1970

The effect of isothermal heat treatment on the ferrite grain size and properties of large carbon manganese steel castings

Raymond M. Hemphill
Lehigh University

Recommended Citation

Hemphill, Raymond M., "The effect of isothermal heat treatment on the ferrite grain size and properties of large carbon manganese steel castings" (1970). *Theses and Dissertations*. 3811.
https://preserve.lehigh.edu/etd/3811

THE EFFECT OF ISOTHERMAL HEAT TREATMENT ON THE FERRITE GRAIN SIZE AND PROPERTIES OF LARGE CARBON MANGANESE STEEL CASTINGS

by

Raymond M. Hemphill

A Thesis
Presented to the Graduate Faculty
of Lehigh University
in Candidacy for the Degree of
Master of Science
in Metallurgical Engineering

Lehigh University
1970

CERTIFICATE OF APPROVAL

Approved and recommended for acceptance as a dissertation in partial fulfillment of the requirements for the degree of Master of Science.

March 2, 1970
(date)

Alan W. Pense
Professor in Charge

Accepted May 11, 1970
(date)

G. P. Conard
Head of Department of
Metallurgical Engineering

ACKNOWLEDGEMENTS

The author extends his sincere appreciation to Dr. Alan W. Pense for his technical assistance and guidance throughout the course of this investigation. Special thanks are due to Mr. Jesse Muir and Mr. James McKerihan for their support of this study and the subsequent implementation of the findings into production procedures.

Acknowledgement is made to Bethlehem Steel Corporation for payment of the author's tuition. Mr. George Cartwright, Mr. Michael Guerriere, Mr. Joseph Falcone, and Mr. Richard Kravits, all employees of Bethlehem Steel Corporation, are commended for their special effort in specimen preparation and production of the final report.

The author sincerely appreciates the patience and understanding extended to him by his wife, Ingrid.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES(cont'd)

LIST OF FIGURES(cont'd)

LIST OF FIGURES(cont'd)

LIST OF FIGURES(cont'd)

LIST OF FIGURES(cont'd)

ABSTRACT

This investigation was a study of the applicability of isothermal annealing treatments to heavy section steel castings for the improvement of mechanical properties. The study showed that for a wide variety of cast C - Mn steels an isothermal anneal achieved superior properties in massive sections without an increase in heat treatment time. The isothermal anneal involved air cooling to 1050 degrees Farenheit for grain refinement and holding at 1100 degrees Farenheit to avoid embrittlement. The improvement in properties apparently resulted from a more desirable microstructure. The two major effects were that the ferrite grain size was decreased and the amount of ferrite was increased.

As a result of an improved structure superior Charpy "V" notch properties were produced. An equation to predict the 50 percent fibrous transition temperature was developed as follows:

$$\text{FATT } (^{\circ}\text{F.}) = 30 + 4\ (\%\ \text{pearlite}) - 15d^{-\frac{1}{2}} (\text{mm}^{-\frac{1}{2}})$$

A decrease in the amount of pearlite precipitated and finer ferrite grains both tended to lower the fracture appearance transition temperature. The energy absorption was also higher, with the 15 ft. lb. transition temperature being depressed by 40 to 80 degrees Farenheit.

Ferrite grain refinement improved the yield strength. A minimum yield strength of 38,000 psi was obtained for .20 to .25 percent

ABSTRACT

This investigation was a study of the applicability of isothermal annealing treatments to heavy section steel castings for the improvement of mechanical properties. The study showed that for a wide variety of cast C - Mn steels an isothermal anneal achieved superior properties in massive sections without an increase in heat treatment time. The isothermal anneal involved air cooling to 1050 degrees Farenheit for grain refinement and holding at 1100 degrees Farenheit to avoid embrittlement. The improvement in properties apparently resulted from a more desirable microstructure. The two major effects were that the ferrite grain size was decreased and the amount of ferrite was increased.

As a result of an improved structure superior Charpy "V" notch properties were produced. An equation to predict the 50 percent fibrous transition temperature was developed as follows:

$$\text{FATT}\ (^{\circ}\text{F.}) = 30 + 4\ (\%\ \text{pearlite}) - 15d^{-\frac{1}{2}}(\text{mm}^{-\frac{1}{2}})$$

A decrease in the amount of pearlite precipitated and finer ferrite grains both tended to lower the fracture appearance transition temperature. The energy absorption was also higher, with the 15 ft. lb. transition temperature being depressed by 40 to 80 degrees Farenheit.

Ferrite grain refinement improved the yield strength. A minimum yield strength of 38,000 psi was obtained for .20 to .25 percent

carbon steels with .50 to .75 percent manganese, while a minimum yield strength of 41,000 psi occurred for .25 to .30 percent carbon steels. High manganese (1.20% to 1.36% manganese) cast steels gave yield strengths in excess of 50,000 psi at the .25 to .30 percent carbon level. A correlation was found between yield strength and the Petch parameter, $d^{-\frac{1}{2}}$. The Hall-Petch relationship for .50 to .70 manganese steels was:

$$\sigma_{yp} \text{ (psi)} = 20,000 + 2,500\ d^{-\frac{1}{2}}\ \text{mm}^{-\frac{1}{2}}$$

The isothermal anneal was more effective when applied to heavy sections than it was with the smaller test sections normally employed. The results indicated that the isothermal anneal is a practical method to provide superior strength and toughness for large C - Mn steel castings without a loss in furnace time.

INTRODUCTION

The Composition and Properties of Carbon Steel Castings

A large steel casting in the steel foundry industry generally implies a weight in excess of 2,000 lbs. and a section thickness ranging from a few inches to several feet. The number of alloys used is considerable, but most of the tonnage is produced from C - Mn steels with ferrite pearlite microstructures. The minimum properties acceptable which can be expected for commonly used alloys in the annealed condition are listed in Table 1.

Table 1 - Composition and Minimum Properties as Specified by ASTM for Cast Steel Materials (Ni - $.\overline{50}$, Cu - $.\overline{50}$, Cr - $.\overline{40}$, Mo - $.\overline{25}$)

ASTM No.	C	Mn	P	S	Si	T. S. ksi	Y. S. ksi	EL	RED
A27-65 60/30	.30	.60	$.\overline{05}$	$.\overline{06}$	.80	60	30	24%	35%
A216-66 WCA	.25	.70	$.\overline{05}$	$.\overline{06}$	.60	60	30	24%	35%
A27-65 65/35	.30	.70	$.\overline{05}$	$.\overline{06}$	.80	65	35	24%	35%
A352-66 LCB	.30	1.00	$.\overline{05}$	$.\overline{06}$	.60	65	35	24%	35%
A216 WCB	.30	1.00	$.\overline{05}$	$.\overline{06}$	.60	70	36	22%	35%
A27 70/36	.35	.70	$.\overline{05}$	$.\overline{06}$	.80	70	36	22%	30%
A148-65 80/40	-	-	$.\overline{05}$	$.\overline{06}$	-	80	40	18%	30%

When a buyer requests strength or impact resistance higher than usual he often specifies the properties while the foundry supplies the analysis and heat treatment procedures. It is then the responsibility of the foundry metallurgist to meet the properties and provide a maximum in fracture resistance at a minimum cost. Generally, C - Mn steels are the cheapest and their possibilities should be exploited before alloy grades are considered.

By adjustments of composition, heat treatment and deoxidation the properties of carbon steel castings can be maximized. When both strength and toughness are required the heat treatment and composition should refine the ferrite grain size. Deoxidation can enhance the results obtained from variations in analysis and treatment.

Influence of Deoxidizers

The deoxidation practice can have a pronounced effect on the heat treated properties of C - Mn steels. However, the primary purpose of any deoxidizer is to eliminate porosity due to gas evolution. The most common deoxidizers are silicon, manganese and aluminum although titanium, zirconium, selenium, tellurium, calcium, magnesium, sodium, barium, potassium, lithium and the rare earths are all possible choices.

Silicon and manganese are universally present as deoxidizing agents in plain carbon steel castings. As the temperature drops silicon deoxidizes more efficiently, but is is ineffective in the presence of water vapor. Manganese is not capable of deoxidizing by itself but makes silicon and aluminum more effective.[1] Despite this lack of ability to deoxidize manganese does serve a useful purpose. Manganese will combine with sulfur in preference to iron and can therefore help to alleviate hot tearing. It is also useful as an alloying element.

A common deoxidizer for large C - Mn steel castings is aluminum. Like other deoxidizers its primary purpose is to eliminate porosity. Aluminum may also have a pronounced effect on properties. In amounts just sufficient to suppress gas evolution, aluminum may cause grain boundary Type II sulfides to form. In larger amounts the sulfide morphology is changed from Type II to Type III and the ductility and impact resistance are restored. To guarantee Type III sulfides Sims[2] demonstrated that aluminum in excess of 0.02 percent was necessary. He also stated that the sulfide morphology problem is eliminated when less than 0.015 percent sulfur is present.

Overdoses of aluminum are dangerous because aluminum nitride may precipitate at prior austenite grain boundaries and cause "rock candy" fracture. Steck[3] demonstrated that slow cooling rates made steel castings more susceptible to aluminum nitride precipitation (see Figure 1) and thus "rock candy" fracture. Since electric furnace steels generally contain from .006 percent to .012 percent nitrogen, aluminum concentrations in excess of .05 percent could cause "rock candy" fracture. Open hearth steels usually have a maximum of 0.010 percent nitrogen and can tolerate up to .07 percent aluminum before "rock candy" fracture would be considered a problem.

Aluminum is also a grain refiner for C - Mn cast steels in the heat treated condition. Aluminum concentrations as low as .02 percent have been reported to produce substantial inhibition of the grain growth in high temperature austenite. Chatterjea and Nijhawan[4] report grain refinement of .018 percent aluminum steel to 1650° F. At temperatures above 1650° F. grain growth occurred at a rate of approximately 2.5 ASTM grain size numbers for each 100° F. rise in temperature. In a steel with an aluminum concentration of .03 percent grain growth did not occur beyond one half grain size number, when heating to 1750° F. They concluded that the maximum grain growth inhibition occurred between 0.02 and 0.05 percent residual aluminum.

Aluminum has a favorable effect on impact properties when used in the proper concentrations. Briggs[5] reported a maximum in impact properties with aluminum concentrations between 0.02 and 0.04 percent. A .30 percent C - Mn - Mo steel with an aluminum concentration of .008 percent was reported to have only half the impact resistance of the same steel with .036 percent aluminum, for the normalized and tempered condition. Whether the superior impact resistance was due to grain refinement or some other effect of aluminum was not investigated.

The Effect of Ferrite Grain Size on Mechanical Properties

There is a general recognition among metallurgists that a finer grain structure will produce superior properties. Recent studies have shown that grain refinement, is, in fact, the only way to improve the fracture resistance and the tensile properties simultaneously. Any attempt to increase the tensile properties through precipitation hardening, solid solution strengthening, or dispersion hardening will all be accomplished by a reduction in the fracture resistance as long as the grain size remains constant.

The fracture resistance of steels is most commonly measured by the Charpy "V" notch transition curve, although fracture mechanics specimens with carefully controlled cracks are occasionally used. When steels are tested at decreasing temperatures, less energy is absorbed in the fracture process. This phenomena is known as the ductile - brittle transition and is generally described as the temperature at which either a certain fracture appearance is obtained or a specific energy level is reached.

The fracture of Charpy "V" notch specimens may be divided into two stages; crack initiation and crack propagation. Once the crack has started energy is absorbed by the formation of new crack surface, and by plastic deformation at the crack tip. Failure by brittle fracture implies that there is low energy absorption and the plastic zone size is small. Ductile fracture occurs when large amounts of energy are absorbed at the crack tip and extensive plastic deformation takes place during crack propagation.

Petch[6] derived a mathematical relationship which indicated that the transition temperature was a function of four factors: (1) the grain size, (2) the friction on unlocked dislocations, (3) the strength of the locking of dislocations, and (4) the degree of triaxiallity of the applied stress. As a result of this derivation Petch predicted that the transition temperature should be a linear function of $\ln d^{-\frac{1}{2}}$ where d is the ferrite grain diameter in milimeters. With a slight decrease in accuracy the transition temperature should be a linear function of $d^{-\frac{1}{2}}$. Petch confirmed this linear relationship for alpha iron.

Pickering and Gladman[7] undertook an investigation of carbon steels in order to confirm or deny the predictions made by Petch. Actually they found a closer relationship between transition temperature and $d^{-\frac{1}{2}}$ than with $\ln d^{-\frac{1}{2}}$. The results of Pickering and Gladman indicated a decrease of 4.1 degrees Farenheit for each unit reduction in $d^{-\frac{1}{2}}$, while the results of Petch on alpha iron indicated a stronger relationship of 7.2 degrees Farenheit for each unit decrease in $d^{-\frac{1}{2}}$.

The same linear improvement of properties with the square root of the ferrite grain diameter has been observed for the lower yield point. The yielding of polycrystalline materials depends on two factors, that of the intrinsic resistance of the lattice to plastic deformation and the additional effect of grain boundaries. Ferrite/pearlite steels are composed of grains with various lattice misorientation at the grain boundaries. Because of the misalignment, plastic deformation cannot spread easily from one grain to another. The grains which are not in a favorable position for deformation exert an elastic constraint effect on the surrounding grains and can raise the yield point of the metal.

Petch[8] derived a relationship for the lower yield point based on dislocation models. His derivation indicated that the yield point of single phase poly-crystals should be a linear function of the square root of the grain diameter. Mathematically,

$$\sigma_{lyp} = \sigma i + K_y d^{-\frac{1}{2}} \qquad \text{Equation 1}$$

Petch confirmed his results for alpha iron over a relatively narrow range of grain diameters.

Morrison[9] checked the work of Petch for steels containing .005 to 0.20 percent carbon. He was able to achieve grain sizes of approximately 2 microns (ASTM 14) and confirmed that the lower yield point was a true linear relationship with $d^{-\frac{1}{2}}$ over a wide range of values. His results also indicated that the amount of carbon had no effect on the yield stress other than to aid in grain refinement. Most recent studies have confirmed that carbon precipitated as pearlite does not influence the yield strength of ferritic pearlitic steels.

Grange[10] applied the results of Petch in a practical way to a wide variety of steels. He was able to achieve very fine grain sizes using either a thermo-mechanical or a strictly thermal technique. As expected, there was a linear increase in the yield strength with the square root of the ferrite grain diameter. He also found that isothermal transformation from fine grained austenite caused an increase in the percentage of the ferrite precipitated. The properties Grange achieved with coarse, fine and ultra-fine isothermal transformation products showed that the ultimate tensile strength remained essentially constant despite changes in the percentage of pearlite in the microstructure.

There has been no major deviations from the Petch relationship (Eqn. 1) in the literature, although a $d^{\frac{1}{3}}$ and d^{-1} correlation have occasionally been suggested. Morrison's[9] data compared these correlations to the $d^{-\frac{1}{2}}$ plot and found the best straight line correlation with the $d^{-\frac{1}{2}}$ relationship even for extremely fine (1.5 micron) grain sizes. The value of the slope (K_y) has not been exactly determined but it is in the range of 2000 to 3500 psi per millimeter to the minus one half (some of the typical values are shown in Table 2).

The value of σi (the yield point of a single crystal) depends on such factors as solid solution strengthening, precipitation hardening, and interstitial solid solution effects. Therefore, the value of σi is a variable that depends on the alloying elements dissolved in the steel. The percentage of pearlite has not been found to increase the yield strength unless the increase is accompanied by grain refinement[7, 11]

Carbon, Manganese and Silicon

The factors which influence the properties of cast C - Mn steels are ferrite grain size, the proportion of pearlite in the structure, the pearlite spacing, solid solution hardening and precipitation effects. Composition and heat treatment are the two variables by which the metallurgist can control these factors.

Carbon (the most inexpensive alloying element) has a pronounced effect on properties. When carbon is added to C - Mn cast steels in large sections there is some grain refinement reflected by an increase in yield strength, but the major effect of carbon is to increase the percentage of pearlite in the microstructure. However, increasing the percentage of pearlite reduces the fracture resistance and should be employed only when other strengthening mechanisms have been exhausted.

Silicon is capable of solid solution strengthening and deoxidizing. As a deoxidizer silicon has a beneficial effect but in larger amounts it is detrimental. For instance, silicon raises the AC_3 temperature. The resulting higher normalizing temperatures can produce grain growth if the grain refiner becomes ineffective. Silicon additions can also lead to a reduction in yield strength. In a .10 percent carbon, 1.45 percent Mn steel with various silicon additions, Irvine[11] et. al. discovered a loss in yield strength because of ferrite grain coarsening. They attributed this effect to the ferrite stabilizing tendencies of silicon which could raise the temperature of ferrite formation, thereby increasing the ferrite grain size. The Metals Handbook[12] recommends 0.15 to 0.30 percent silicon combined with .02 to .05 percent aluminum for a maximum in impact resistance.

Manganese increases the yield strength through grain refinement and solid solution strengthening. Owen[13] investigated the effect of an increase in manganese upon the variables of the Hall-Petch relationship (Equation 1). He found that the greater yield strength was due to an increase in σi as well as $d^{-\frac{1}{2}}$ with very little change in K_y.

The effectiveness of manganese in increasing both strength and toughness is reflected in its influence on transition temperature. Rinebolt and Harris[14] report a decrease in transition temperature of approximately 1.0° F. per 0.01 percent manganese added up to 1.5 percent. In the above amounts 1.00 percent manganese can lead to banite formation but this would not be a problem with heavy section castings. In amounts above 1.50 percent, manganese develops a very different microstructure. A 2.00 percent manganese steel was reported by Rinebolt and Harris to have a transition temperature in excess of 200° F.

In concentrations above .75 percent manganese can increase the depth from the surface to which low temperature transformation to pearlite occurs. Manning et.al.[15] report that increasing manganese from 1.0 percent to 1.4 percent will double the depth to which a particular fineness of pearlite will form. The general conclusion reached by these investigators is that strength and toughness are best achieved in C - Mn steels by decreasing the carbon and raising the manganese. One steel which is known to have a good combination of strength and toughness contains 0.15 - 0.20 percent carbon and 1.2 - 1.4 percent manganese and has been used in many studies as a base composition from which the effect of other alloys such as titanium, vanadium and niobium are studied.

Pickering and Gladman[7] investigated the effects of manganese, silicon, percent pearlite and grain size on the strength and toughness with the results shown in Table 3. As would be expected grain refinement tends to increase all the properties while greater percentage of pearlite is only beneficial for tensile strength.

This regression analysis also indicates that manganese is the only alloying element which will increase the tensile properties without producing a decrease in the toughness.

Phosphorous, Sulfur and Other Residuals

The residual elements such as phosphorous, sulfur, tin, arsenic and antimony strongly affect the fracture toughness of C - Mn cast steels. These elements are all detrimental because they can produce grain boundary weakening if they are present in sufficient quantities.

Sulfur is harmful in concentrations above 0.015 percent primarily because Type II grain boundary sulfides may form. These inclusions result in a marked decrease in both ductility and impact properties. In order to eliminate the problem in high sulfur steels special deoxidation procedures are used to insure the less harmful Type I or Type II inclusions.

Phosphorous may act in combination with sulfur to produce poor properties in plain carbon cast steels. Mickelson[16] found that the transition temperature decreased by about 5 to 10° F. for each .01 percent of either phosphorous or sulfur. He demonstrated that the transition temperature of .35 C .85 Mn steel varied directly with the total phosphorous and sulfur content. Briggs[17] found that Type II sulfides influences the energy levels more than the transition temperatures. Phosphorous also lowered the energy level but was capable of lowering the fracture appearance transition when an embrittling heat treatment was employed.

The role of the residual elements is particularly critical because antimony, phosphorous, tin and arsenic can result in temper brittleness of cast steels with ferrite pearlite microstructures. Woodfine[18] found that embrittlement of pearlite at 500° C. (932° F.) for 32 hours raised the transition temperature by 51 degrees. The same embrittling procedure for banitic and martensitic microstructure resulted in approximately the same transition temperature of between +121 and +162 degrees Centigrade (250° - 323° F.)

At present the embrittlement model which most closely accounts for various observations is grain boundary precipitation. During austenitization the embrittling elements segregate to the austenite grain boundaries and remain there during quenching. Above the embrittling range antimony, phosphorous, tin and arsenic are "boiled off" the boundaries and driven back into solution.[19]

Jaffe and Buffman[20] plotted isoembrittlement curves for a .39 C, 1.26 Ni, .77 Cr steel. Their results indicated that the major embrittlers are driven back into solution if the holding temperature was in excess of 1075° F.

Holloman[21] plotted the results of Greaves and Jones[22] for a

.26C, .66Mn, 3.53Ni, .84Cr and .026 phosphorous steel and found the same "C" curve behavior with maximum embrittlement occurring at 520° C. (970° F.). Vidal[23] found that 525° C. (980° F.) produced a maximum amount of embrittlement in a .25C, 1.38Cr, .044 phosphorous steel.

The embrittlement problem becomes more severe as the manganese concentration is increased.[24, 25] If high manganese steels are to be used without molybdenum then special precautions must be taken to heat treat around embrittlement. Fortunately, the embrittlement range is now clearly delineated as being approximately 1050° F. for holding times of about an hour and 1000° F. for times of about 10 hours. If high manganese steels with ferrite pearlite structures are held at about 1100° F. then a minimum amount of embrittlement might be expected. The time high manganese steels are allowed to remain between 950° F. and 1050° F. should be kept to a minimum in order to prevent prior austenite grain boundary decohesion.

Heat Treatment for Maximum Properties

The toughness of cast steel is determined by its composition, deoxidation practice and heat treatment. The highest toughness values for small pieces are achieved by water quenching followed by an 1100° - 1150° Farenheit temper. Homogenization austenitization, furnace cooling, air cooling, tempering and stress relieving are the most commonly employed techniques for large plain carbon steel castings.

Once the "green" casting is received the first step in treatment is to recrystallize the structure in order to eliminate the dendritic segregation which occurred during solidification. Because faster heating rates result in a superior fracture toughness, all other things being equal,[26] heating to the austenitization temperature should be accomplished as quickly as possible. However, large castings cannot be heated at very high rates (400°F/hr) because extreme temperature gradients can occur. A practical heating rate for large plain carbon steel castings is two hundred degrees Farenheit per hour. Preheating to 1200 degrees Farenheit, equalizing and then heating at 400 degrees Farenheit/hr. to the austenitization temperature, is also a feasible method.

After reaching the austenitizing temperature large castings are normally soaked until the thermal gradients have been eliminated and all carbides are in solution. Austenitization also helps to eliminate dendritic segregation. This can only be achieved with thorough soaking at as high a temperature as the grain refiner will allow. For large .20 to .30 percent carbon steel castings with .02 to .05 percent aluminum, this maximum temperature should be about 1675 degrees Farenheit.

Briggs[27] found that homogenization treatments did not increase toughness or tensile properties. In a study of .30 carbon, .83 manganese plain carbon steel a 1550 degree Farenheit treatment for 15 minutes resulted in the same properties as 1650 degree Farenheit for two hours for the normalized condition with 1" sections. Despite Briggs' findings most foundries homogenize for at least one hour per inch for large cast sections.

Air cooling is generally recognized to produce finer ferrite grains, superior "breaking up" of dendritic segregation, and lower temperature transformation products. The normalize and temper treatment used by most foundries involves air cooling to room temperature with subsequent tempering. Because large plain carbon steel casting contain insufficient alloy to harden to banite or martensite the additional coding below 1000 degrees Farenheit does not appear to have any purpose. Theoretical considerations of pearlite growth[28] confirmed by the experimental evidence of Pellisier et. al.[29] indicate that the interlamellar spacing of the pearlite is essentially constant provided the temperature of transformation is lower than 1150 degrees Farenheit.

These observations may be used when heat treating for maximum properties with large C - Mn steel castings. Since pearlite is the structure which will be formed with air quenching of massive plain carbon steel pieces, 1000 degrees Farenheit is the lowest temperature which should be used. Any further cooling will only create additional residual stresses. However, the center of the casting will achieve the finest possible pearlite spacing only when it is cooled below 1150 degrees Farenheit. If surface temperature measurements are used, allowances must be made for higher temperatures at the mid-thickness. Combining these observations, air cooling to 1000 to 1050 degrees Farenheit appears to be a sound approach toward achieving maximum properties with large C - Mn steel castings.

Since plain-carbon steel castings are subject to temper embrittlement this problem should be minimized during heat treatment, particularly for castings with high manganese concentrations. Maximum embrittlement occurs at about 1000 degrees Farenheit for tempering times of 10 hours. De-embrittling at 1100 to 1150 degrees Farenheit tends to "boil" the embrittling elements away from the prior austenite grain boundaries.

Once a fine pearlite spacing has been achieved with air cooling to 1000 - 1050 degrees Farenheit, care must be taken to minimize the effects of temper embrittlement wherever possible. Holding at 1100 degrees Farenheit should not only avoid embrittlement, but should also allow the embrittling elements, such as arsenic, phosphorous, tin and antimony, to diffuse away from the prior austenite grain boundaries. If the steel is tempered for a sufficiently long time, the embrittling elements will be far enough from the grain boundaries to minimize the risk of re-embrittlement when cooling to room temperature. An 1100 degree Farenheit hold should also provide for the relief of any stresses which might have accumulated during air cooling from the austenitizing temperature.

After tempering, the casting must be brought to room temperature. Water quenching from 1100 degrees Farenheit would be the most desirable procedure from a metallurgical stantpoint. However, quenching or even air cooling from the tempering temperature will result in residual stresses. These stresses are caused by thermal gradients during cooling and have been described mathematically by Hardwick[30] for ferrite steel as

$$\sigma \text{max} = \frac{\triangle T}{8} \qquad \text{Equation 2}$$

where σmax is the maximum residual stress and $\triangle$T is the thermal gradient experienced by the casting. Since large steel castings usually have complex shapes, a furnace cool from 1100 degrees Farenheit would normally be necessary, although air cooling might be used for simple shapes in order to save furnace time.

Double normalizing is often suggested as a way to grain refine plain carbon cast steels. For a .30 carbon, 1.50 manganese steel Sims[31] suggested a heat treatment involving a high temperature normalize with a second normalize at about 50 degrees Farenheit above the AC_3 temperature. His steel did not have an active grain refiner and was subject to grain growth even at 1550 degrees Farenheit for two hours. Therefore double treatments for grain size control was absolutely necessary to achieve maximum properties.

Not all investigators have found an improvement with double treatments. Briggs[27] found that double normalizing did not result in grain refinement or any improvement in properties for plain carbon steels with active grain refiners and suggested that single normalizing was just as effective as double normalizing for both one and three inch sections. The general conclusion is that most of the improvement attainable by air cooling of steels with active grain refiners is achieved during the first cycle and multiple treatments are of limited value.

The size of thick section steel castings also has an effect on properties. Increasing the casting thickness results in a decreased cooling rate regardless of the cooling medium. Briggs[27] found a 5 to 10 percent decrease in the tensile values for large sections, which he attributed to high temperature transformation products. Ductility was found to decrease not more than 5 to 10 percent unless micro-shrinkage was present. In these cases ductility values might be decreased as much as 90 percent.

With large sections finer ferrite grain sizes are more difficult to achieve. One of the major purposes of this program is to demonstrate how fine grain sizes may be attained economically for plain carbon steels with heavy walls. With a practical method of grain refining large steel castings, the foundry metallurgist is in a position to make the most of plain carbon steels. The major benefit of ferrite grain refinement is a combination of high tensile and toughness values. Even for castings which do not require this superior toughness and strength, it always is beneficial for any foundry to provide the maximum possible properties, especially if they may be achieved with little or no increase in cost.

EXPERIMENTAL PROCEDURE

Approach

This experiment was designed to compare current commercial practice to isothermal annealing. Air cooling to 1050 degrees Farenheit was expected to refine the ferrite grain size and reduce the pearlite spacing, resulting in increased yield and ultimate tensile strengths. An 1100 degree Farenheit hold should relieve cooling stresses and minimize the danger of temper embrittlement. Therefore, an isothermal annealing cycle might be expected to improve both the strength and toughness simultaneously.

The effects of air cooling cycles and successive recrystallization in the properties of large C - Mn steel castings was investigated. The emphasis was placed on carbon concentrations between .20 and .30 percent and manganese concentrations between .50 and .90 percent. One special group of castings with .25/.30 carbon and 1.20/1.36 manganese was also studied to see if superior impact properties as well as strength might be achieved through special handling of this steel. A few castings with higher carbon concentrations were also included in order to extend the low carbon results to these grades.

The testing procedure can be divided into two steps. First, a "keel" block investigation was performed and the physical properties and microstructural features compared to standard annealing procedures. A "keel" block is a standard test used by most foundries to measure the physical properties of a cast structure and is defined by The American Society of Testing Materials as a cast test bar at least 5 inches long, 1-1/4 inches thick and 3-1/4 inches high.[33] All "keel" block test coupons used in this study were attached as an integral part of various production castings.

Three types of "keel" blocks were tested; as cast, annealed, and isothermally annealed. Those castings which were annealed were compared to isothermally treated "keel" blocks. The effect of successive recrystallizations, with isothermal holding, was also studied.

Testing of cast 12 inch cubes comprised step two. A test mould was prepared which measured 12 inches by 12 inches at the bottom and was poured 24 to 36 inches high. The tests taken from these castings were expected to simulate the properties to "keel" block tests wherever possible. The 12" cubes were tested in the annealed and isothermally treated condition.

The Isothermal Anneal

The term "isothermal anneal", when applied to steel, is used to describe a cycle of heating, cooling and holding at some specific temperature. In this study the term "isothermal anneal" means full austenitization, air cooling, and holding at 1100 degrees Farenheit. The exact cycle is as follows:-

I. Heat 200° F. per hour to 1675° F.

II. Hold 1675° F., one hour per inch (eight hours minimum)

III. Remove from furnace and air cool to 1050° F.

IV. Replace in furnace and hold at 1100° F., one hour per inch

V. Furnace cool to 300° F.

A notation was developed to describe how many isothermal anneals had taken place on a particular test piece. Iso 1 indicates that the piece had one isothermal anneal. Similarly, Iso 2 means that the piece had been isothermally treated twice. Iso 8 would mean that the test piece had been austenitized, air cooled and held at 1100 degrees Farenheit eight separate times.

The cooling rate on the air cool varied depending on the size of the production castings to which the tests were attached. The "normal" time, for about 80% of the tests, was between three and four hours. The minimum time was two hours while the maximum time was six hours. These variations in cooling rate had no apparent effect on either the properties or the microstructure and hence the time for cooling from 1675 degrees Farenheit was not recorded.

Materials Tested

A series of plain carbon steels containing carbon contents up to .52 percent were tested, the analyses being given in Table 4. The steels break down into classes of carbon and manganese concentration and correspond roughly to figures that could probably be relied upon in a production situation. The first two groups are typical of the steels currently being produced to meet A. S. T. M. specifications. Group I contained .20 to .25 percent carbon with .50 to .75 percent manganese. Group II had the same manganese limits as Group I but contained .25 to .30 percent carbon.

Two semi-experimental higher manganese groups were also used. The first was a modification of A. S. T. M. A27-65 .65/35, which normally contains .25/.30 percent carbon and .65/.70 percent manganese. For this group the carbon was lowered to .23 to .28 percent and the manganese was raised to .85 to .95 percent. The other high manganese group was designed to produce a maximum in strength and toughness. In this case the carbon concentration was held at .25 to .30 percent while the manganese varied from 1.20 to 1.36 percent. Three high carbon steels were also tested. Two of these contained .30 to .35 percent carbon while the other had a carbon concentration of .52 percent.

All steels were melted in basic electric furnaces of 65 ton capacity with the exception of heat numbers 703Z019, 703Y020 and 703Y021 which were produced in an induction furnace of 600 pound capacity. A double slag melting procedure was used on all electric furnace heats with a standard oxidizing and then reducing slag. Deoxidization was accomplished with two pounds of aluminum per ton, except for the annealed steels cited in Table 6 which were deoxidized with one and one-half pounds of aluminum per ton of molten steel.

Mechanical and Microstructural Testing

Room temperature tensile properties were determined using a standard A. S. T. M. .505 inch diameter tensile bar machined from the "keel" blocks and tested using standard A. S. T. M. procedures. Charpy "V" notch transition temperature curves were also determined with standard size Charpy bars and uniform temperature control before testing.

In the case of the 12 inch cube investigation all tensile and Charpy bars were taken away from the cooling surface. The outer 2 inches of the cube were not used, nor was the innermost 2 inches for fear of segregation and porosity.

The microstructural features were determined by cutting samples from the broken tensile bars. The threaded portion was cut off, polished and etched in nital for 15 seconds to provide clear delineation of the ferrite grain boundaries.

The ferrite grain size was determined using the Jeffries circle method and the percent pearlite in the microstructure was found using the line intercept technique.

PRESENTATION AND DISCUSSION OF RESULTS

Effect of Heat Treatment on Ferrite Grain Size

Even standard annealing procedures can produce substantial grain refinement if coarsening during austenitization is not a problem. The isothermal anneal and standard annealing are the same up to the point where cooling from the austenitizing temperature begins. Therefore, the austenite grain size is the same for either cycle, at least during the first recrystallization.

Results showing the effect of heat treatment on ferrite grain size are found in Figures 7, 10, 13, 15, 17, 19, 21, 23, 25, 28, 30, 32, 34, 36, 39, 41, 44, 47, 50, 53, 56 and 58. The A. S. T. M. ferrite grain size of the "keel" blocks tested in the "as cast" condition was between 2.0 and 3.5. Standard annealing procedures refined the ferrite to A. S. T. M. 6.5 to 7.0, while the first isothermal anneal resulted in a ferrite grain size of 7.5 to 9.0. For manganese concentrations between .50 and .75 percent, the .20 to .30 percent carbon cast steels produced ferrite grain sizes between 7.5 and 8.0 with the first isothermal treatment.

Figures 39, 41, 44, 47, 50 and 53 show the substantial grain refinement achieved with cast steels which have high manganese to carbon ratios. Isothermal annealing produced more grain refinement with the .23 to .28 percent carbon, .85 to .95 percent manganese steel than it did with the .50 to .75 percent manganese group. Steels with .25 to .30 percent carbon and 1.16 to 1.36

percent manganese were very fine grained with only one isothermal treatment. An A. S. T. M. ferrite grain size of 9 was achieved with these steels on the first cycle.

With two treatments the 1.20 to 1.36 manganese group gave A. S. T. M. ferrite grain sizes of 9.5 to 10.0. Despite the fact that these grain diameters were achieved only for "keel" blocks, they were substantially better than any of the other integrals tested. The "keel" blocks of the low manganese groups gave A. S. T. M. ferrite grain sizes of 8.75 to 9.0 with two isothermal treatments, while the .23 to .28 carbon, .85 to .95 manganese group produced 9.0 to 9.5 with the same number of recrystallizations.

