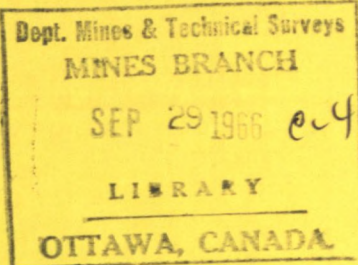




**CANADA**



# **PROPERTIES OF SAND-CAST MAGNESIUM ALLOYS**

**Part VII: The Effect of Wall  
Thickness on Tensile Properties  
of Mg-Al-Zn Alloy Castings**

**DEPARTMENT OF MINES AND  
TECHNICAL SURVEYS, OTTAWA**

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**PHYSICAL METALLURGY DIVISION**

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PROPERTIES OF SAND-CAST MAGNESIUM ALLOYS  
PART VII: THE EFFECT OF WALL THICKNESS ON  
TENSILE PROPERTIES OF Mg-Al-Zn ALLOY CASTINGS

by

A. Couture \* and J. W. Meier \*\*

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ABSTRACT

It has been shown in earlier investigations that, under favourable solidification conditions (e.g., in premium-quality castings), high mechanical properties may be obtained regardless of wall thickness. In commercial castings, however, it is not always possible (or economical) to avoid some reduction of mechanical properties in heavier sections of the casting.

The present investigation was carried out to explore the effect of section thickness on properties of alloys AZ80, AZ91 and AZ92 in various temper conditions. To eliminate other factors affecting solidification conditions, all castings were produced using standard foundry practice for green sand casting, without the use of any chills or insulating materials.

Tensile properties of the castings were correlated with section thickness, grain size, surface area/volume ratio, cooling rate, and solidification time. It was found that tensile properties decrease gradually with decreasing surface area/volume ratio (decreasing cooling rate) until this ratio drops to about 3 (cooling rate below 30°C/min or 54°F/min); beyond this, tensile properties drop very rapidly, but specification minima can usually be met when the ratio is higher than 2 and the cooling rate exceeds 20°C/min (36°F/min).

The ratio between the diameter of round bars and the thickness of plate castings to obtain similar tensile properties is 1.4 to 1.7.

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Direction des mines

Rapport de recherches R 153

## PROPRIÉTÉS DES ALLIAGES DE MAGNÉSIUM MOULÉS EN SABLE

7e Partie: Effet de l'épaisseur des parois sur  
les propriétés mécaniques des moulages en  
alliage Mg-Al-Zn.

par

A. Couture\* et J. W. Meier\*\*

### RÉSUMÉ

On a démontré, lors de recherches antérieures, que sous des conditions de solidification favorables (e.g., moulages de première qualité) on peut obtenir d'excellentes propriétés mécaniques quelle que soit l'épaisseur des parois. Dans les moulages commerciaux, cependant, il n'est pas toujours possible (ou économique) d'éviter un certain appauvrissement des propriétés mécaniques dans les parties les plus épaisses du moulage.

Les auteurs ont effectué les recherches présentes pour étudier l'effet de l'épaisseur de la paroi sur les propriétés des alliages AZ80, AZ91 et AZ92 sous diverses conditions. Pour éliminer les autres facteurs qui influencent les conditions de solidification, tous les moulages ont été effectués selon la méthode de coulage en sable vert employée couramment dans les fonderies, sans l'aide de refroidisseurs ou d'isolants.

Les propriétés mécaniques des moulages ont été mises en corrélation avec l'épaisseur de la paroi, la grosseur des grains, le rapport surface-volume, la vitesse de refroidissement et le temps de solidification. On a trouvé que les propriétés mécaniques diminuent graduellement avec une diminution du rapport surface-volume (vitesse décroissante de refroidissement) jusqu'à ce que ce rapport s'établisse aux environs de 3 (vitesse de refroidissement inférieure à 30°C ou 54°F à la minute). Au delà, les propriétés mécaniques faiblissent très rapidement mais on peut ordinairement satisfaire aux prescriptions techniques minimales lorsque le rapport est supérieur à 2 et que la vitesse de refroidissement dépasse 20°C (ou 36°F) à la minute.

Le rapport entre le diamètre de barres rondes et l'épaisseur de moulages plats pour obtenir les mêmes propriétés mécaniques doit se situer entre 1.4 et 1.7.

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## INTRODUCTION

It has been shown that, under favourable solidification conditions (e.g., in premium-quality castings), high mechanical properties may be obtained regardless of casting wall thickness<sup>(1,2,3)</sup>. However, in commercial castings, which are the backbone of the foundry economy, it is not always possible (or profitable) to avoid some reduction of mechanical properties in heavier sections of the casting. Section thickness per se has of course no influence on the properties, but contributes to changes of the solidification conditions, which in turn affect the alloy structure (grain size, dendritic cell size, alloy constituents) and the distribution (size, shape) of microporosity.

The great majority of commercial castings (that is, castings for general applications where the highest strength-to-weight ratio or the properties at elevated temperatures are not essential) are produced in Mg-Al-Zn alloys, which show the best casting characteristics and are, therefore, cost-wise the most competitive of all magnesium casting alloys.

The present investigation was carried out, some time ago, to explore the effect of section thickness on properties of alloys AZ80, AZ91 and AZ92 in various temper conditions. To eliminate other factors affecting the solidification conditions, all test castings were produced using standard foundry practice for green sand casting, without the use of any chills or insulating materials.



## Survey of Literature

The effect of section thickness on properties of castings has been investigated for many years, mostly for cast iron, aluminum and copper alloys; some of the few references pertaining to magnesium alloys are mentioned here.

Fox and Lardner <sup>(4)</sup> determined the grain sizes of test bars of different cross-sections in magnesium alloy AZ80 (Elektron A8) and found that the rate of cooling had a more marked effect on unsuperheated than on superheated material.

Eastwood and Davis <sup>(5)</sup> studied magnesium casting alloys AZ63, AZ80, AZ91 and AZ92, and established an interrelation of pouring temperature and section thickness with the grain size of cast plates. The results indicate an appreciable increase in grain size as the plate thickness is increased.

Busk and Phillips <sup>(6)</sup> determined the relationship between mechanical properties and grain size for alloys AZ63 and AZ92; in all cases the mechanical properties decrease with increasing grain size. Their results indicate that the effects of grain size and porosity are not additive, within the range of commercial practice.

Busk <sup>(7)</sup> investigated the effect of microporosity on mechanical properties of magnesium alloy plates (AZ63, AZ92) of various thicknesses

and found no difference between the properties of plates of different thickness having the same porosity rating.

Pearson (8) developed a "slope casting" which possessed a range of section sizes to provide tensile properties equivalent to those obtained from typical production sand castings. This is not a pure section size test but, rather, a solidification rate test producing a casting showing all the effects of solidification rate on grain size, compound distribution, porosity, etc. A study of a series of Mg-Al-Zn alloys revealed that maximum properties and soundness in thick sections are obtained with the less highly alloyed compositions.

In the discussion of Pearson's paper it was pointed out (9) that the reported slope casting results are misleading from a commercial foundry point of view, because they were based on incomplete heat treatment of the castings and included highly defective samples which would normally be rejected.

Dietz (10) investigated the effect of section thickness on the tensile properties of AZ91-T6 alloy plate castings of various thicknesses and found that a relatively accurate (90%) estimate of tensile properties can be made from the grain size and microstructure (pearlitic precipitation) of the cast section. He proposed to base specifications for alloy AZ91-T6 on a maximum grain size and pearlitic precipitate percentage.

McCreery <sup>(11)</sup> presented graphs showing the effect of section thickness on mechanical properties of AZ91-T6 found in commercial castings and in castings produced with "extremes of metal control, etc.".

Green <sup>(12)</sup> investigated the effect of the cooling rate on the grain size of alloys AZ63, AZ81 and AZ92, and found that the grain size of these alloys is established at 28 °C (50 °F) below the liquidus. The grain size decreases as the cooling rate increases to 110 °C/min (200 °F/min), and then remains constant with further increases in cooling rate.

Lagowski and Meier <sup>(2, 3)</sup> showed that, under proper solidification conditions and with some modifications in heat-treating schedules, properties in heavy sections of magnesium alloy castings can be obtained that are equal to or exceed those typical for separately-cast test bars or thinner sections.

## EXPERIMENTAL PROCEDURE

### Alloy Preparation

The compositional limits of the alloys studied in this investigation - AZ80, AZ91 and AZ92 - are given in Table 1. The alloys were prepared from commercial alloy ingots and melted under a cover of "Domal" crucible flux in a steel crucible, grain refined with lampblack, degassed for 10 min with chlorine and cast into green sand moulds.

## Test Castings

### (a) Cylindrical Bars

The moulding arrangement for cylindrical test castings is shown in Figure 1, the dimensions given being for the parting line level. The bars were 3/4, 1, 1-1/2, 2 and 2-1/2 in. in diameter and 6-1/2 in. in length. For each melt the pouring procedure was as follows: Separately-cast test bar moulds ("Dow" type) \* were poured first at a temperature of 750°C (1380°F); test castings were thereafter cast in the order of increasing casting diameter, the 2-1/2 in. bars being poured at a temperature of approximately 700°C (1290°F). Melts were sufficiently large to yield four castings of each size. The moulds were tilted for pouring in order to decrease turbulence and to reduce the possibility of introducing oxide inclusions in a critical part of the castings. Three melts of AZ80 and AZ91 alloys and four melts of AZ92 alloy were prepared, two bars of each size from each melt being tested in the as-cast (F) condition and two in the solution-treated-and-aged (T6) condition. Test bars from three additional AZ80 melts were tested in the solution-treated (T4) condition. Standard 0.505 in. tensile test bars were machined from the centre of the cylindrical castings and, in cases where castings were heat-treated, the heat treatment was carried out before machining.

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\*According to Canadian Standard CSA.HG.1.5-1963, Fig. 1, similar to U.S. Federal Specification QQ-M-56, p.6, Fig. 1A.

(b) Plates

The plate castings studied were 4-1/2 x 6 in. and their thicknesses were: 1/2, 3/4, 1, 1-1/2 and 2 in. Figure 2 shows the moulding arrangements for the thinnest and thickest plates, the dimensions given being for the parting line level. Casting was carried out as previously described, the 2 in. plates being poured at a temperature of approximately 700°C (1290°F). There was only one plate to a mould, and only one plate of each thickness was cast from each melt. Three melts of AZ80 and AZ91 alloys and four melts of AZ92 alloy were tested in the "F" and "T6" conditions (Table 1). Plates were longitudinally cut into four coupons of equal width, the two coupons from one half of each plate being left in the "F" condition and the other two being solution treated and aged (T6 condition). Two additional melts of AZ80 plate were cast, cut as previously described, and solution treated only (T4 condition). As already mentioned, all heat treatments were carried out before machining. The 1/2 in. thick coupons were machined into substandard size test bars having a 0.313 in. diameter and a 2-1/2 in. long reduced section, and the thicker coupons into standard 0.505 in. test bars from the centre of the coupons.

## RESULTS

### Chemical Composition

The chemical composition of all melts used in this investigation, as determined on samples taken from the grip portions of separately-cast test

bars, was within the limits imposed by the specifications (Table 1).

## Mechanical Properties

### (a) Cylindrical Bars

Mechanical property results from bar castings are presented graphically in Figures 3, 4 and 5. Results are averages of six tests for the AZ30-F, AZ80-T6, AZ91-F and AZ91-T6 series, of twelve tests for the AZ80-T4 series, and of eight tests for the AZ92-F and AZ92-T6 series.

It can be seen that the mechanical properties decrease with increasing bar diameter. Mechanical property results were statistically analysed and it was found that, within the range of casting diameters studied, the relationship between mechanical properties and bar diameter could, in general, be represented by a straight line. The only exceptions were the ultimate tensile strength and elongation of AZ80-T4 (Figure 3) and the ultimate tensile strength of AZ91-T6 (Figure 4) bars, where the relationship is better represented by a second-degree equation. It was thought that 95% confidence limits would be more useful than only the lines corresponding to the average properties. Such limits, which may be used for predicting averages but not for single values, are shown in Figures 3, 4 and 5.

### (b) Plates

The mechanical property results from plates of different thicknesses are presented graphically in Figures 6, 7 and 8. Results are averages of

six tests for the AZ80-F, AZ80-T6, AZ91-F and AZ91-T6 series, and of six to eight tests for the AZ80-T4, AZ92-F and AZ92-T6 series.

Mechanical property results were statistically analysed and it was found that results from the outside bars were in several cases, significantly higher than those from the inside ones. The cases in which the properties are not different were all the yield strength results, the "F" elongation of the AZ80 and AZ91 plates, and all the AZ92 results. Consequently, separate graphs for the outside and inside bars are given in Figures 6 and 7 and, in cases where results were identical for both locations, the same lines have been reproduced in both graphs.

