultimate Strength (6061 Alloy--50% Boron Filaments)

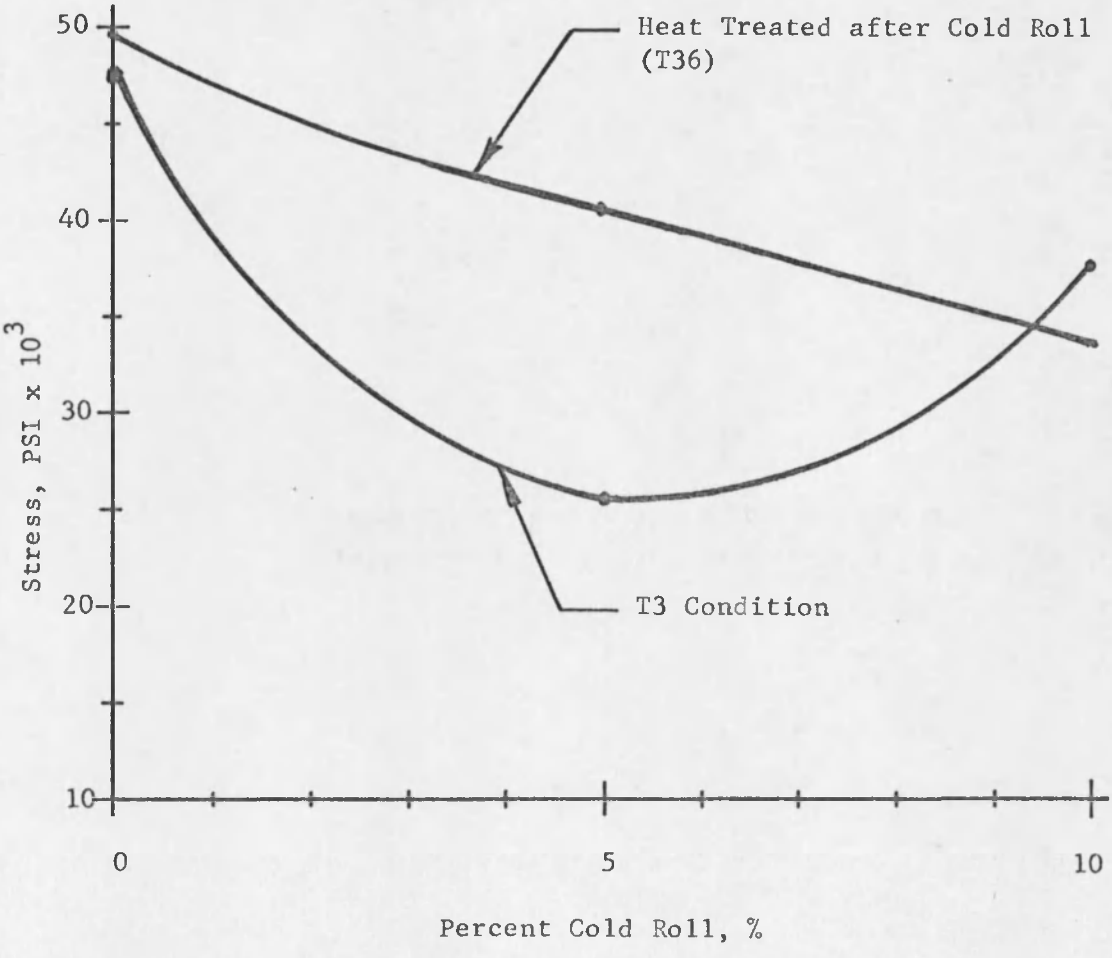


Figure 26. Effect of Cold Rolling on Transverse Yield Strength (2024 Alloy--25% Boron Filaments)