More than two heat treatments did not produce further grain refinement. Heat number 123Y260 (.23% C - .74% Mn) was given seven isothermal treatments, but remained substantially the same after the first two. The smallest or "terminal" grain size for this steel was 8.75. Heat number 121Y117 (.24% C - .70% Mn) produced a finer "terminal" grain size of A. S. T. M. 9.0. Like heat number 123Y260, the finest grain size was achieved after two treatments. The .35 percent carbon steel also reached a "terminal" value after two recrystallizations. In this case the final grain size was 9.25.

The 12 inch cube tests followed the same pattern as the "keel" blocks. The ferrite grain size was substantially lower with isothermal annealing than with standard furnace cooling. Annealing of the .50 to

.75 percent manganese cubes gave A.S.T.M. grain size of 6.0 to 6.5, only slightly coarser than the 6.5 to 7.0 achieved with the same treatment for "keel" blocks.

Isothermal annealing of 12 inch cubes with the .50 to .75 percent manganese group gave A.S.T.M. grain sizes of between 7.5 and 8.75. The 8.75 grain size heat had .26 percent carbon and .72 percent manganese, while the 7.5 grained steel contained .30 percent carbon and .50 percent manganese. Although these are only two heats, higher manganese contents did appear to provide a deeper grain refinement.

The isothermal anneal was considerably more effective in providing grain refinement in depth for the higher manganese groups for a 12 inch cube. An A.S.T.M. grain size of 9.0 occurred after one isothermal treatment of heat number 121Z154 (.28%C - .91%Mn). This is more refinement than was achieved with "keel" blocks of heat number 121Z091 (.26%C - .88%Mn). The high manganese (1.20/1.36% Mn) group gave the most substantial grain refinement for 12 inch cubes. After one isothermal treatment, heat number 703Z019 (.26%C - 1.16% Mn) gave a ferrite grain size of 9.25.

The increase in ferrite precipitation with grain refinement occurred for both the 12 inch cubes and the "keel" block studies. Annealing produced less ferrite than the isothermal anneal after one treatment. Normalizing to room temperature precipitated more pearlite than did isothermal treating. After two treatments the amount of ferrite in the isothermally treated steels increased by 5 to 10 percent. This increase in ferrite precipitation might be expected to improve the toughness but the tensile strength should have decreased with less pearlite precipitated.

Effect of Grain Refinement on Ultimate Tensile Strength

Despite the increase in ferrite precipitation with grain refinement the tensile strength did not decrease. The ultimate tensile strength was essentially the same whether the steel was annealed, normalized and tempered, or isothermally treated. Even successive treatments did not change the results.

The only factor which appeared to be capable of lowering the ultimate tensile strength was dendritic segregation. Annealed steels had more segregation than did isothermally treated steels and did result in a suppressed tensile strength for heat number 121Z154 (.28% C - .91% Mn).

Figure 2 shows that isothermally treated steels provide ultimate tensile strengths somewhat higher than annealed steels. With furnace cooling only 60,000 psi can be guaranteed for .20%/.25% carbon steels, while 65,000 psi can be expected at the .25%/.30% carbon level. The isothermally treated steels provided a minimum of 72,000 psi tensile strength with .25%/.30% carbon, and at least 69,000 psi with .20%/.25% carbon.

The high manganese steels (.25%/.30% carbon, 1.20%/1.36% manganese) provided a tensile strength of at least 81,000 psi. The results are apparently due to ferrite solid solution strengthening and would be expected to reduce the impact properties were it not for the substantial grain refinement which also occurred with this grade. More careful control of carbon could probably give consistent ultimate tensile strengths above 90,000 psi. Heat number 122X451-B achieved this result with only .30 percent carbon. This steel (122X451-B) also had a very high yield strength of 59,000 psi. This yield point for plain carbon steel appeared to be a direct result of substantial ferrite grain refinement.

Effect of Grain Refinement on Yield Point

The most important physical property of engineering components is the yield point since their further usefulness is limited after plastic deformation. Isothermally annealed plain carbon steel castings have yield points which exceed their annealed counterparts by 5,000 to 10,000 psi. The lowest yield strength (0.2% offset) for isothermally annealed "keel" blocks was 38,000 psi for .20%/.25% carbon steels and 42,000 psi for .25%/.30% carbon steels. The lowest yield strength of the high manganese (1.20%/1.36% manganese) group was 51,000 psi.

The improvement in yield strength achieved with the isothermal anneal can be directly attributed to ferrite grain refinement. Figure 3 is a plot of yield strength versus $d^{-\frac{1}{2}}$ for both annealed and isothermally treated "keel" blocks. This figure indicated that the yield strength of plain carbon steel is a linear function of d according to the Petch relationship (Equation 1).

For the low manganese group the yield strength of a single crystal (σ_i) is about 20,000 psi. The high manganese group parallels the lower manganese steels and in this cast the intersept value appears to be about 26,000 psi. The value of K_y (or the amount of yield strength increase achieved with each decrease in $d^{-\frac{1}{2}}$) is approximately the same for both the high manganese and the low manganese groups. The value of the slope is about 25oo psi/$mm^{-\frac{1}{2}}$. Therefore, the Petch equation for low manganese steels reads:

$$\sigma_{yp} \quad 20,000 + 2,500^{-\frac{1}{2}}$$

Equation 3

For the 1.20 to 1.36 percent manganese group the Petch equation is:

$$\sigma_{yp} \quad 26,000 + 2,500^{-\frac{1}{2}}$$

Equation 4

In the range of grain diameters between A.S.T.M. 6 and 10 there is a great variation in the number of grains per square inch at 100X. Since this region is of primary interest, an expanded plot was prepared plotting yield strength versus grains per square inch at 100X (Figure 3). This plot is not a straight line. Although the results were obtained only for A.S.T.M. 6 through 10, Figure 3 is of practical value since large variations in the grains per square inch at 100X lead to only small variations in the A.S.T.M. grain size number of $d^{-\frac{1}{2}}$ ($mm^{-\frac{1}{2}}$).

The results of this study indicate that larger percentages of pearlite do not increase the yield point. The yield strength of the .52 percent carbon steel was dependent on the ferrite grain size in much the same way as were the .20 to .30 percent carbon steels. When the ferrite grain size decreased, the yield point went up. However, this does not exclude carbon as a useful alloy. The .25 to .30 percent carbon steels grain refined more readily than did the .20 to .25 percent carbon group. Therefore, carbon should be used only as a grain refiner and the metallurgist should recognize that increased concentrations of carbon have a detrimental effect on toughness.

Manganese also aided in ferrite grain refinement, particularly with the high manganese group. In the case of the high manganese group an increase in σ_i also occurred. The combination of these two effects increased the yield strength by 6,000 to 11,000 psi. However, manganese did not have an adverse effect on toughness.

Carbon is known to decrease the impact values of most steels. Since solid solution strengthening also reduces the impact resistance, the effect of manganese on impact properties is of interest. In this case the question to be asked is, "Does manganese grain refine enough to overcome its adverse effect on σ_i"?

The Effect of Grain Refinement on Impact Properties

The Charpy "V" notch impact properties of isothermally annealed castings was superior to annealed castings. Both the fracture mode transition temperature and the energy levels were improved, although the superiority of the energy levels was more dramatic. Without increasing the furnace time isothermal annealing provided improved fracture toughness, as well as higher yield strength and more consistent tensile values.

The seventy-five Charpy "V" notch energies (average of two tests) measured at +32 degrees Farenheit provide a good example of what effect isothermal annealing has on Charpy "V" notch energy levels. For the .20 to .25 percent carbon group the Charpy "V" notch bars absorbed from 30 to 71 ft. lbs. The test which absorbed 30 ft. lbs. when isothermally treated, required only 20 ft. lbs. for fracture in the annealed condition. The same relationship was true for the 71 ft. lb. steel. This .22 percent carbon, .74 percent manganese steel absorbed 26 ft. lbs. when it was annealed. In many cases the impact properties were twice as high with isothermal treatments (Figures 9, 16, 29, 55 and 57).

Those steels with full impact series also showed that more energy was absorbed at temperatures both below and above +32 degrees Farenheit. Table 4 shows that the 15 ft. lbs. transition temperature (ISTT) was from 40 to 50 degrees Farenheit lower with the .20 to .25 percent carbon group. For the .25 to .30 percent carbon steels the difference was from 45 to 90 degrees Farenheit. A similar comparison is not available for the high manganese group (1.20 to 1.36 manganese) but they also had a low ISTT. For these steels the ISTT varied from -50 to -65 degrees Farenheit.

The fracture mode transition of isothermally treated castings was also lowered by isothermal annealing. Two factors which may be of primary importance in this behavior are the increased amount of ferrite precipitation which occurred with the isothermal treatment and the finer ferrite grain size. The straight line correlation between fracture mode transition and $d^{-\frac{1}{2}}$ predicted by Petch did not occur. However, his prediction was based on the absence of a second phase such as pearlite. For steels, carbon (in the form of pearlite) is well recognized for decreasing the impact properties. Pickering and Gladman[7] found pearlite to increase the fracture mode transition temperature by approximately four degrees Farenheit for each percent increase in pearlite. The analysis for the effect of ferrite of fracture mode transition shown in Figure 5 carries this correction.

Once the effect of pearlite has been accounted for, the relationship between ferrite grain refinement and fracture mode transition may be analyzed more carefully. Figure 5 shows the results of this analysis and indicates a decrease in the fracture mode transition temperature of 15 degrees Farenheit for each decrease in the square root of the ferrite grain diameter. This study indicates that the 50 percent fibrous fracture mode transition temperature may be approximated by:

$$\text{FATT}(^{\circ}\text{F.}) = +30 + 4(\%\ \text{pearlite}) - 15(d^{-\frac{1}{2}})(\text{mm}^{-\frac{1}{2}}) \quad \text{Equation 5}$$

It should be noted that this result was obtained for A. S. T. M. ferrite grain sizes between 7 and 10.

Since carbon aided in grain refinement a curious situation arose whereby the FATT of .20 to .25 percent carbon steels was approximately equal to .25 to .30 percent carbon steels provided the manganese concentration was low. Those steels with a high manganese to carbon ratio also grain refined substantially, but without the same adverse effect due to increases in pearlite. Therefore, the best combination of strength and toughness came with the high manganese (1.20 to 1.36 percent) group.

Comparison of "Keel" Blocks and 12 Inch Cubes

The 12 inch cubes generally had lower properties than "keel" blocks of the same analysis and heat treatment. The question was, "Can a greater decrease be expected with isothermal annealing or with furnace cooling"? The answer to this question was that the properties of an isothermally treated 12 inch cube corresponded more closely to the "keel" blocks than did the "keel" blocks and 12 inch cubes of annealed castings. In other words, the increase in yield strength and impact properties observed for "keel" blocks was just as pronounced in the 12 inch cubes.

The percentage increase in yield strength and impact properties was greater for the 12 inch cubes than it actually was for the "keel" blocks.

Heat numbers 121Y176 (.30% C - .50% Mn) is typical of the results obtained. Isothermal annealing increased the yield strength of toe "keel" blocks by 20 percent. The yield strength of the 12 inch cubes was increased by 24 percent. For heat number 122Y398 (.26% C - .72% Mn) the yield strength of both the "keel" blocks and the 12 inch cubes increased by 15 percent. The Charpy "V" notch properties at +32° F. increased by 50 percent for the "keel" blocks of heat number 122Y398 (.25% C - .72% Mn). For the 12 inch cubes the increase was 77 percent. For heat number 121Y176 (.30% C - .50% Mn) Charpy "V" notch impact energy for the "keel" blocks increased by 92 percent. With 12 inch cubes, the increase was 113 percent. Therefore, the isothermal anneal was an effective means to increase both the strength and toughness of large C - Mn steel castings, without increasing the heat treatment time.

SUMMARY AND CONCLUSIONS

1. The strength and toughness of isothermally treated steels were superior to those treated by standard furnace cooling procedures. The improvement in properties apparently resulted from ferrite grain refinement. The isothermal anneal produced a greater increase in properties with 12" cubes than with "keel" blocks.

2. As the grain size decreased the percentage of ferrite increased.

3. The size of the grains did not get smaller after two isothermal treatments.

4. The Hall-Petch relationship predicted the yield strength:

$$\sigma_{yp} \text{ (psi)} = 20{,}000 + 2{,}500\ d^{-\frac{1}{2}}\ (\text{mm}^{-\frac{1}{2}})$$

5. The transition temperature is lowered by 15 degrees Farenheit for each decrease in $d^{-\frac{1}{2}}\text{mm}^{-\frac{1}{2}}$.

$$\text{FATT} = +30 + 4(\%\ \text{pearlite}) - 15\ d^{-\frac{1}{2}}(\text{mm}^{-\frac{1}{2}})$$

6. With higher manganese concentrations the ferrite grain size decreased more rapidly than with lower manganese steels. Carbon increased the percentage of pearlite, but also provided some grain refinement. If the best combination of strength and toughness is required, a high manganese to carbon ratio is desirable.

REFERENCES

1. Briggs, C. W., "The Effect of Deoxidation Variables on the Toughness of Cast Steels", Steel Founders' Society of America, Research Report No. 43 (May, 1959) p. 18.

2. Sims, C. E., "Economic Control of Aluminum Contents in Steel", Steel Foundry Facts, (December, 1963) p. 3.

3. Steck, A. B., "Effect of Nitrogen on Cast Steel", Session VI, T and O Conference, Steel Founders' Society of America (1963).

4. Chatterjea, A. B., and Nijhawan, B. R., "Micro-Metallurgy of Austenite Grain Size Control of Steels - Effect of Aluminum on Physical Properties", Iron and Steel (July, 1967) p. 288.

5. Briggs, C. W., "The Effect of Deoxidation Methods on the Low Temperature Impact Properties of Cast Steel", Steel Founders' Society of America Research Report No. 9 (April, 1946) p. 14.

6. Petch, N. J., "The Ductile - Cleavage Transition in Alpha Iron", Fracture by Averback et. al., The Technology Press of Massachusetts Institute of Technology, Cambridge, Mass. (1959) p. 55.

7. Pickering and Gladman, "An Investigation into Some Factors Which Control the Strength of Carbon Steels", Metallurgical Developments in Carbon Steels, Iron and Steel Institute, London (1963) pp. 12 - 13.

8. Petch, N. J., "The Cleavage Strength of Polycrystals", Journal of the Iron and Steel Institute, Vol. 174, (1953) p. 25.

9. Morrison, W. B., "The Effect of Grain Size on the Stress-Strain Relationship in Low Carbon Steel", Transactions of the American Society for Metals, Vol. 59 (1968) p. 824.

10. Grange, R. A., "Strengthening of Steel by Austenite Grain Refinement", Transactions of the American Society for Metals, Vol. 59 (1968) pp. 29 - 33.

11. Irvine, K. J., et. al., "Grain Refined C - Mn Steels", Journal of the Iron and Steel Institute, (February, 1967) p. 161.

12. American Society for Metals. "The Selection of Steels for Notch Toughness", Metals Handbook, Vol 1, 8th Ed. (1961) p. 228.

13. Owen, W. S., "The Yield and Fracture of Mild Steel", Metallurgical Developments in Carbon Steels, Iron and Steel Institute, London (1963) p. 8

14. Rinebolt, J. A., and Harris, W. J., "Effect of Alloying Elements on Notch Toughness of Pearlitic Steels", Transactions of the American Society for Metals, Vol. 43 (1951) p. 1190.

15. Manning, R. D. et. al., "A Pearlite Hardenability Concept as a Basis for Alloy Development", Symposium: Transformation and Hardenability in Steels, Climax Molybdenum Company, Ann Arbor, Michigan (1967) p. 172.-

16. Mickelson, C. G., "How do Sulfur and Phosphorous Affect Cast Steel", Metal Progress, (January, 1964) p. 86.

17. Briggs, C. W., "The Effect of Sulfur and Phosphorous on the Dynamic Properties of Cast Steel", Steel Founders' Society of America, Research Report No. 71, p. 26.

18. Woodfine, B. C., "Some Aspects of Temper Brittleness", Journal of the Iron and Steel Institute, Vol. 173 (1953) p. 245.

19. McMahon, C. J. Jr., "Temper Brittleness - An Interpretive Review", ASTM Symposium on Temper Embrittlement, Philadelphia (October 3 and 4, 1967) p. 33.

20. Jaffe, L. P., and Buffman, D.C., "Isothermal Temper Embrittlement", Transactions of the American Society for Metals, Vol. 42 (1950) p. 604 - 618.

21. Holloman, J. H., "Temper Brittleness", Transactions of the American Society for Metals, Vol. 36 (1946) pp. 473 - 540.

22. Greaves, R. H., and Jones, J. A., "Temper Brittleness of Nickel Crome Steel", Journal of the Iron and Steel Institute, Vol. 102 (1927) p. 171.

23. Vidal, G., "Sur la Fragilite de Revenu des Aciers au Crome, au Molybdene, au Tungstene", Revue Metallurgy, Vol. 42 (1945) pp. 149 - 155.

24. Preece, A., and Carter, R.D., "Temper Brittleness in High Purity Iron-Base Alloys", *Journal of the Iron and Steel Institute*, Vol. 173 (1953), pp. 387 - 398.

25. Low, J. R. Jr. et. al., "Alloy and Impurity Effects on Temper Brittleness of Steel", to be published.

26. Nicolic, Velizar, et. al., "Thermal Treatment of Steel Involving an Increased Rate of Heating", *Technika* (1967) p. 22.

27. Briggs, C. W., "The Effect of Heat Treatment Variables on the Toughness of Cast Steels", Technical Research Committee, Steel Founders' Society of America, Research Report No. 41 (June, 1958) pp. 36 - 89.

28. Sundquist, B. E., "The Edgewise Growth of Pearlite", *Acta Metallurgica*, Vo. 16 (December, 1968) pp. 1413 - 1427.

29. Pellisier et. al., "The Interlamellar Spacing of Pearlite", *Transactions of the American Society for Metals*, Vol. 30 (1942) p. 1073.

30. Hardwick, D., "Metallurgical Aspects of Heat Treatment of Large Steel Forgings", *Journal of the Iron and Steel Institute*, (April, 1967) p. 413.

31. Sims, C. E., "Heat Treatment for Grain Size in Cast Steel", *Metal Progress* (September, 1934) p. 22.

32. Briggs, C. W., "Properties of Thick Section Steel Castings", Steel Founders' Society of America, Research Report No. 56 (October, 1964) p. 23.

33. American Society for Testing and Materials. *1965 Book of ASTM Standards, Part 2 Ferrous Castings*, Philadelphia, Pennsylvania (1965) p. 145.

TABLE 2

Value of K_y in the Petch

Relationship ($\sigma_{yp} = \sigma i + K_y d^{-\frac{1}{2}}$)

Petch	3250 psi/mm$^{-\frac{1}{2}}$
Hall	2800 psi/mm$^{-\frac{1}{2}}$
Morrison	2630 psi/mm$^{-\frac{1}{2}}$
Grange	2200 psi/mm$^{-\frac{1}{2}}$

TABLE 3

Results of Regression Analysis
on 60 C - Mn Heats
After Pickering and Gladman

$$\text{U.T.S., tons/in.}^2 = 1.91 + 1.78(\%\ \text{Mn}) + 5.35(\%\ \text{Si}) + 0.253(\%\ \text{pearlite}) + 0.100(d^{-\frac{1}{2}})$$

$$\text{L.Y.P., tons/in.}^2 = 6.74 + 2.11(\%\ \text{Mn}) + 5.44(\%\ \text{Si}) + 0.225(d^{-\frac{1}{2}})$$

$$\%\ \text{Reduction in Area} = 78.5 + 5.39(\%\ \text{Mn}) - 0.53(\%\ \text{pearlite}) - 8399(d)$$

$$\text{I TT, }^\circ\text{C.} = 63 + 44.1(\%\ \text{Si}) + 2.2(\%\ \text{pearlite}) - 2.3(d^{-\frac{1}{2}}) - f(\text{Al})$$

TABLE 4

15 Ft. Lbs. Charpy "V" Notch Transition Temperature for Annealed vs. Isothermically Annealed "Keel" Blocks Treated as an Integral Part of the Casting.

.20/.25C

.20C - .66 Mn	0° F.	.21C - .70 Mn	-40° F.
.20C - .72 Mn	-10° F.	.22C - .74 Mn	-60° F.
.24C - .68 Mn	-10° F.		
Average	- 7° F.	Average	-50° F.

.25/.30C

.27C - .57 Mn	+40° F.	.28C - .72 Mn	-40° F.
.28C - .69 Mn	+15° F.	.28C - .91 Mn	-55° F.
.29C - .57 Mn	+40° F.		
Average	+32° F.	Average	-47° F.

.32C

.32C - .69 Mn	+20° F.	.32C - .60 Mn	-35° F.
Average	+20° F.	Average	-35° F.

.25/.30C - 1.20/1.40 Mn

	.25C - 1.36 Mn	-65° F.
(12" Cube)	.26C - 1.16 Mn	-50° F.
	.26C - 1.26 Mn	-55° F.
	.30C - 1.20 Mn	-60° F.
	Average	-56° F.

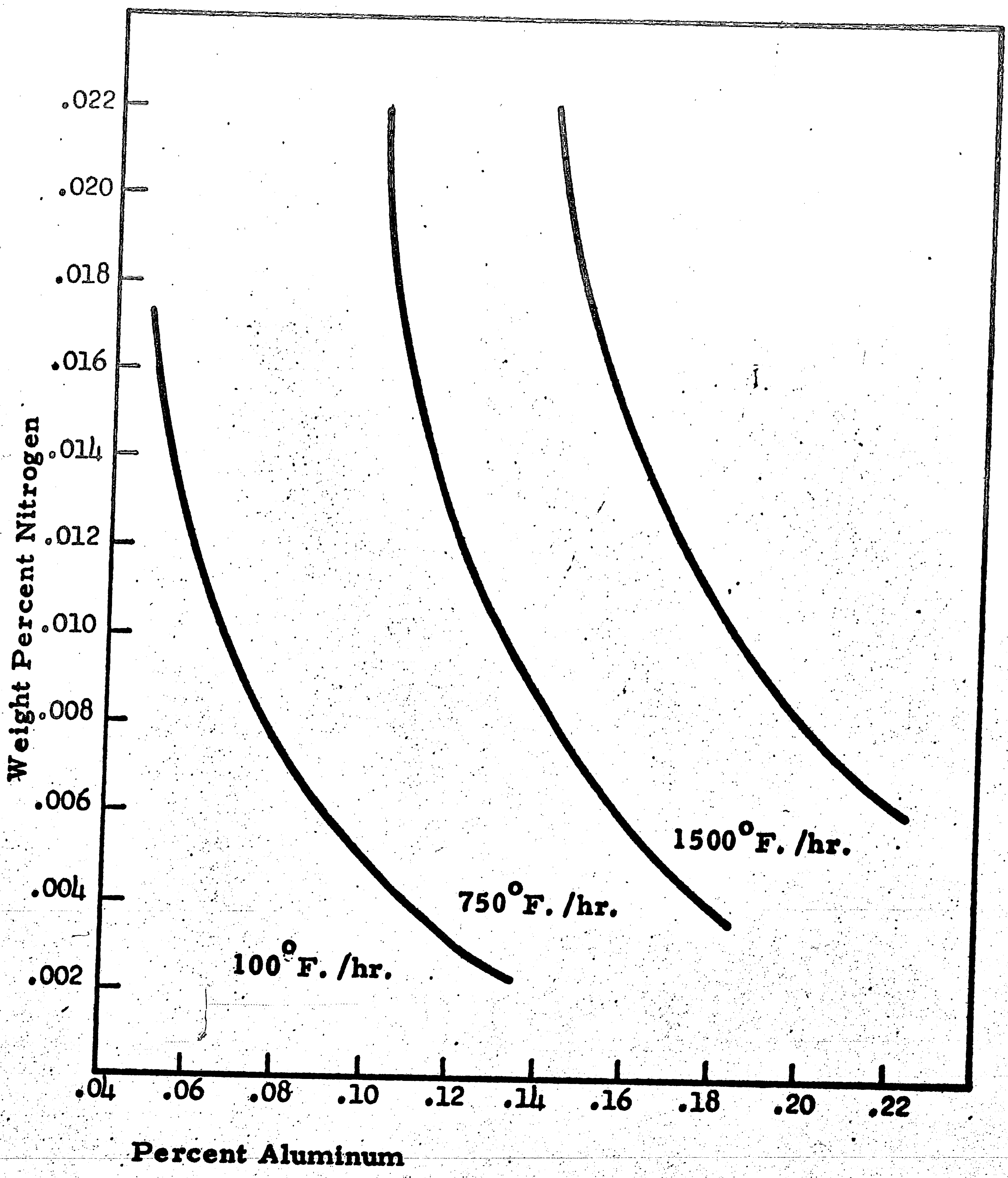

FIGURE 1: Approximate Limits of Nitrogen and Aluminum to Minimize "Rock Candy" Formation

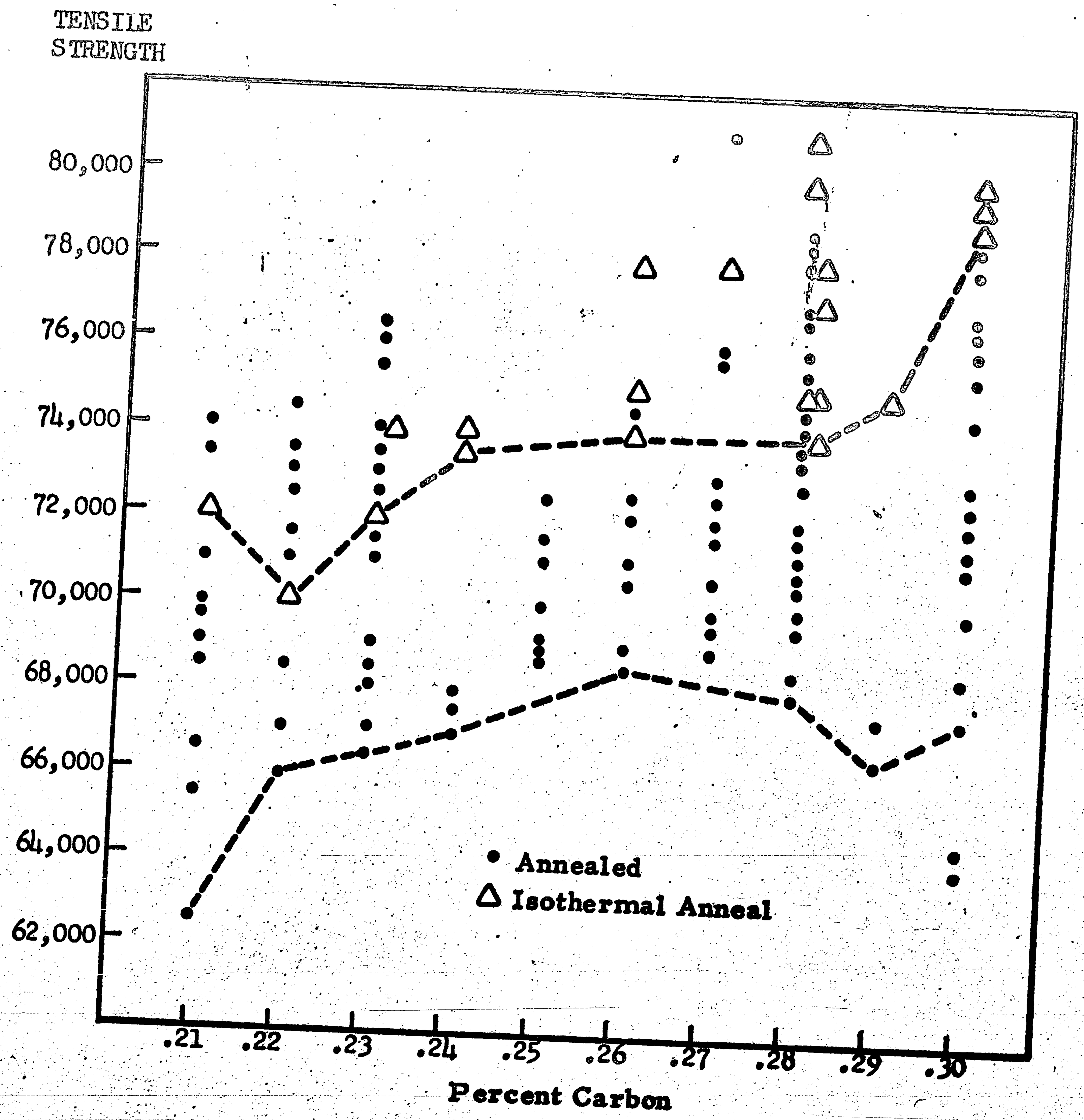

FIGURE 2: Comparison of Ultimate Tensile Strength of Annealed and Isothermally Treated Cast .50/.90 Mn "Keel" Blocks

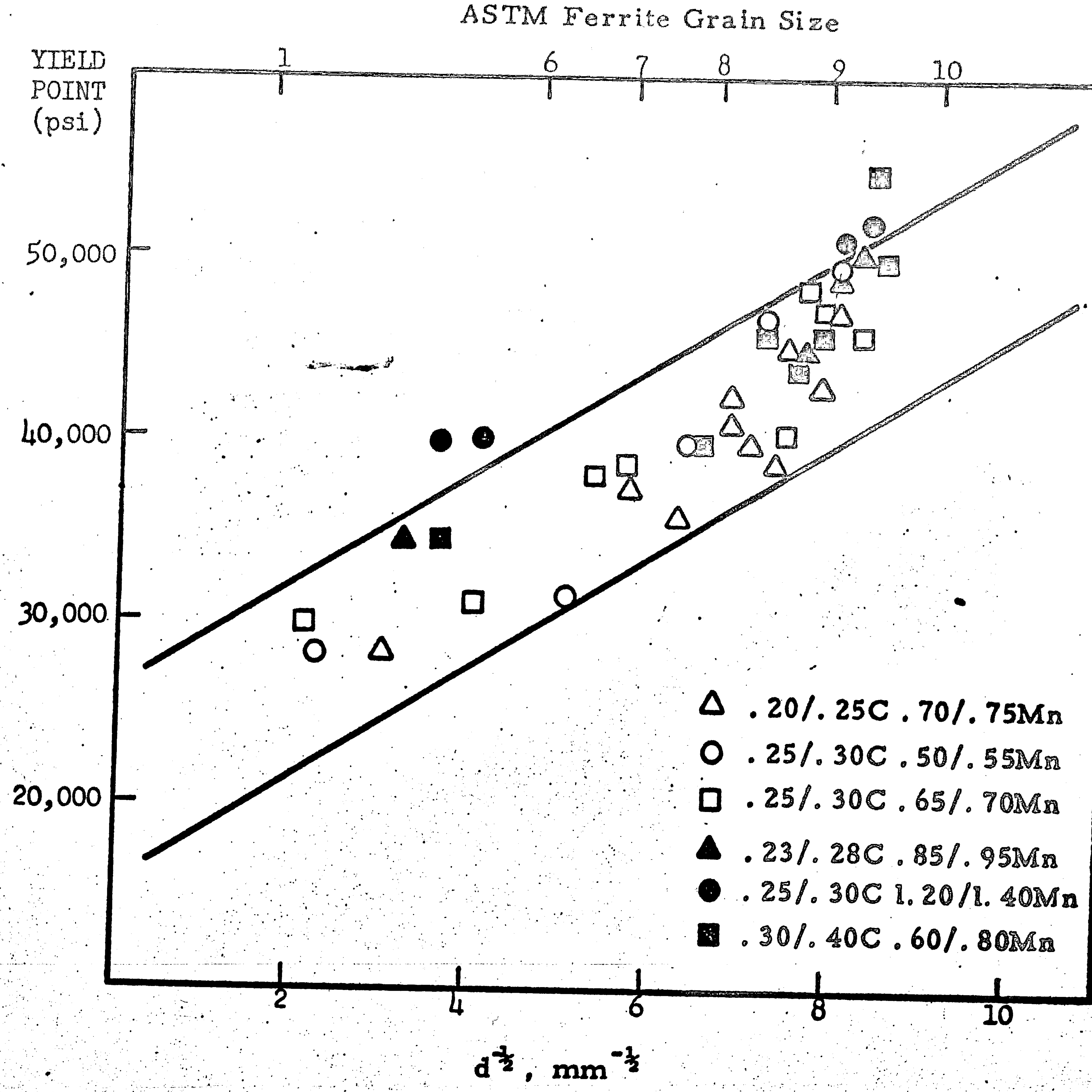

FIGURE 3: Hall-Petch Plot of Carbon-Manganese Cast Steels

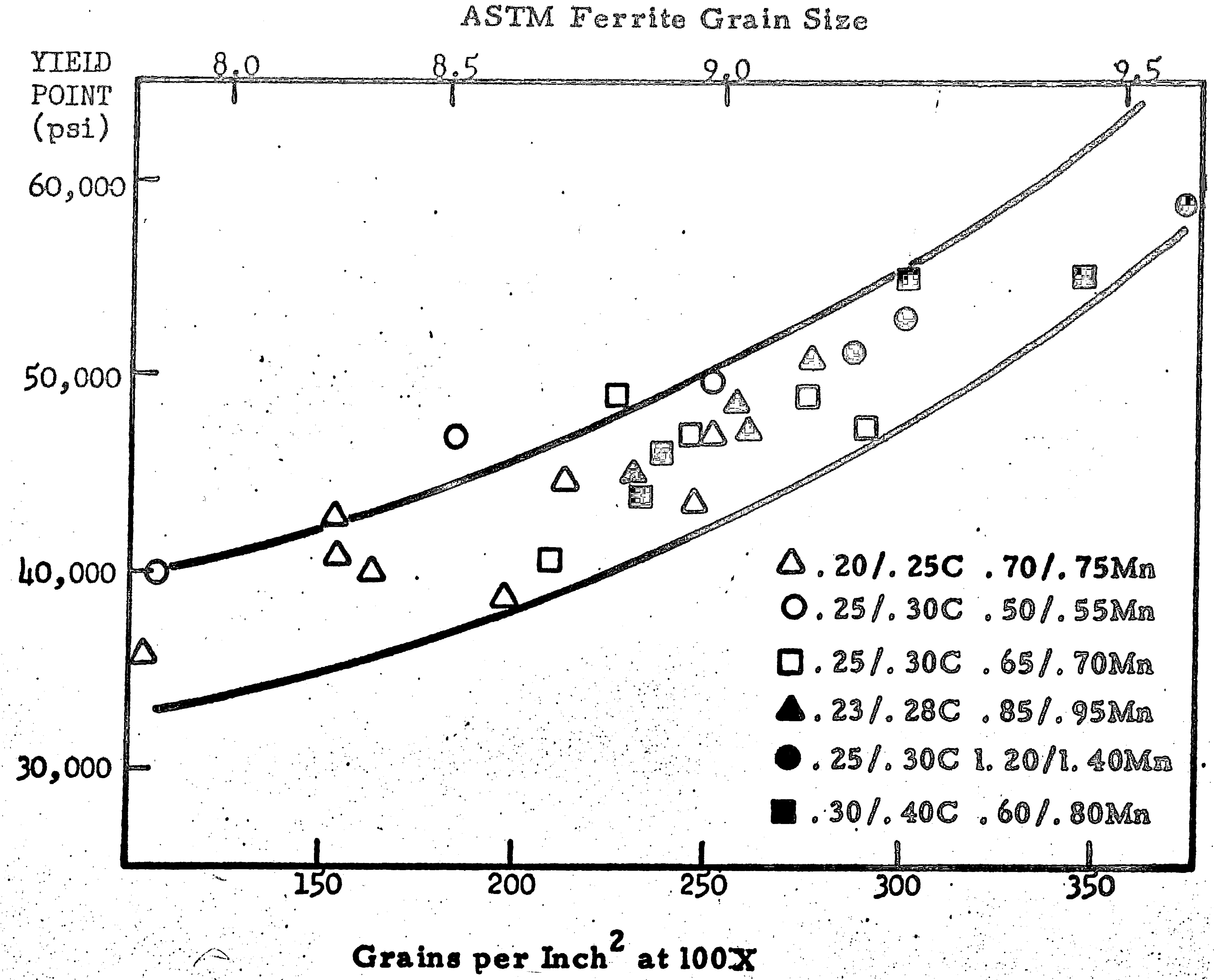

FIGURE 4: Yield Point of Ferrite/Pearlite Carbon Manganese Cast Steels with .20 to .40 Percent Carbon