It was found that the properties decrease with increasing plate thickness and that the relationship between mechanical properties and casting thickness could be represented by a straight line in the range of thicknesses considered. In this case also 95% confidence limits were established, and these are shown in Figures 6, 7 and 8.

### Microstructure

Although it was not expected that any single factor would be fully responsible for the decrease in mechanical properties with increasing section thickness, attempts were made, nevertheless, to correlate mechanical property results with the average grain size and the amounts of microporosity and pearlitic precipitate (the percentage of pearlitic precipitate



in the microstructure was measured only in AZ92 castings).

Figures 9, 10 and 11 show the relationship between mechanical properties and average grain size for AZ80, AZ91 and AZ92 respectively. For simplicity, the properties from plate castings were averaged even when the outside bars yielded significantly different results from the inside ones. It was found that the results from cylindrical and plate castings could be represented by the same lines.

The curves clearly indicate that the ultimate tensile strength, the yield strength and the elongation decrease with increasing grain size. The trend is represented by straight lines in some cases and by curves in others. For the yield strength results, straight lines were adequate as the absolute variation is small in every case.

Although it is accepted that grain size has a pronounced influence on the mechanical properties, it is doubtful that the increase in grain size, noticed in Figures 9, 10 and 11, would alone have caused such a marked reduction in properties. It is therefore suggested that other factors such as the amount, distribution and size of microporosity, pearlitic precipitate, massive compound, etc., also had a detrimental influence on the properties. These other factors, whose effects are cumulative, may be so important that the relationship between mechanical properties and grain size may not be as significant as it appears. If that is the case, the decrease in mechanical properties would be due to solidification conditions, which manifest themselves

by a number of interrelated factors, the most readily measurable being the grain size.

Attempts to correlate the mechanical properties with the amount of pearlitic precipitate (in the case of AZ92 alloy) and microporosity as assessed on X-ray films proved unsuccessful, because of program limitations.

### Casting Geometry

As the quantity of heat given off by a casting during pre-freezing cooling and during freezing can be dissipated only through the casting surfaces that are in contact with sand, attempts were made to correlate the mechanical properties and grain size of each casting with its surface area/volume ratio. It should be noted that in calculating the surface area, only those casting surfaces were considered that were in direct contact with the sand, excluding gating and risers. (Because of the configuration of the castings, this modifies somewhat the surface area calculation from what might be expected from a purely theoretical approach.)

Figures 12, 13, 14 and 15 show that the mechanical properties decrease and grain size increases when the surface area/volume ratio of the casting decreases. This is to be expected as, all other factors being equal, with decreasing ratios more heat has to flow through a unit surface area, and this results in a lower cooling rate, usually accompanied by lower mechanical properties and coarser grain size.

An interesting observation one can make from these graphs is that the relationship between properties and surface area/volume ratio can be shown by the same line whether results were taken from cylindrical or plate castings. The agreement is usually good but, in cases where discrepancies occur, results from plates tend to be a little higher than those from bars. However, as such discrepancies are more apparent in the heat-treated results, it is possible that the heat treatment was more efficient for thicker plates, because plates were cut in one-inch-wide coupons before heat treatment, whereas the cylindrical castings were heat-treated without removing any metal, thus making their solution treatment less efficient. Differences in grain size between plates and bars were more pronounced than for mechanical properties, with the exception of AZ92 alloy, in which the grain size results from both types of castings are substantially identical. AZ80 and AZ91 results were identical at the lower part of the curves but differ as the surface area/volume ratio decreases, the maximum differences being of the order of 1-1/2 to 2 units at the top of the curves (Figure 15).

In spite of these small discrepancies, results were sufficiently close to suggest that mechanical property values are identical, whether they are obtained from plate or cylindrical castings, so long as the surface area/volume ratios of the castings are similar.

Examination of Figures 12, 13 and 14 also reveals that mechanical properties decrease gradually with decreasing surface area/volume ratio, at high ratio values. However, when the ratio becomes lower than about 3, properties drop more rapidly. Similarly, grain size increases more rapidly when the ratio becomes less than 3.

When test bars are machined directly from a production casting, the average properties of such test specimens should not be less than 75% of the ultimate tensile strength and yield strength, and 25% of the elongation required for separately-cast test bars for magnesium alloys \*. When the rule is applied to the properties specified in Table 1, it is seen that the required properties can usually be obtained when the surface area/volume ratio is greater than 2 (Figures 12, 13 and 14).

Because it was already established that, at least for the magnesium alloys investigated, tensile property values and average grain size are identical in both plates and round bars as long as the surface area/volume ratios of the castings are identical, it was decided to correlate the wall thickness, i.e. casting diameter or plate thickness, with the surface area/volume ratio. This is shown in Figure 16. It can be derived from the graph that, for the type of castings used in this investigation and sketched in Figures 1 and 2, cylindrical bar and plate castings have similar properties when the bar diameter/plate thickness ratio is 1.4 to 1.7. It is noticed that this ratio is a

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\* According to Canadian Standard CSA.HG.9-1963.

little lower than that given in the literature for aluminum alloys (and cast irons) and which is approximately 2.

### Cooling Rate

The effect of cooling rate on tensile properties, grain size and the relationship with the surface area/volume ratio is graphically presented in Figures 17 and 18 for one of the alloys studied - AZ80. Thermocouples were placed in the centre of the cylindrical bars and in the centre of the inside coupons of the plate castings. The curves are based on the average cooling rates between 602 and 572 °C (1115 and 1060 °F), as it was claimed (12) that grain size is established very early during solidification. It can be seen that the properties decrease gradually with decreasing cooling rate until the 30 °C/min (54 °F/min) level is reached, after which the drop is appreciably more pronounced. As expected, grain size varies inversely with the mechanical properties and does not markedly increase until the cooling rate is lower than 30 °C / min (54 °F/min). It is interesting to note that this rate corresponds to a surface area/volume ratio of about 3 (Figure 18), which was considered for all alloys - AZ80, AZ91 and AZ92 (Figures 12, 13 and 14) - as being the ratio below which the mechanical properties drop very rapidly. For alloy AZ80, the specification minima can be met when the cooling rate exceeds 20 °C/min (36 °F/min).

### Solidification Time

Figures 19 and 20 show the relationship between the tensile properties and grain size and the solidification time for alloy AZ80 (the solidification range is 602-420°C, 1115-790°F, according to (13)). Some differences in the lines showing the ultimate tensile strength for the T6 temper and the surface area/volume ratio are apparent and would indicate a difference in the solidification time for round bars and plate castings, respectively.

### DISCUSSION

Mechanical properties of cast products depend entirely on the solidification conditions (thermal gradients, cooling rate, solidification time). Our knowledge of the various aspects of solidification and heat extraction in the mould is growing and a considerable number of publications on these subjects are available. Some of the more pertinent claims may be repeated.

Ruddle (14) reported good correlation between the tensile properties and the longitudinal temperature gradients existing during the later stages of freezing, when interdendritic feeding was occurring. Eastwood and Davis (15) found that optimum soundness (freedom from porosity) in Mg-Al-Zn alloy plates was obtained in 1/2 in. sections and that the greatest difficulties in producing sound material were found in much thicker or much thinner sections.

Green (16) showed that to produce porosity-free plates in the AZ63 alloy, a minimum thermal gradient of 5 °F/inch must be established before the metal temperature falls more than about 28 °C (50 °F) below the liquidus. Flemings (17), in discussing Green's paper, stated that much higher thermal gradients, in the order of 100 °F/inch or above, are necessary to avoid finely dispersed microporosity and its effect on the mechanical properties of the casting.

Similarly, Chamberlin and Mezoff (18) demonstrated the importance of sufficiently high thermal gradients in securing sound castings, and showed good correlation between thermal gradients and mechanical properties of AZ63 alloy castings. No correlation was found between the cooling rate (at 1000 °F, 540 °C) and tensile strength.

Watkins and Kondic (19) consider the alloy composition and the solidification cooling rate as the two most important variables affecting cast structure and related mechanical properties. It is claimed by Form, Ahearn and Wallace (20) that average thermal gradients in the solidifying casting do not correlate with tensile strength. The actual thermal gradient at the instant of solidification is significant but difficult to determine experimentally. Good correlation is obtained between strength and solidification time. They suggest, therefore, that the important factor controlling the strength of a casting is time of solidification, not the casting section size ("metallurgical size factor").



Although some of the above opinions are contradictory, all evidence shows that the mechanical properties are strictly related to solidification conditions. In general, the cooling rate determines the fineness of the structure and the other variables affect the soundness of the casting.

The results of the present investigation show the correlations of tensile properties with section thickness, grain size, surface area/volume ratio, cooling rate, and solidification time.

It is known that the drastic reduction of tensile properties, often shown by heavy casting sections, is not unavoidable. As shown in a previous study (3), high tensile properties in heavy sections can be achieved if favourable solidification conditions are established by proper mould design (gating, risering, and especially chilling) and modified heat treatment. Table 2, abstracted from this work, presents some results obtained on AZ91-T6 and AZ92-T6 castings of various cross-sections.

It has already been mentioned that solidification conditions necessary for premium quality are uneconomical in the regular production of commercial castings. It is, therefore, important that the designer and/or user of cast products realize the level of tensile properties to be expected in heavier sections of regular production castings. This may lead to more realistic design calculations, or may convince the user that it is often cheaper to pay more for a higher-quality product.

## CONCLUSIONS

1. Tensile properties decrease with increasing wall thickness, and the relationship between properties and casting thickness is generally linear in the range of bar diameters and plate thicknesses surveyed.
2. It was found that the tensile properties and grain size are the same for both round bars and plate castings, provided the surface area/volume ratios are identical.
3. Tensile properties drop rapidly when the surface area/volume ratio decreases below about 3, but specification minima could usually be met when the ratio is higher than 2.
4. The ratio between the diameter of round bars and the thickness of plate castings to obtain similar tensile properties was found to be 1.4 to 1.7.
5. In the case of AZ80 alloy, properties of round bars and plate castings are the same when the cooling rate is the same. Properties start to drop rapidly when the cooling rate is lower than  $30^{\circ}\text{C}/\text{min}$  ( $54^{\circ}\text{F}/\text{min}$ ), but specification minima can be met when the cooling rate exceeds  $20^{\circ}\text{C}/\text{min}$  ( $36^{\circ}\text{F}/\text{min}$ ).

6. Correlation of tensile properties of alloy AZ80 with solidification time is somewhat less pronounced, because of differences shown in results obtained on round bars and plate castings.

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TABLE 1

## Specifications for Chemical Composition and Minimum Tensile Properties (a)

Alloy Designation <sup>(b)</sup>	Chemical Composition, %			Temper <sup>(c)</sup>	Minimum Tensile Properties					
	Al	Zn	Mn		Separately-Cast Test Bars			Test Bars cut from Castings <sup>(e)</sup>		
					UTS, kpsi	0.2% YS, kpsi	Elong., % in 2 in.	UTS, kpsi	0.2% YS, kpsi	Elong., % in 2 in.
AZ80	7.5-8.5	0.3-0.7	0.15-0.40	-F	23	-	3	17	-	1
				-T4	34	-	7	25	-	2
				-T6	34	12	4	25	9	1
AZ91	8.1-9.3	0.4-1.0	0.13 min.	-F	23	11	(d)	17	8	(d)
				-T6	34	16	3	25	12	1
AZ92	8.3-9.7	1.6-2.4	0.10 min.	-F	23	11	(d)	17	8	(d)
				-T6	34	18	1	25	13	-

(a) According to Canadian Standard CSA.HG.9-1963 (AZ80) and ASTM Specification B80-63 (AZ91 and AZ92)

(b) According to Canadian Code CSA.H.1.1-1958

(c) According to Canadian Code CSA.H.1.2-1958

(d) Not required

(e) According to CSA.HG.9-1963 and U.S. Federal Specification QQ-M-56b.

TABLE 2

Properties of Premium-Quality Magnesium Alloy Castings (3)

Alloy Designation	Test Casting (a)	0.2% YS, kpsi	UTS, kpsi	El, % in 4D
AZ91-T6	A	21.2	42.2	4.5
	B	23.8	41.2	6.5
	C	22.4	41.4	5.0
	D	21.0	41.3	5.5
	E	21.1	44.9	6.5
AZ92-T6	A	24.8	43.7	2.5
	B	27.5	45.1	4.0
	C	26.8	42.9	3.5
	D	25.7	45.1	3.0
	E	29.1	46.3	3.0

- (a) A - separately-cast test bar, 1/2-inch diameter .  
 B - 1/8-inch-thick unchilled plate .  
 C - 1/4-inch-thick unchilled plate .  
 D - 1/2-inch-thick unchilled plate .  
 E - 2-inch-thick, end-chilled plate (adjacent to chill) .