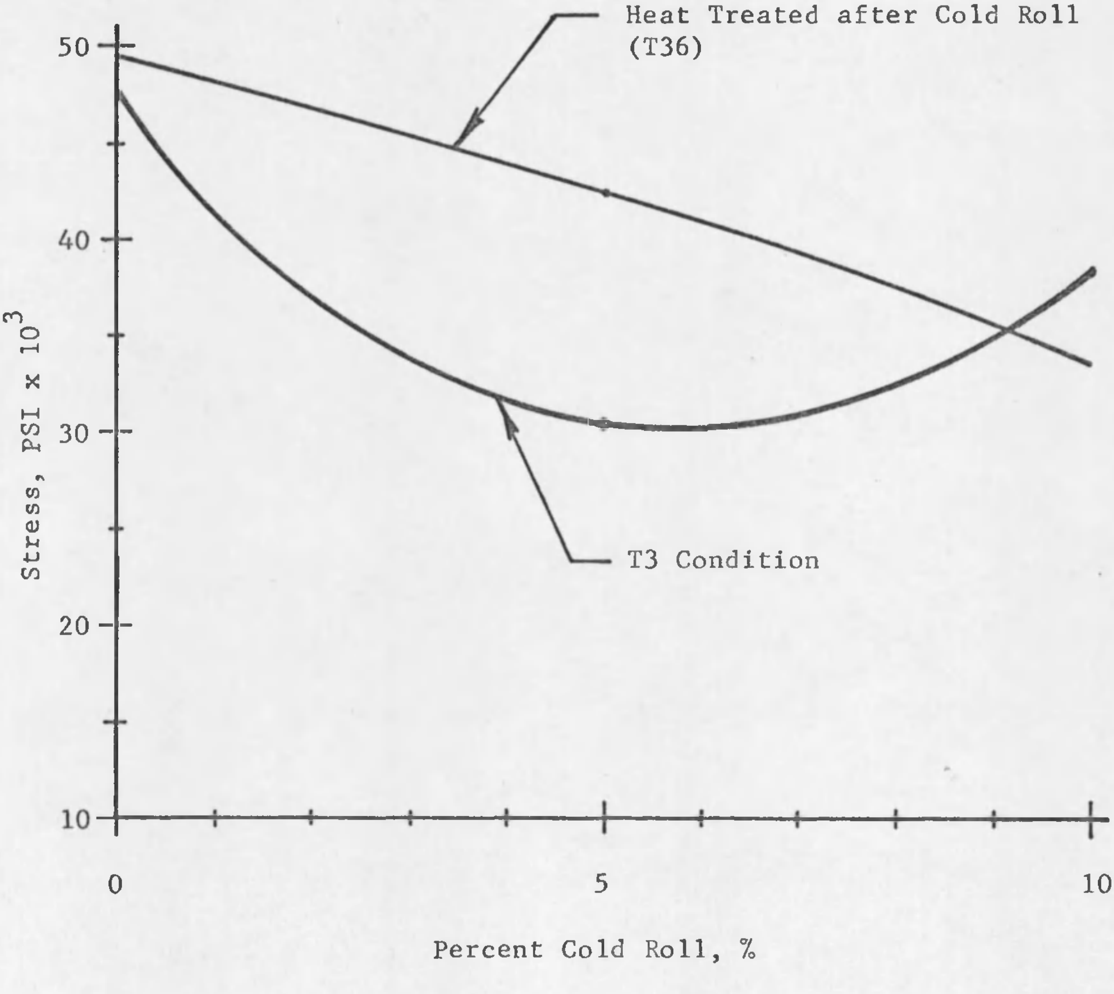


Figure 27. Effect of Cold Rolling on Transverse Ultimate Strength (2024 Alloy--25% Boron Filaments)

Cold rolling of 2024 alloy composite with 25% boron filaments, using 5% and 10% cold roll (T3) as well as subsequent heat treatment (T36), has the effect upon transverse yield stress as shown in Figure 26. The effect upon transverse ultimate tensile strength is shown in Figure 27. For this composite, the cold rolling procedure appears to degrade the mechanical properties.

The effect upon transverse yield and ultimate strength of 2024 alloy composite with 50% boron filaments, of cold rolling using 5% and 10% cold roll (T3) as well as subsequent heat treatment (T36), is as shown in Figure 28. Again, for the 2024 alloy composite, cold rolling appears to degrade the strength properties.