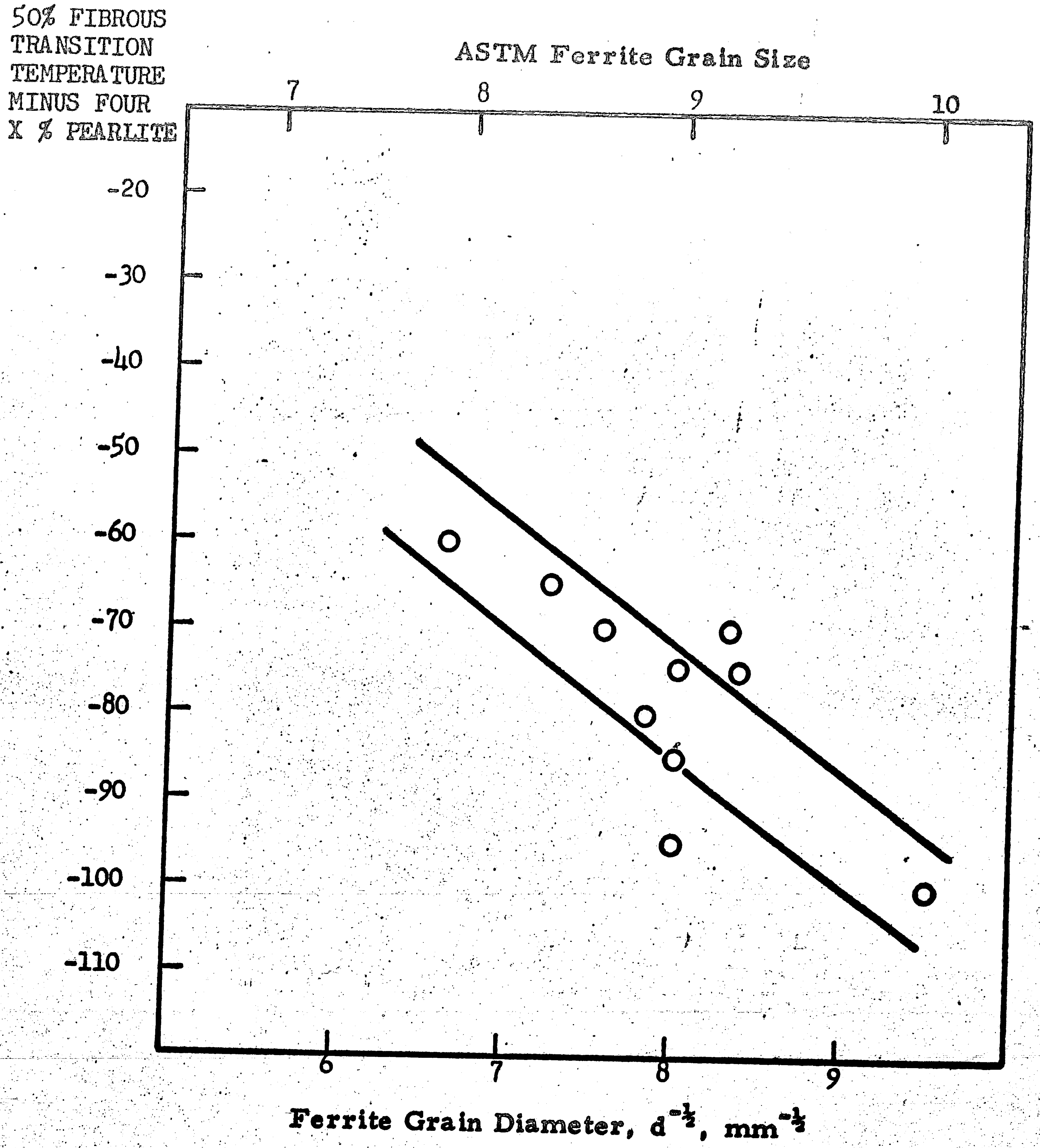

FIGURE 5: FATT vs. $d^{-\frac{1}{2}}$ Corrected for % Pearlite According to Pickering and Gladman

TABLE 5 - Properties of Cast .21C .70Mn "Keel" Blocks

Grade - Carbon Steel .21C .70Mn

Heat No. - 122Z232

Chemical Analysis

C	Mn	P	S	Si	Ni	Cr	Mo
.21	.70	.006	.007	.36	.09	.04	.02

Heat Treatment - Annealed 1675° F. - 8 hrs.
Air Cooled - 1050° F.
Isothermal Hold - 1100° F. - 4 hrs.
Furnace Cooled

Mechanical Properties

TS	YS(.2%)	Elong.	RA
72,000	43,500	32%	59.3%

Impact Properties - Charpy "V" Notch

Temp. °F.	Ft. Lbs.
+175	98, 97
+125	89, 87
+ 75	70, 52
+ 32	54, 53
0	30, 20
- 25	25, 11
- 50	11, 5
FATT	+50° F.
ISTT	-30° F. (Temperature at which 15 ft. lbs. is obtained)

(Test material was heat treated as an integral part of the casting.)

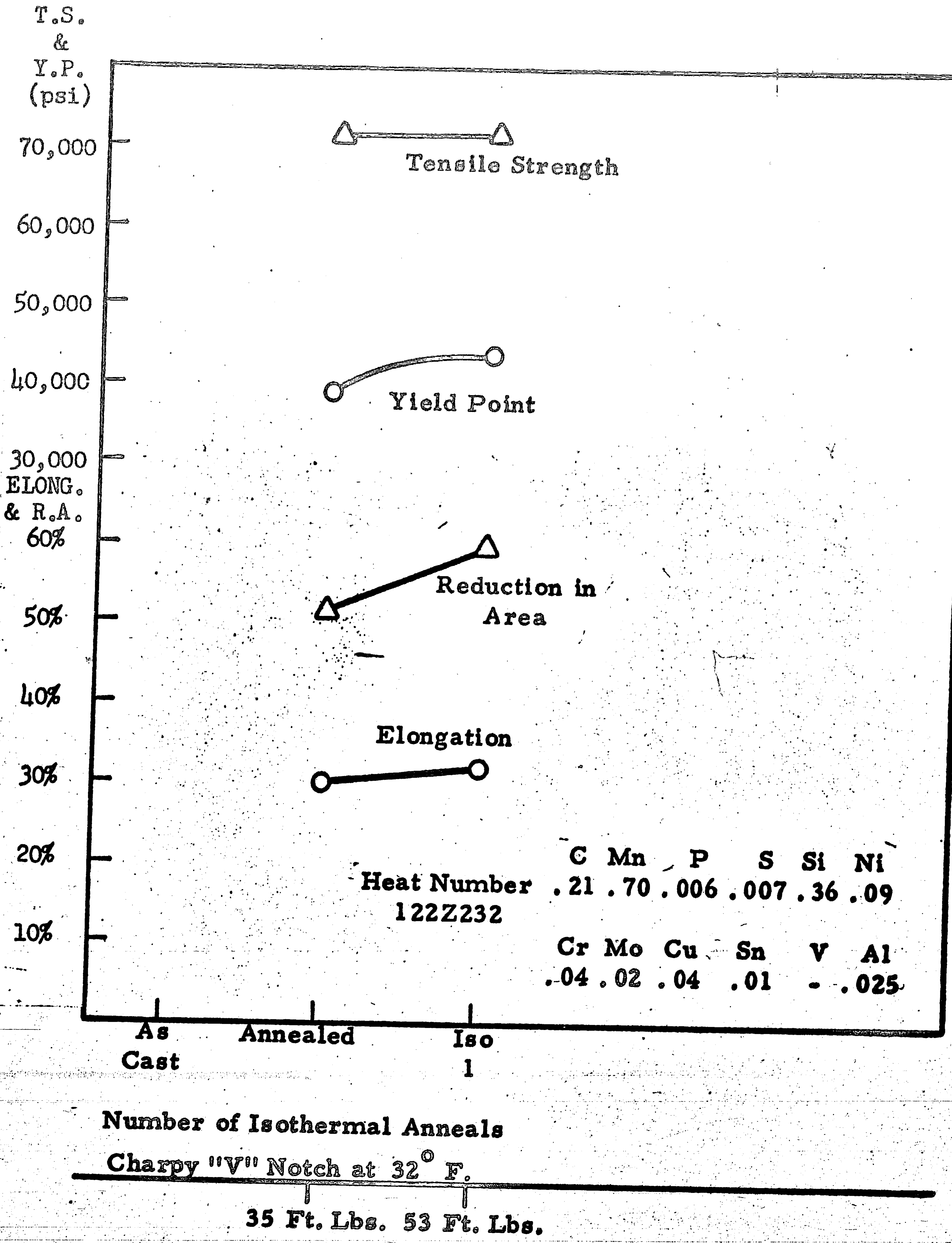

FIGURE 6: Mechanical Properties of Cast .21 C .70 Mn "Keel" Blocks

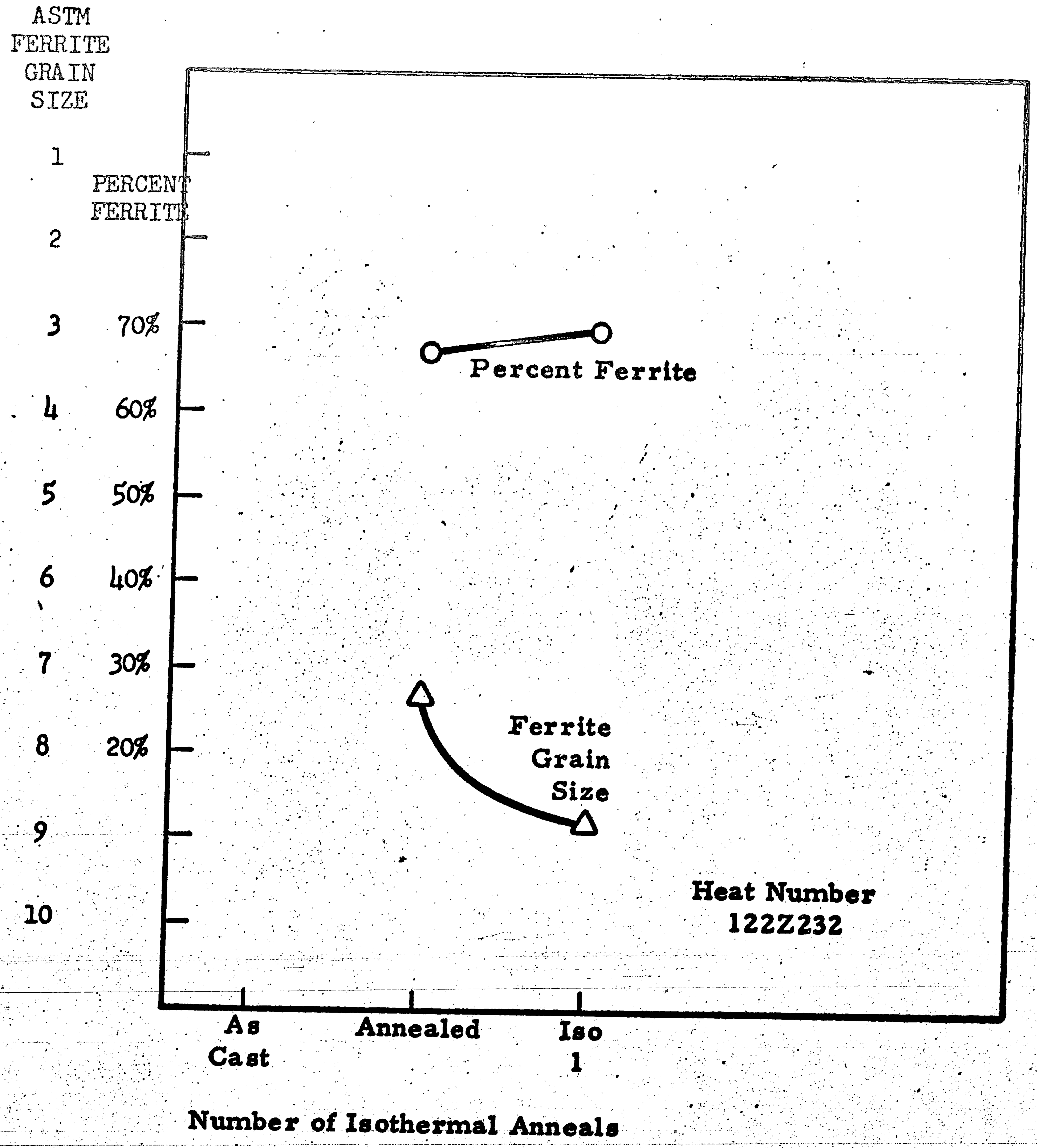

FIGURE 7: Microstructural Features of Cast

.21 C .70 Mn "Keel" Blocks

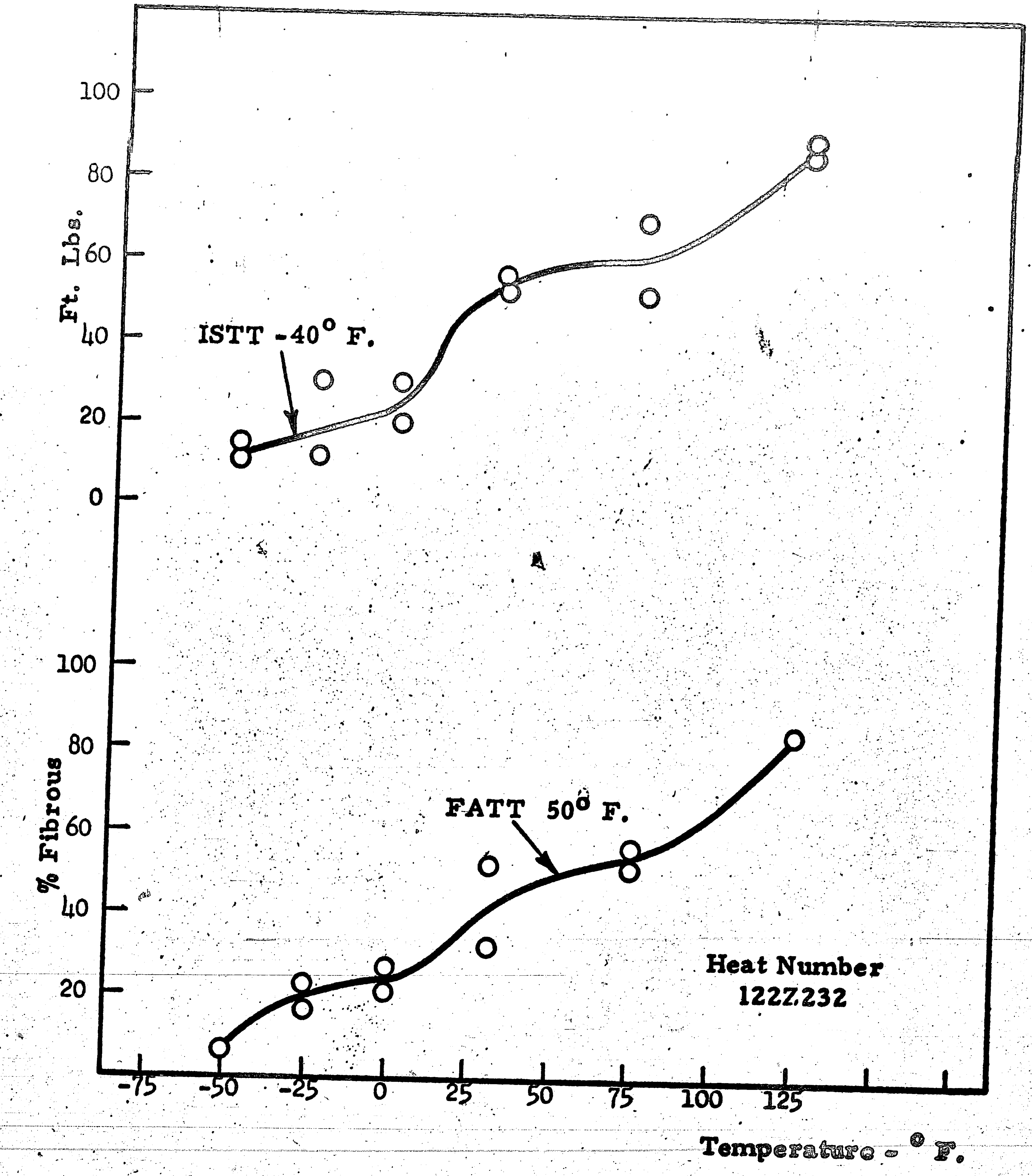

FIGURE 8: Charpy "V" Notch Properties of .21C .70Mn "Keel" Blocks After One Isothermal Anneal

TABLE 6 - Properties of Cast .22 C .74 Mn "Keel" Blocks

Grade - Carbon Steel .22 C .74 Mn

Heat No. - 122Z246

Chemical Analysis

C	Mn	P	S	Si	Ni	Cr	Mo
.22	.74	.013	.014	.56	.06	.07	.02

Heat Treatment - Annealed 1675° F. - 8 hrs.
Air Cooled - 1050° F.
Isothermal Hold 1100° F. - 6 hrs.
Furnace Cooled

Mechanical Properties

TS	YS(.25%)	Elong.	RA
68,000	38,000	35%	63.5%

Impact Properties - Charpy "V" notch

Temp. °F.	Ft. Lbs.
+125	113, 108
+ 75	93, 92
+ 32	75, 67
0	74, 72
- 25	47, 38
- 50	31, 9
-100	4, 2
FATT	+55° F.
ISTT	-60° F. (Temperature at which 15 ft. lbs. is obtained)

(Test material was heat treated as an integral part of the casting.)

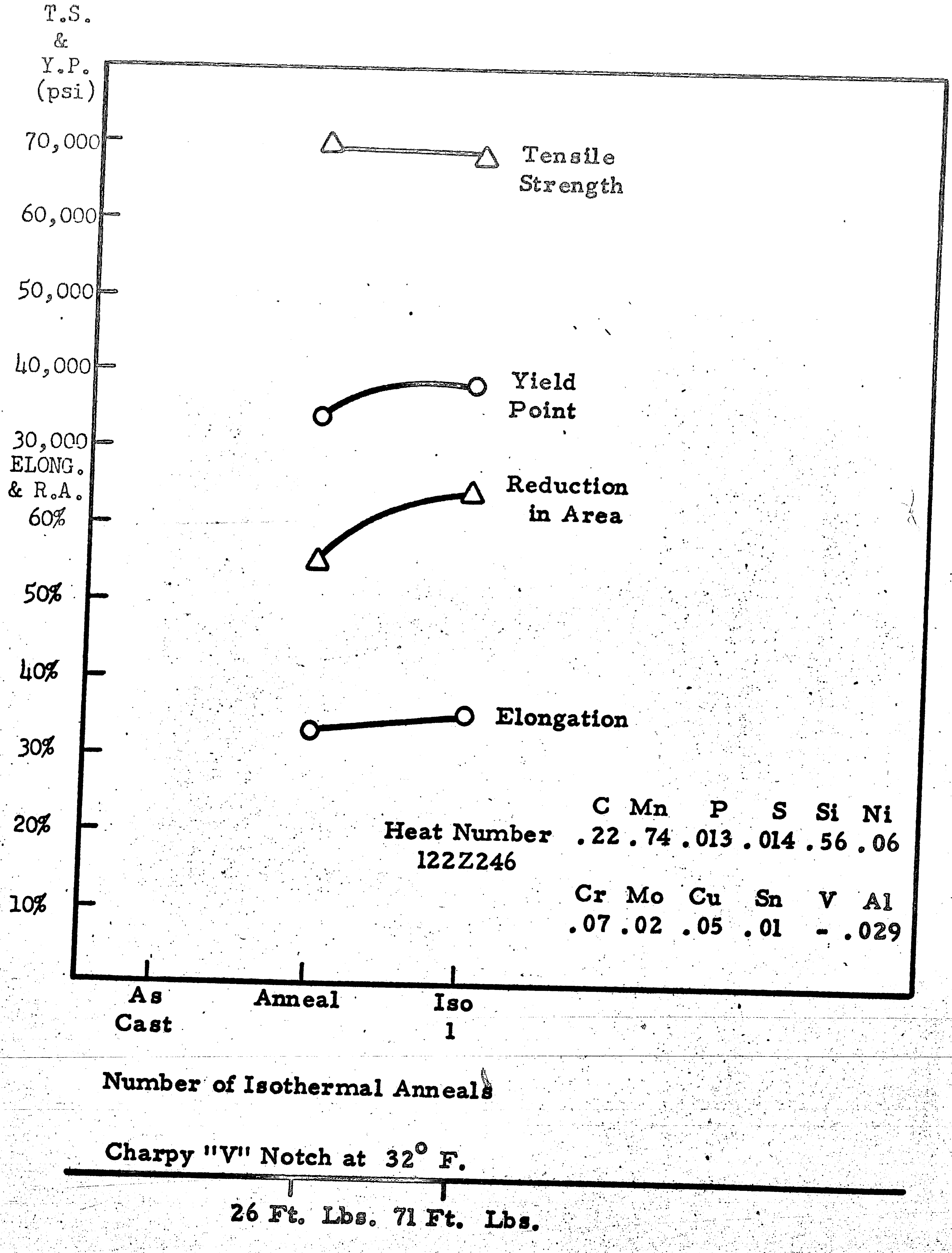

FIGURE 9 : Mechanical Properties of Cast .22 C .74 Mn "Keel" Blocks

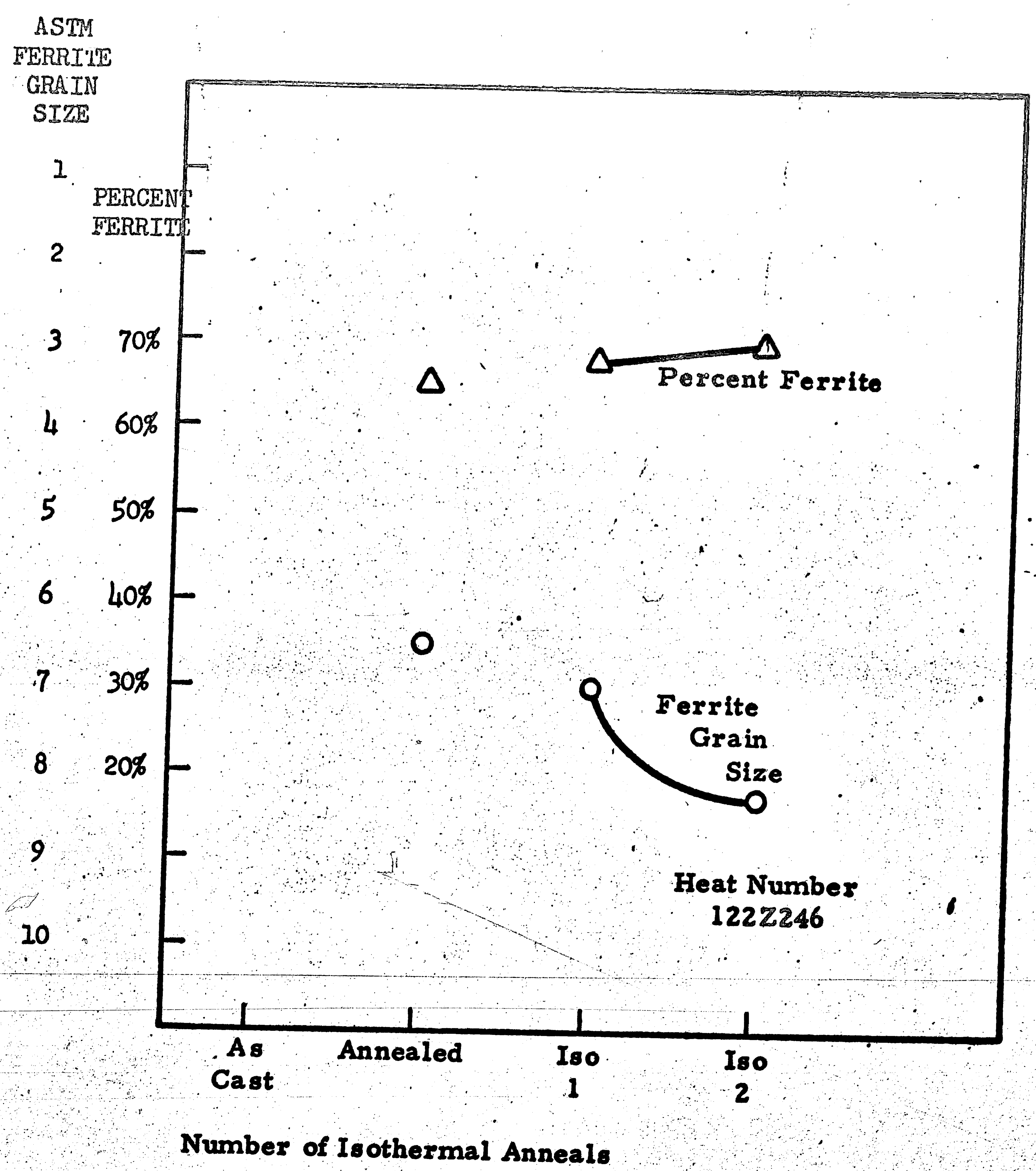

FIGURE 10: Microstructural Features of Cast

.22C .74Mn "Keel" Blocks

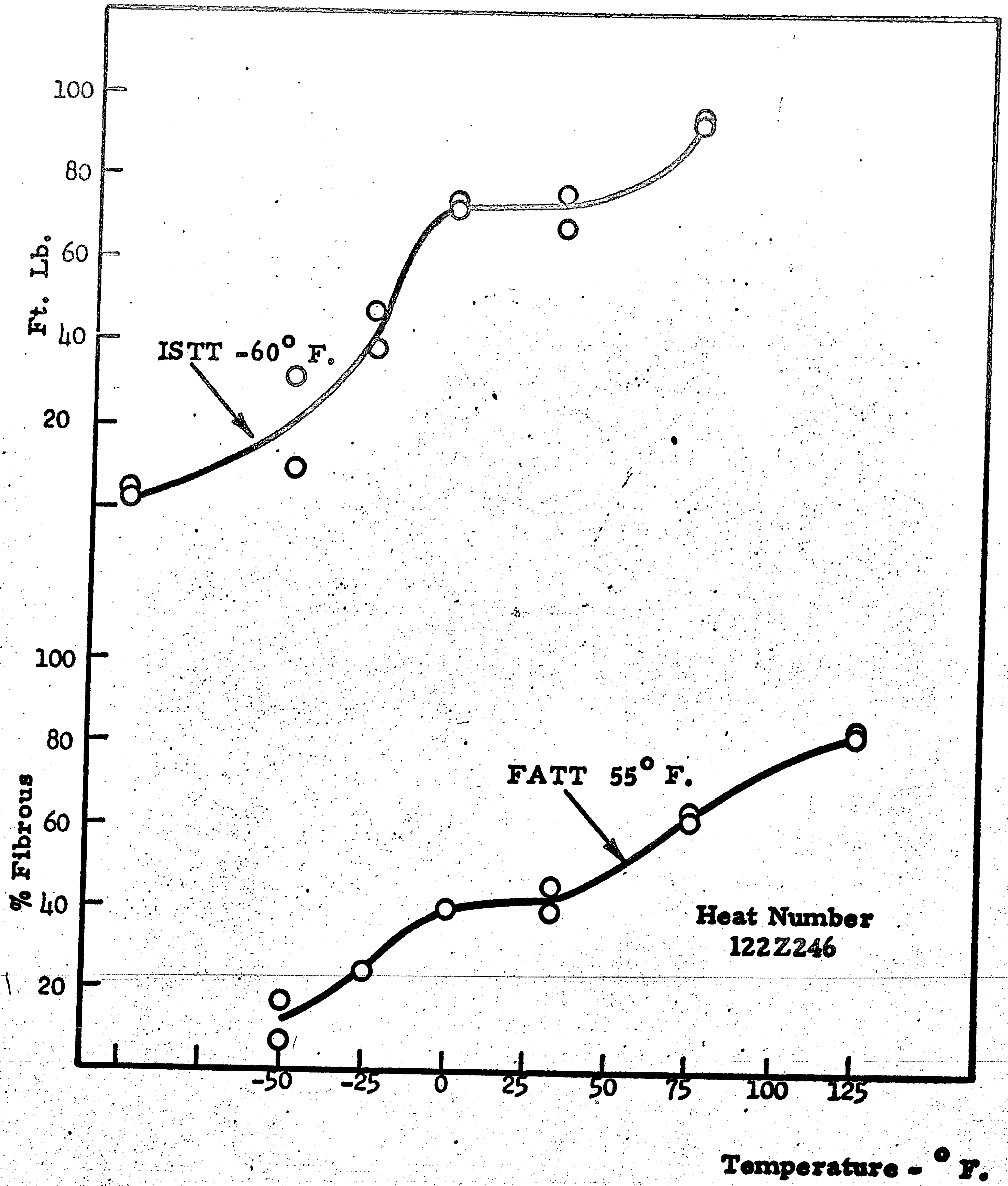

FIGURE 11: Charpy "V" Notch Properties of Cast .22 C .74 Mn "Keel" Blocks After One Isothermal Anneal