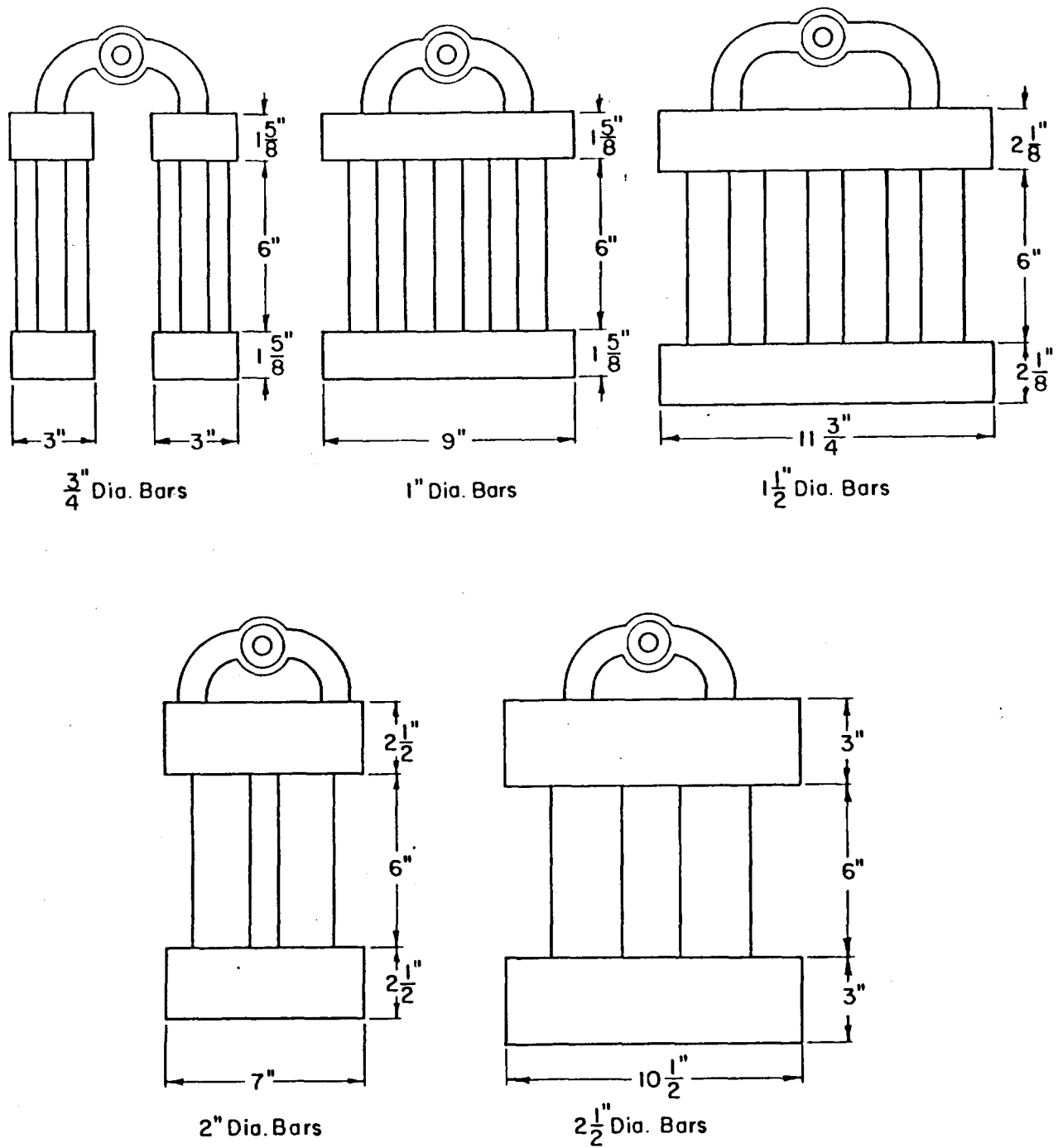


Figure 1. Sketch of Cylindrical Bar Castings .



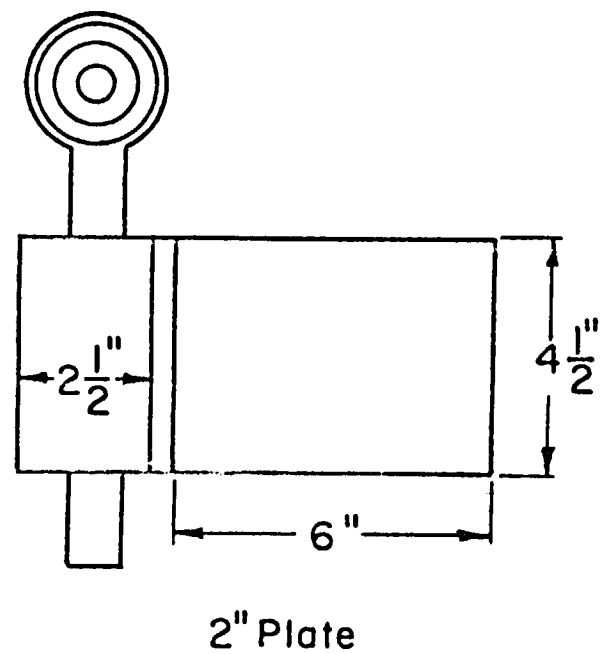
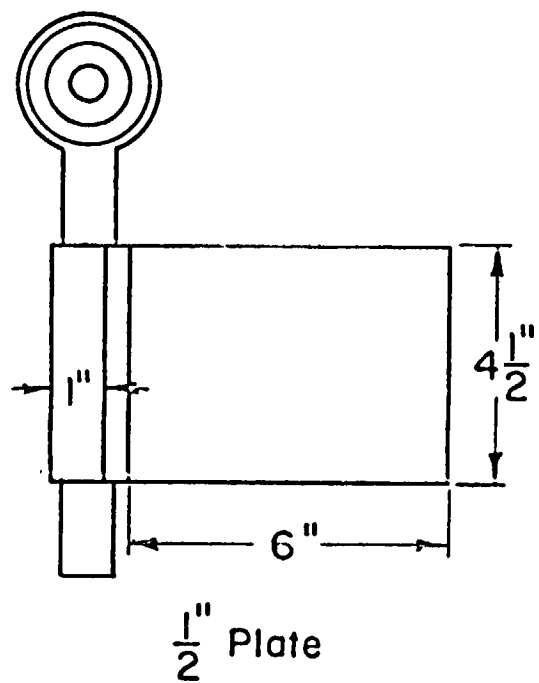


Figure 2. Sketch of Plate Castings.

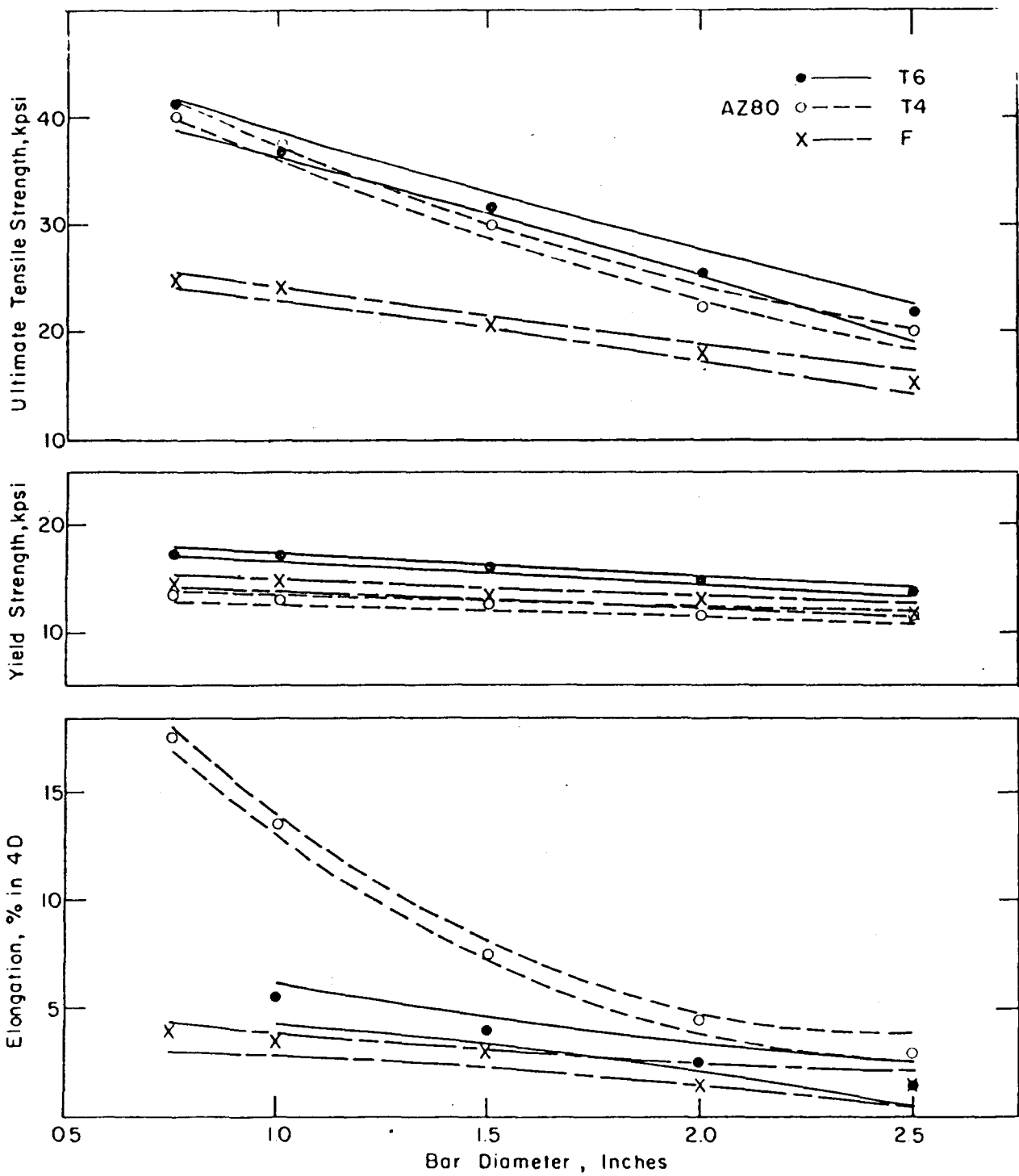


Figure 3. Confidence Limits for Tensile Properties of AZ80 Bars.

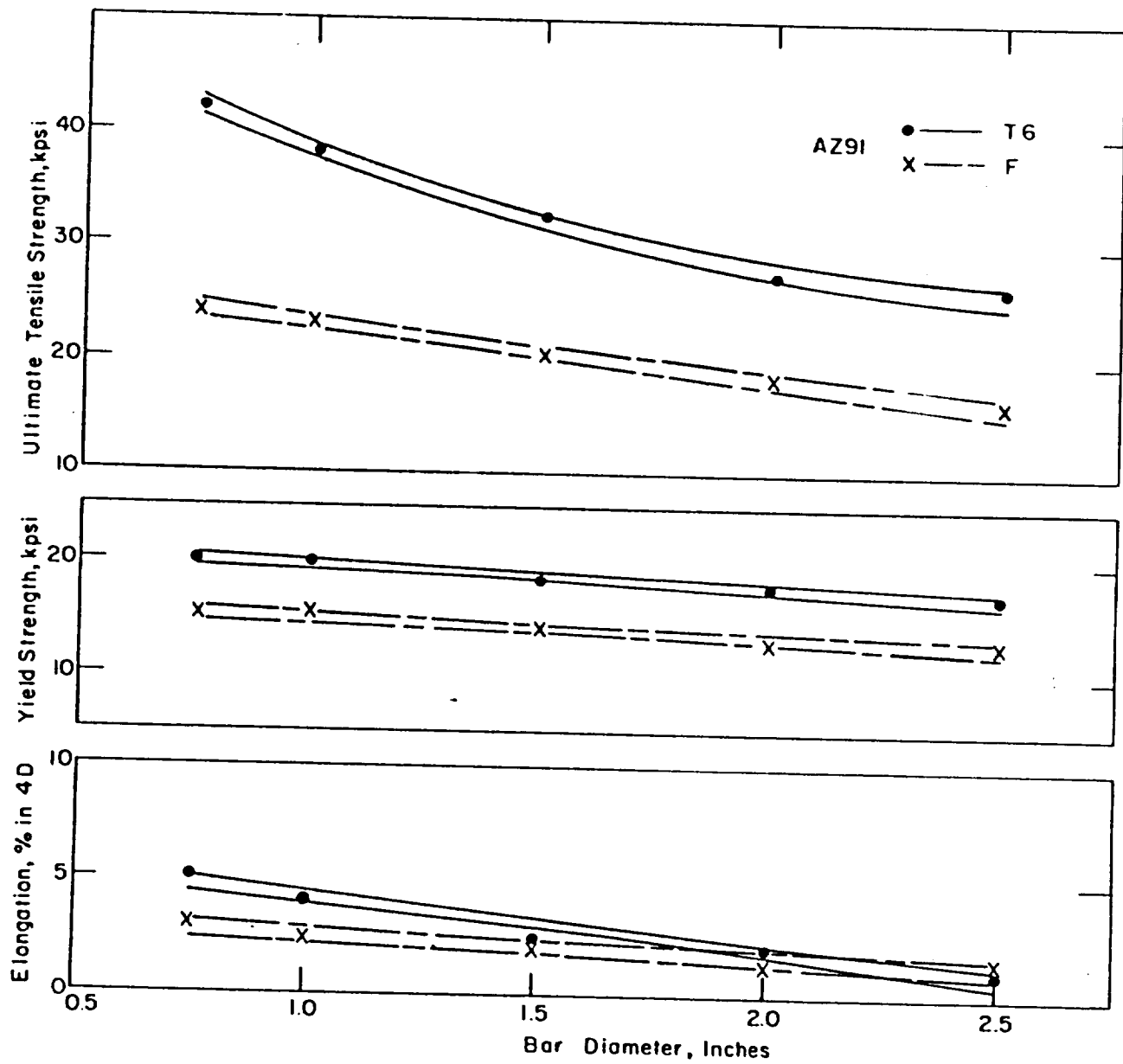


Figure 4. Confidence Limits for Tensile Properties of AZ91 Bars.