The apparent modulus of elasticity in the transverse direction of 6061 alloy composite with either 25% or 50% boron filaments, is affected by cold rolling as shown in Figure 29. The composite of 2024 alloy is affected by cold rolling as shown in Figure 30. In the 6061 case, one must conclude that cold rolling to 5% has a tendency to increase the apparent modulus somewhat. In the 2024 composite, the cold rolling was definitely detrimental to the modulus of elasticity.

6.4 Effect of Strain Cycling

As shown in Figures 13 and 14 for the 2024 composite and in Figures 15 and 16 for the 6061 composite, the strain cycling of the cycles of 10% of the UTS before testing the specimens was very detrimental to the material. The results were about one-half of those obtained from the standard T6 condition.

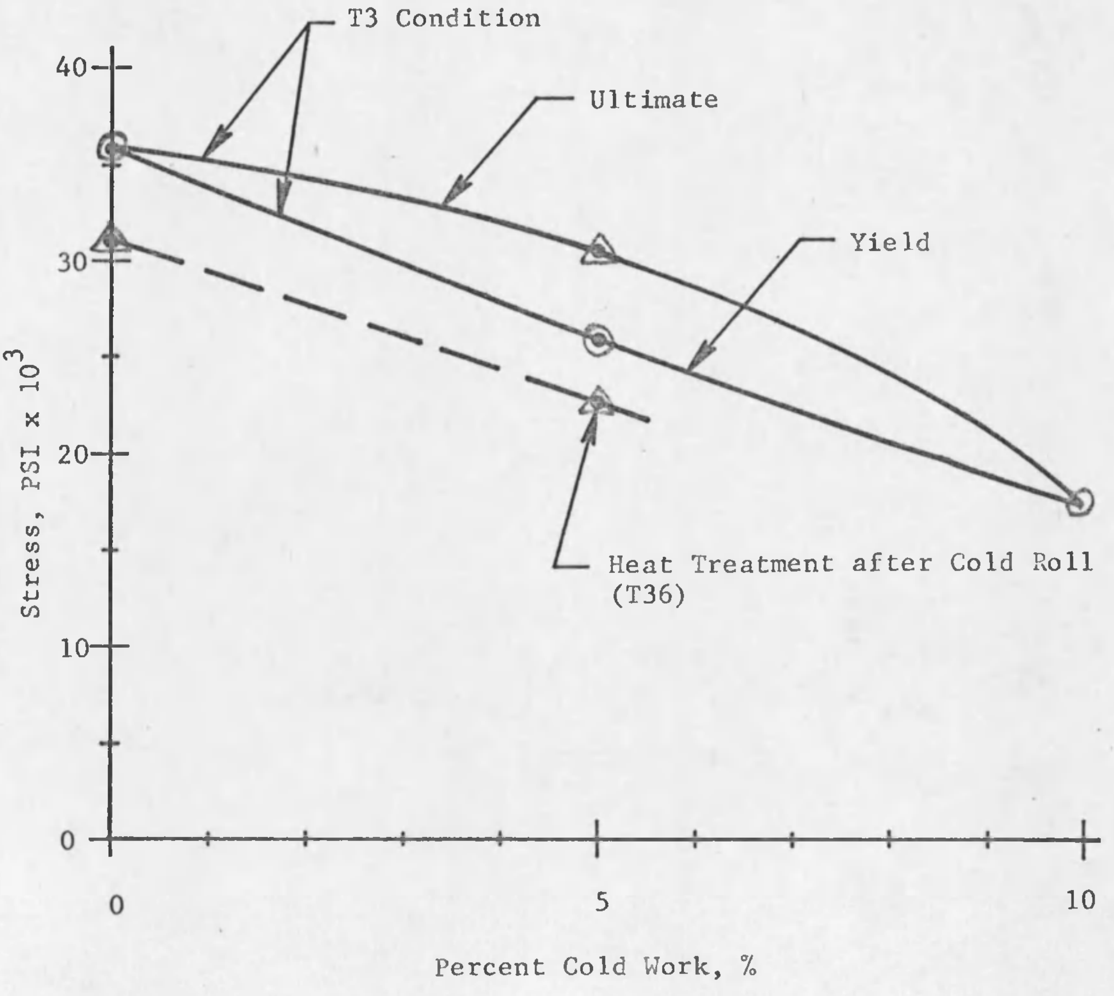


Figure 28. Effect of Cold Rolling on Transverse Ultimate and Yield Strength (2024 Alloy--50% Boron Filaments)