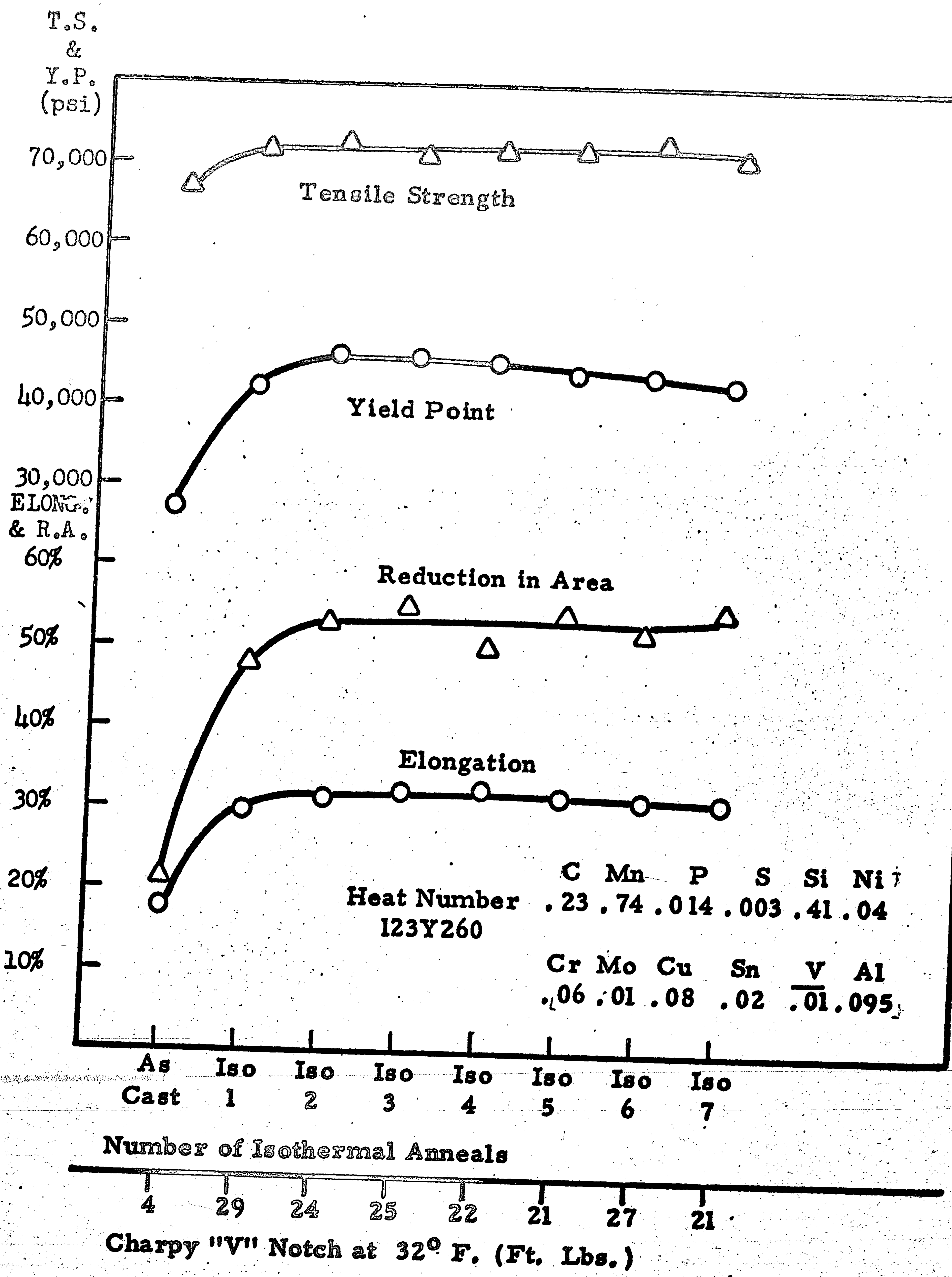

FIGURE 12: Mechanical Properties of Cast .23 C .74 Mn "Keel" Blocks

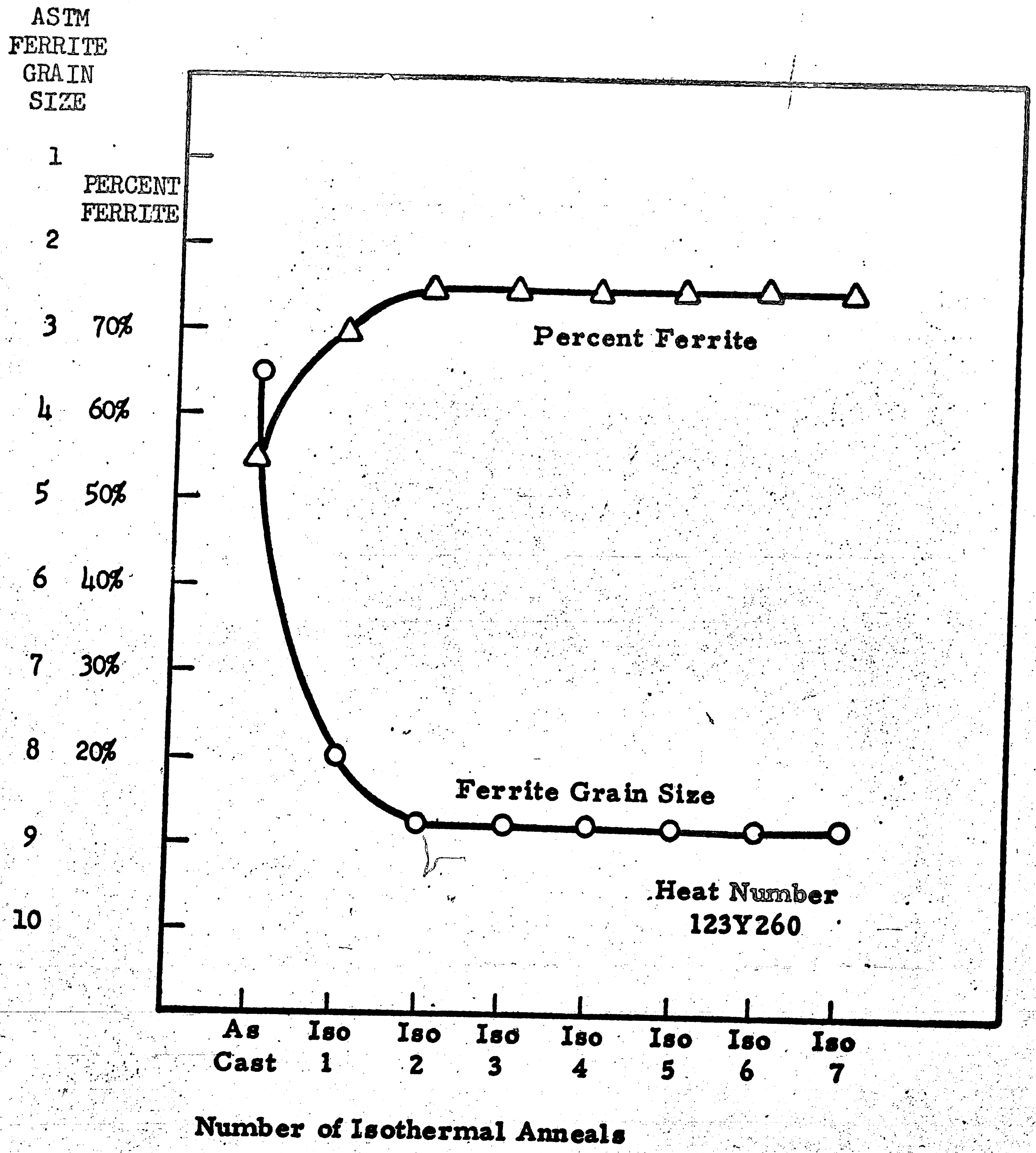

FIGURE 13: Microstructural Features of Cast .23 C .74 Mn "Keel" Blocks

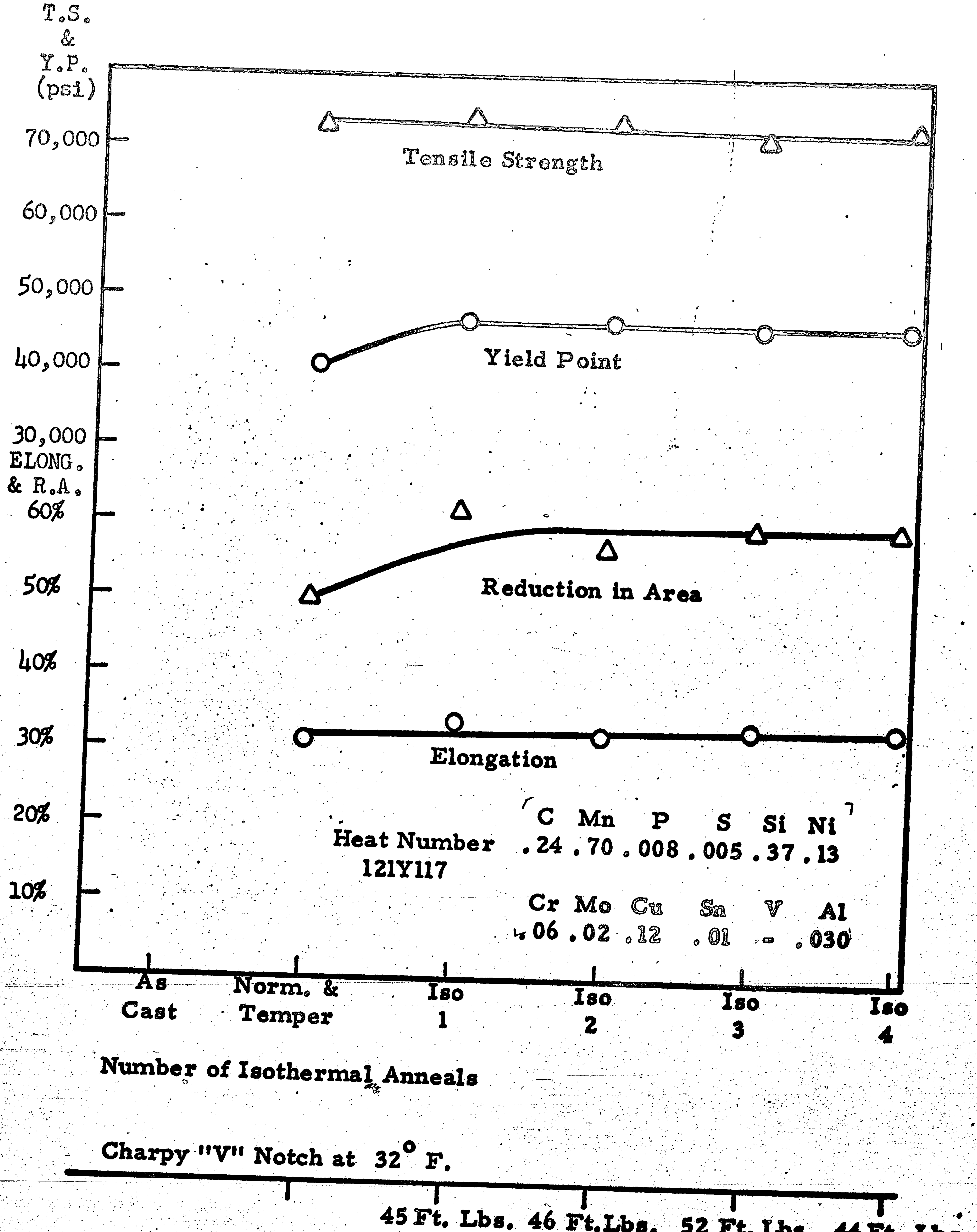

FIGURE 14: Mechanical Properties of Cast .24C .70Mn "Keel" Blocks

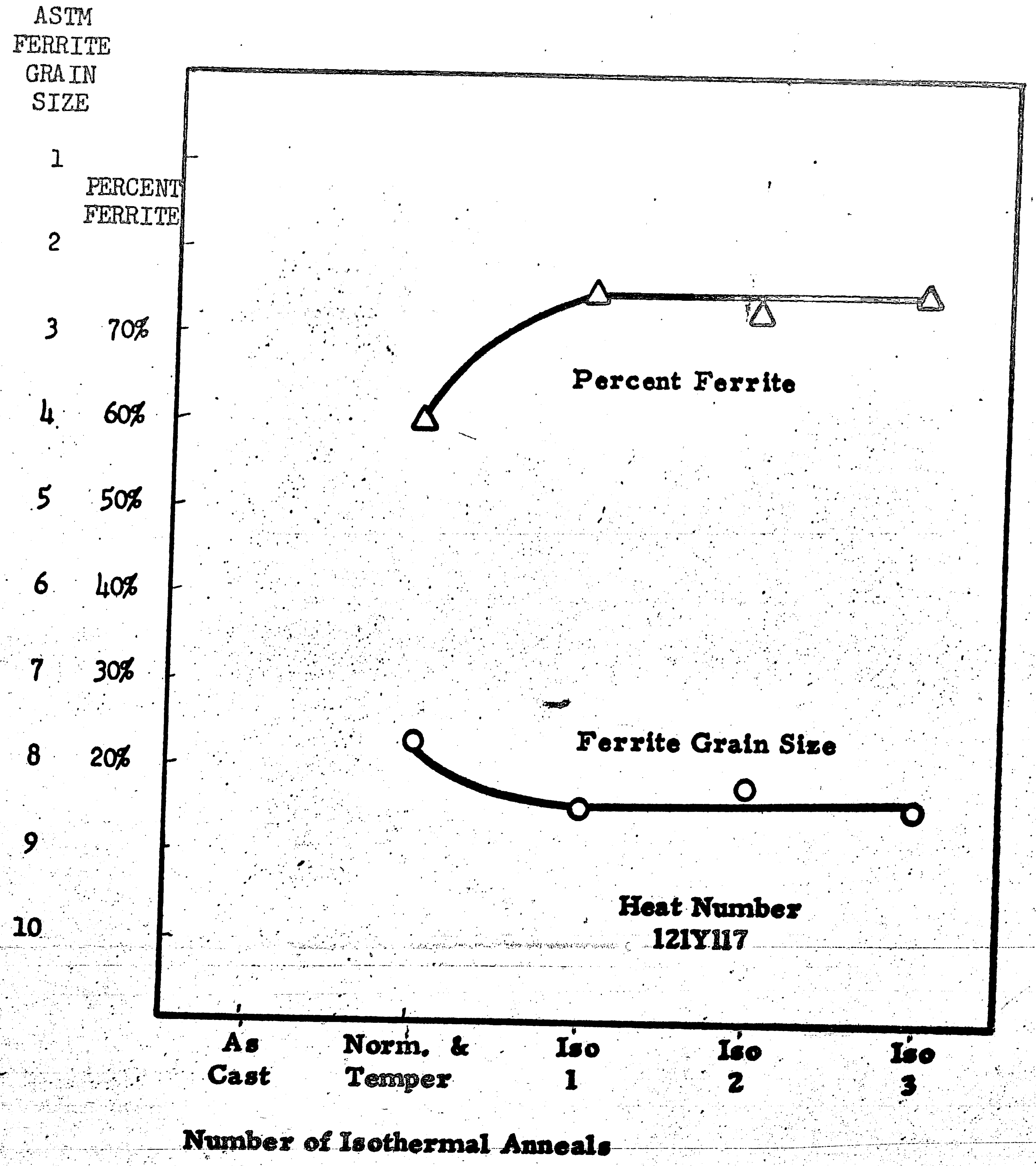

FIGURE 15: Microstructural Features of Cast .24 C .70 Mn "Keel" Blocks

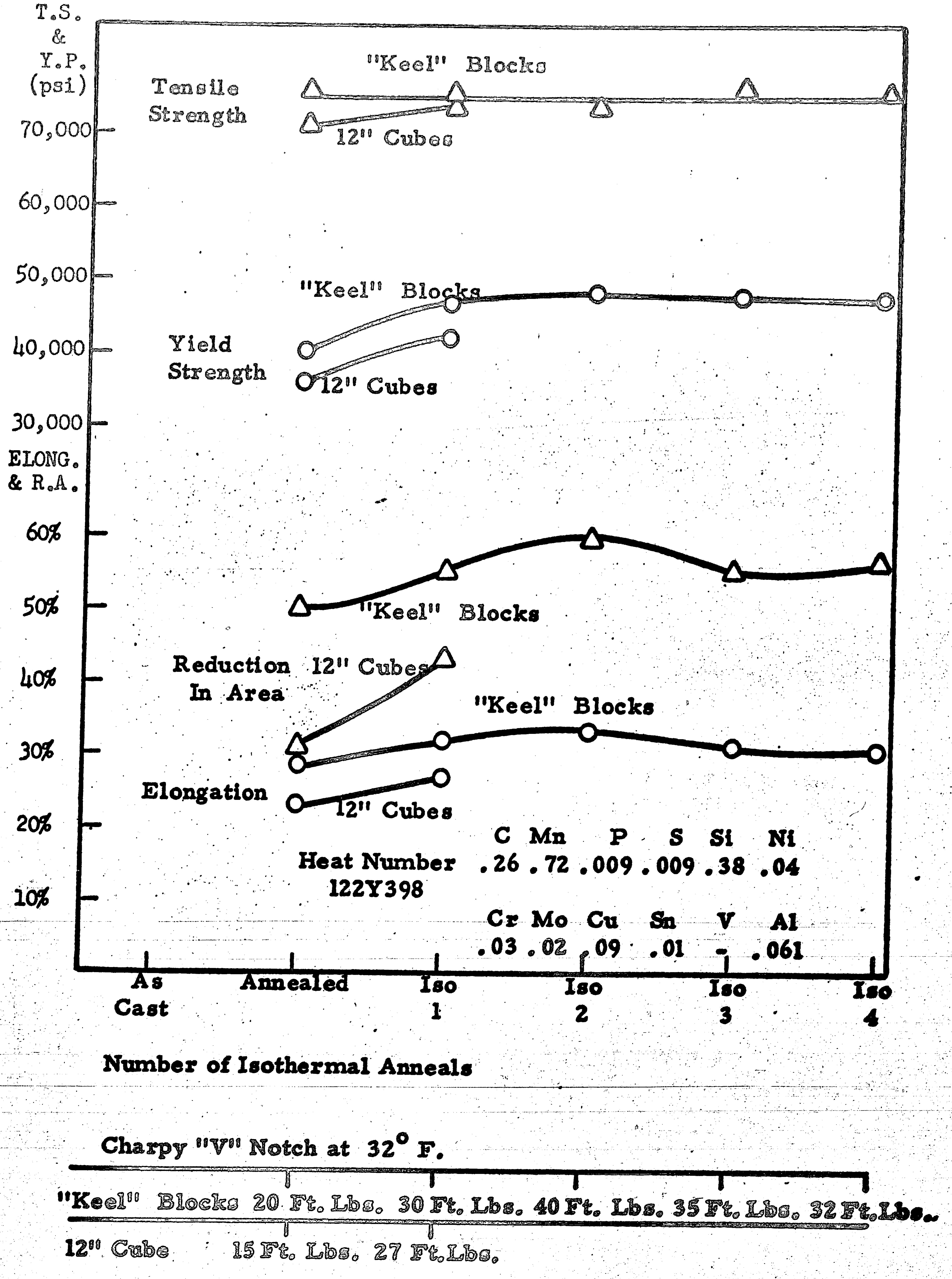

FIGURE 16: Mechanical Properties of Cast .26 C .72 Mn "Keel" Blocks and 12" Cubes

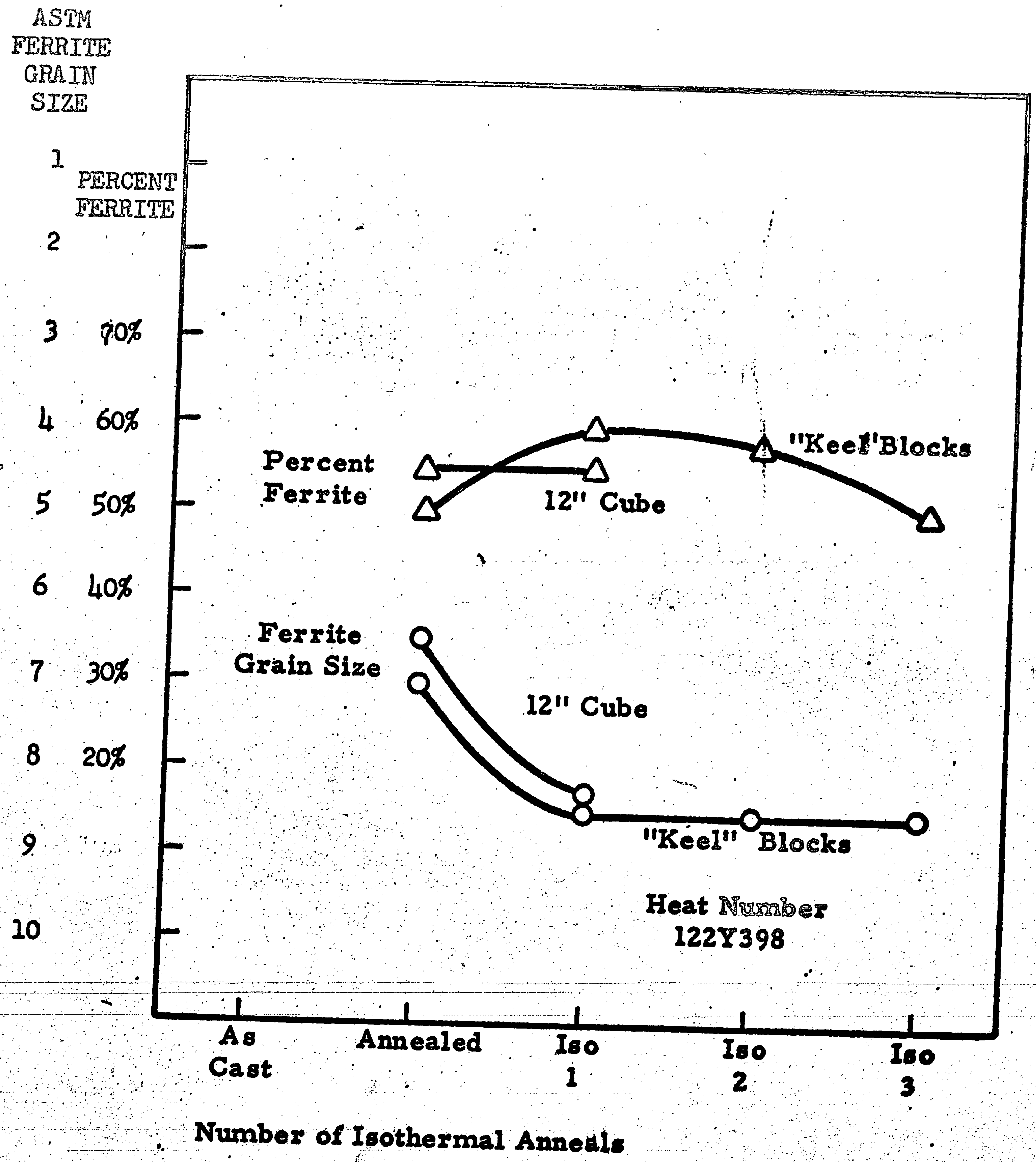

FIGURE 17: Microstructural Features of Cast .26C .72 Mn "Keel" Blocks and 12" Cube