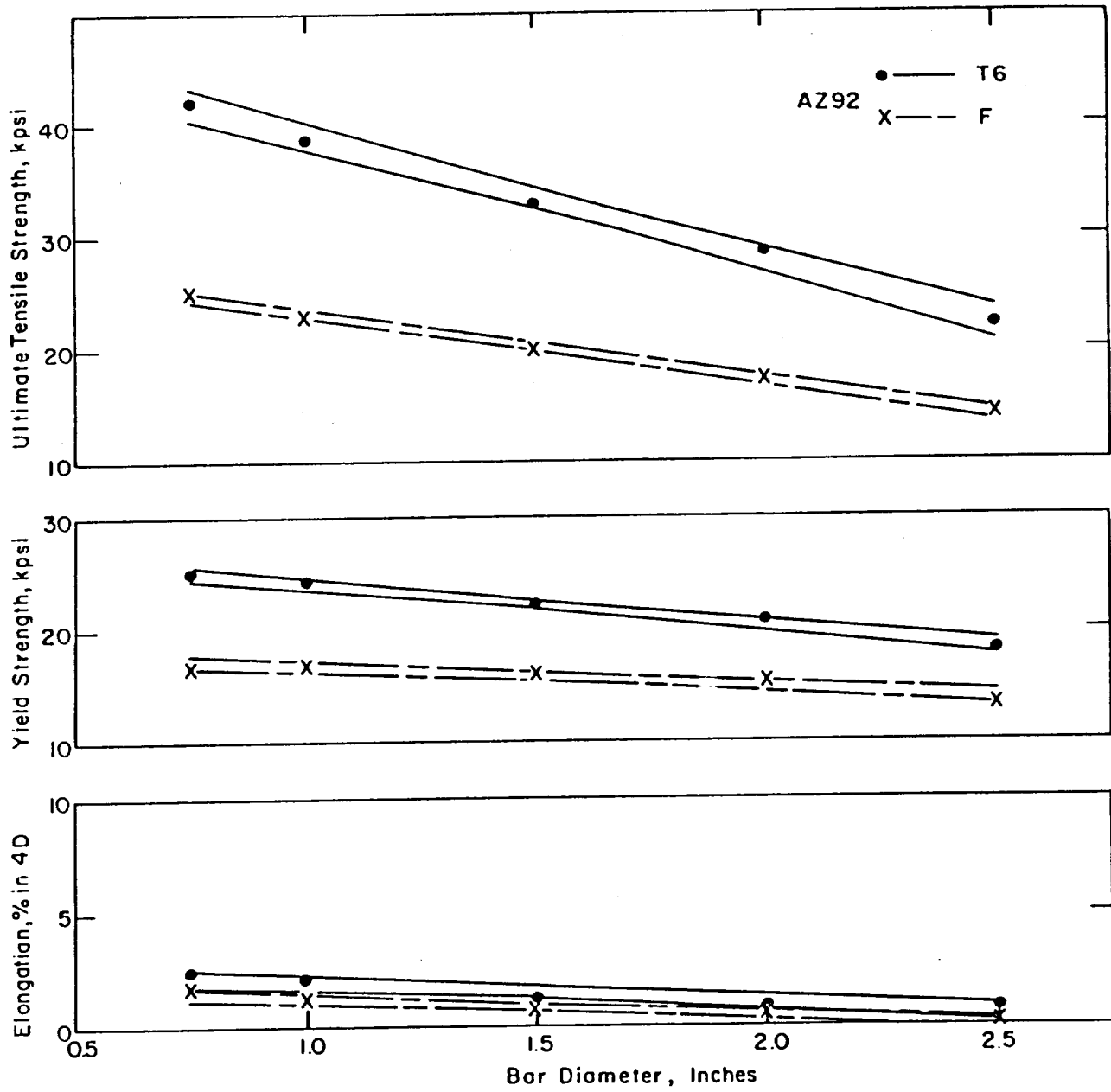


Figure 5. Confidence Limits for Tensile Properties of AZ92 Bars.

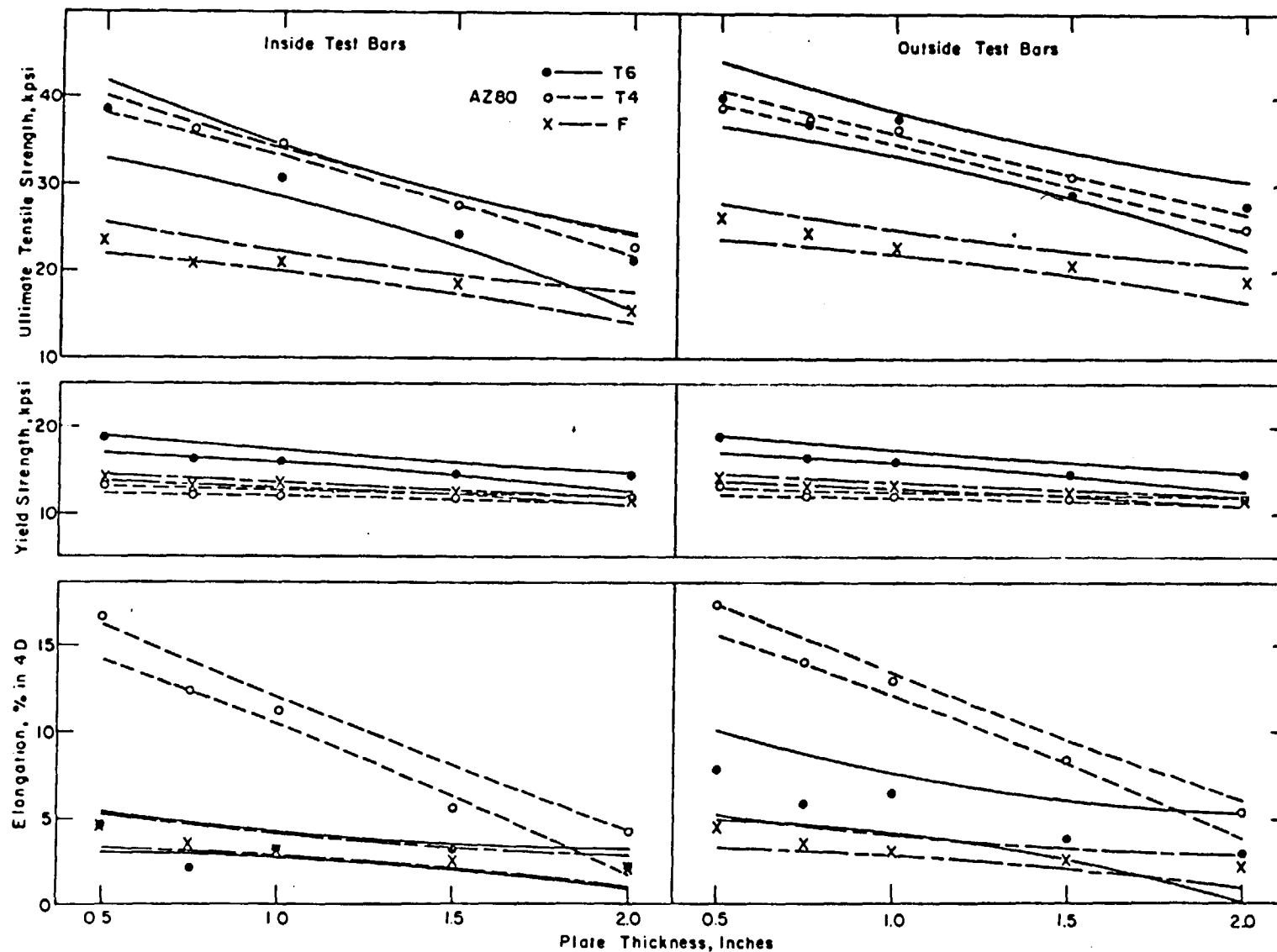


Figure 6. Confidence Limits for Tensile Properties of AZ80 Plates.

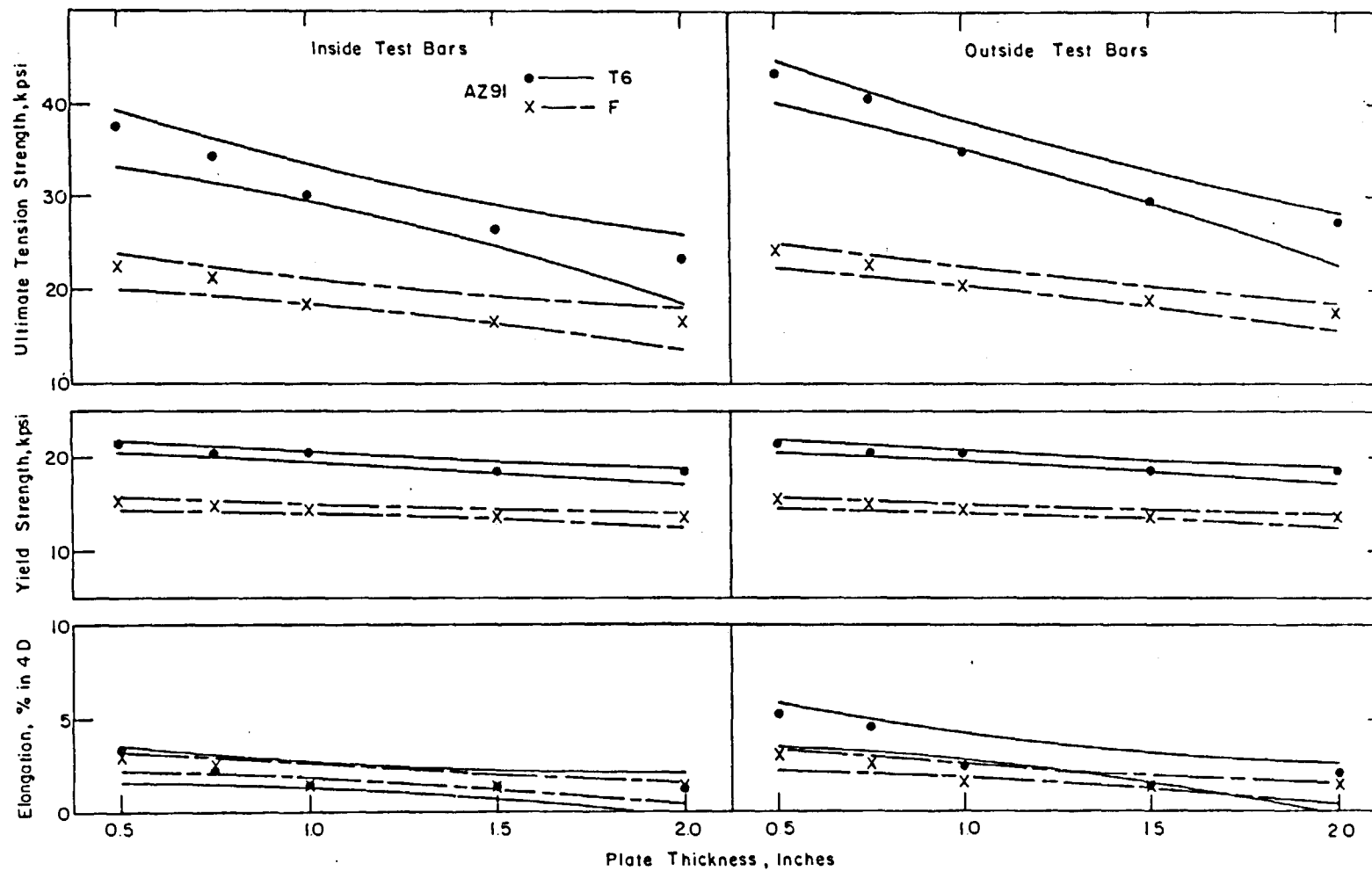


Figure 7. Confidence Limits for Tensile Properties of AZ91 Plates.