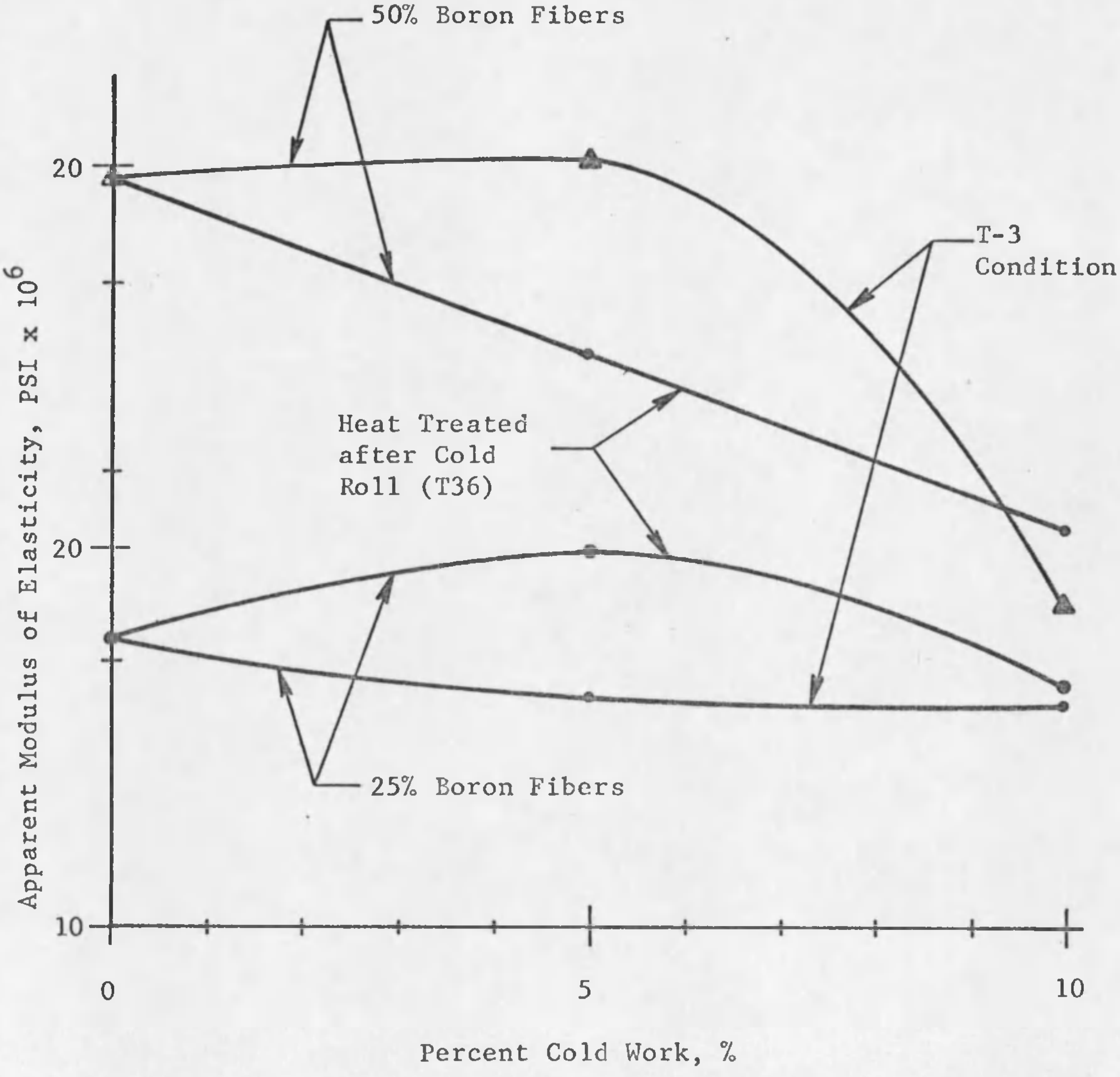


Figure 29. Effect of Cold Rolling on Apparent Transverse Modulus of Elasticity (6061 Alloy)