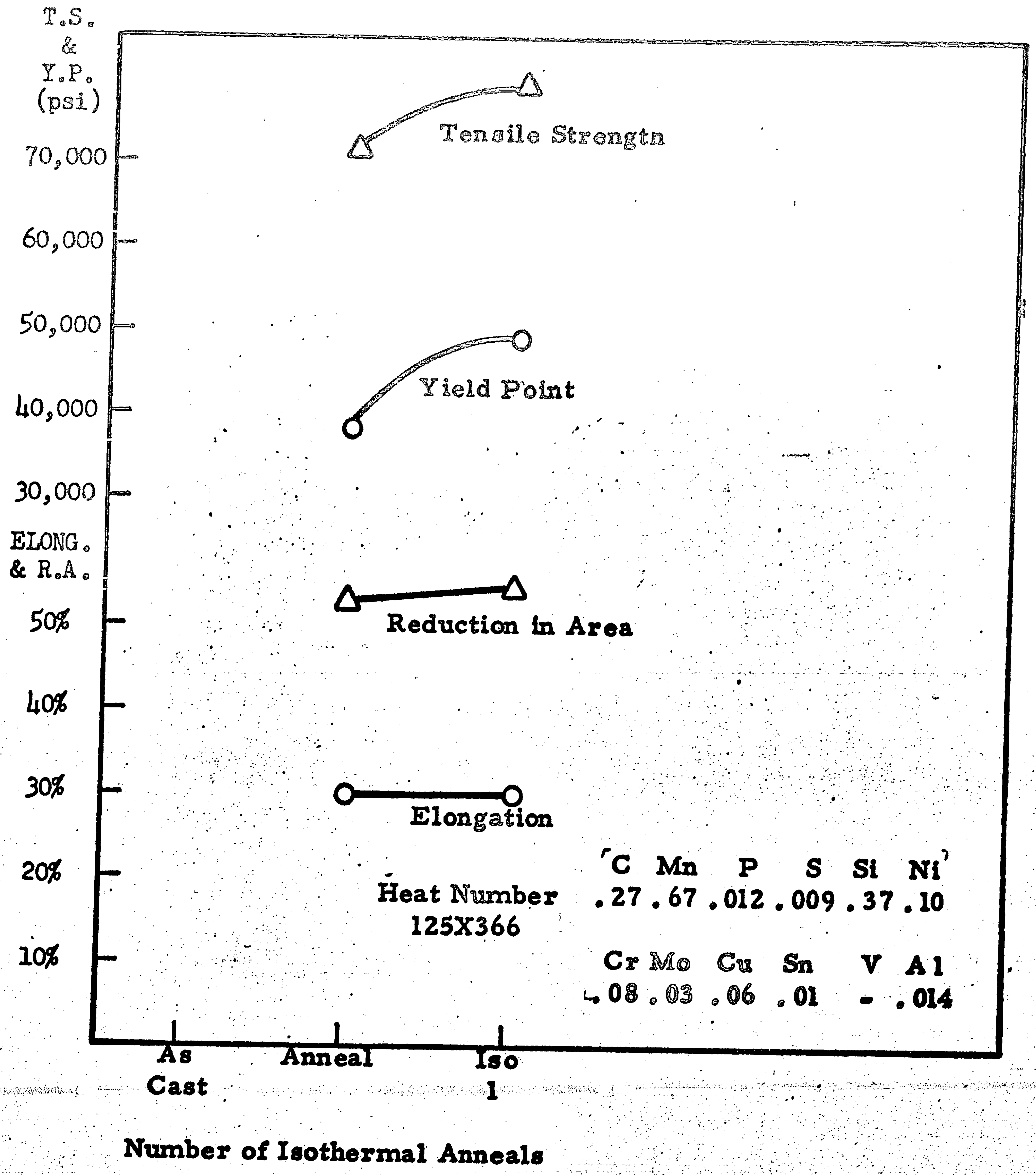

FIGURE 18: Mechanical Properties of Cast .27C .67Mn "Keel" Blocks

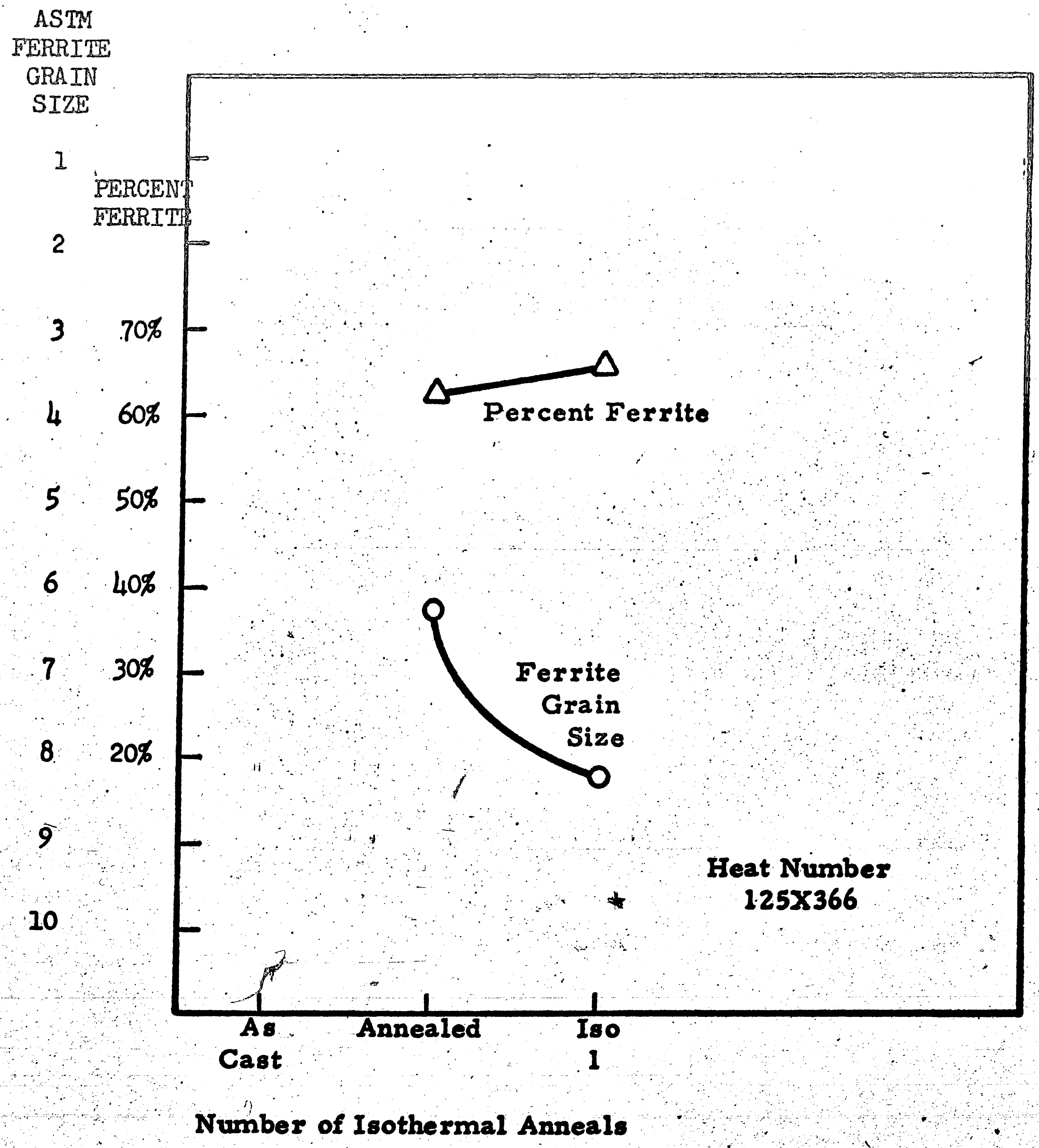

FIGURE 19: Microstructural Features of Cast .27C .67Mn "Keel" Blocks

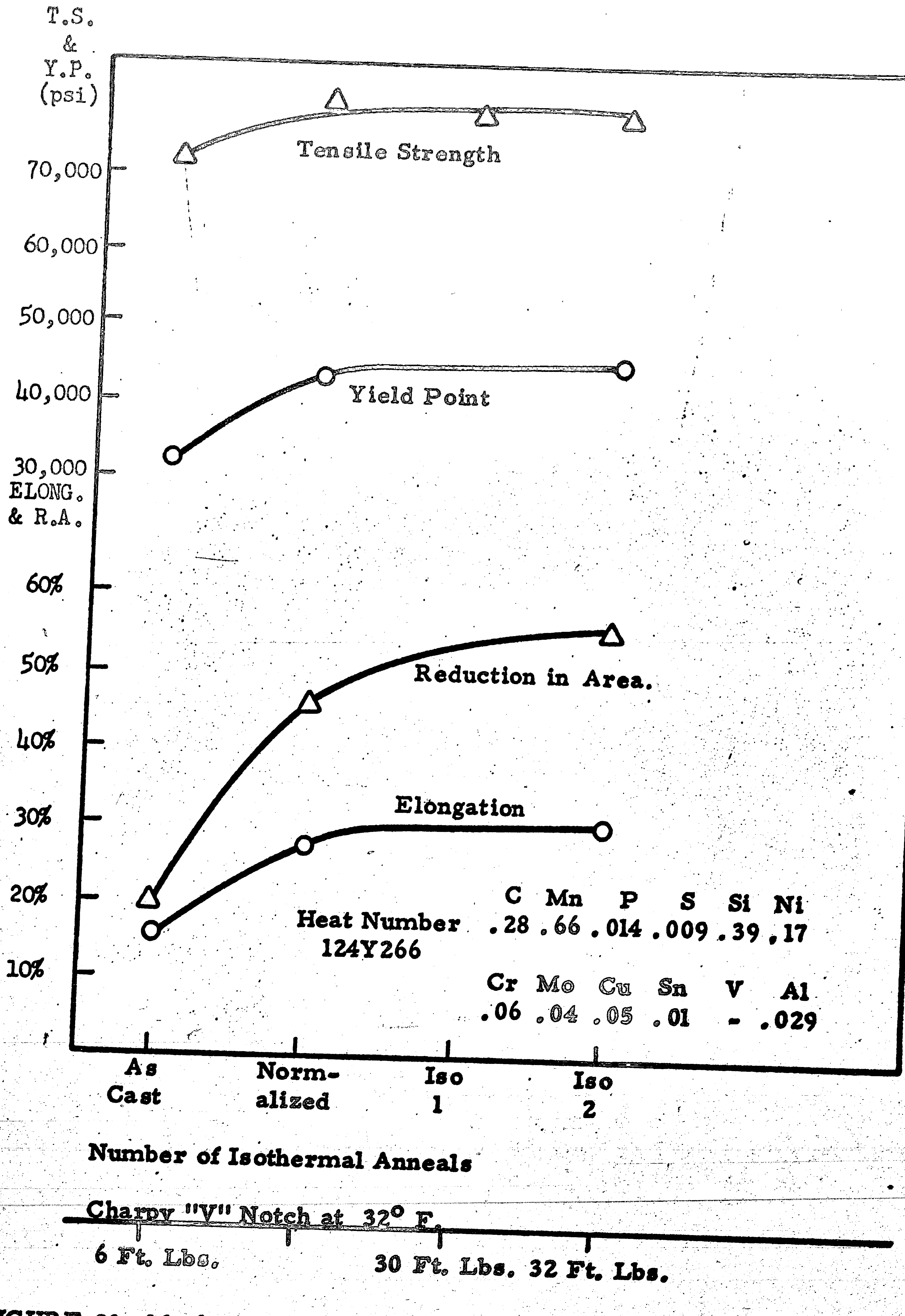

FIGURE 20: Mechanical Properties of Cast

.28 C .66 Mn "Keel" Blocks

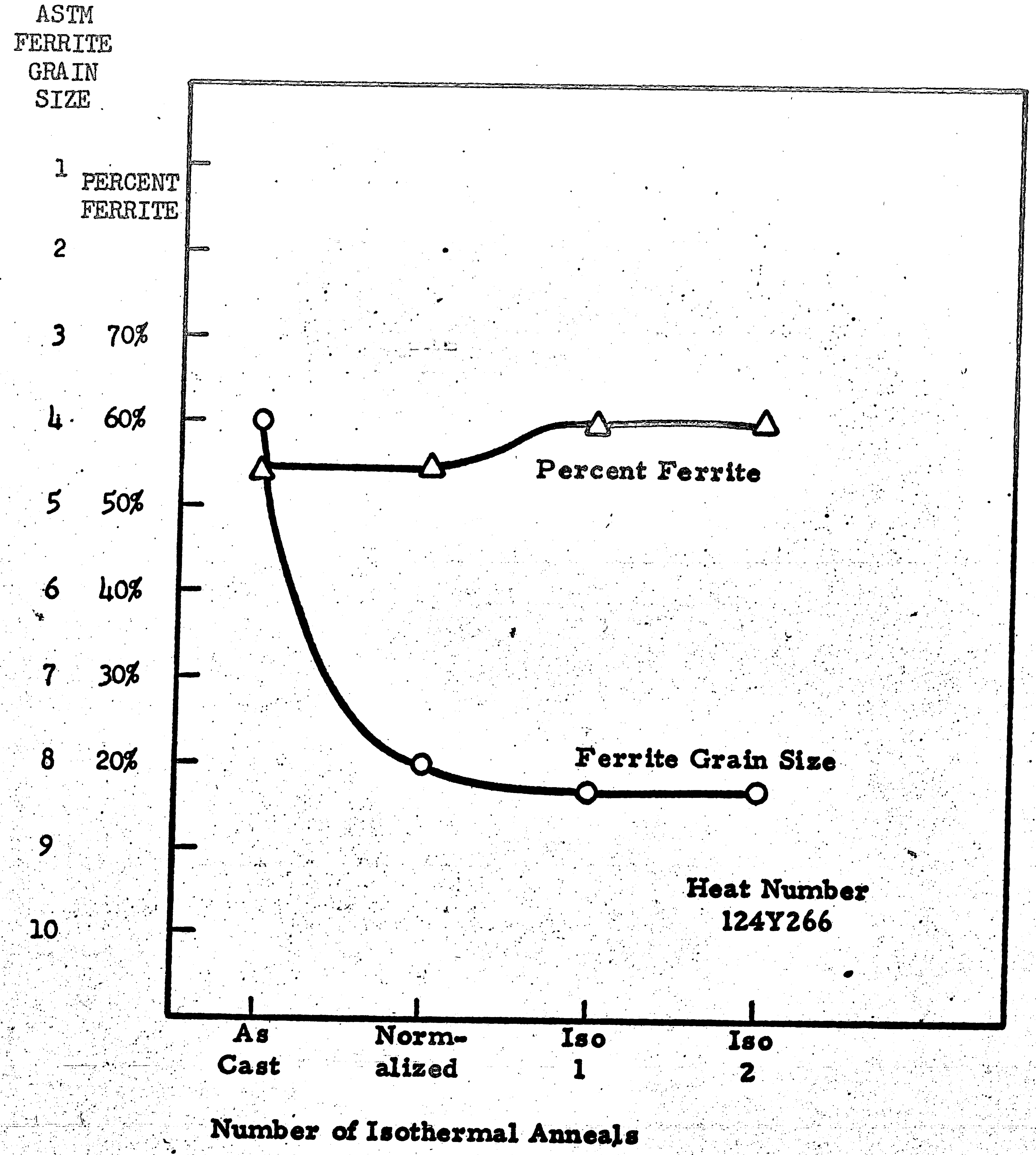

FIGURE 21: Microstructural Features of Cast .28 C .66 Mn "Keel" Blocks

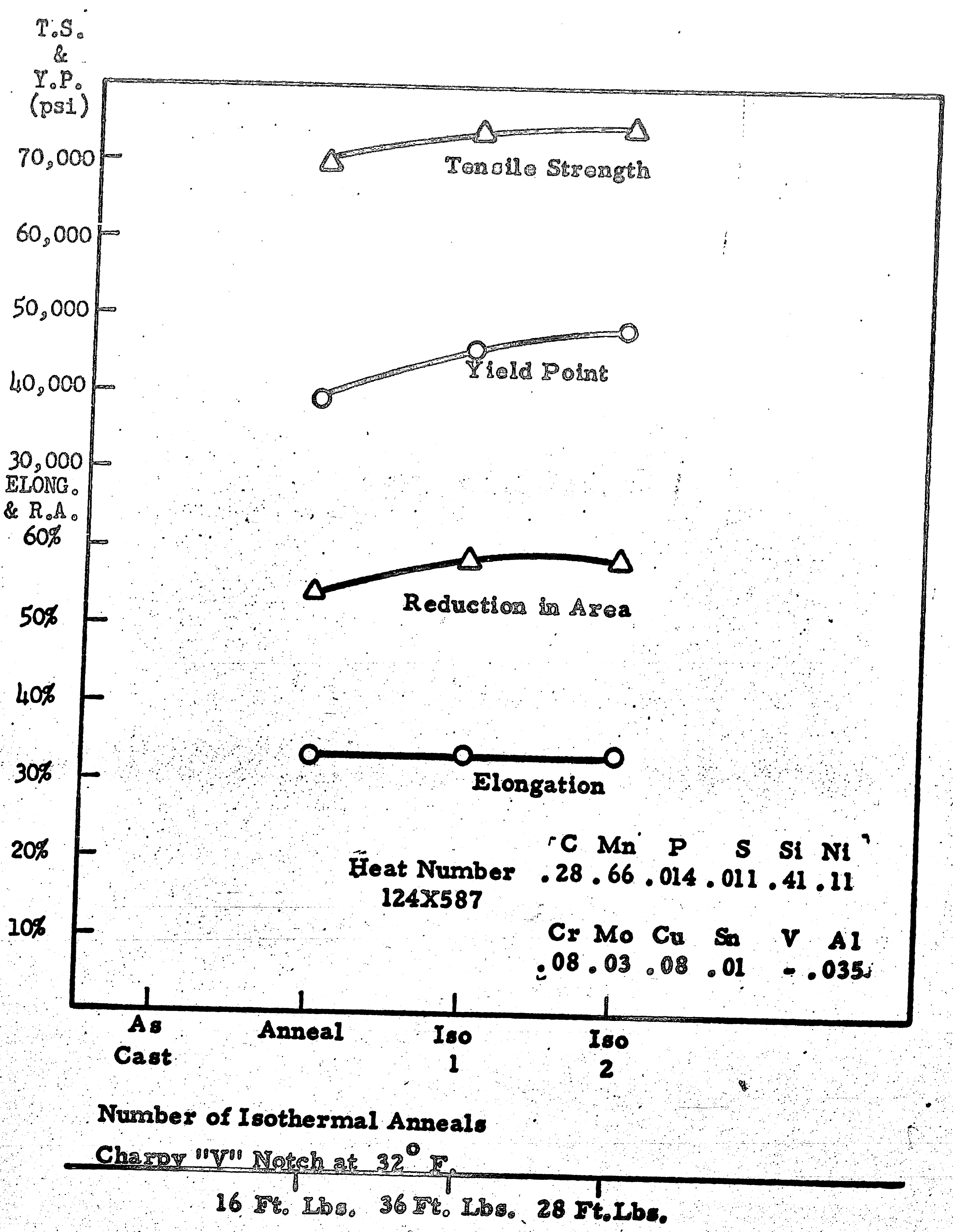

FIGURE 22: Mechanical Properties of Cast .28C .66Mn "Keel" Blocks

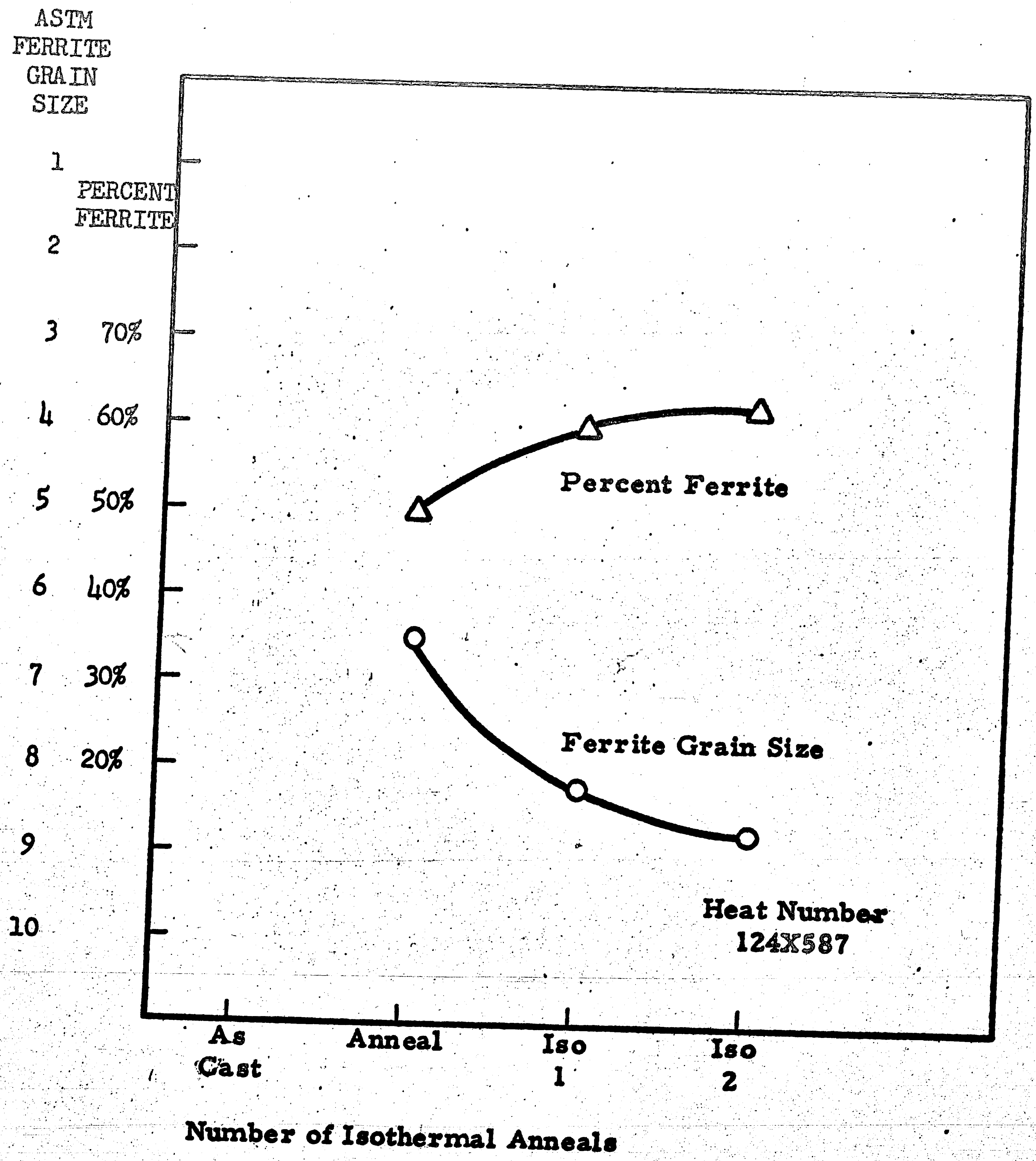

FIGURE 23: Microstructural Features of Cast .28 C .66 Mn "Keel" Blocks

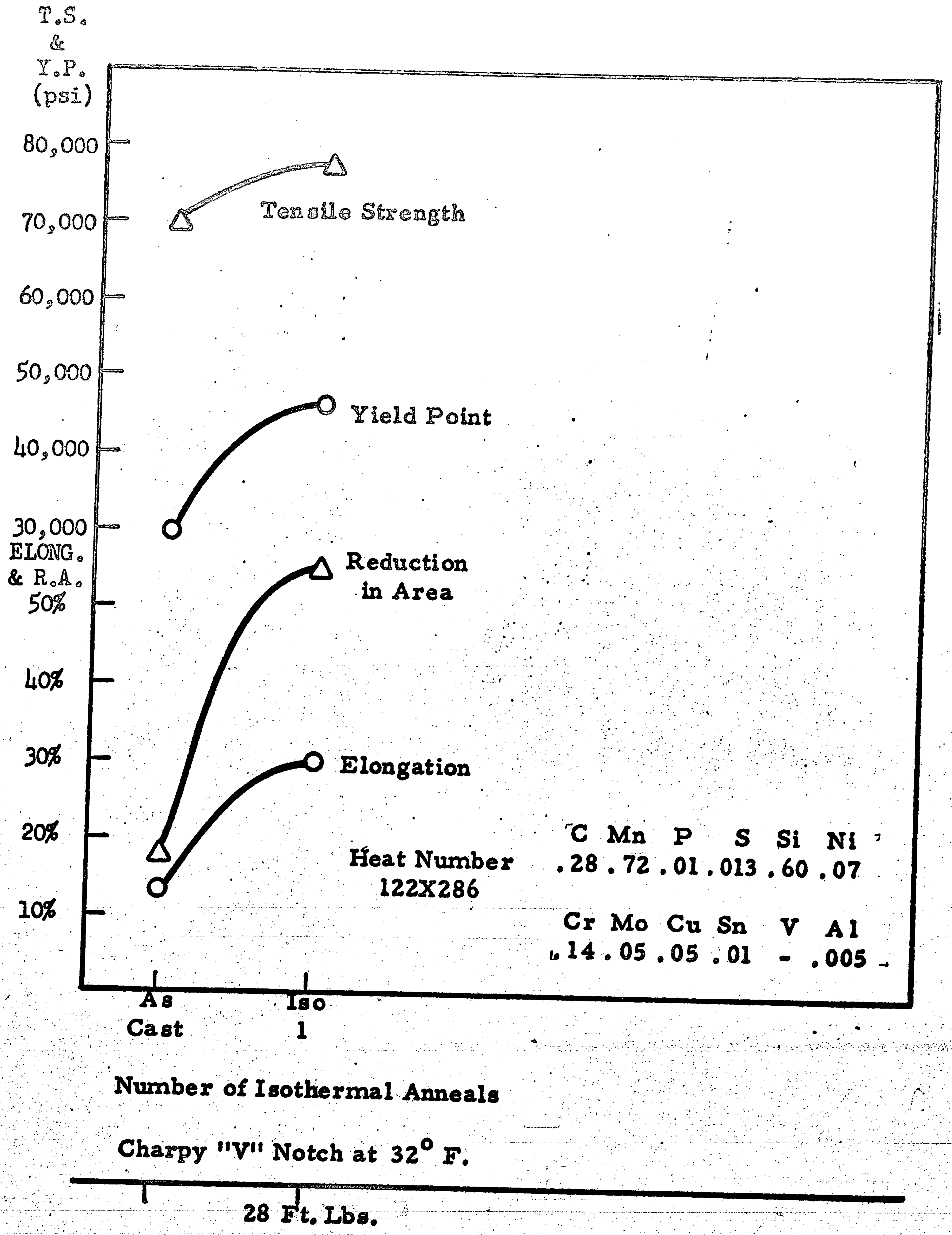

FIGURE 24: Mechanical Properties of Cast .28 C .72 Mn "Keel" Blocks (900° F. Hold)

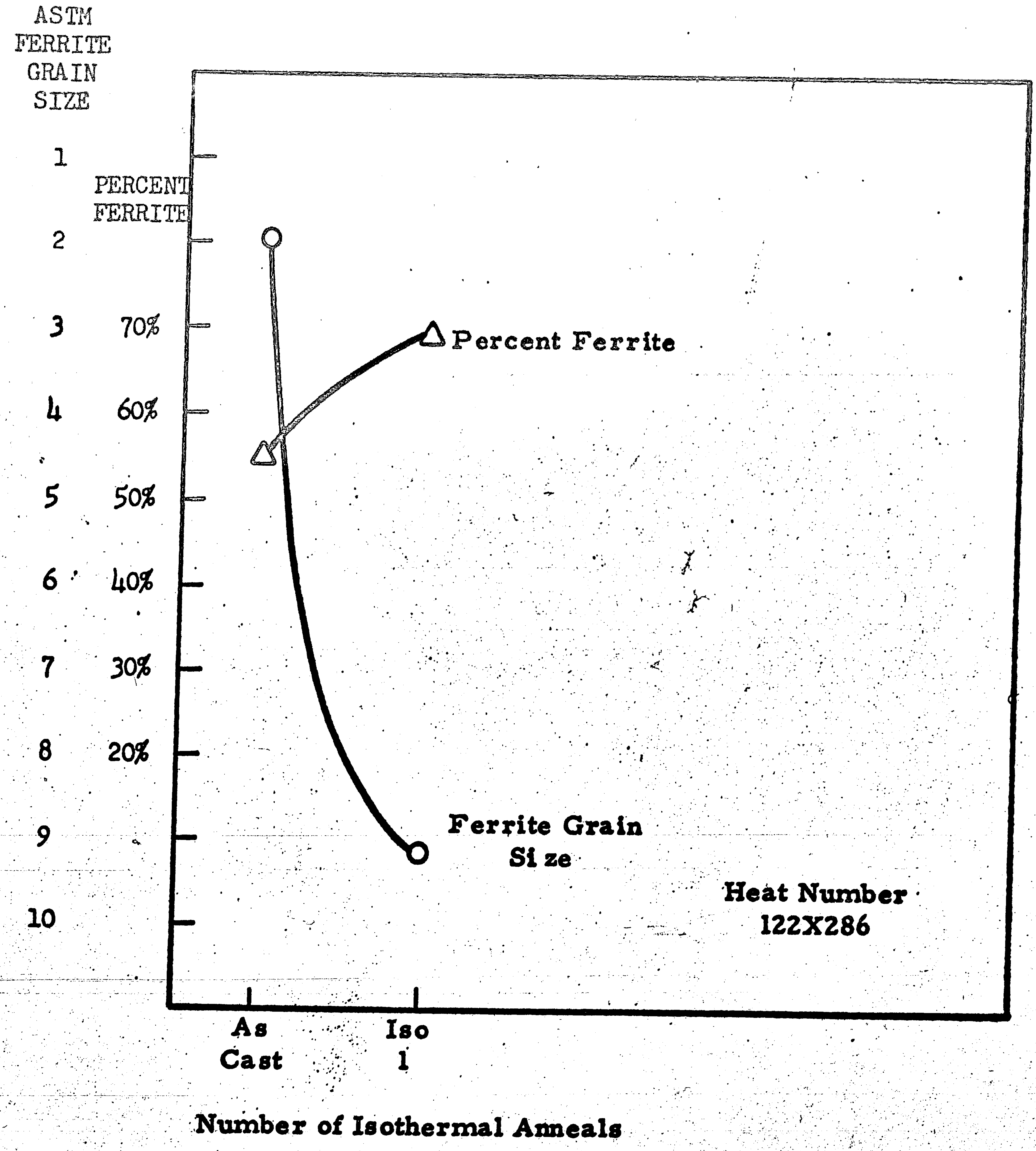

FIGURE 25: Microstructural Fractures of Cast .28 C .72 Mn "Keel" Blocks (900° F. Hold)

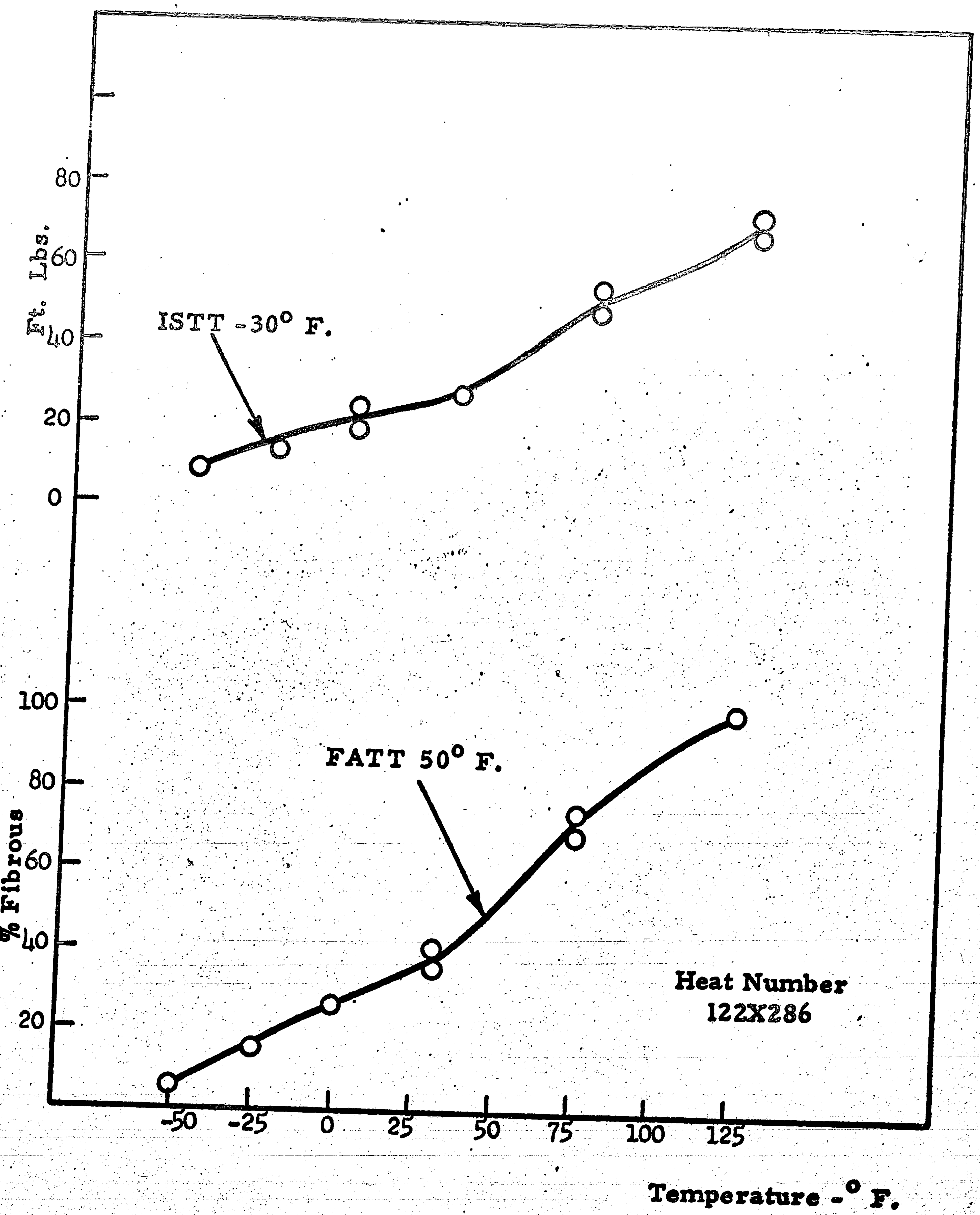

FIGURE 26: Charpy "V" Notch Properties of .28 C .72 Mn "Keel" Blocks after One Isothermal Anneal (900° F. Hold)