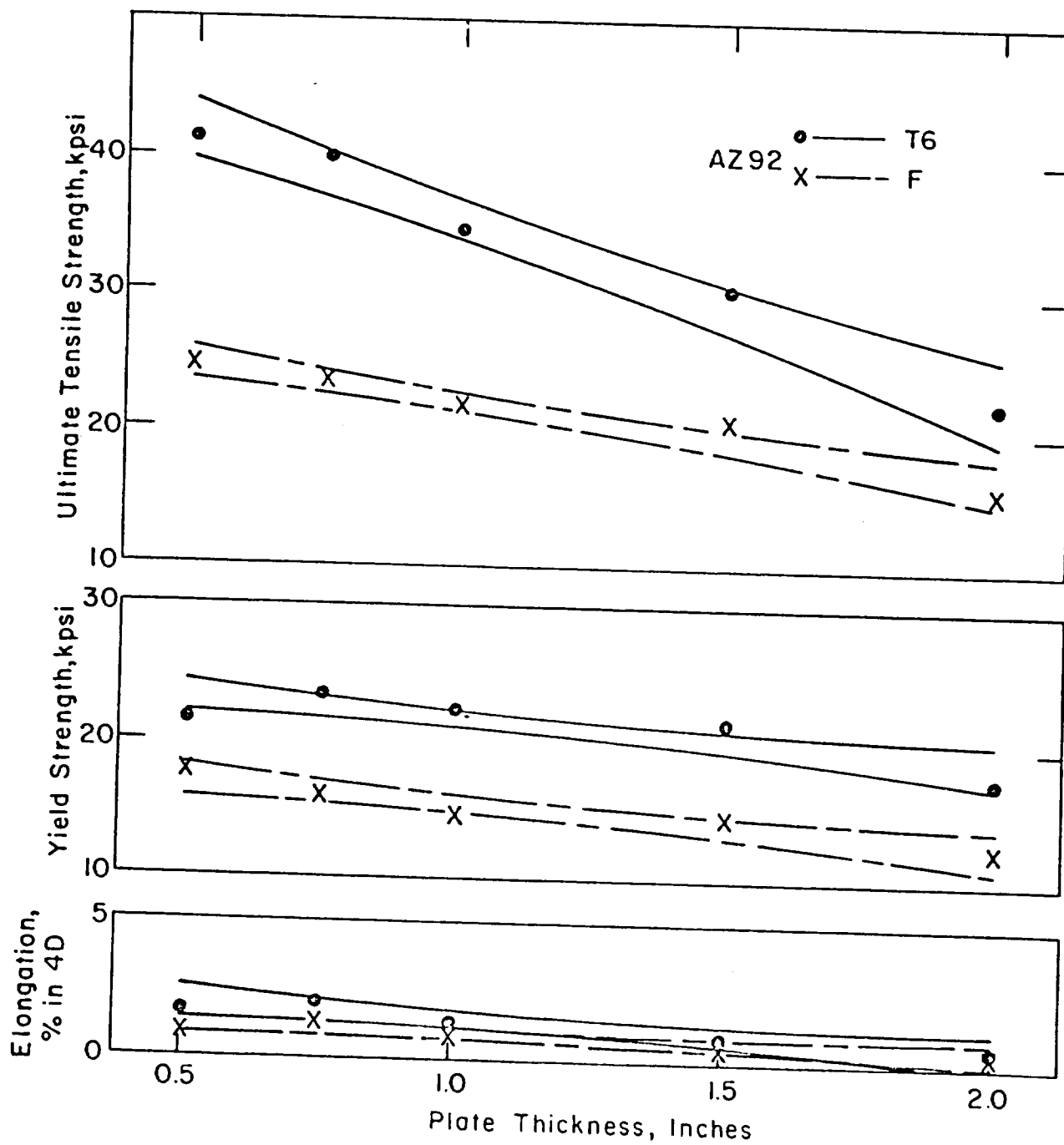


Figure 8. Confidence Limits for Tensile Properties of AZ92 Plates.



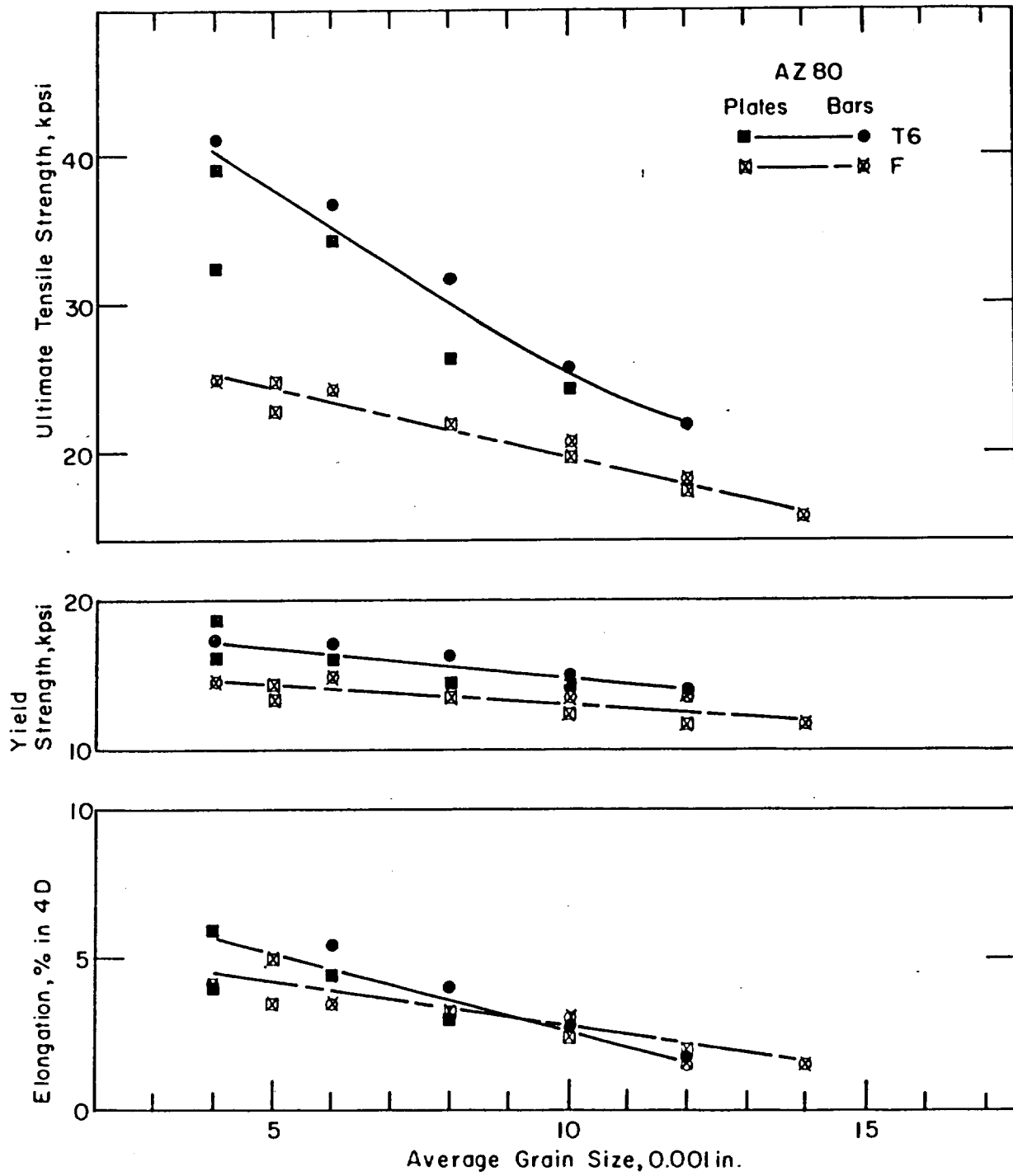


Figure 9. AZ80 Tensile Properties vs Average Grain Diameter .

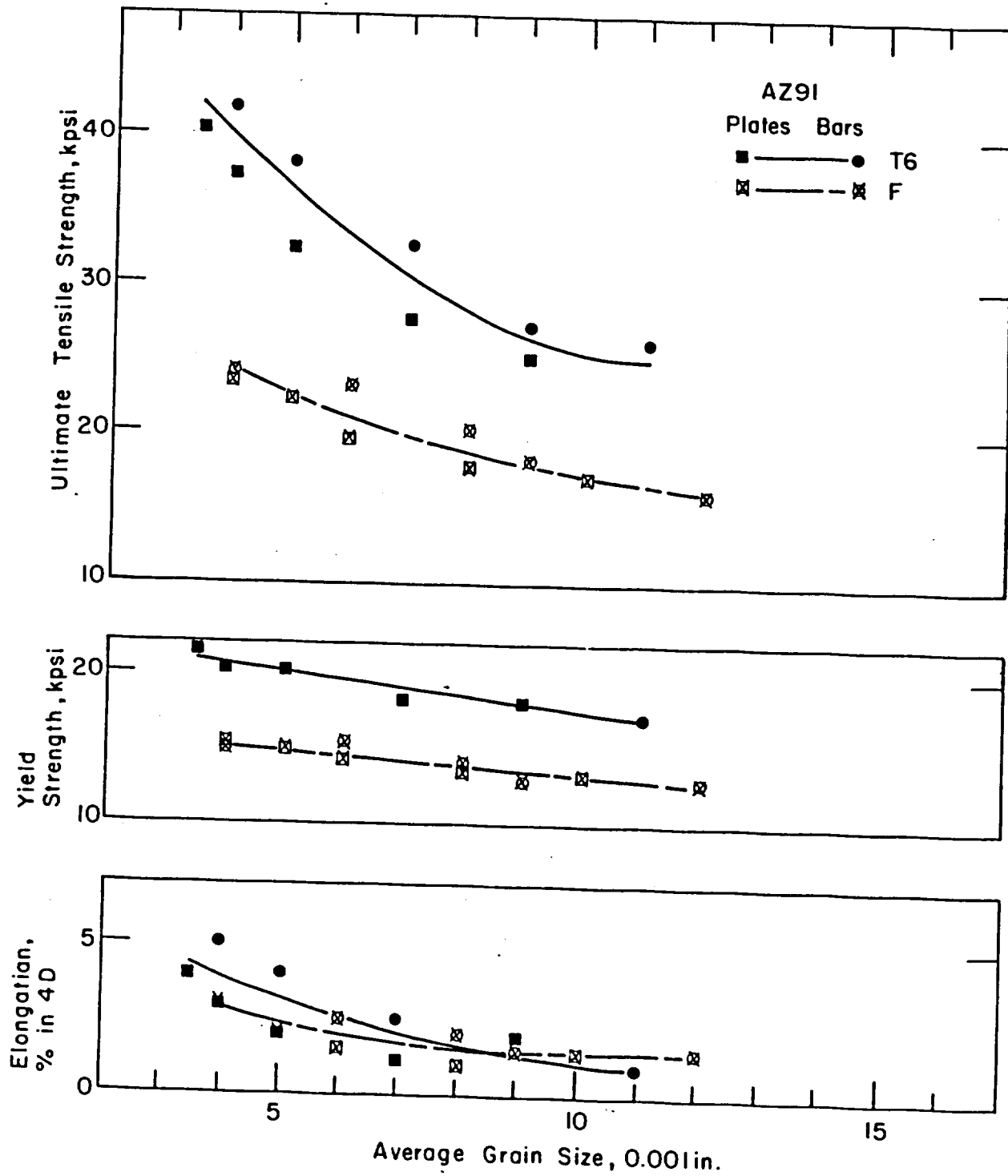


Figure 10. AZ91 Tensile Properties vs Average Grain Diameter.