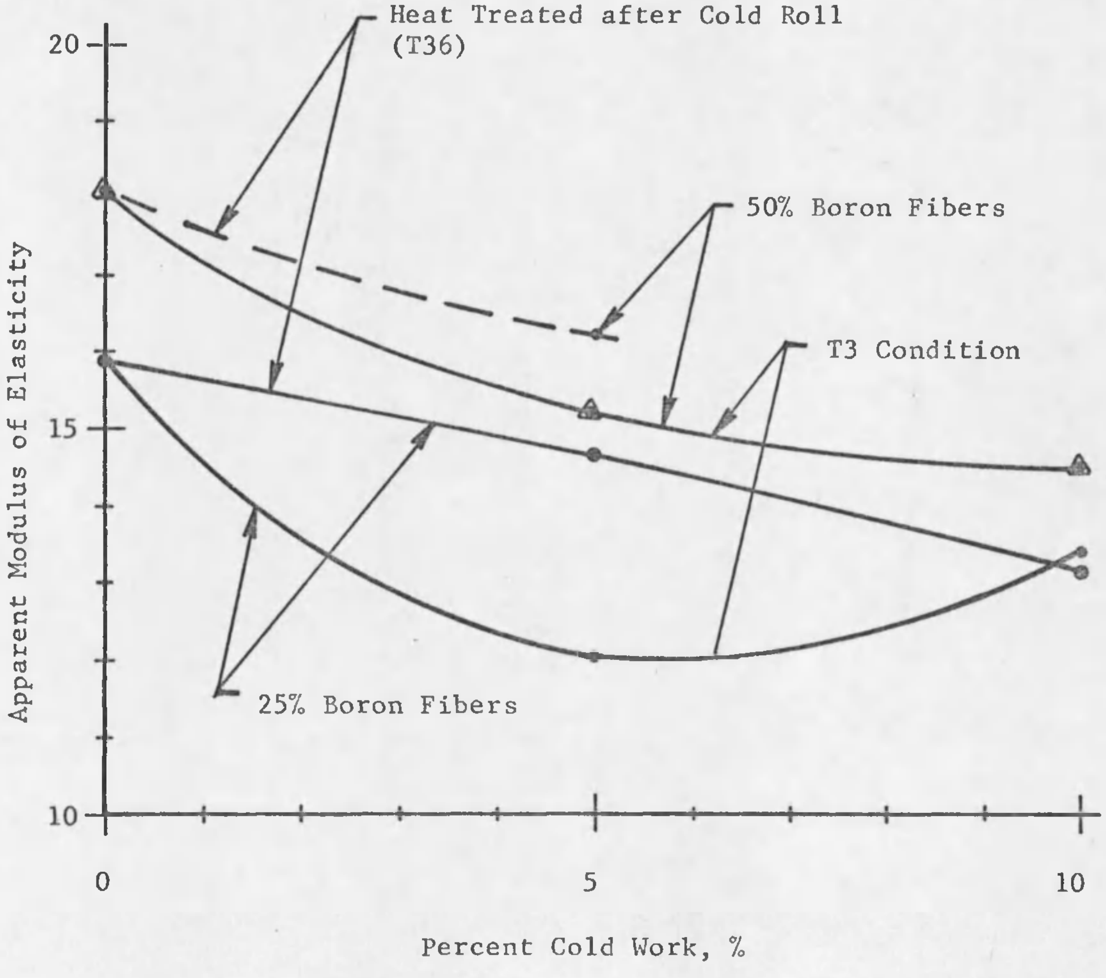


Figure 30. Effect of Cold Rolling on Apparent Transverse Modulus of Elasticity (2024 Alloy)

6.5 Mode of Fracture

The mode of fracture in general was fracture of the matrix. No bond failures of the aluminum matrix to the boron filaments were observed. There was some splitting of the filaments in the fracture surfaces, however, except for one case; there was no way to determine if the splitting initiated at the filament free ends (due to fabrication cracks) or originated within the test area due to inherent subsurface cracks. In one case, noted in Table 6, there was one fiber completely split in the reduced width test area but not in the free ends.