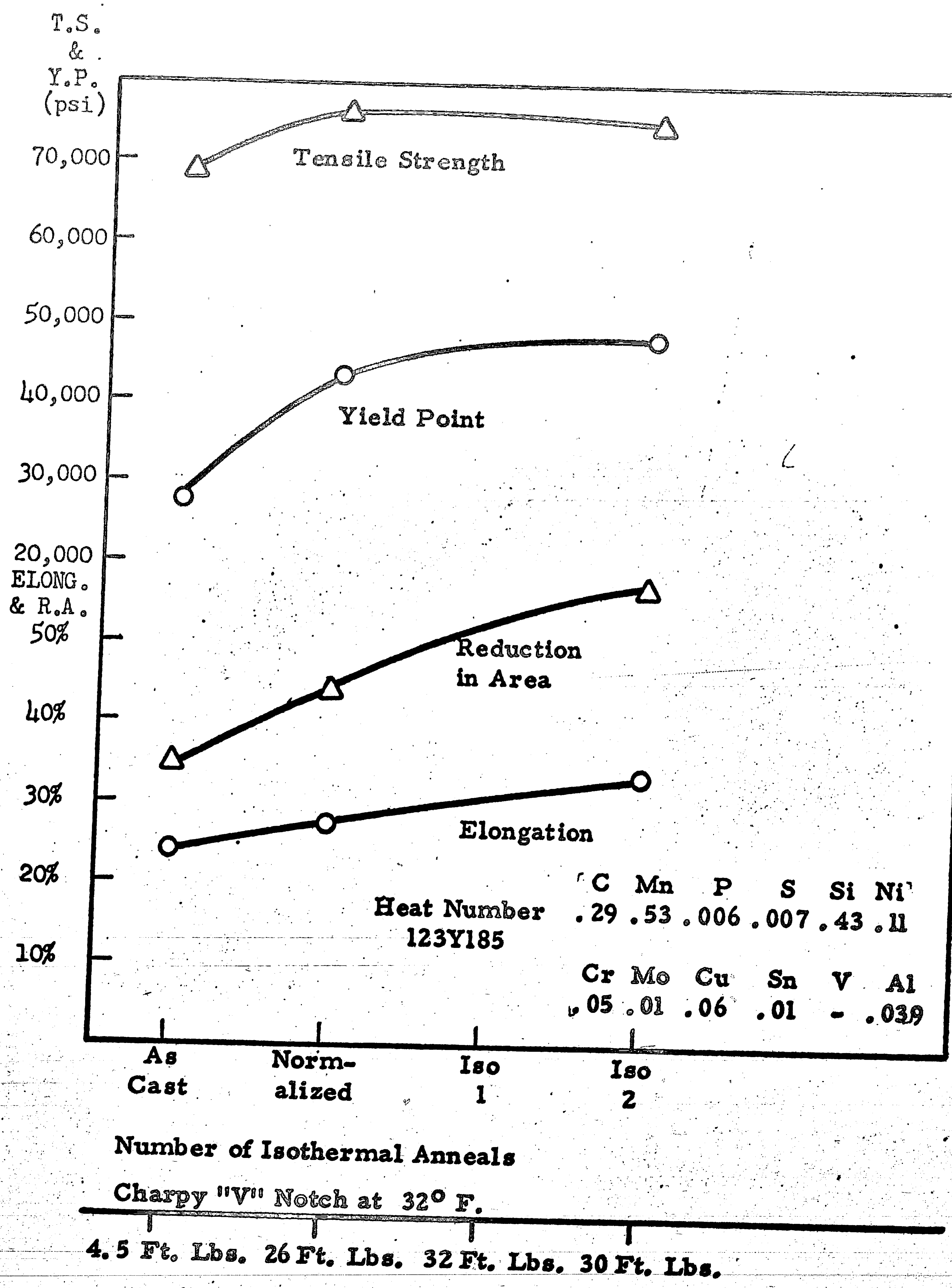

FIGURE 27: Mechanical Properties of Cast .29 C .53 Mn "Keel" Blocks

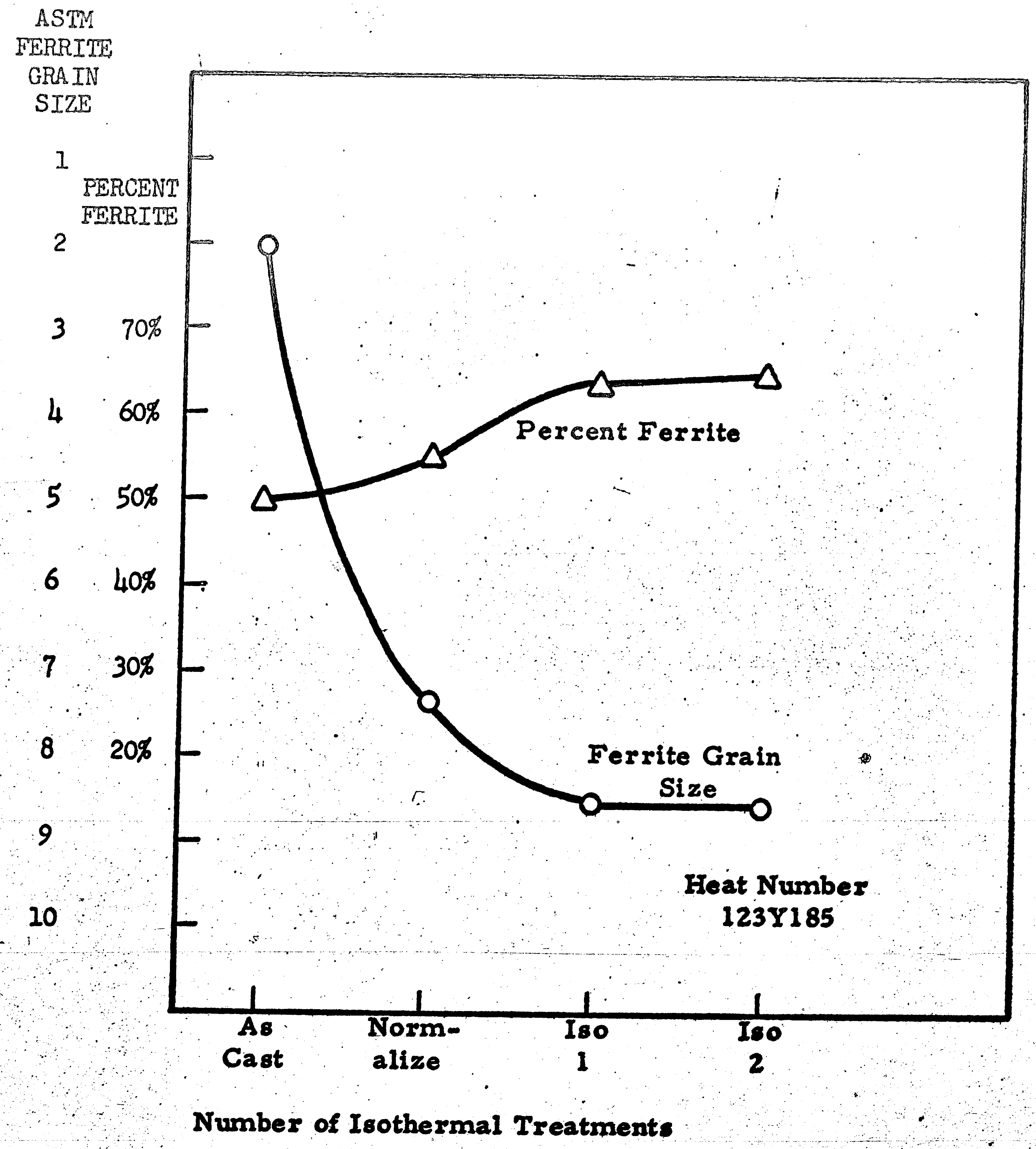

FIGURE 28: Microstructural Features of Cast

.29 C .53 Mn "Keel" Blocks

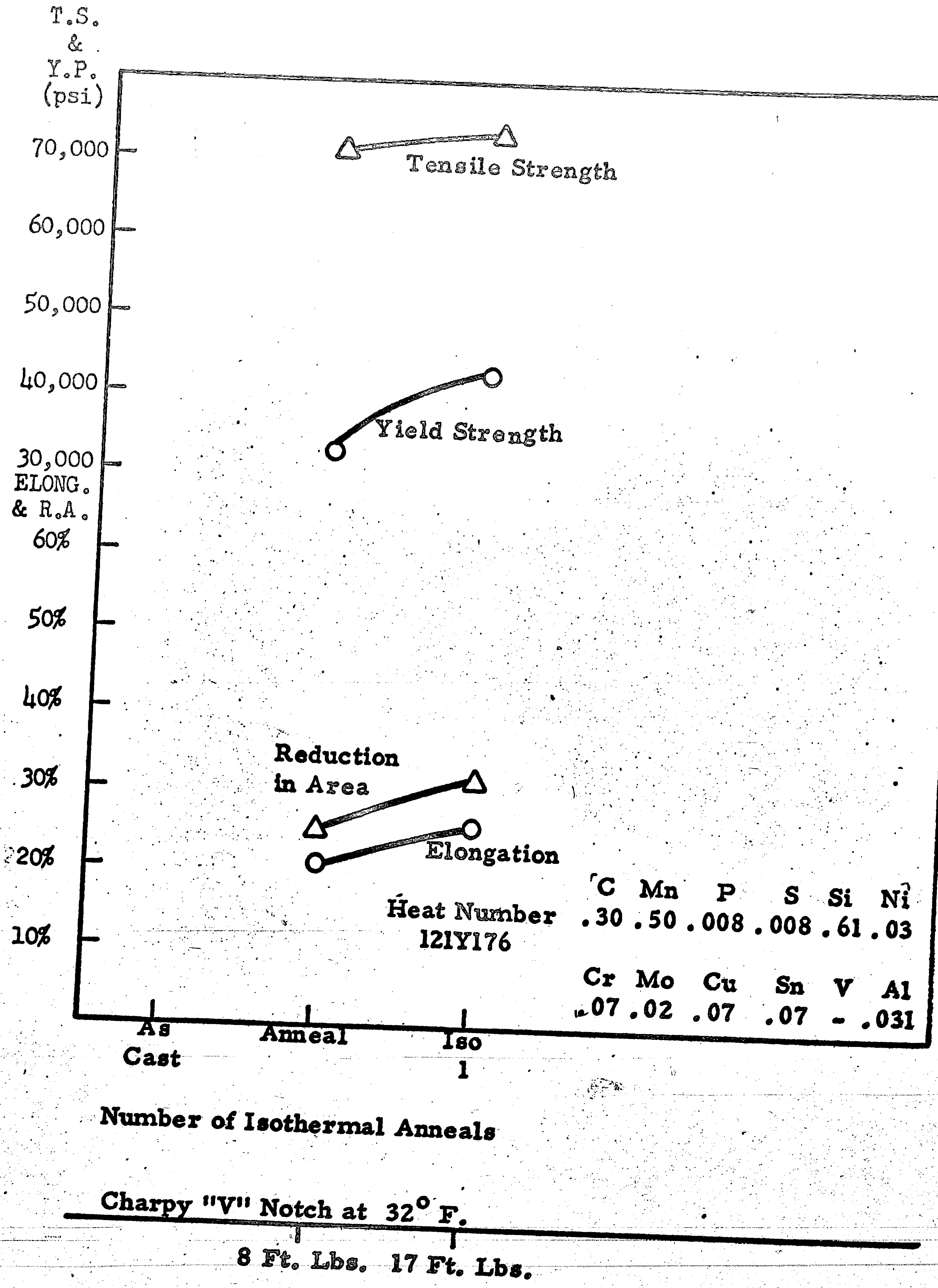

FIGURE 29: Mechanical Properties of Cast .30 C .50 Mn 12" Cubes

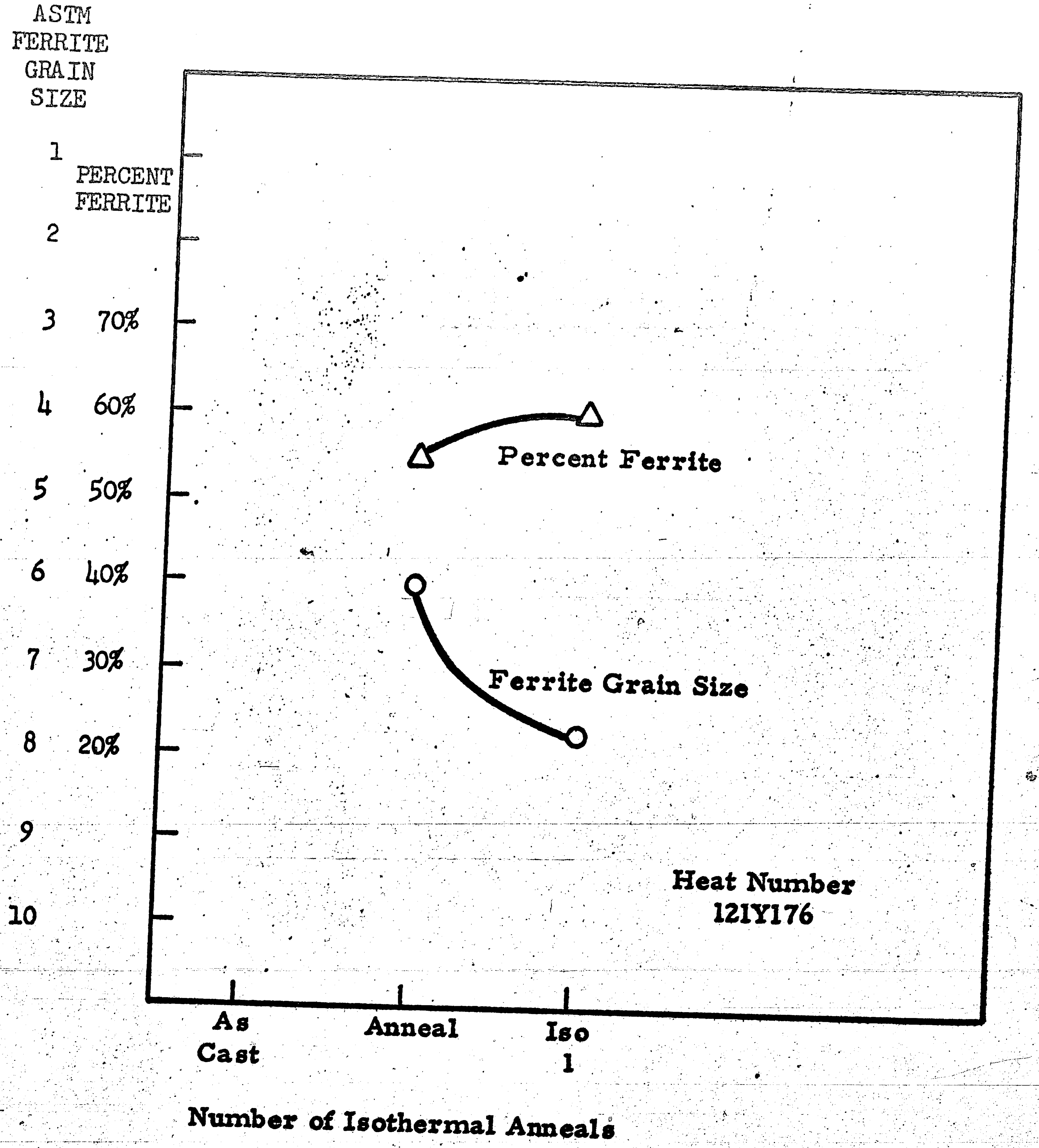

FIGURE 30: Microstructural Features of

Cast .30 C .50 Mn 12" Cube

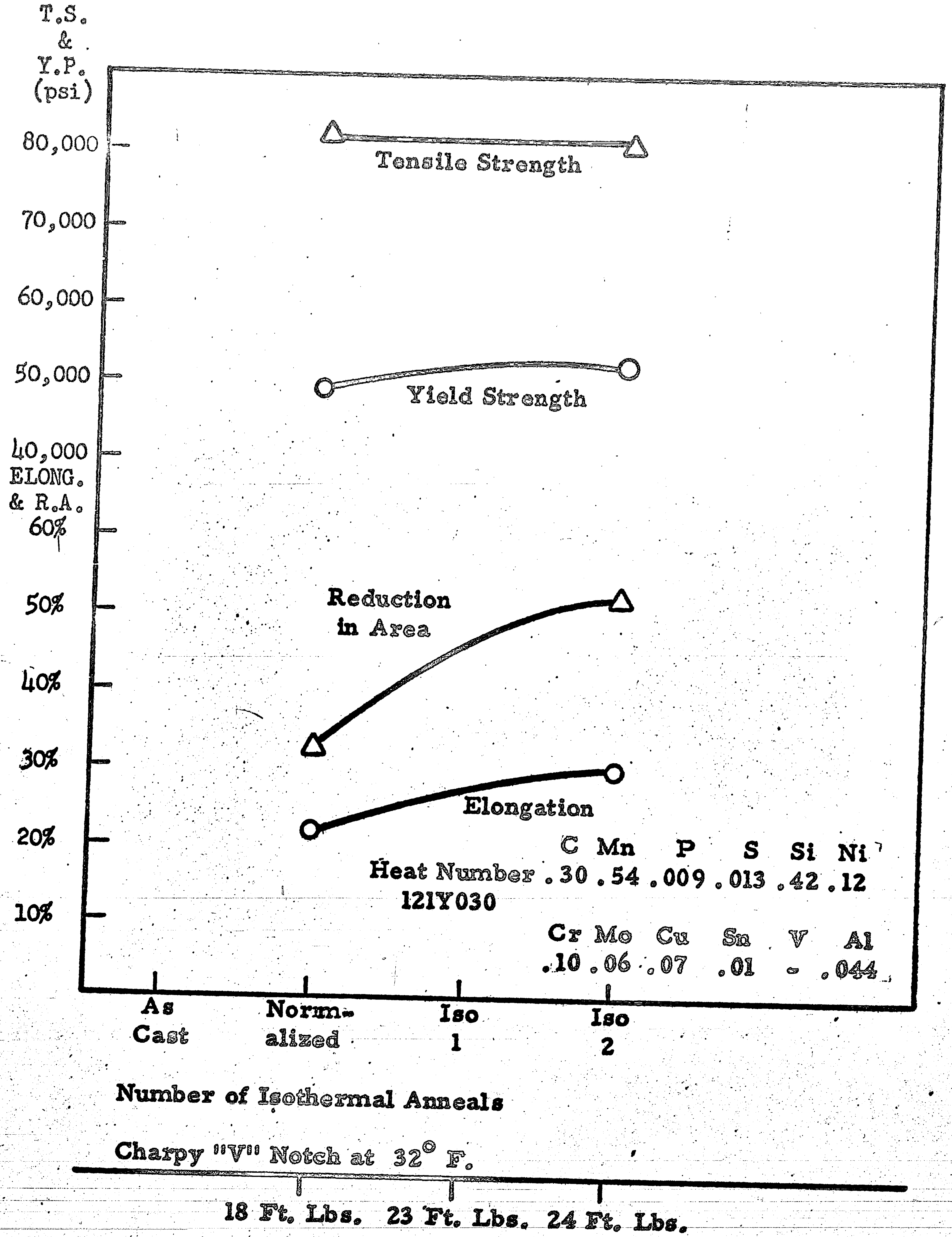

FIGURE 31: Mechanical Properties of Cast .30 C .54 Mn "Keel" Blocks

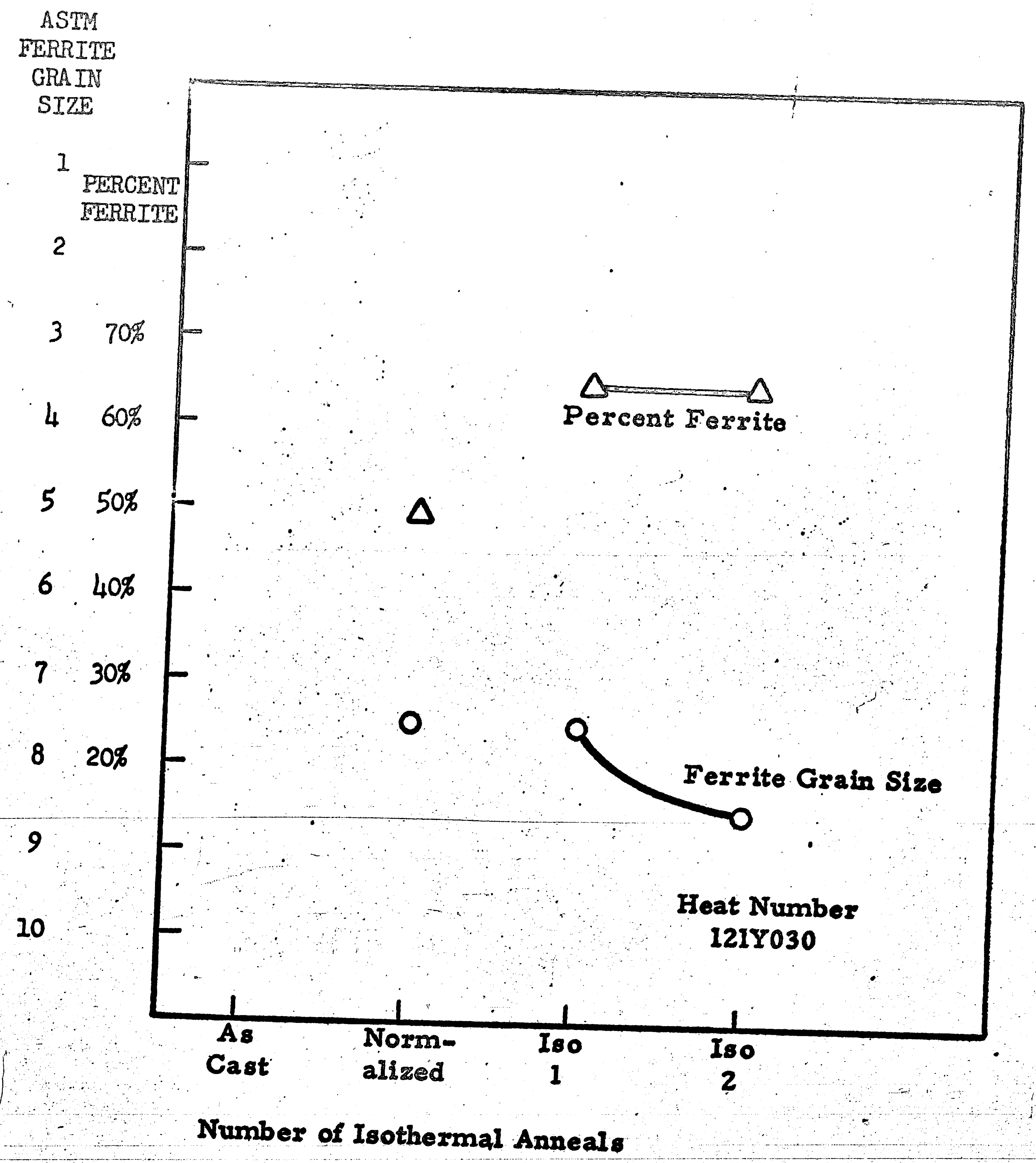

FIGURE 32: Microstructural Features of Cast

.30 C .54 Mn "Keel" Blocks

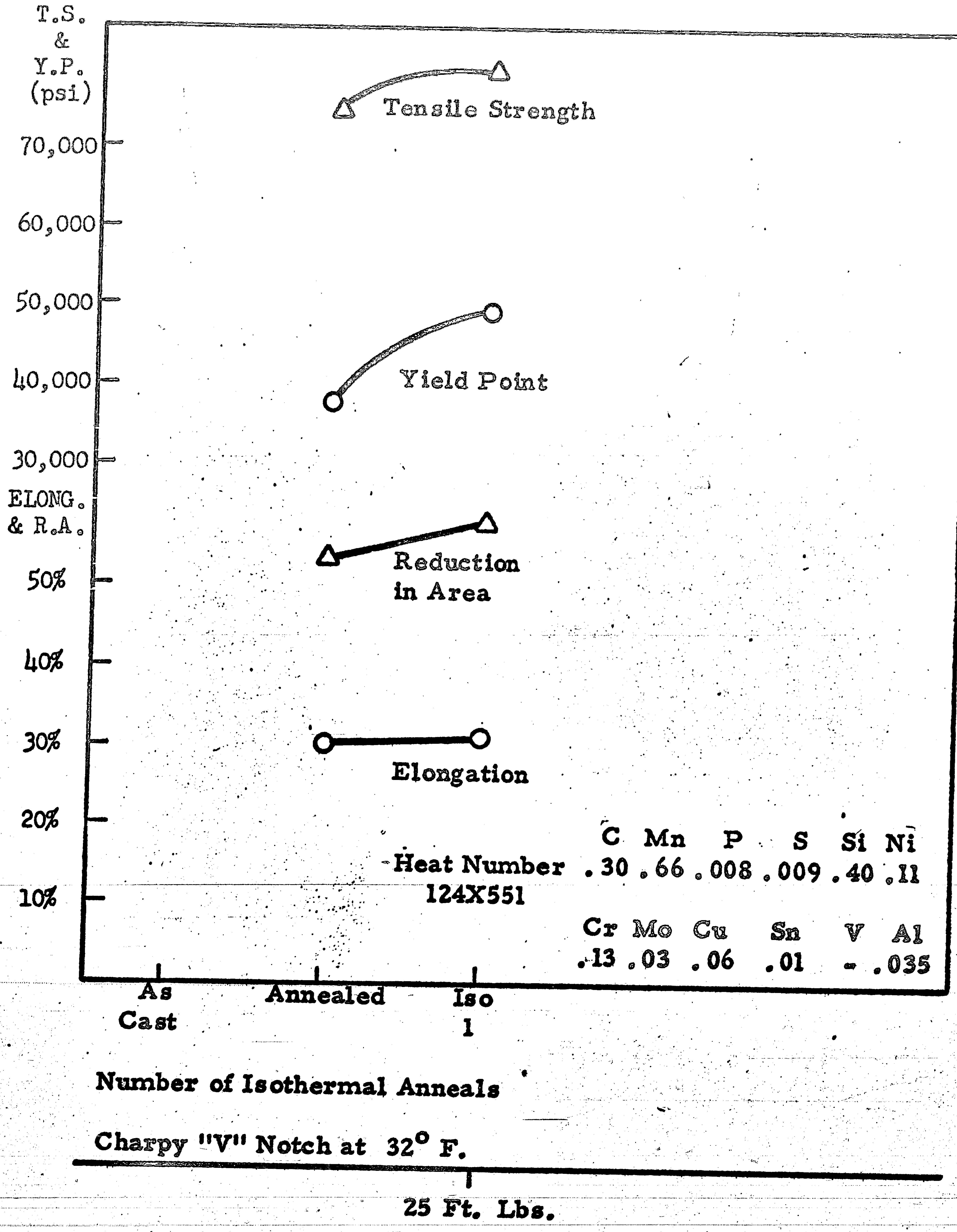

FIGURE 33: Mechanical Properties of Cast .30 C .66 Mn "Keel" Blocks

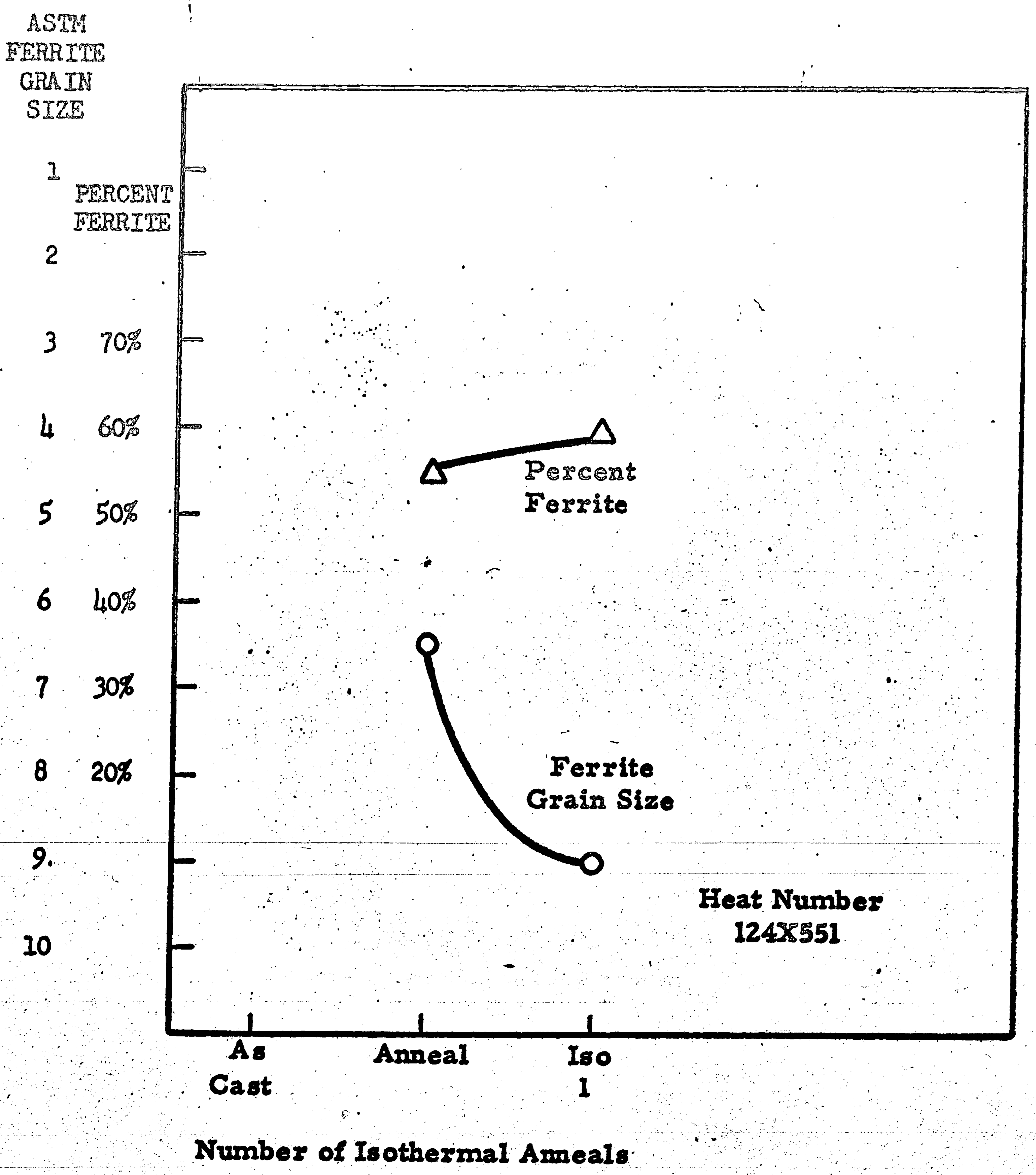

FIGURE 34: Microstructural Features of Cast .30 C .66 Mn "Keel" Blocks

TABLE 7 - Properties of Cast .32 C .60 Mn "Keel" Blocks and 12" Cubes

Grade - Carbon Steel .32 C .60 Mn

Heat No. - 121Z172

Chemical Analysis

C	Mn	P	S	Si	Ni	Cr	Mo
.32	.60	.01	.007	.37	.09	.11	.03

Heat Treatment - Annealed 1675° F. - 8 hrs.
Air Cooled - 1050° F.
Isothermal Hold - 1100° F.
Furnace Cooled - 300° F.

Mechanical Properties

	TS	YS(.2%)	Elong.	RA
"Keel" Block	**81,000**	**46,000**	**29.5%**	**51.1%**
12 Inch Cube	**78,000**	**39,000**	**24.0%**	**36.0%**

Impact Properties - Charpy "V" Notch

Temp. °F.	Ft. Lbs. "Keel"	Ft. Lbs. Cubes	
+175		75, 66	
+125	71, 71	55, 55	
+ 75	52, 48	34, 34	
+ 32	38, 36	20, 12	
0	25, 22	11, 10	
- 25	22, 13	13, 10	
- 50	12, 11	8, 8	
FATT	+65° F.	+100° F.	
ISTT	-35° F.	+ 30° F.	(Temperature at which 15 ft. lbs. is obtained)

(Test material was heat treated as an integral part of the casting.)

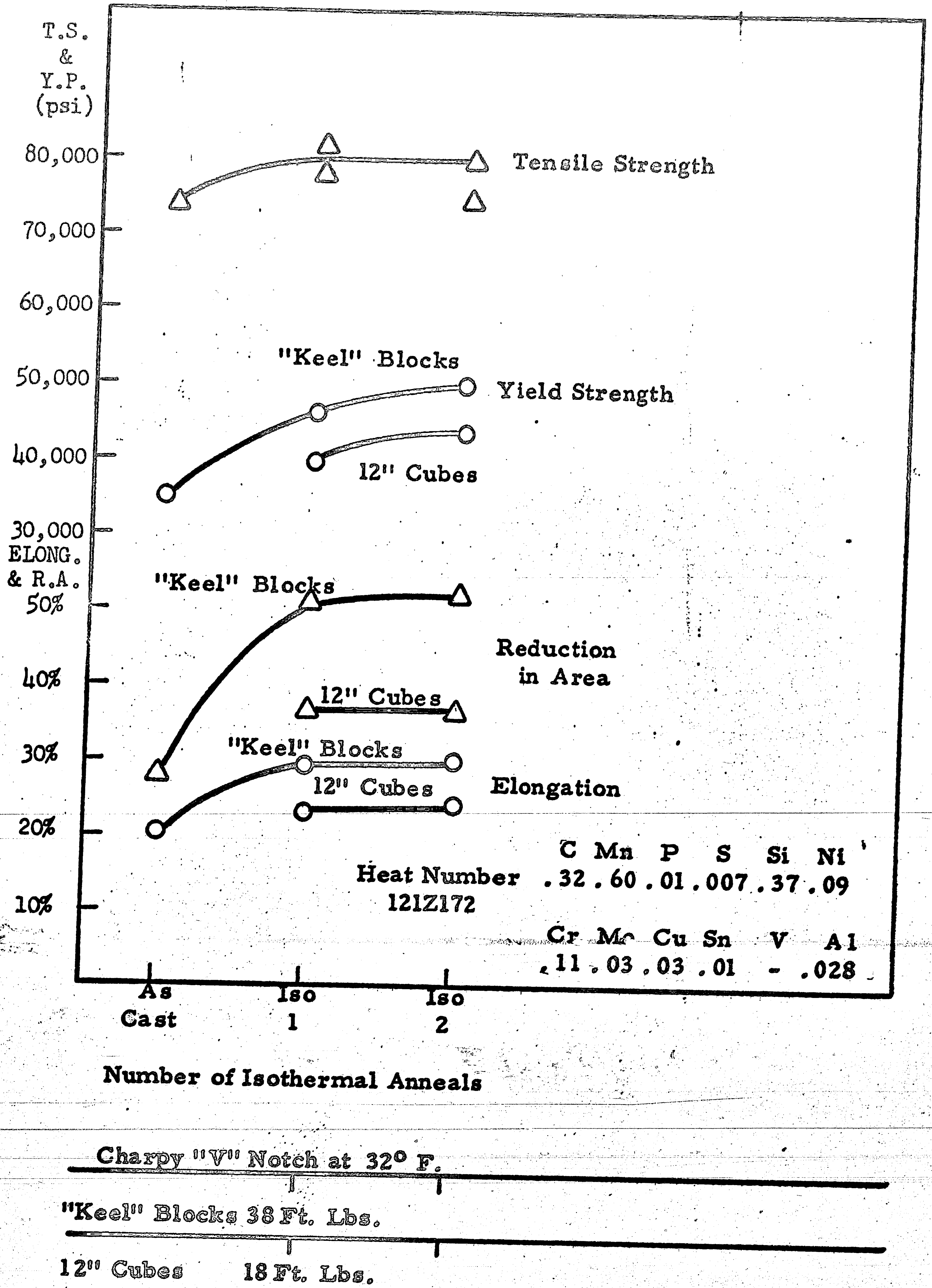

FIGURE 35: Mechanical Properties of Cast C - Mn

"Keel" Blocks and 12" Cubes

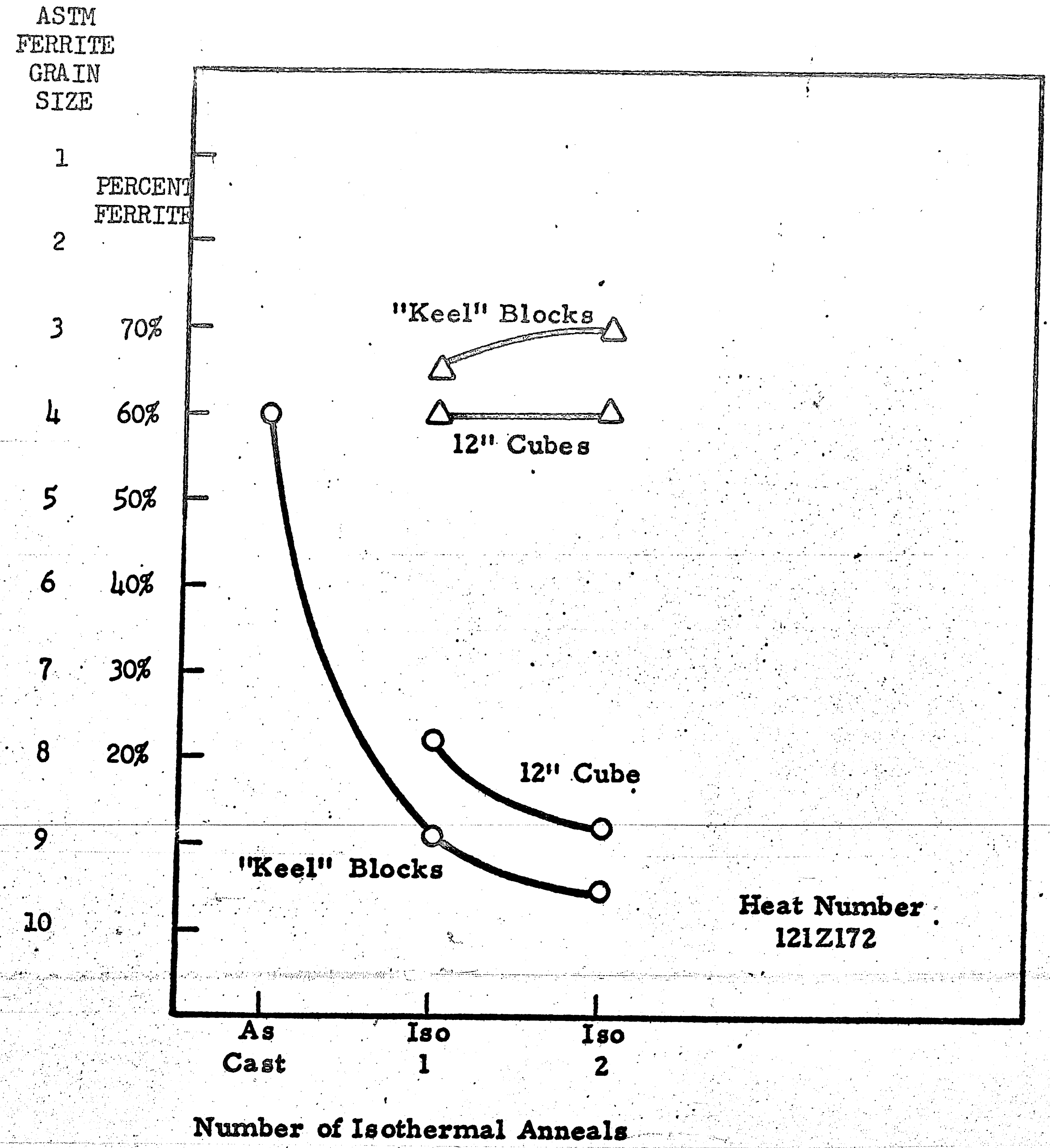

FIGURE 36: Microstructural Features of Cast .32 C .60 Mn "Keel" Blocks and 12" Cubes

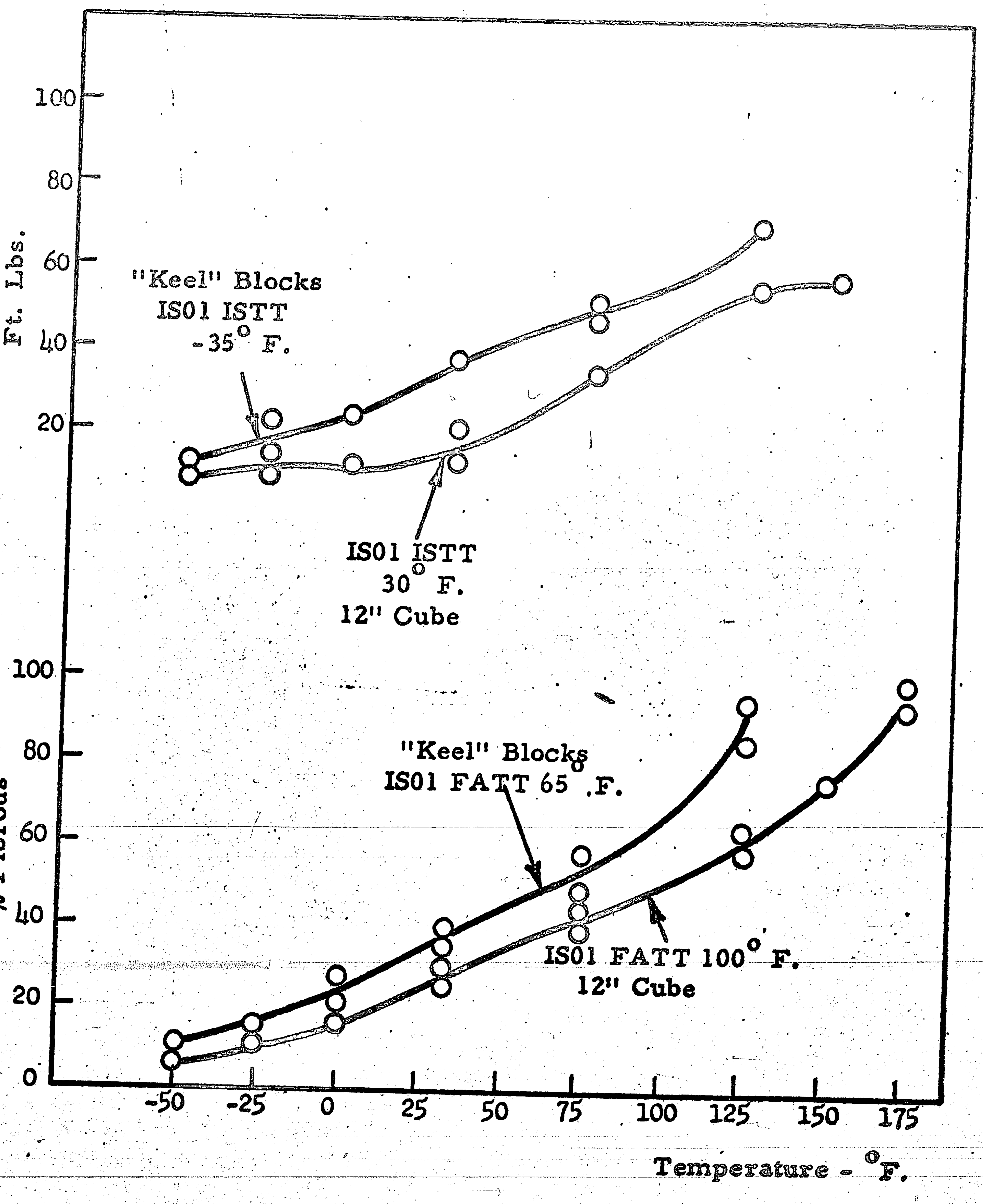

FIGURE 37: Charpy "V" Notch Properties of .32C .60 Mn "Keel" Block and 12" Cube After One Isothermal Anneal

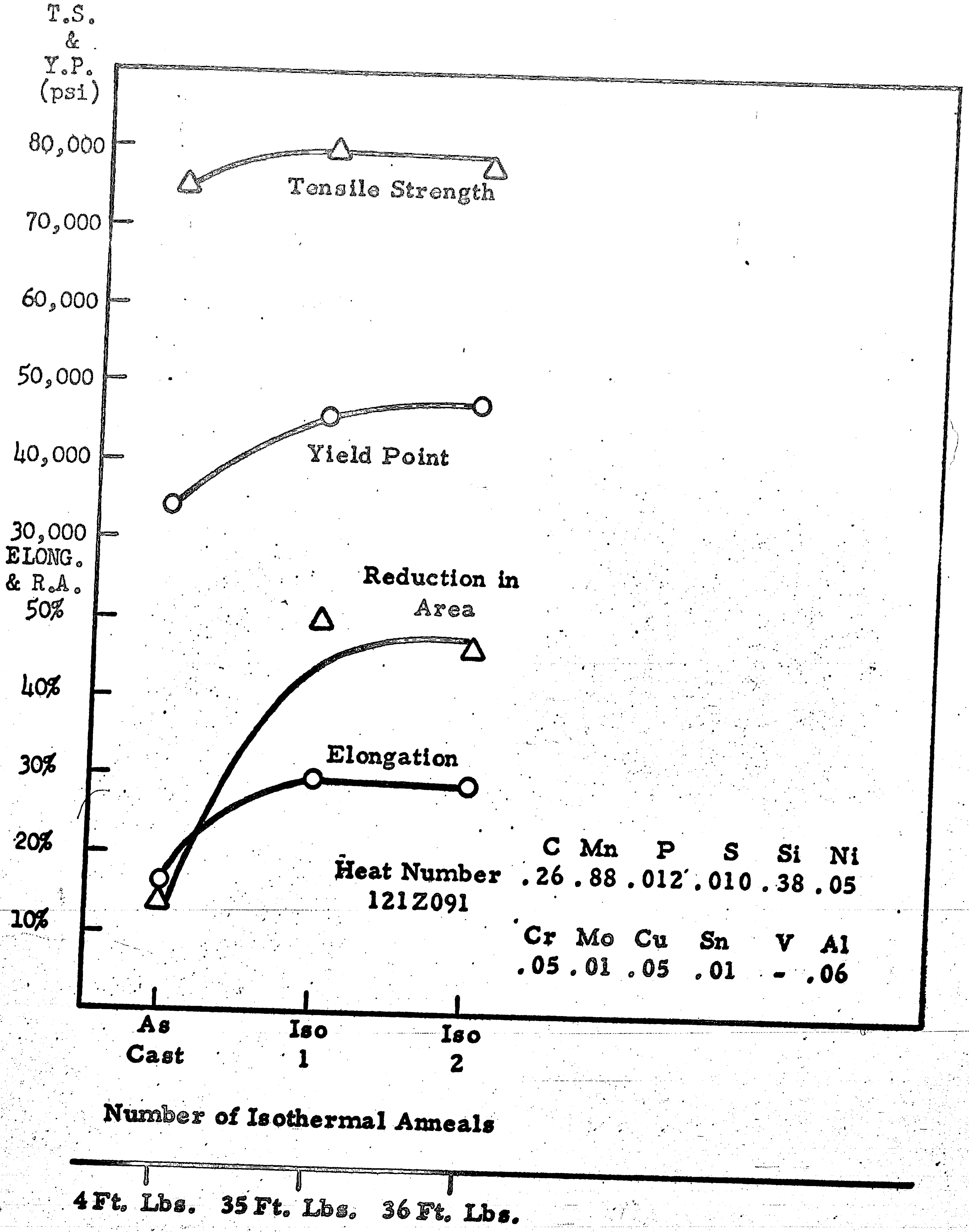

FIGURE 38: Mechanical Properties of Cast

.26C .88Mn "Keel" Blocks

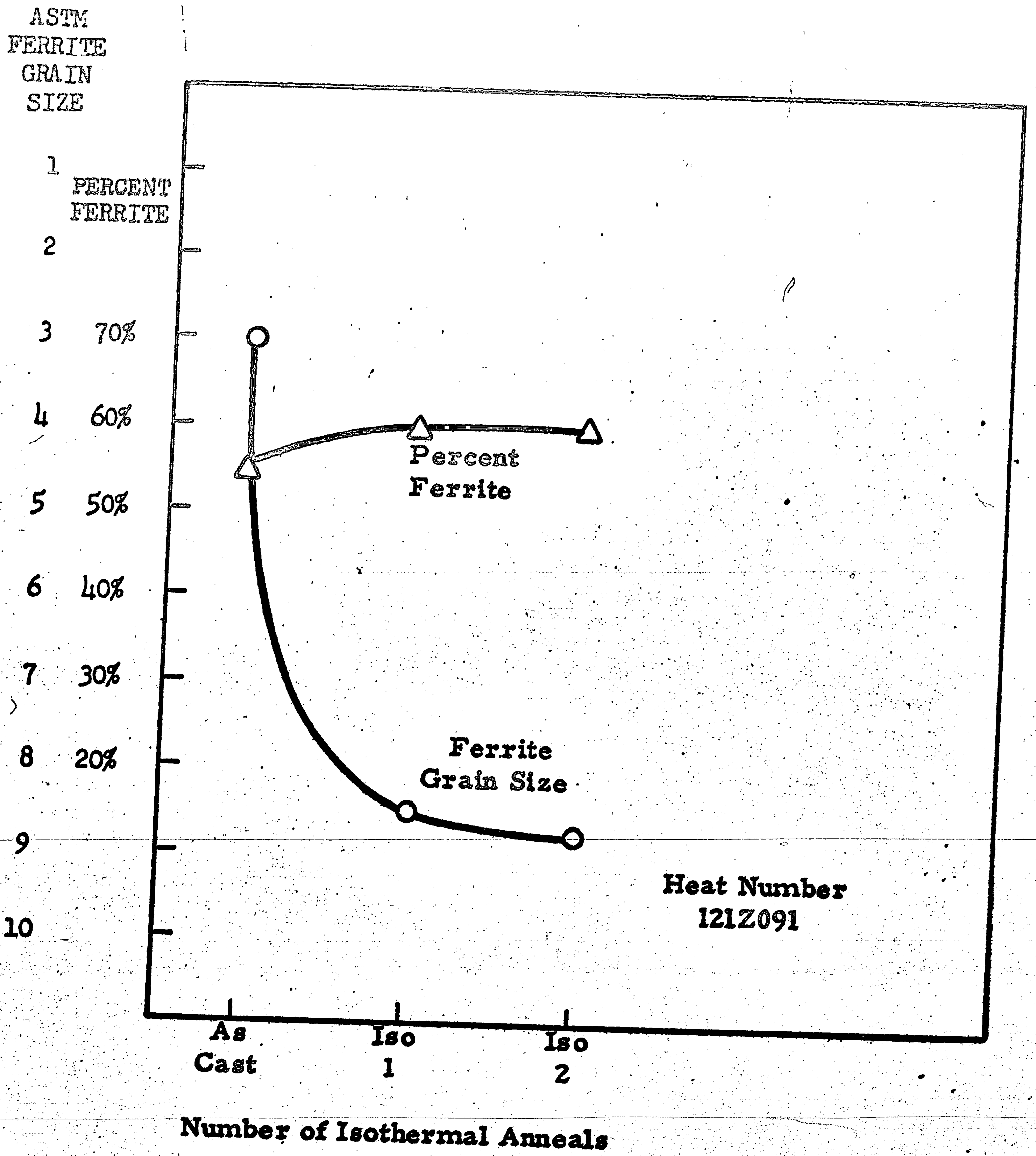

FIGURE 39: Microstructural Features of Cast .26 C .88 Mn "Keel" Blocks

TABLE 8 - Properties of Cast .28C .91Mn "Keel" Blocks

Grade - Carbon Steel .28C .91Mn

Heat No. - 121Z154

Chemical Analysis

C	Mn	P	S	Si	Ni	Cr	Mo
.28	.91	.01	.009	.45	.03	.06	.02

Heat Treatment - Annealed 1675° F. - 8 hrs.
Air Cooled - 1050° F.
Isothermal Hold - 1100° F. - 6 hrs.
Furnace Cooled

Mechanical Properties

TS	YS(.25%)	Elong.	RA
81,000	52,000	33%	58%

Impact Properties - Charpy "V" Notch

Temp. °F.	Ft. Lbs.
+125	89, 86
+ 75	70, 59
+ 32	41, 38
0	31, 27
- 25	23, 18
- 50	22, 12
- 75	8, 4
FATT	+55° F.
ISTT	-55° F. (Temperature at which 15 ft. lbs. is obtained)

(Test material was heat treated as an integral part of the casting.)