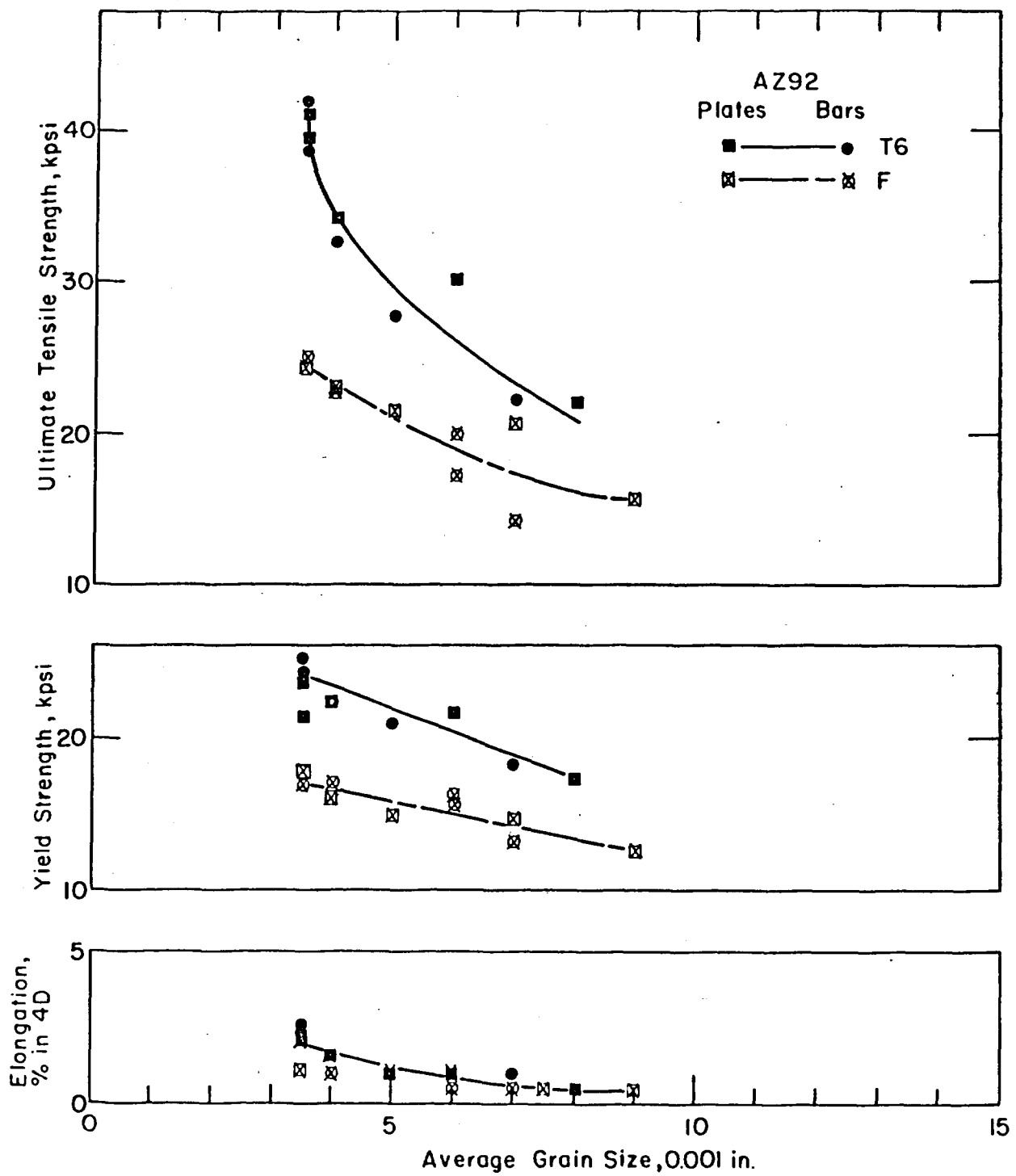


Figure 11. AZ92 Tensile Properties vs Average Grain Diameter .

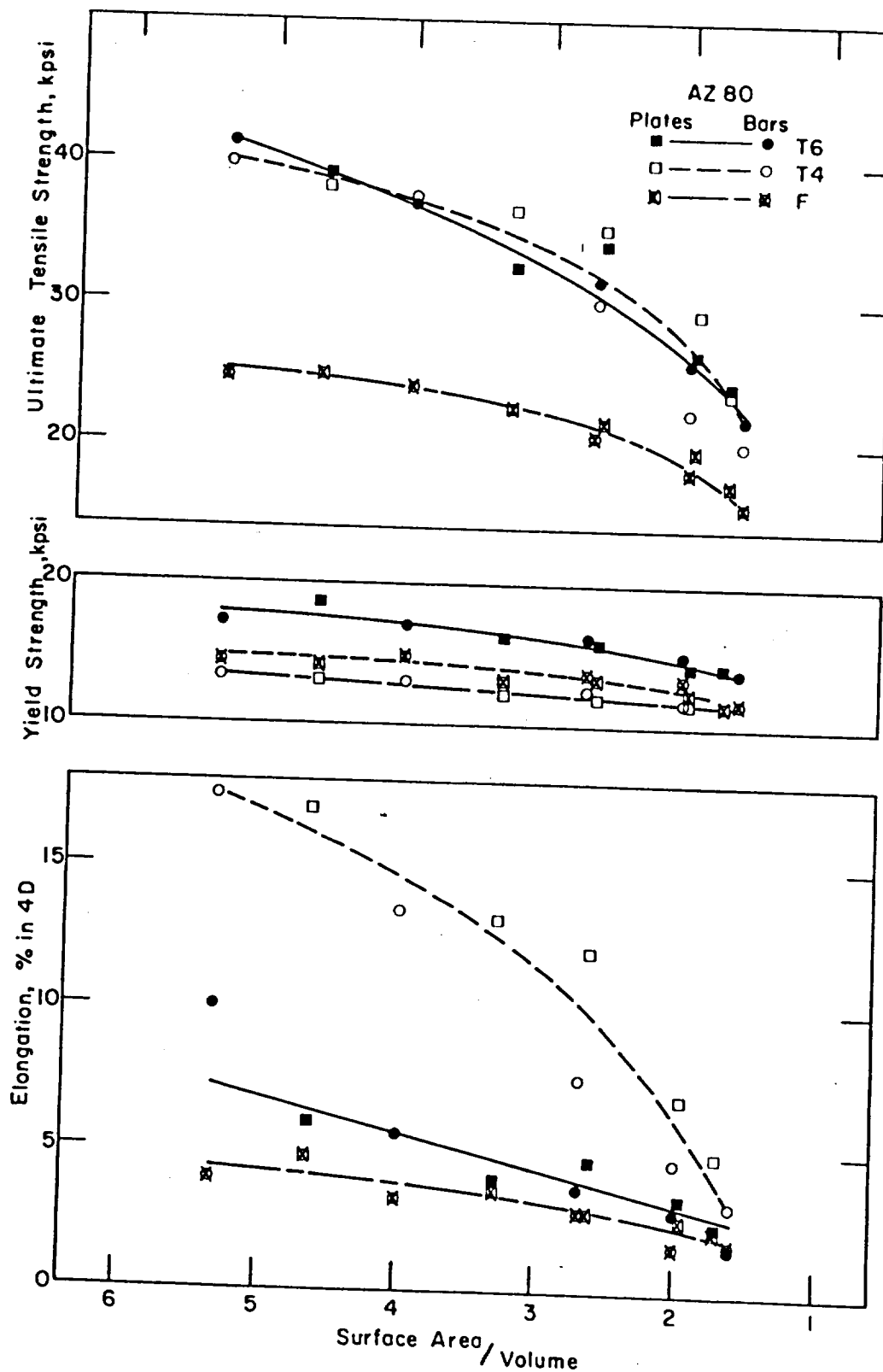


Figure 12. AZ80 Tensile Properties vs Surface Area/Volume Ratio.

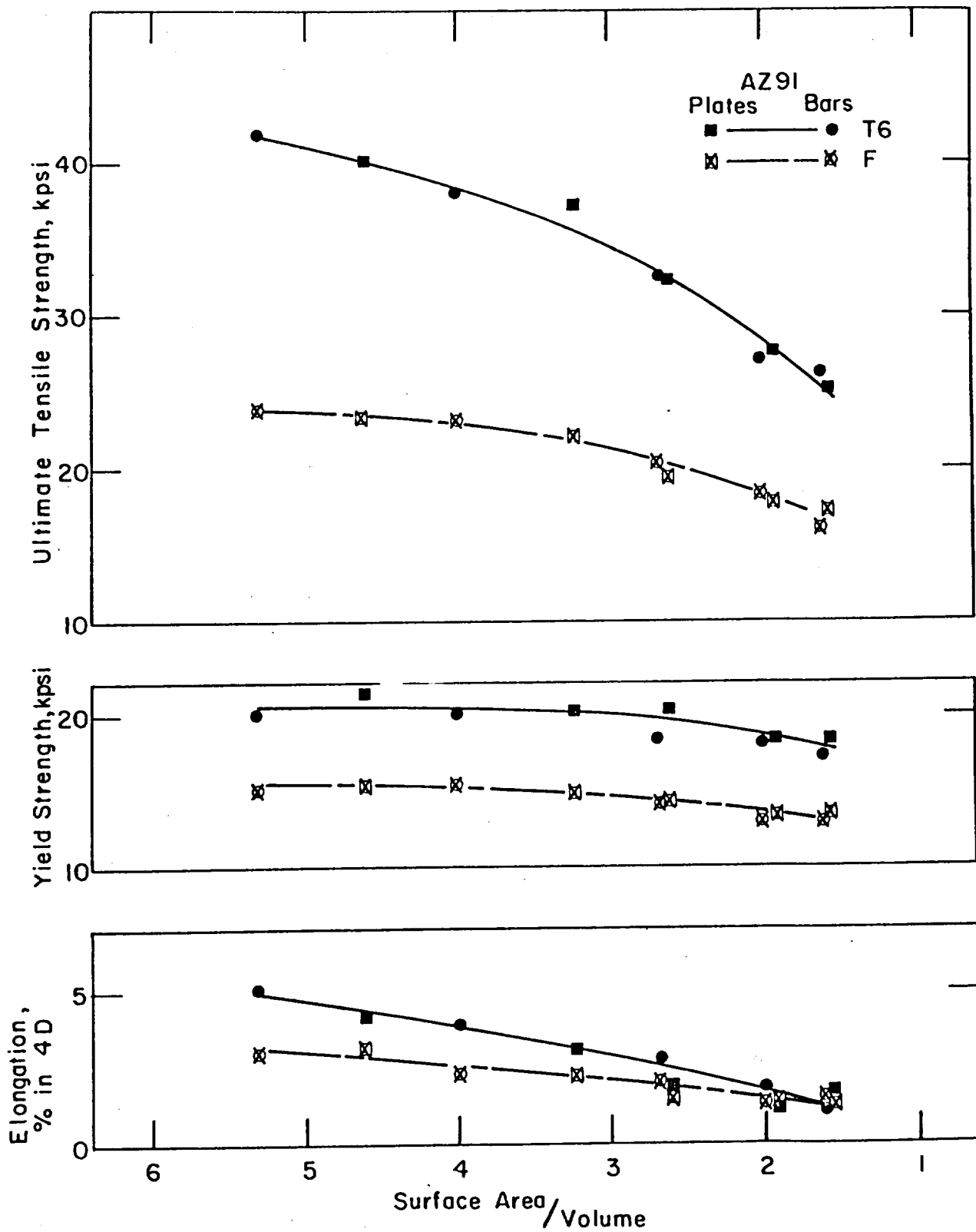


Figure 13. AZ91 Tensile Properties vs Surface Area/Volume Ratio .