A fractographic analysis of the test specimens was not performed, since fractography was not within the scope of this program.

6.6 Discussion

Of the various thermal treatments evaluated in this test program, the standard T6 process appeared to produce the best results for both the 6061 and 2024 aluminum alloy matrix composites. Cold rolling of 5% appeared to be slightly beneficial for 6061 composite while 10% cold rolling was detrimental. For the 2024 composite, all cold rolling appeared to be detrimental.

The strain cycling procedure evaluated in this test program was very detrimental to physical properties.

The test data obtained from the 50% boron test specimens were not as reliable as expected. This was caused by pitting and uneven etching of the thickness of the specimens especially of the 2024 matrix composite specimens. Therefore, any of the results from these 50% boron specimens should not be considered for design purposes.

Since one of the major objectives of this investigation was to evaluate the splitting of the Avco 5.6-mil-diameter filaments, it was encouraging to note that the mode of fracture was chiefly confined to matrix failure.

CHAPTER 7

CONCLUSIONS

The first objective of this investigation, namely, investigate the new transverse tensile specimen preparation technique, produced very consistent test results. The isolation of the filament end splits from the reduced-width test area on the specimens proved to be effective since few filament splits were observed in the test area of fractured specimens. The elimination of this splitting problem produced high transverse strengths since failure was primarily matrix fracture. The fabrication procedure for the 3/8-inch reduced width test specimens described herein was straightforward and was comparable to the data reported by Kreider, Dardi, and Prewo (1970) for one-inch wide specimens etched to a 1/2-inch reduced width test area. The overall technique, however, is highly recommended as a standardized laboratory test procedure for transverse tensile testing.

The second objective of this investigation, namely, observe behavior of transverse strength properties with various thermal post-treatments, showed that the standard T6 heat treatment produced the highest transverse strengths. (The effect of the T6 heat treatment on longitudinal tensile strength was not within the scope of this program.)

The third objective of this investigation, namely, evaluate the new 5.6-mil-diameter boron filaments, showed that they indeed produce few splits as recently reported in the literature (Kreider, Dardi and Prewo, 1970).

REFERENCES

Adsit, N. R. and J. D. Forest. "Compression Testing of Aluminum-Boron Composites," Convair Corporation, ASTM Symposium, New Orleans, La., Published in ASTM STP-460, February, 1969.

Bradstreet, S. W. "The Influence of Modular Ratio in Structural Composites," SAMPG Quarterly, Fall, 1970.

Chen, P. E. and J. M. Lin. "Transverse Properties of Fibrous Composites," Report No. HPC-68-70, Monsanto Research Corp. Contract N00014-67-C-0218, ARPA Order-873 (September, 1968), AD-840592.

Christian, J. L. "Development and Application of High Matrix Strength Aluminum-Boron," Convair Division, General Dynamics, San Diego, California. Paper presented to American Society for Metals Exposition & Congress, Philadelphia, Pennsylvania, October, 1969. NASA Report A70-21857.

Cornsweet, T. M. "Advanced Composites Production Fabrication," Department of the Air Force Manufacturing Technology Division, Western Metal and Tool Conference, Los Angeles, California, March, 1971.

Davis, L. W. "Transverse Properties of Metal Matrix Composites," Harvey Aluminum Company, ASTM Symposium in New Orleans, La., February, 1969.

Davis, L. W. and J. R. Long. "Examining Composite Materials with the Scanning Electron Microscope," Harvey Aluminum Company, Metals Engineering Quarterly, February, 1972.

Dolowy, J. F., Jr. "Effects of Heat Treatment and Cold Work on Mechanical Properties of 6061 Aluminum-Boron," The Marquardt Corporation, Van Nuys, California. Paper presented at the 15th Refractory Composites Working Group Meeting, Anaheim, California, February, 1969a.