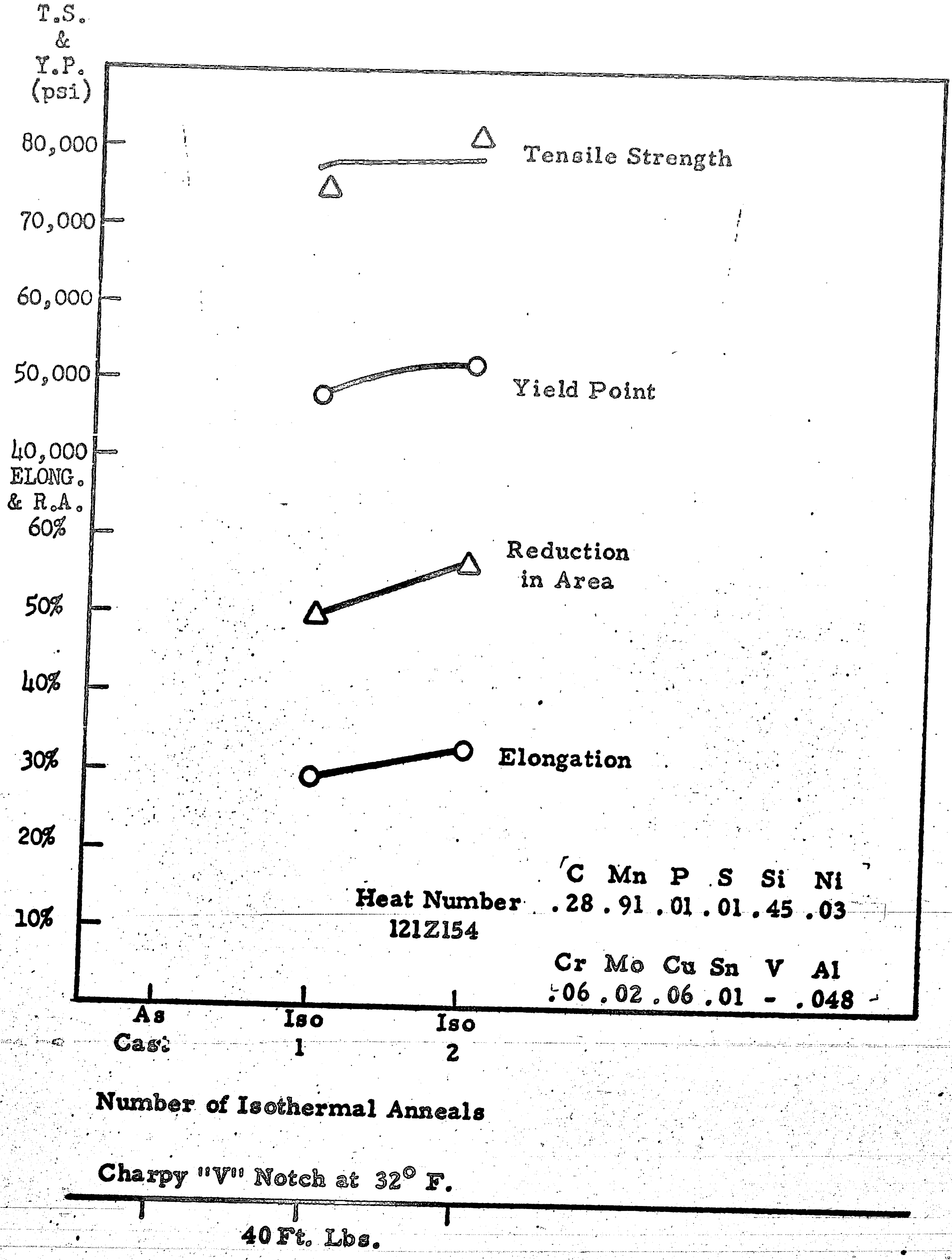

FIGURE 40: Mechanical Properties of Cast .28C .91Mn "Keel" Blocks

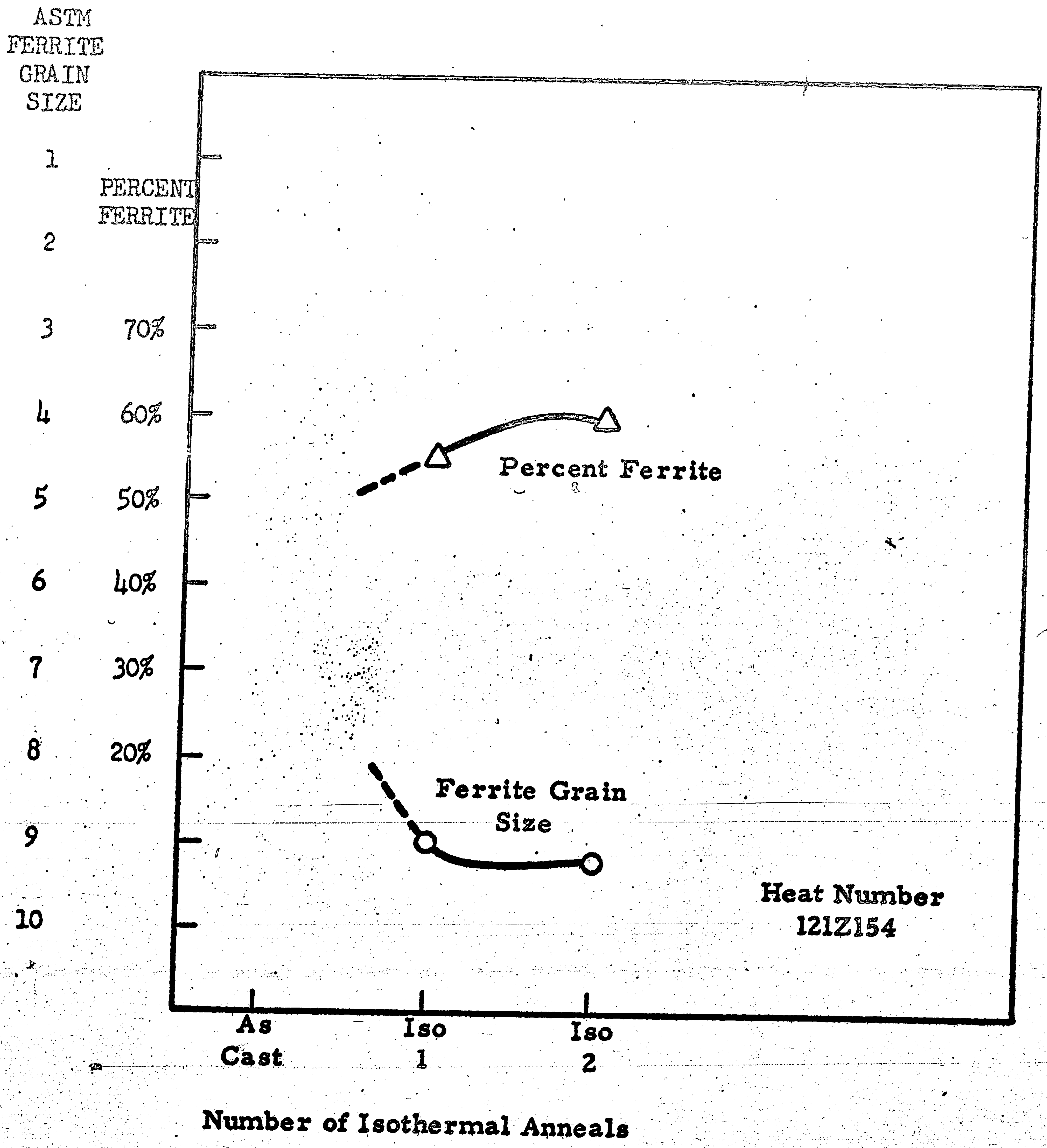

FIGURE 41: Microstructural Features of Cast .28 C .91 Mn

Cast "Keel" Blocks and 12" Cubes

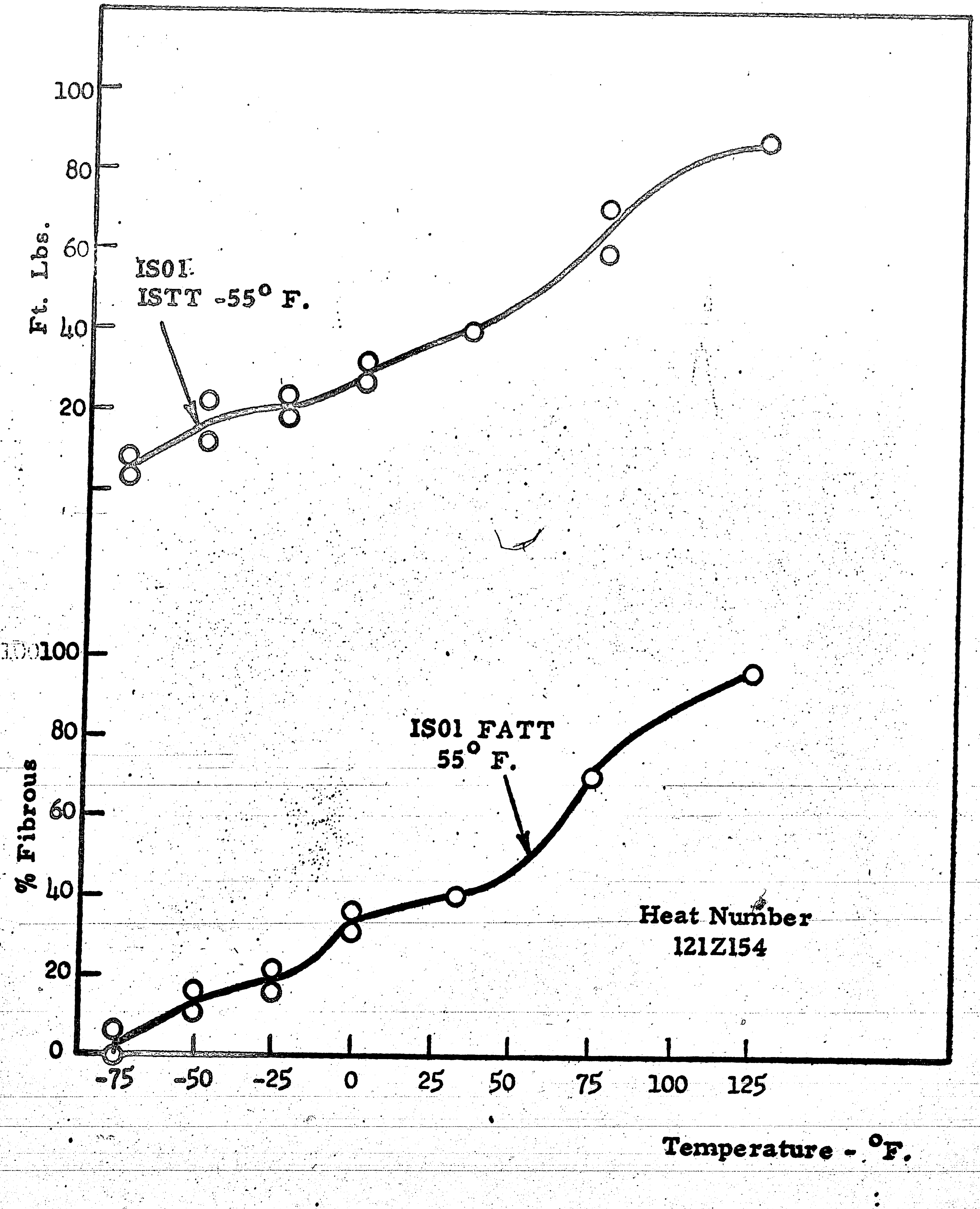

FIGURE 42: Charpy "V" Notch Properties of .28 C .91 Mn "Keel" Blocks After One Isothermal Anneal

TABLE 9 - Properties of Cast .25 C 1.36 Mn "Keel" Block

Grade - Carbon Steel .25 C 1.36 Mn

Heat No. - 703Y020

Chemical Analysis

C	Mn	P	S	Si	Ni	Cr	Mo
.25	1.36	.01	.016	.50	.07	.03	.07

Heat Treatment - Annealed 1675° F. - 8 hrs.
Air Cooled - 1050° F.
Isothermal Hold - 1100° F.
Furnace Cooled

Mechanical Properties

TS	YS(.2%)	Elong.	RA
83,000	53,000	28.5%	54.9%

Impact Properties - Charpy "V" Notch

Temp. °F.	Ft. Lbs.
+175	87, 78
+125	80, 71
+ 75	54, 51
+ 32	47, 35
0	27, 24
- 25	23, 23
- 50	22, 22
- 75	6, 4
FATT	+45° F.
ISTT	-65° F. (Temperature at which 15 ft. lbs. is obtained)

Drop Weight - "P_2" - 10° F.

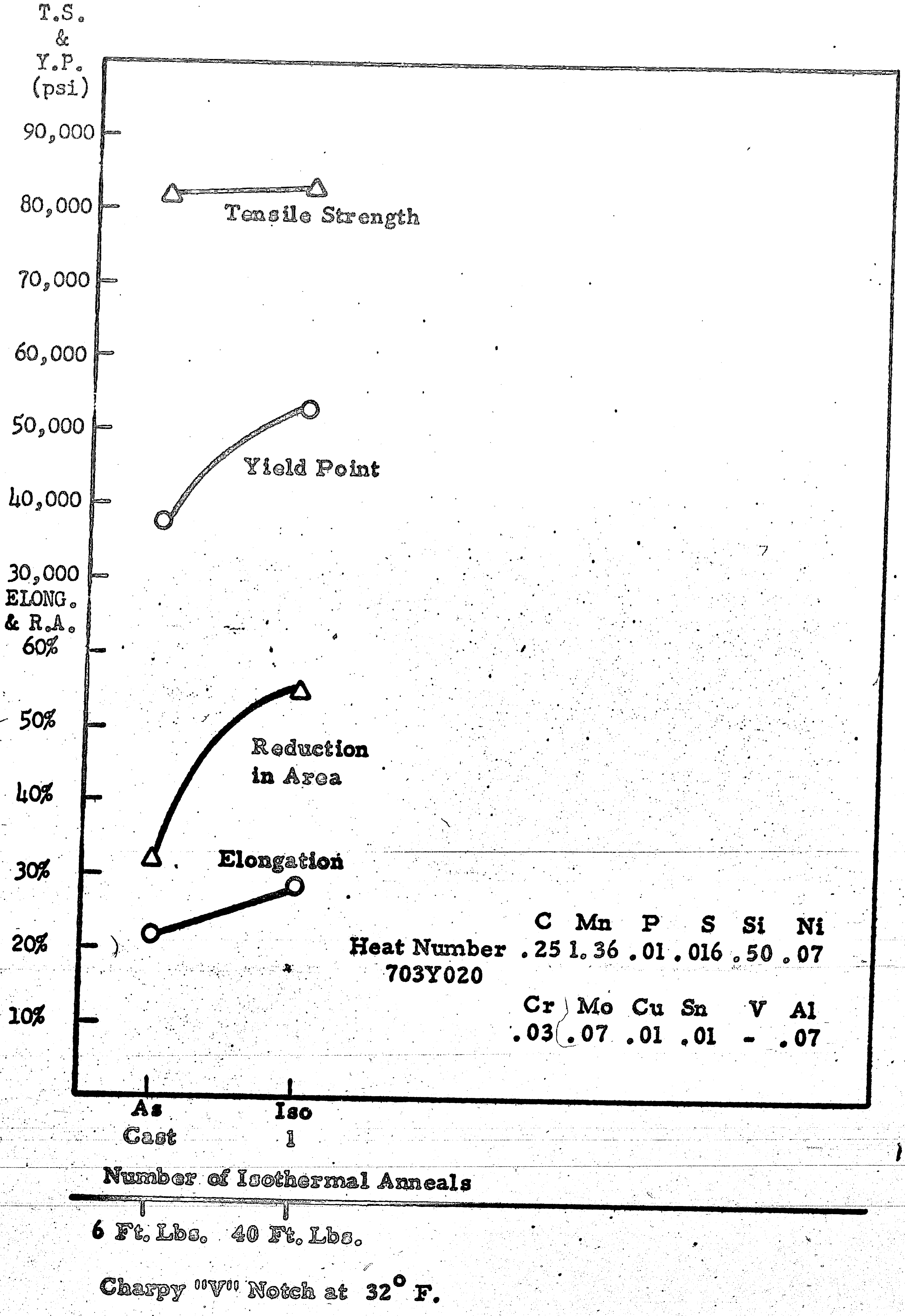

FIGURE 43: Mechanical Properties of Cast .25 C -1.36 Mn "Keel Blocks

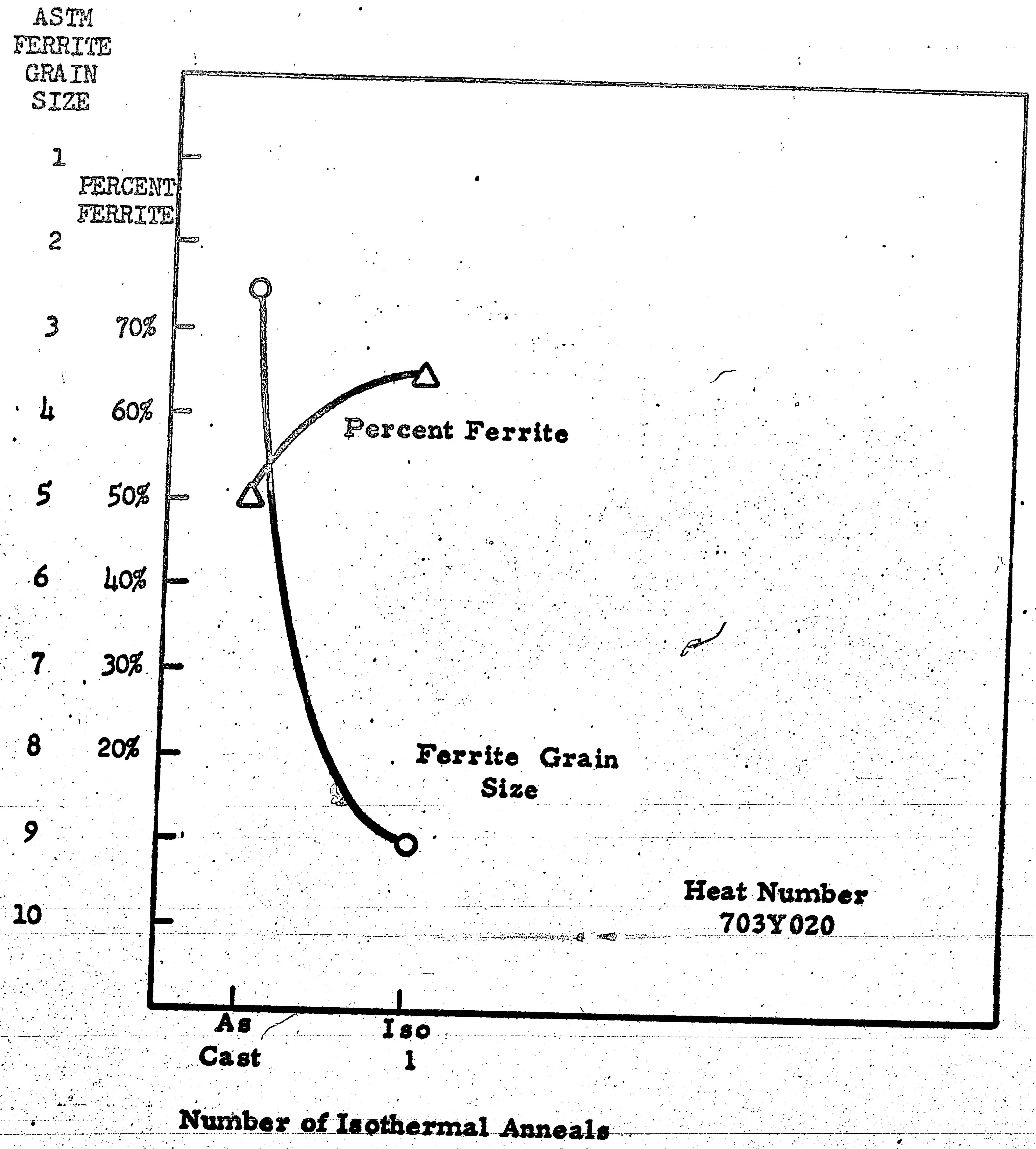

FIGURE 44: Microstructural Features of Cast .25C 1.36Mn "Keel" Blocks

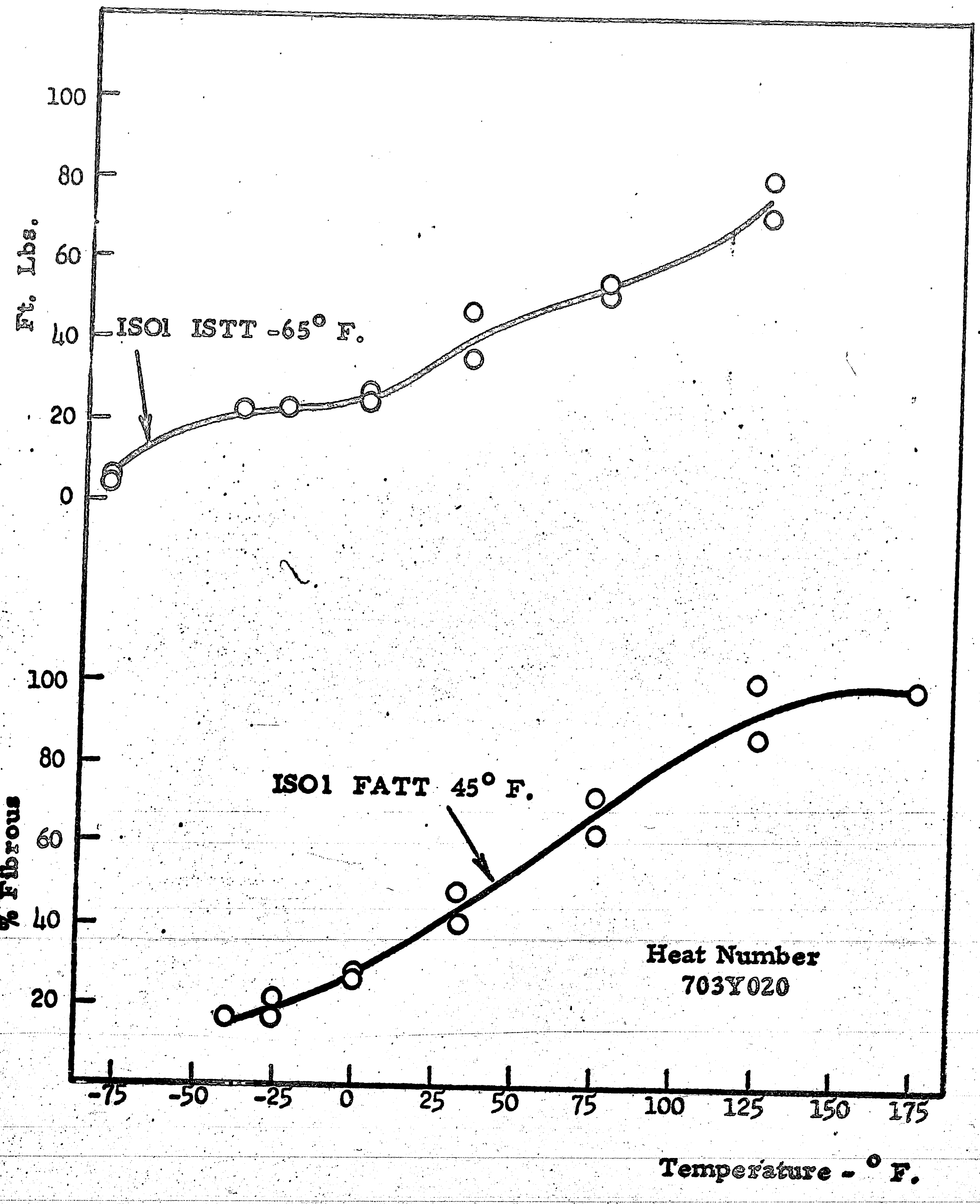

FIGURE 45: Charpy "V" Notch Properties of .25 C 1.36 Mn "Keel" Blocks After One Isothermal Treatment

TABLE 10 - Properties of Cast .26 C 1.16 Mn 12" Cube

Grade - Carbon Steel .26 C 1.16 Mn

Heat No. - 703Z019

Chemical Analysis

C	Mn	P	S	Si	Ni	Cr	Mo
.26	1.16	.006	.004	.38	.08	.04	.07

Heat Treatment - Annealed 1675° F. - 8 hrs.
Air Cooled - 1050° F.
Isothermal Hold - 1100° F. - 6 hrs.
Furnace Cooled - 300° F.

Mechanical Properties

TS	YS(.2%)	Elong.	RA
80,000	49,000	24%	39%

Impact Properties - Charpy "V" Notch

Temp. °F.	Ft. Lbs.
+175	87,86
+125	80,77
+ 75	65,60
+ 32	38,28
0	24,22
- 25	22,18
- 50	18,12
- 75	7, 4
FATT	+65° F.
ISTT	-50° F. (Temperature at which 15 ft. lbs. is obtained)

(Test material was heat treated as an integral part of the casting.)