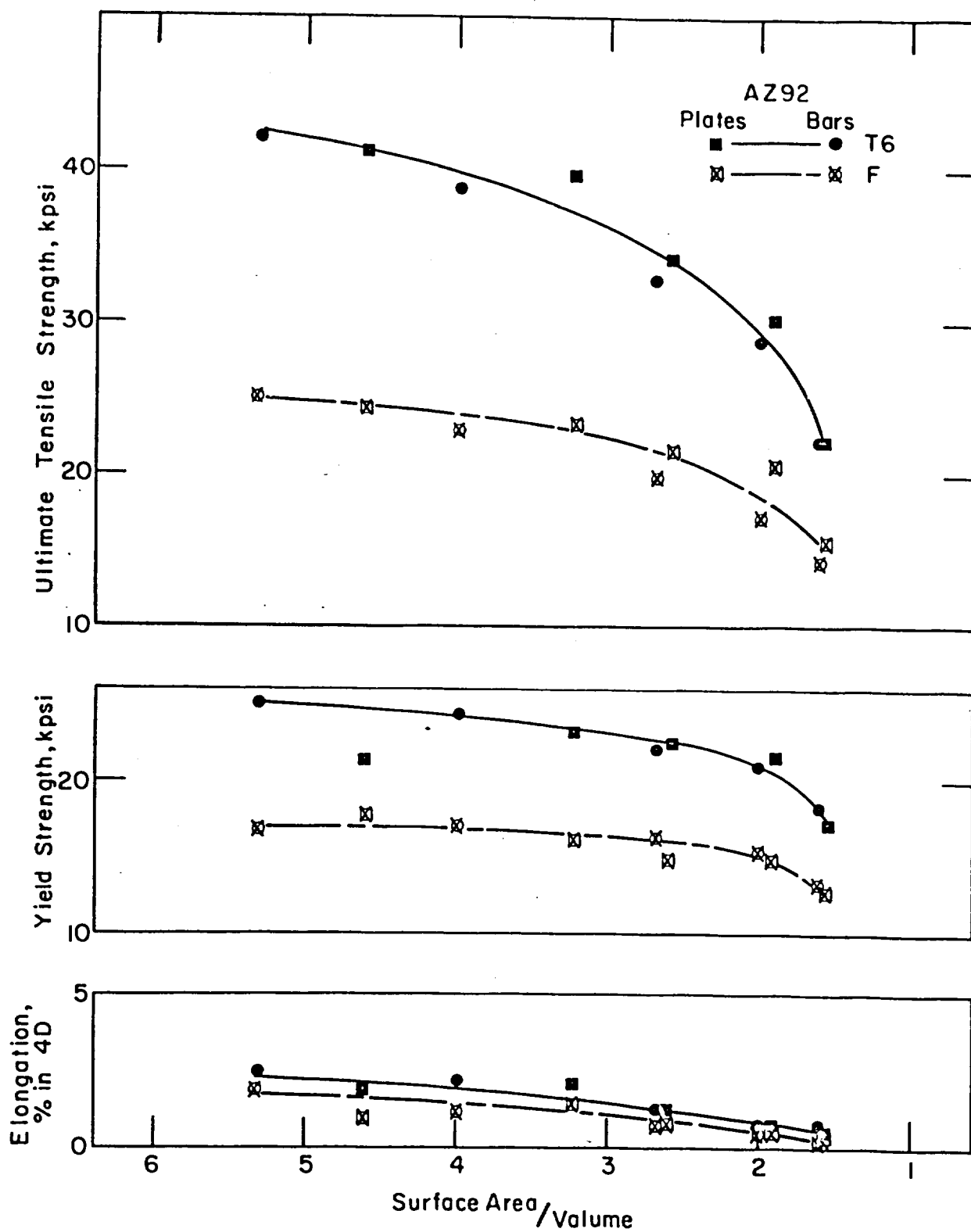


Figure 14. AZ92 Tensile Properties vs Surface Area/Volume Ratio.

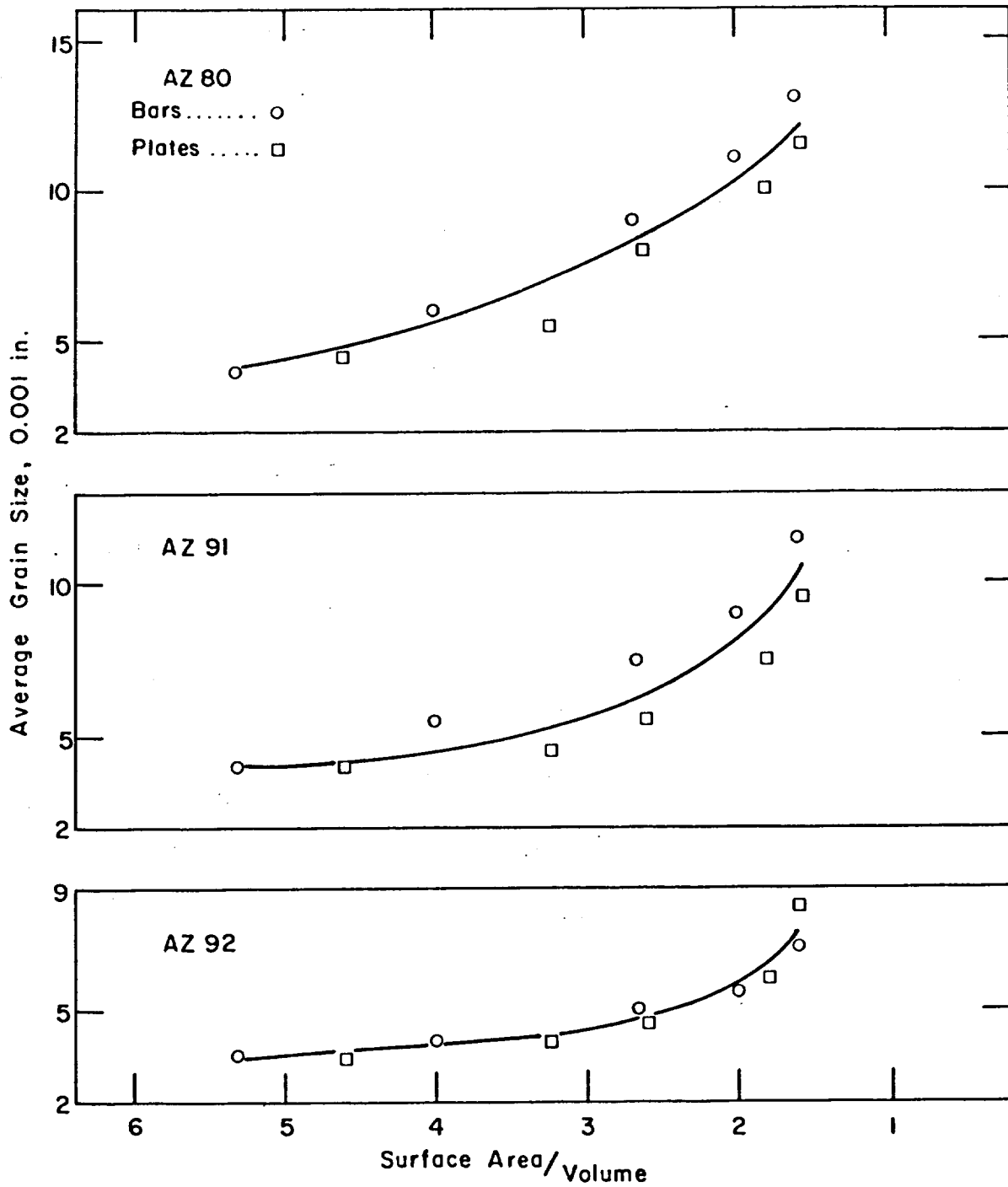


Figure 15. Grain Size vs Surface Area/Volume Ratio.

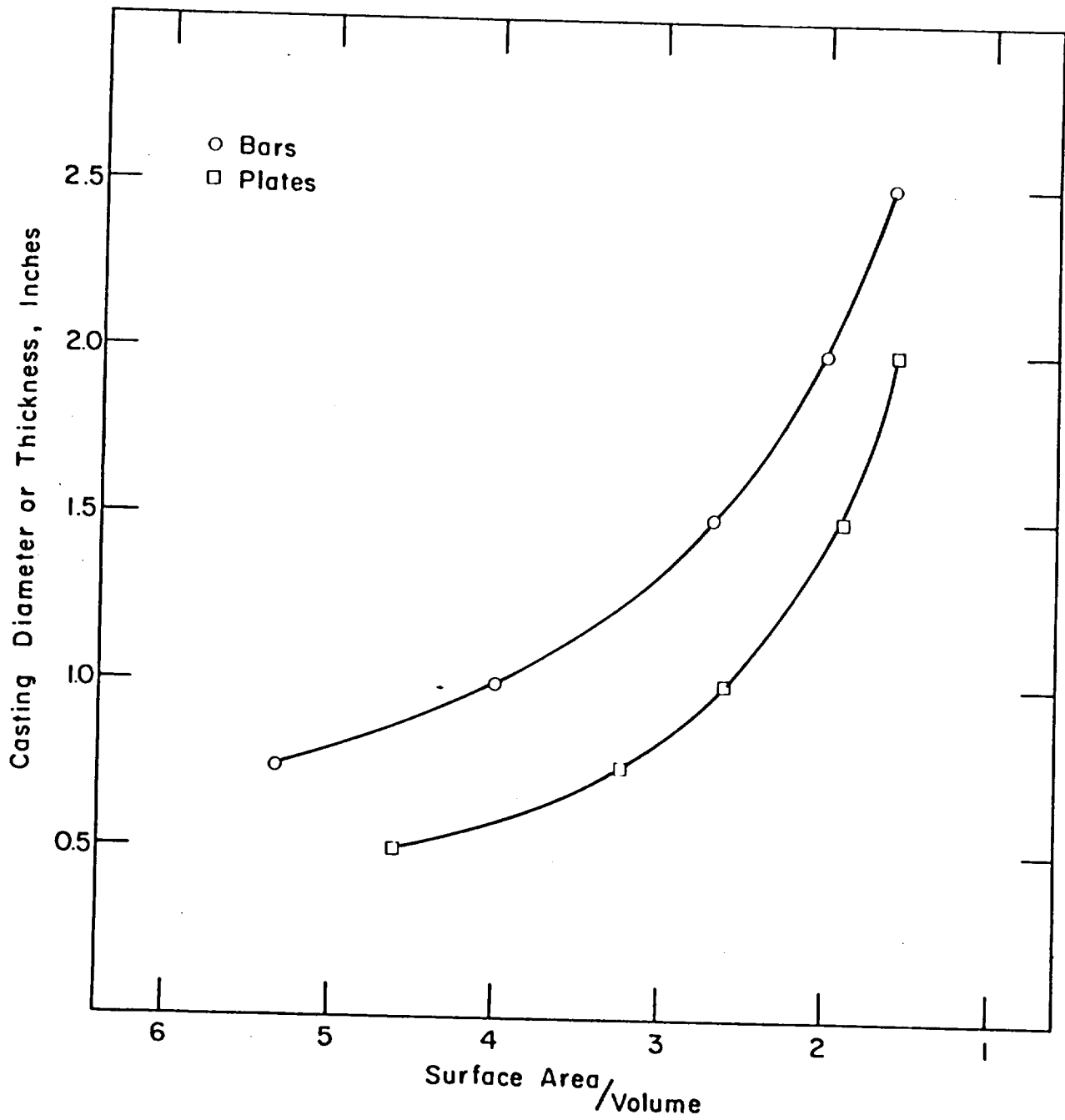


Figure 16. Wall Thickness vs Surface Area/Volume Ratio.



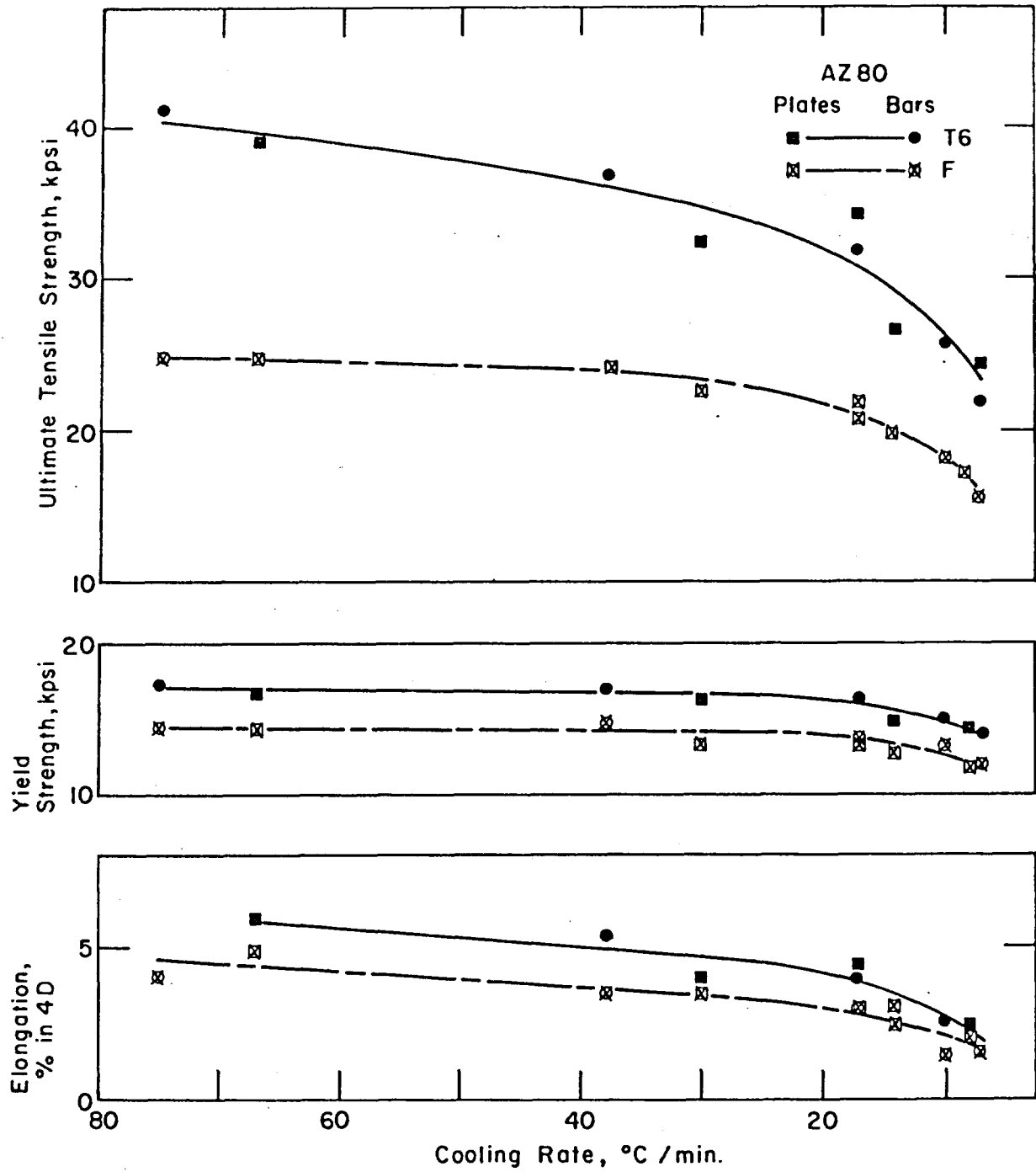


Figure 17. AZ80 Tensile Properties vs Cooling Rate.