Dolowy, J. F., Jr. "Fabrication and Processing Mechanisms Active in Al-B Composites Including Heat Treatment and Cross Rolling Effects," The Marquardt Corporation, Van Nuys, California. Metallurgical Society of AIME, Pittsburgh, Pa., May, 1969b. NASA Report No. A69-38197.

Dolowy, J. F., Jr. and R. J. Taylor. "Thermal/Mechanical Strengthening of 6061 Al-B Composites," The Marquardt Corporation, Van Nuys, California. National SAMPE Conference, Seattle, Washington, September, 1969. NASA Report No. A69-43449.

Ebert, L. J. "Analytical Approach to Composite Behavior," Report AFML-TR-70-104, Case Western Reserve University, Cleveland, Ohio. Contract F33615-67-C-1487, June, 1970.

Forest, J. D. "Development and Application of Aluminum-Boron Composite Materials," Convair Division, General Dynamics Corporation, San Diego, California. Paper presented at AIAA Annual Meeting, Philadelphia, Pa., October, 1968.

Getten, J. R. and L. J. Ebert. "The Cold Rolling Characteristics of Aluminum-Boron Fiber Composites," Case Western Reserve University, Report No. A70-21957, ASM Transactions Quarterly, Vol. 62, July, 1969.

Hamilton, C. H. and L. J. Ebert. "Improved Fiber Composite Tensile Performance by Mechanical Residual Stress Relief," Case Western Reserve University, Cleveland, Ohio, NASA Report No. A70-10737, September, 1969.

Hanby, K. R. "Fiber-Reinforced Metal-Matrix Composites--1969-1970," Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, DMIC Report S-33, July, 1971 a.

Hanby, K. R. "Advanced Composite Materials," Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, November, 1971 b.

Kreider, K. G., L. Dardi and K. Prewo. "Metal Matrix Composite Technology," Technical Report AFML-TR-70-193, United Aircraft Corporation, July, 1970.

Lenoe, E. M. "Micromechanics of High-Strength, Low Density, Boron Filament Reinforced Aluminum Metallic Composites," AVCO Corporation, Space Systems Division, AFML-TR-67-125 (Part I), May, 1967a, AD-824322.

Lenoe, E. M. "Micromechanics of High Strength, Low Density, Boron Reinforced Metal Composites," AVCO Corporation, Space Systems Division, AFML-TR-67-125 (Part II), December, 1967b, AD-834303.

Lin, J. M., P. E. Chen and A. T. Dibenedetto. "Transverse Properties of Unidirectional Aluminum Matrix Fibrous Composites," Report IIPC 69-92, Monsanto/Washington University ONR/ARPA Association, Contract N00014-67-C-0218, August, 1969, AD-861188.

Long, J. R. "The Evaluation of the Mechanical Behavior of Metal Matrix Composites Reinforced with SiC Coated Boron Fibers," Technical Report AFML-TR-69-291, Vol. 1, Harvey Aluminum Co., November, 1969.

Shimizu, H. and J. F. Dolowy. "Fatigue Testing and Thermal-Mechanical Treatment Effects on Aluminum-Boron Composites," The Marquardt Corporation, ASTM Symposium, New Orleans, La., February, 1969, Published in ASTM STP-460.

Swanson, G. D. and J. R. Hancock. "Effects of Interfaces on the Off-Axis and Transverse Tensile Properties of Boron-Reinforced Aluminum Alloys," Report No. 2, Midwest Research Institute, Kansas City, Missouri, Contract No. N00014-70-C-0212, NR 031-743, April, 1971, AD-722020.

Taylor, R. J., H. Shimizu and J. F. Dolowy, Jr. "Mechanical Behavior of Aluminum-Boron Composites," Technical Report AFML-TR-68-385, The Marquardt Corporation, Van Nuys, California, Contract F33615-68-C-1165, August, 1969.

Tsareff, T. C. "Strength Properties of Unidirectional Boron-Aluminum Composites," Allison Division, General Motors Corporation. Symposium of the Metallurgical Society of AIME, May, 1969.

Van Horn, K. R. "Aluminum Volume I, Properties, Physical Metallurgy and Phase Diagrams," American Society for Metals, Metals Park, Ohio, 1967.