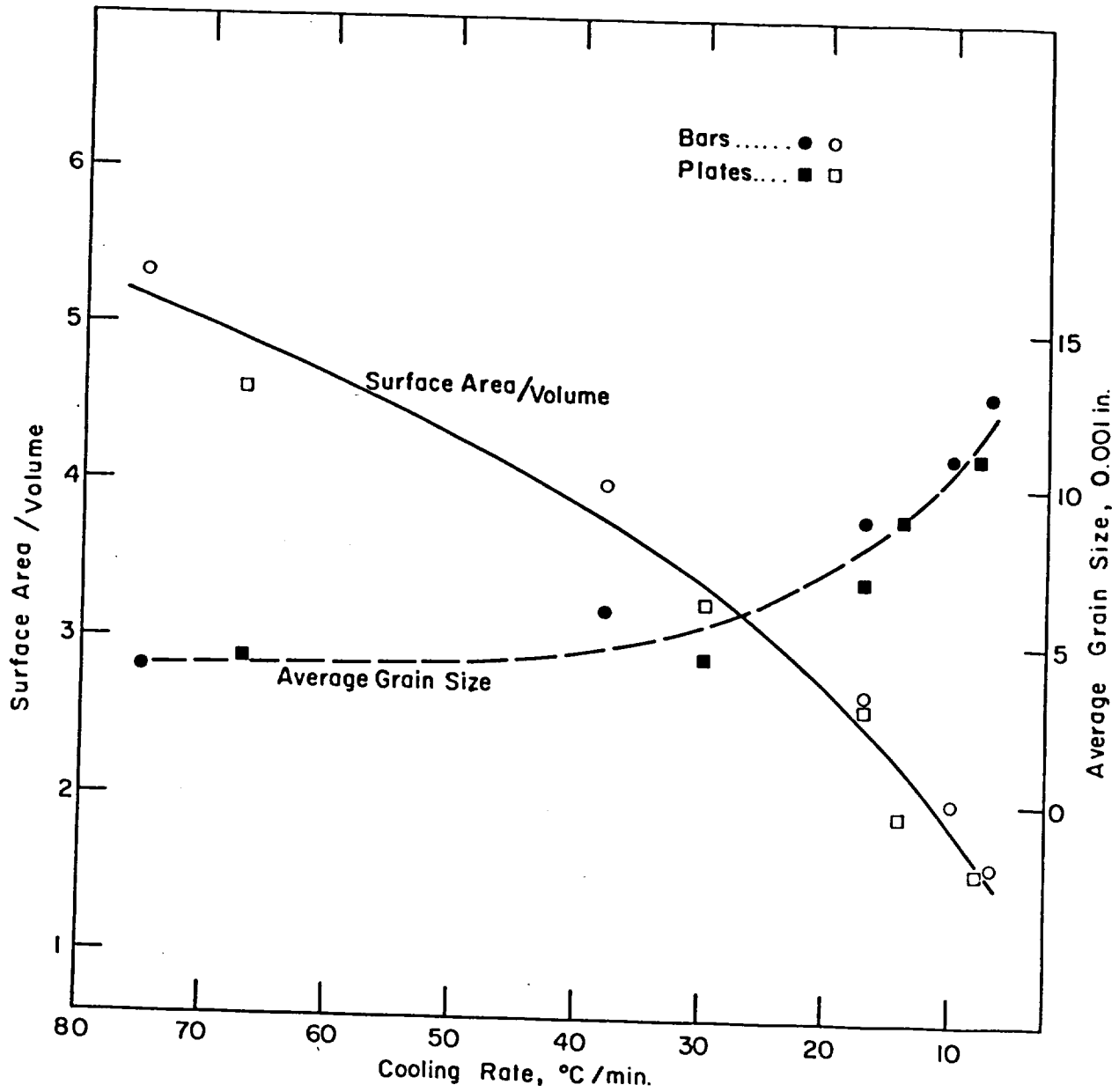


Figure 18, AZ80 Grain Size and Surface Area/Volume Ratio vs Cooling Rate.

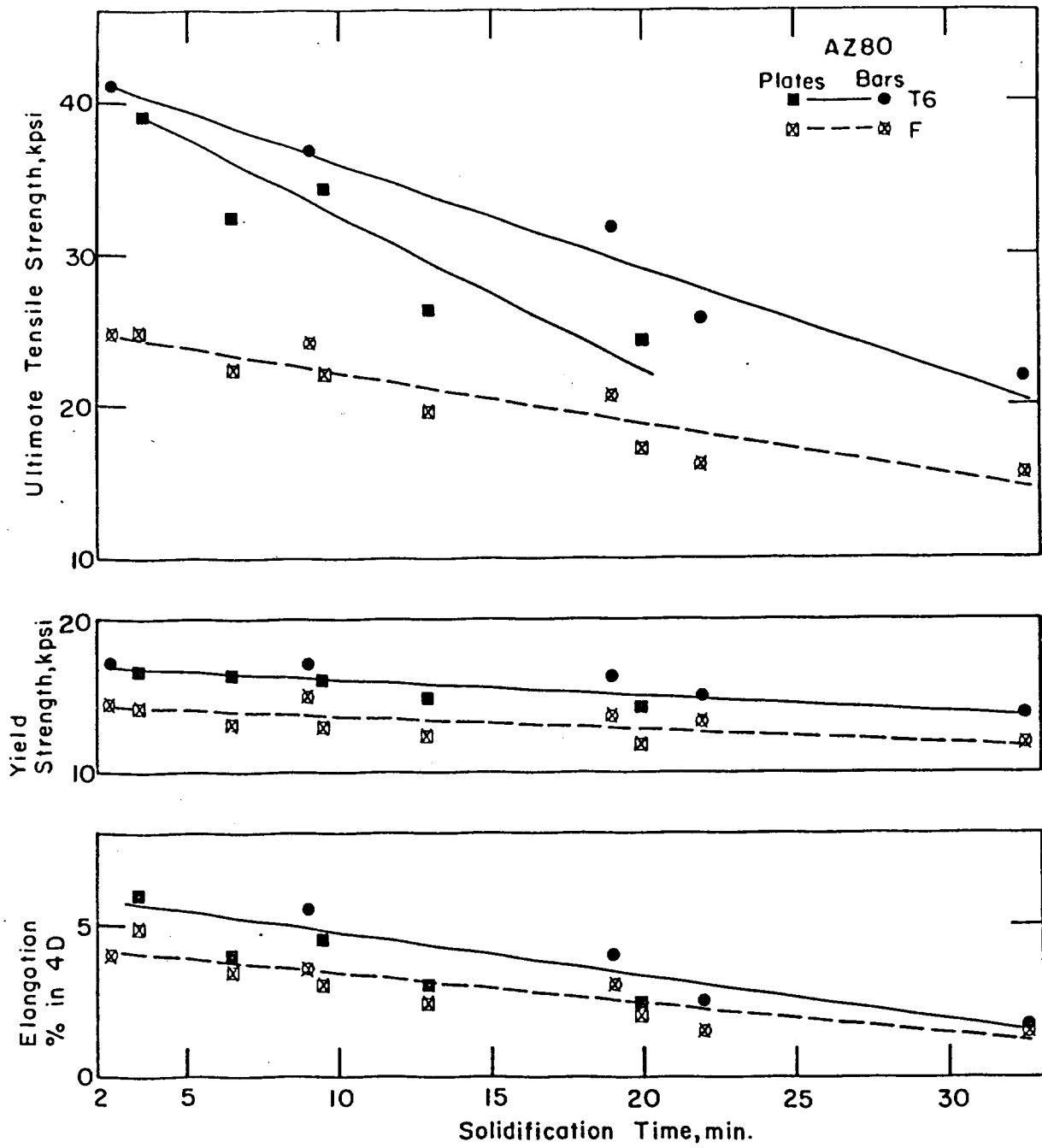


Figure 19. AZ80 Tensile Properties vs Solidification Time .

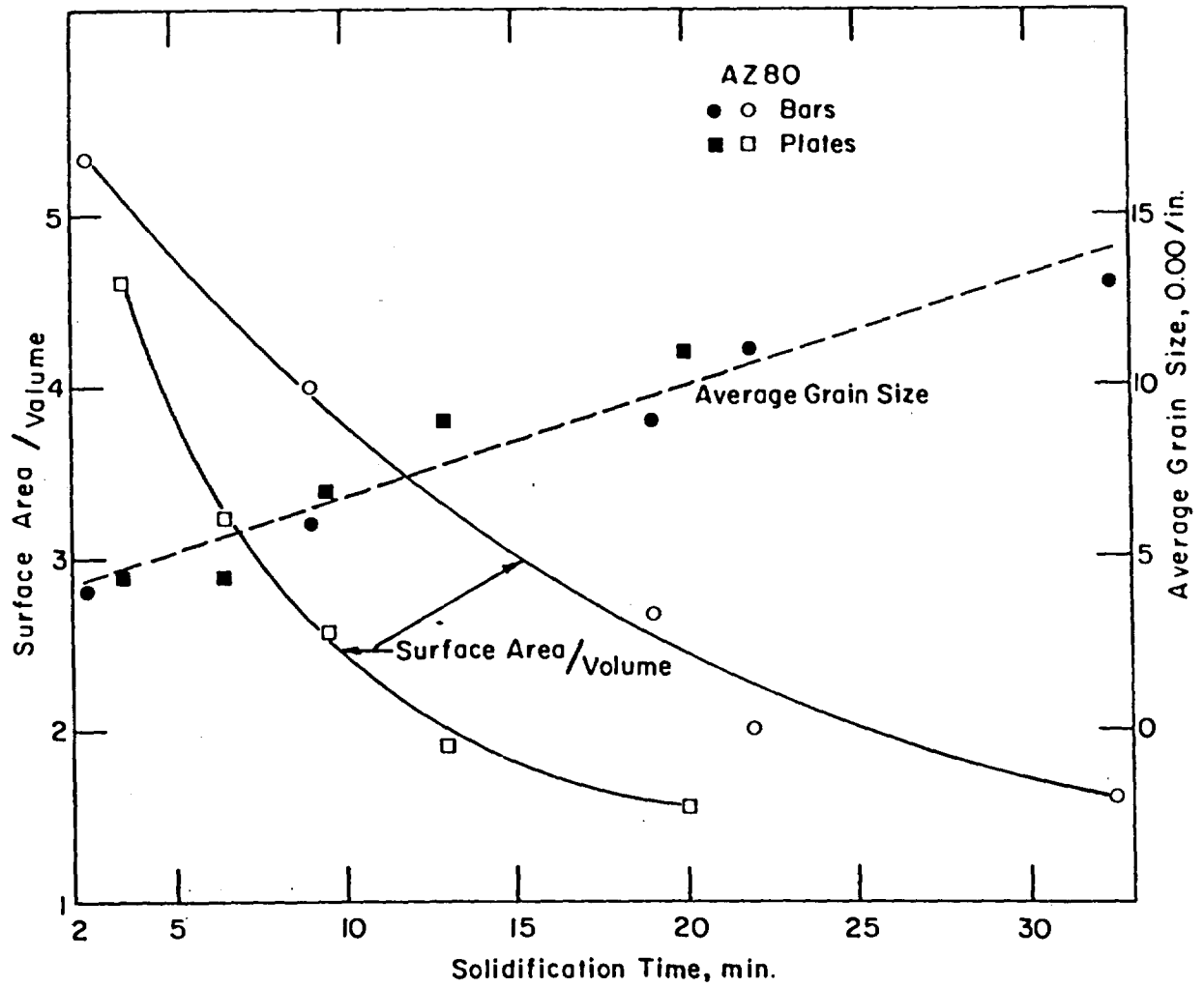


Figure 20. AZ80 Grain Size and Surface Area/Volume Ratio vs Solidification Time .