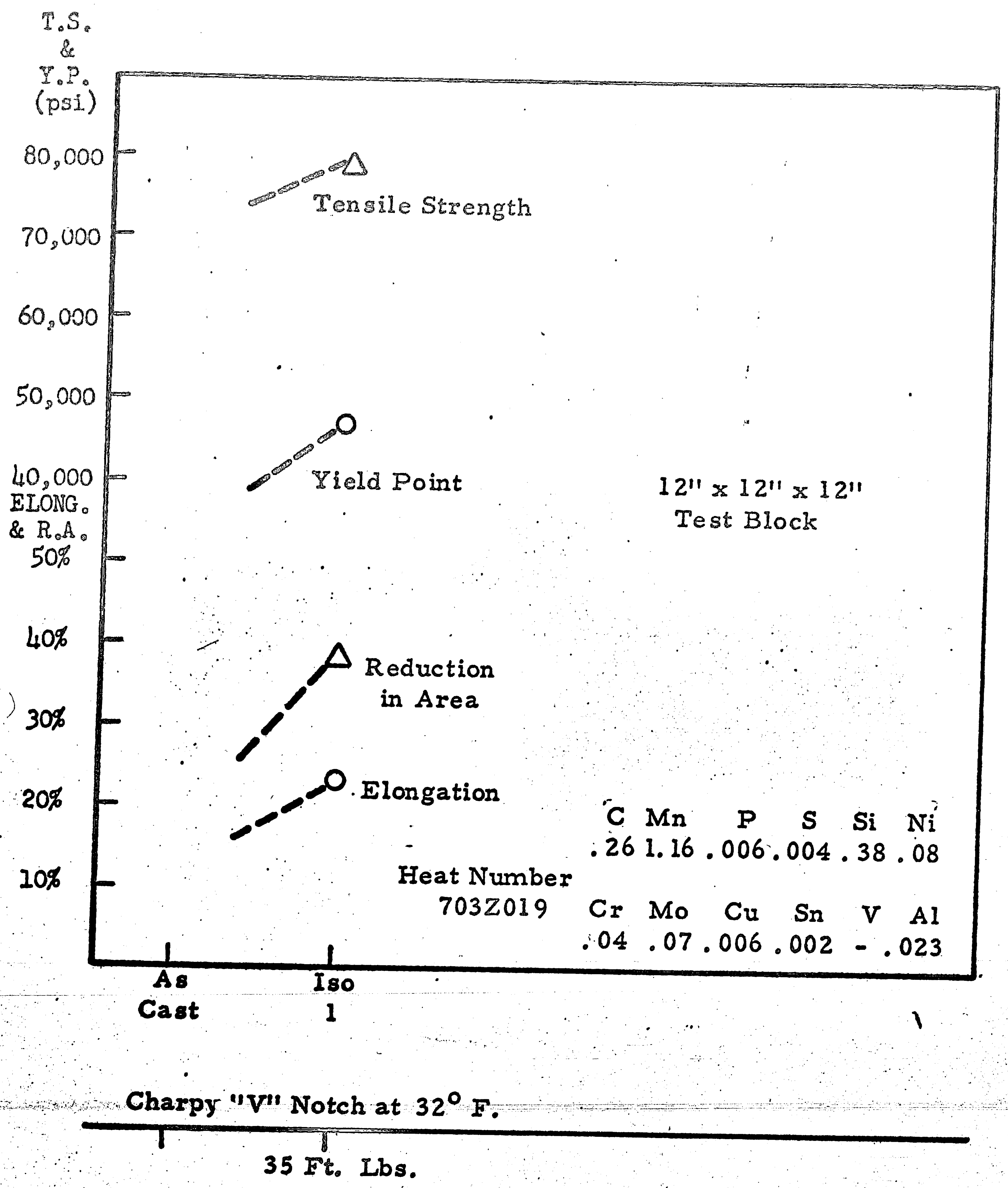

FIGURE 46: Mechanical Properties of Cast

.26 C 1.16 Mn 12" Cube

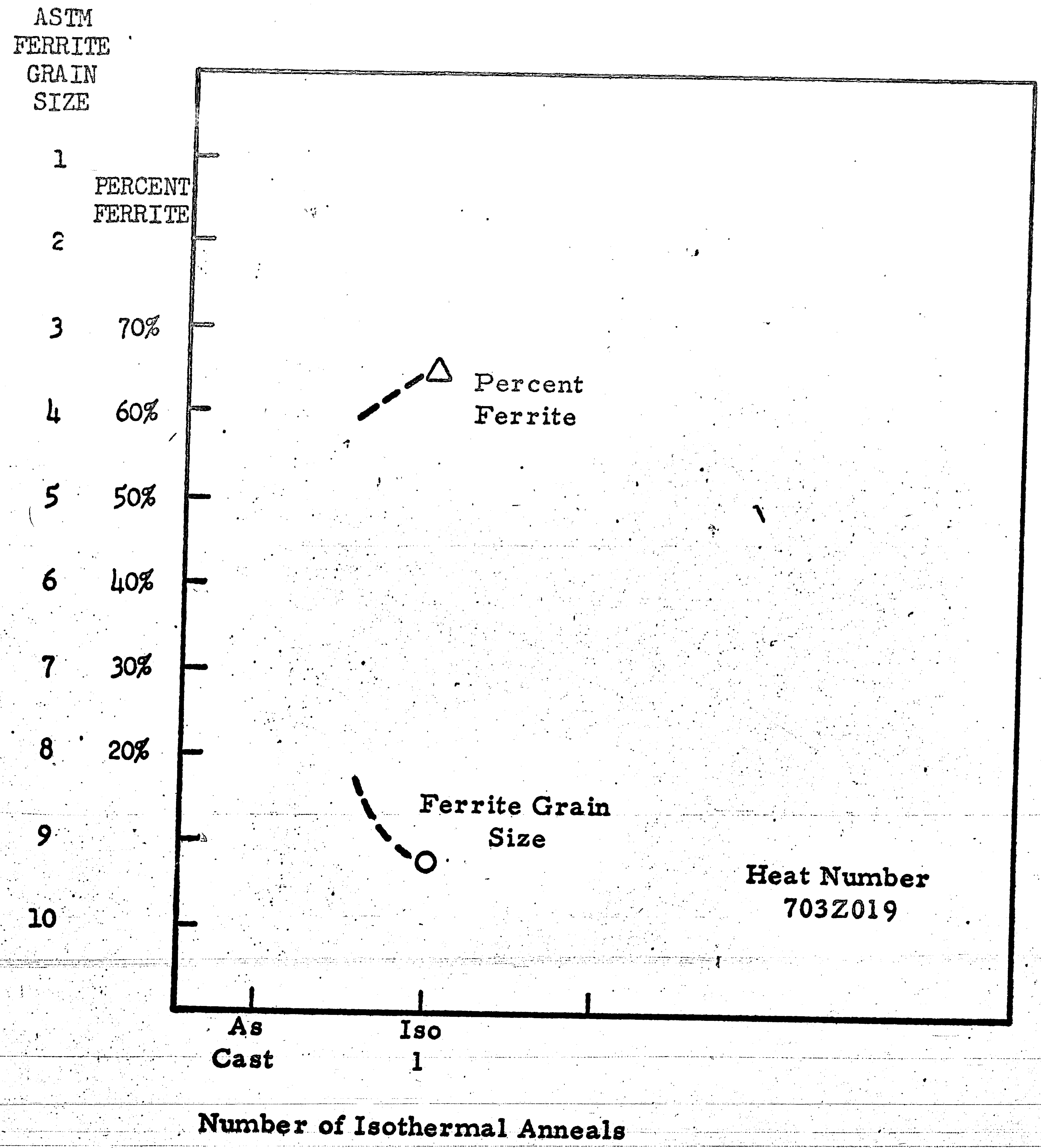

FIGURE 47: Microstructural Features of Cast .26 C 1.16 Mn 12" Cubes

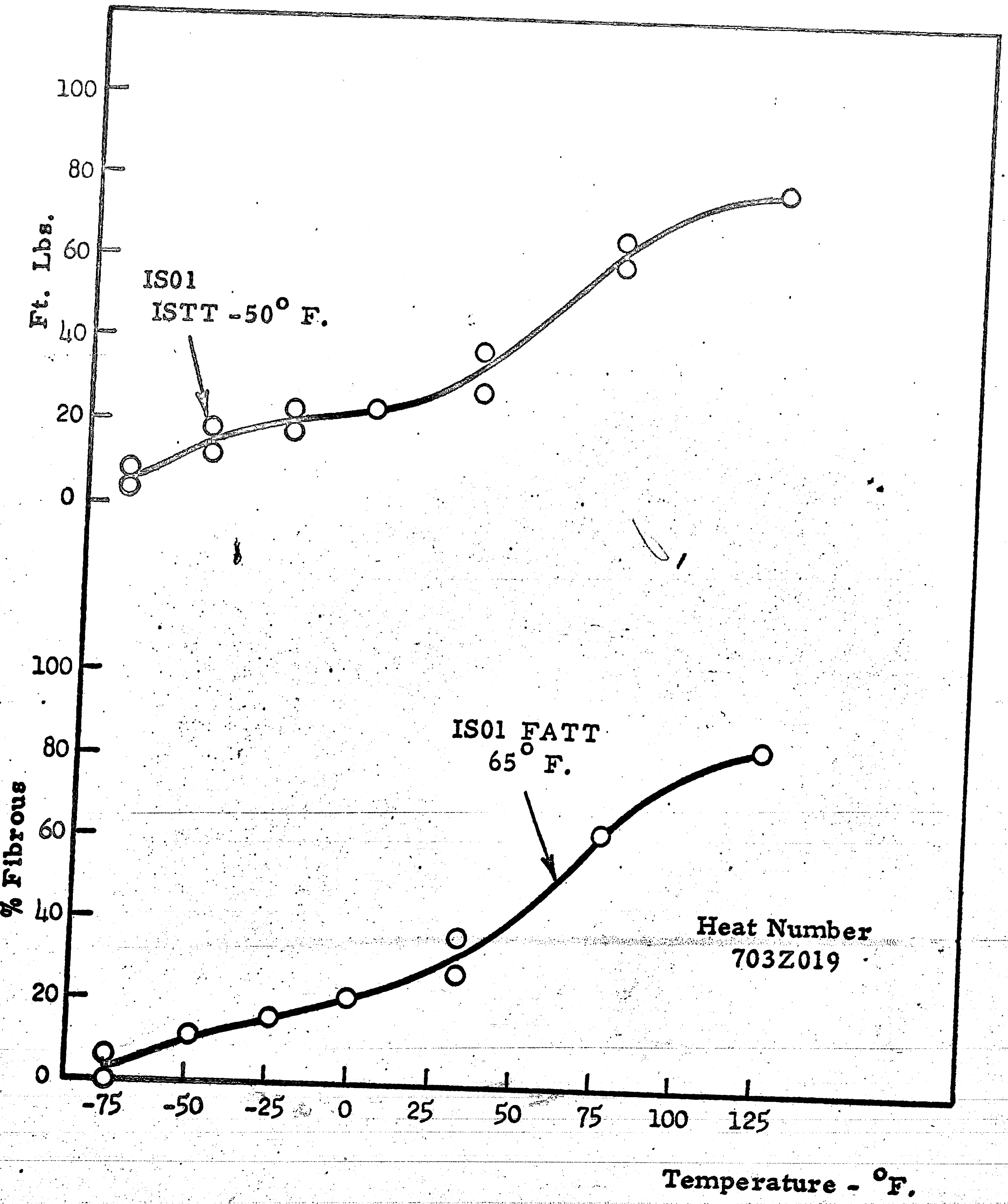

FIGURE 48: Charpy "V" Notch Properties of .26 C 1.16 Mn 12" Cube After One Isothermal Anneal

TABLE 11 - Properties of Cast .26 C 1.26 Mn "Keel" Blocks

Grade - Carbon Steel .26 C 1.26 Mn

Heat No. - 703Y021

Chemical Analysis

C	Mn	P	S	Si	Ni	Cr	Mo
.26	1.26	.017	.018	.36	.03	.02	.02

Heat Treatment - Annealed 1675° F. - 8 hrs.
Air Cooled - 1050° F.
Isothermal Hold - 1100° F. - 6 hrs.
Furnace Cooled

Mechanical Properties

TS	YS(.2%)	Elong.	RA
84,000	52,000	30%	59%

Impact Properties - Charpy "V" Notch

Temp. ° F.	Ft. Lbs.
+150	81,76
+125	69,64
+ 75	53,48
+ 32	30,26
0	26,23
- 25	20,19
- 50	20,11
- 75	3, 2
FATT	+65° F.
ISTT	-55° F. (Temperature at which 15 ft. lbs. is obtained)

(Test material was heat treated as an integral part of the casting)

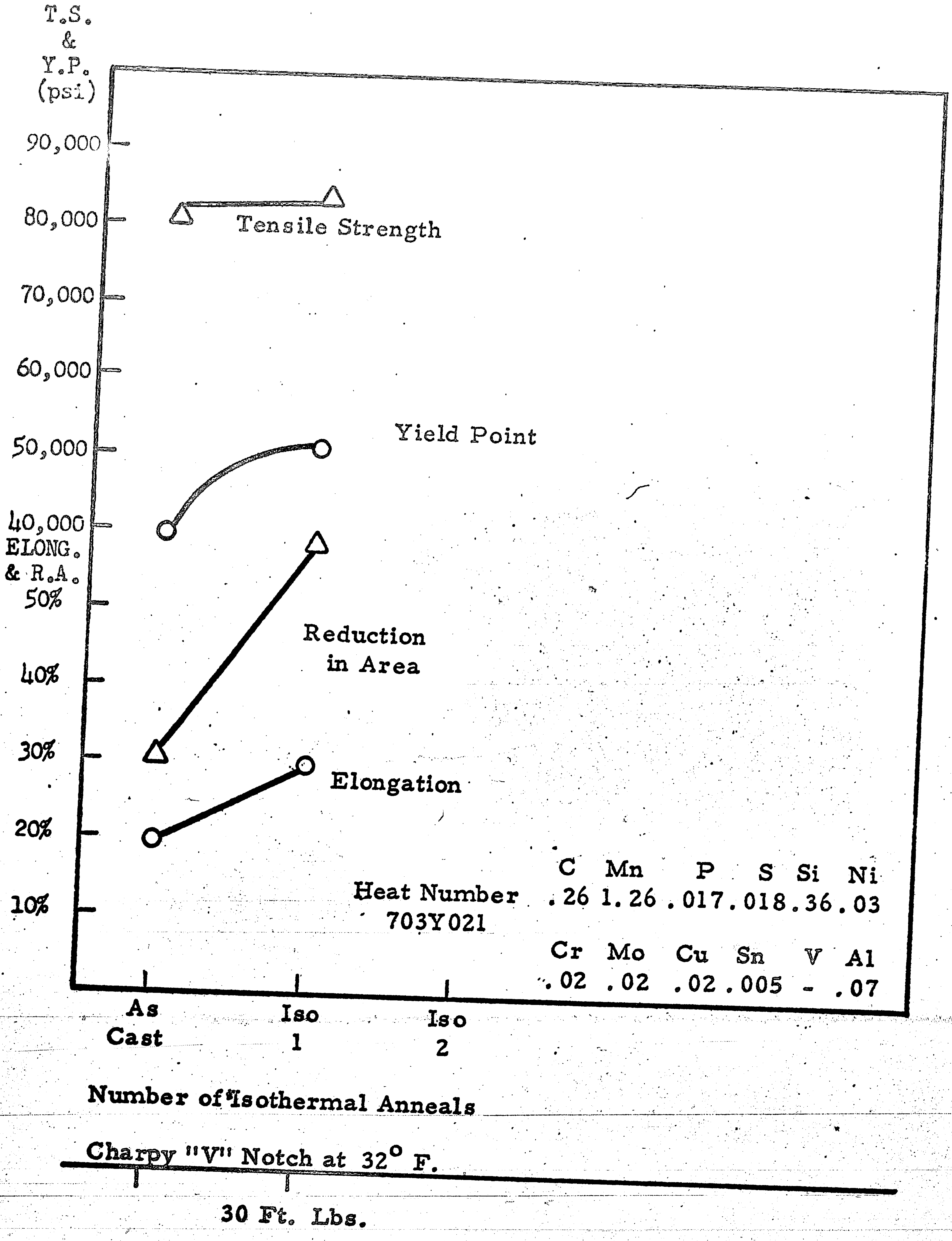

FIGURE 49: Mechanical Properties of Cast .26 C 1.26 Mn "Keel" Blocks

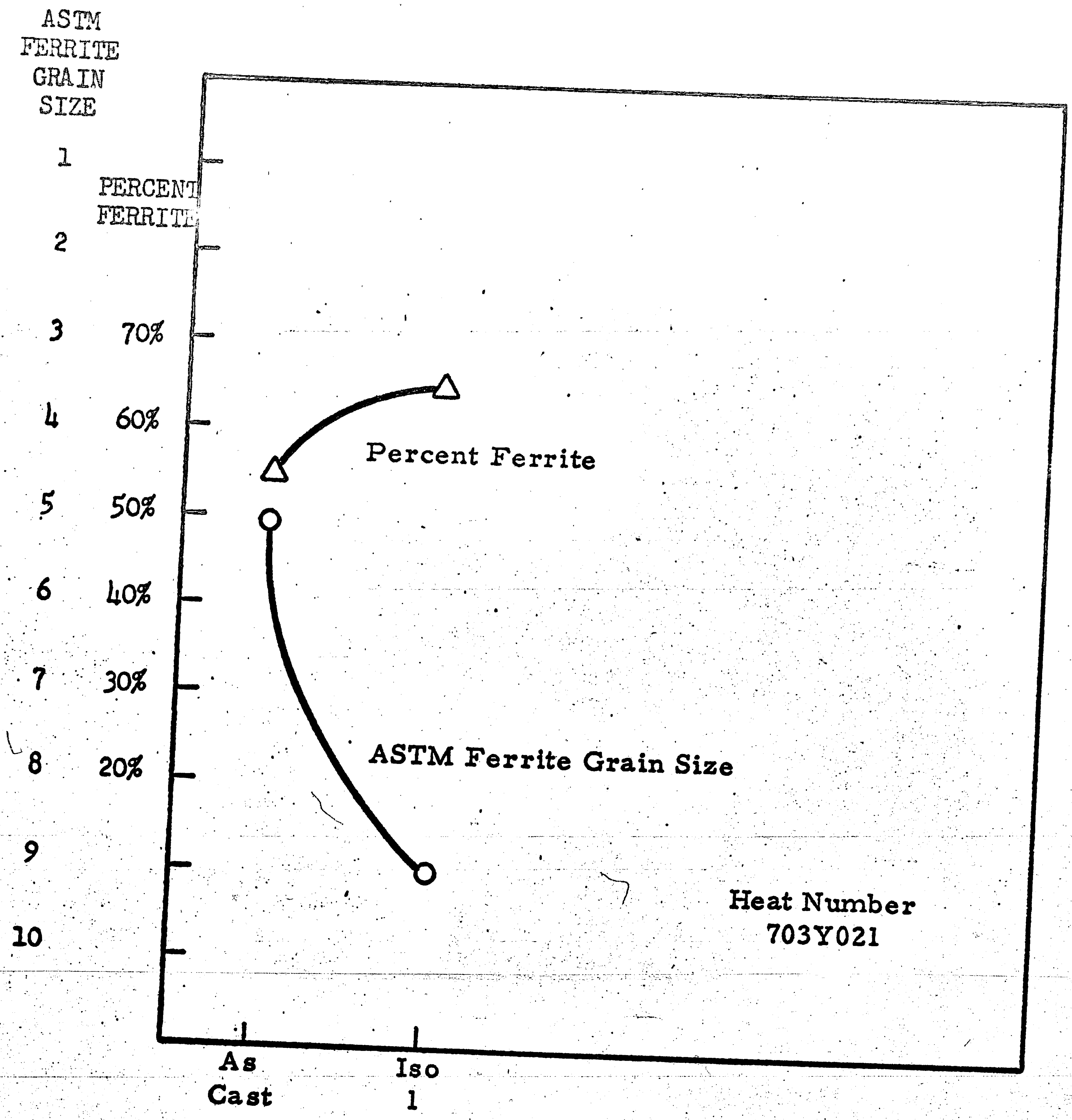

FIGURE 50: Microstructural Features of Cast .26 C 1.26 Mn "Keel" Blocks

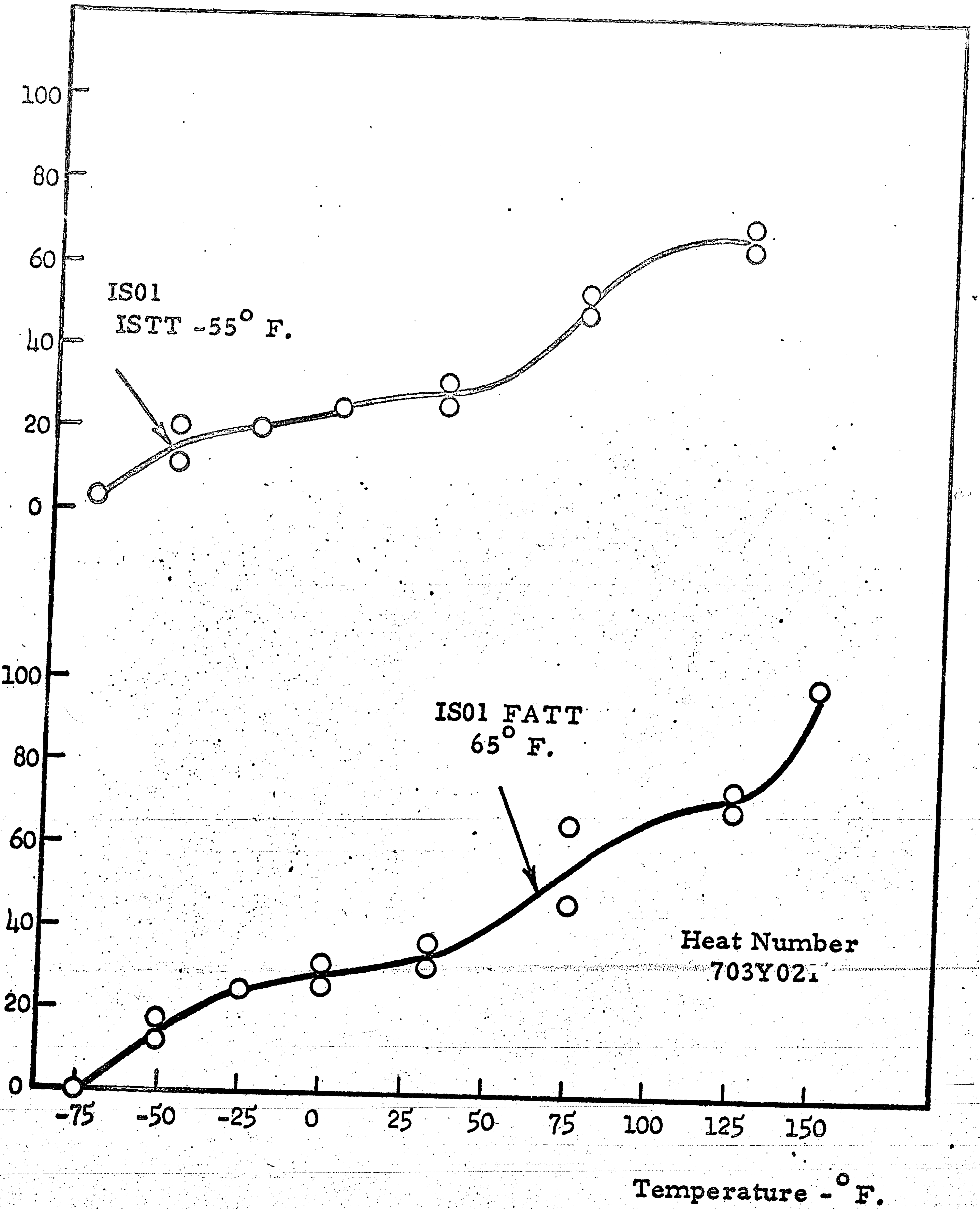

FIGURE 51: Charpy "V" Notch Properties of .26 C 1.26 Mn "Keel" Blocks After One Isothermal Anneal

TABLE 12 - Properties of Cast .30C 1.20 Mn "Keel" Blocks

Grade - Carbon Steel .30C 1.20 Mn

Heat No. - 122X451-B

Chemical Analysis

C	Mn	P	S	Si	Ni	Cr	Mo
.30	1.20	.01	.007	.51	.05	.05	.03

Heat Treatment		
	Annealed 1675° F. - 8 hrs. Air Cooled - Room Temp.	ISO 1
	Annealed 1675° F. - 8 hrs. Air Cooled - 1050° F. Isothermal Hold - 1100° F. - 4 hrs. Air Cooled	ISO 2

Mechanical Properties

TS	YS(.2%)	Elong.	RA
90,000	59,000	29%	59%

Impact Properties - Charpy "V" Notch

Temp. °F.	Ft. Lbs.
+150	91, 82
+ 75	76, 44
+ 32	33, 33
0	27, 24
- 25	27, 26, 20
- 50	21, 18, 17
- 75	5, 3
FATT	+50° F.
ISTT	-60° F. (Temperature at which 15 ft. lbs. is obtained)

(Test material was heat treated as an integral part of the casting.)

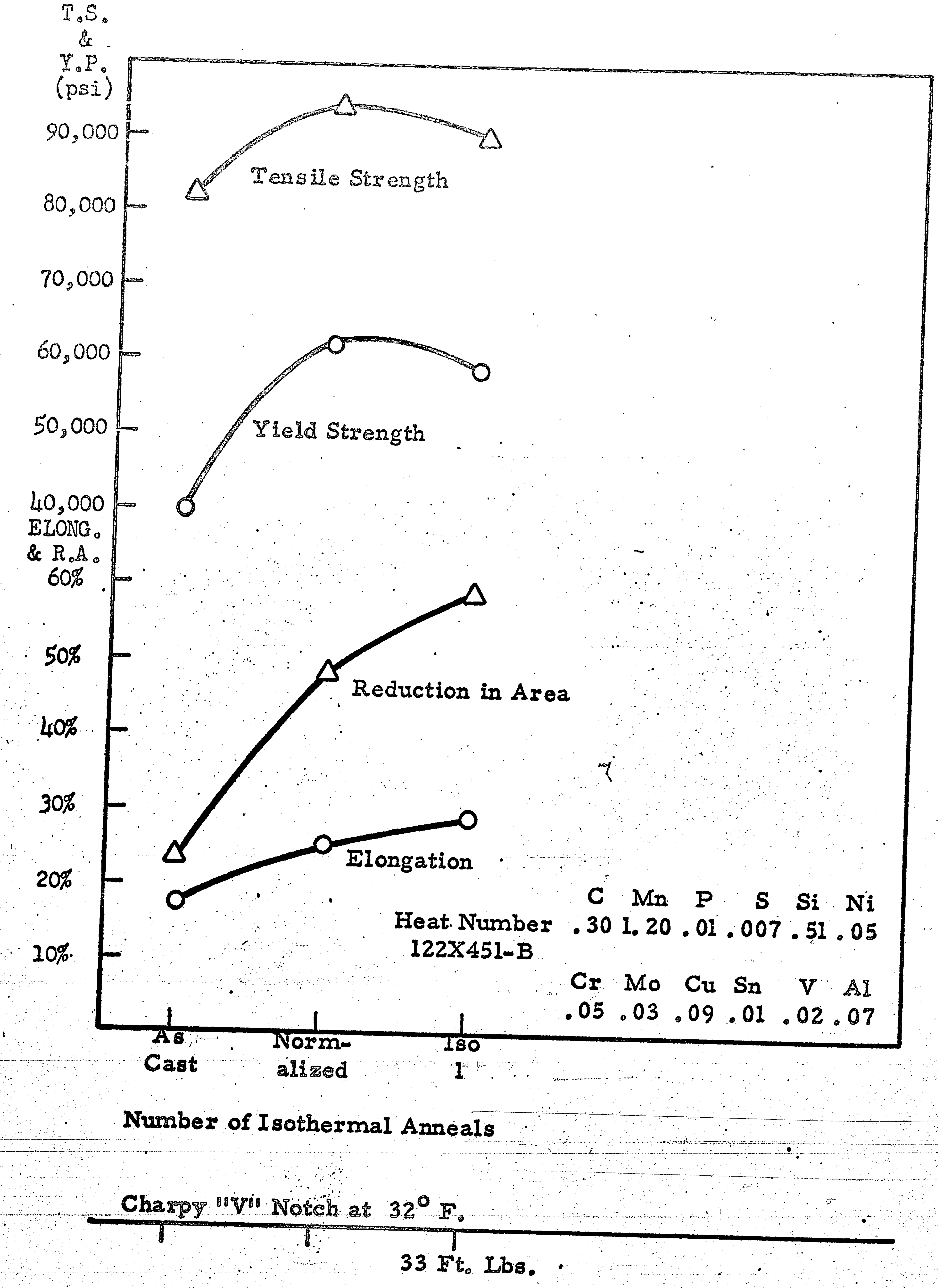

FIGURE 52: Mechanical Properties of Cast .30 C 1.20 Mn "Keel" Blocks

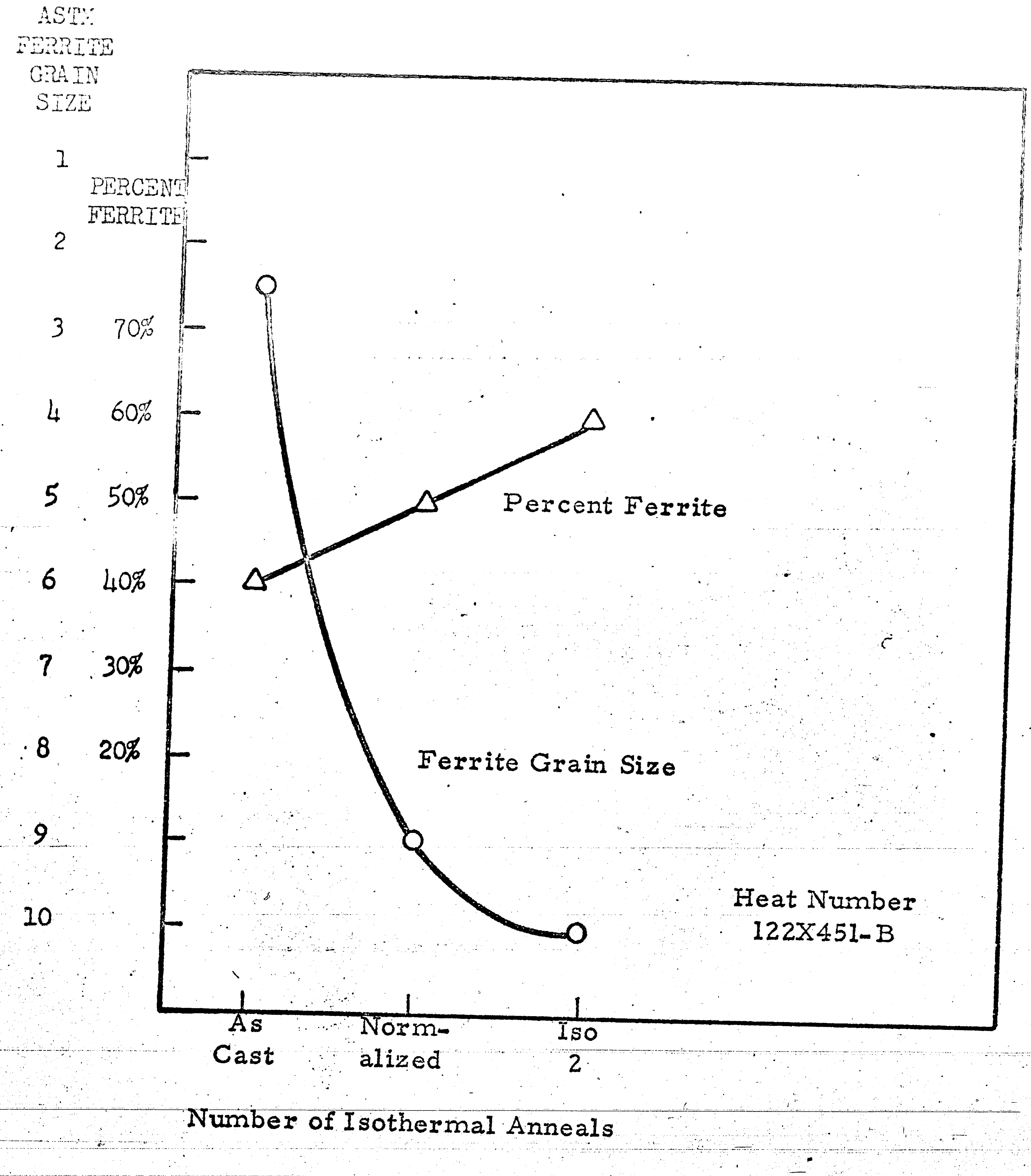

FIGURE 53: Microstructural Features of Cast .30C 1.20 Mn "Keel" Blocks

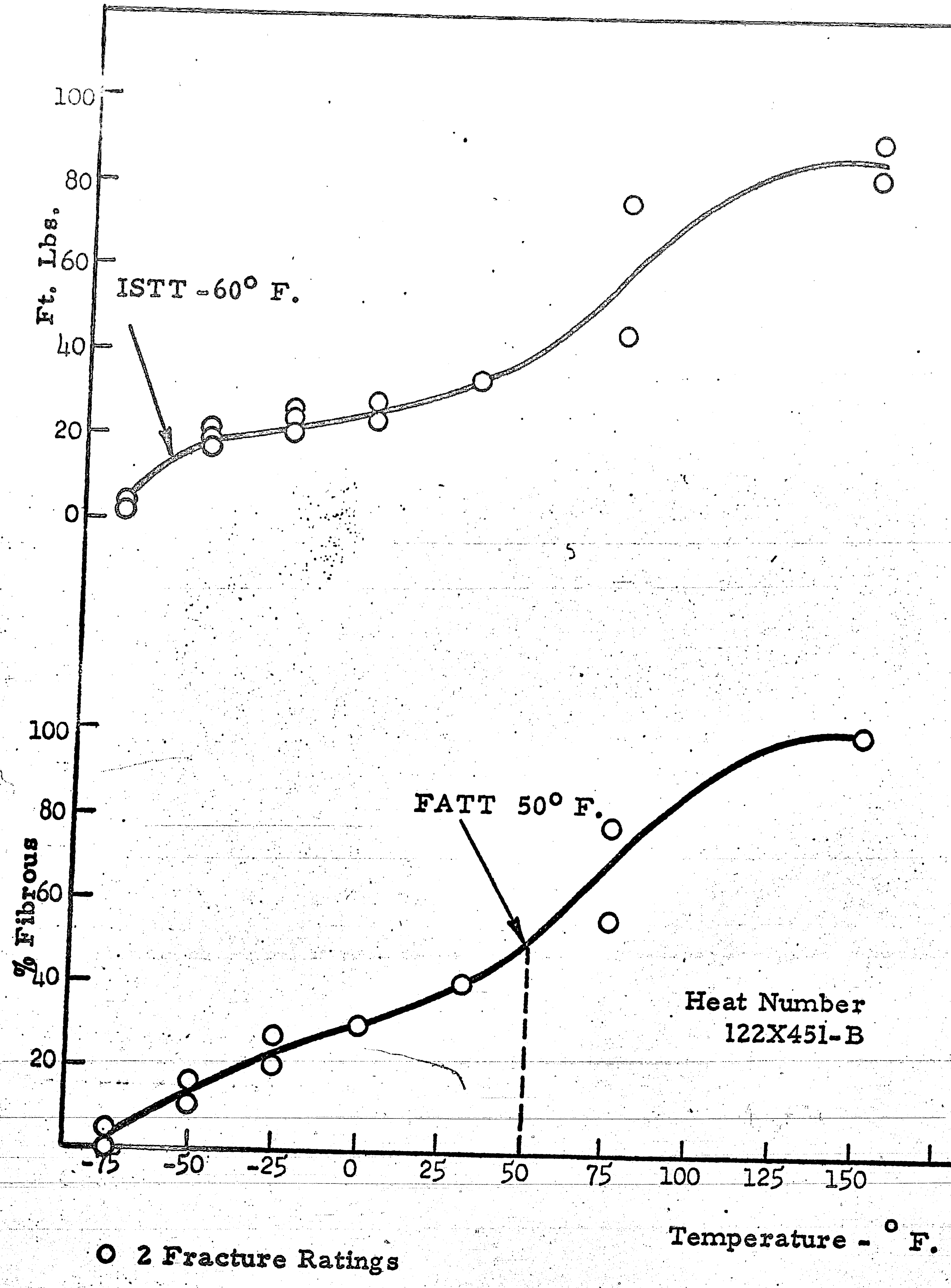

FIGURE 54: Charpy "V" Notch Properties of Cast .30 C 1.20 Mn "Keel" Blocks After Two Isothermal Treatments

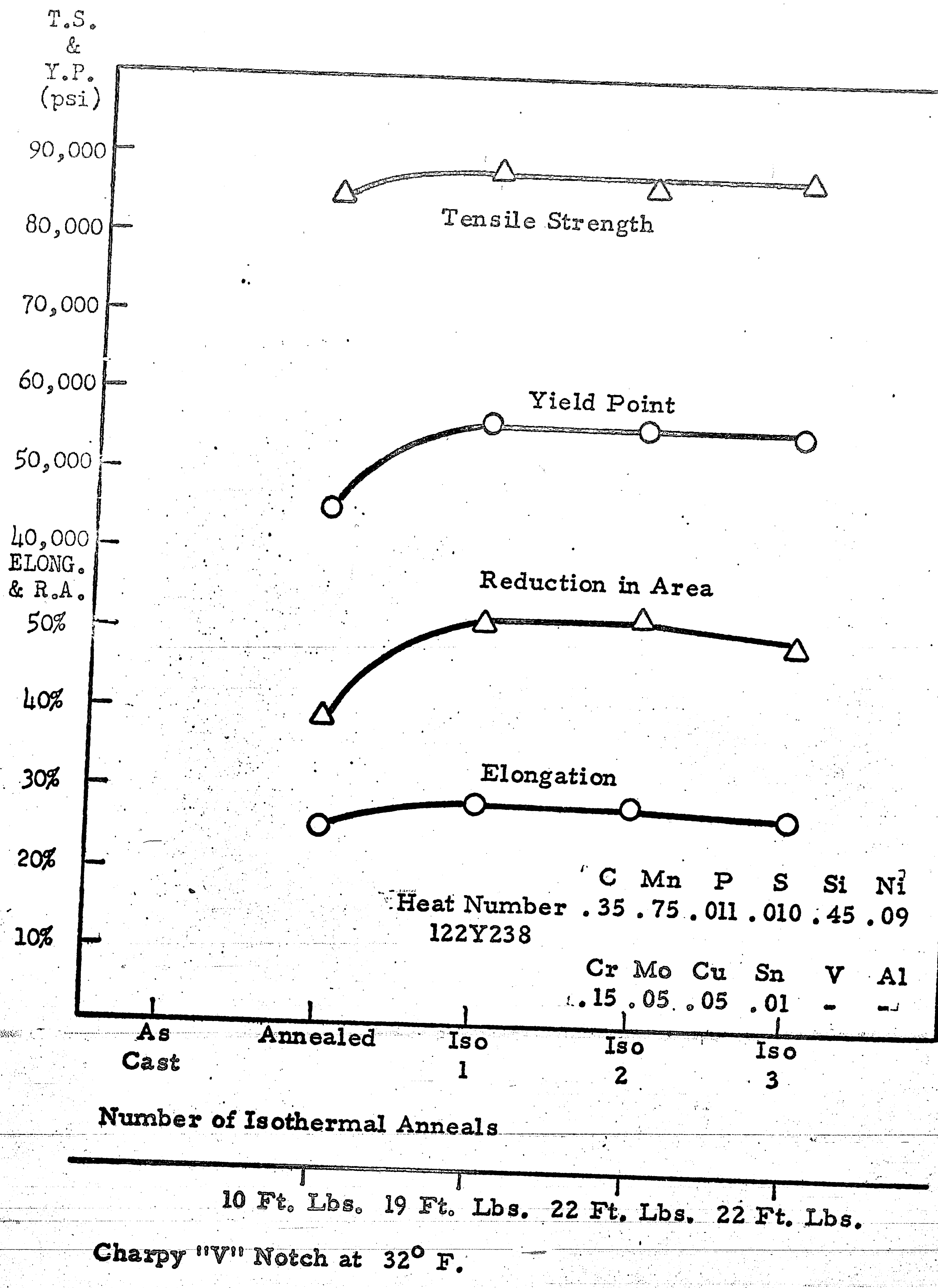

FIGURE 55: Mechanical Properties of Cast .35C .75Mn "Keel" Blocks

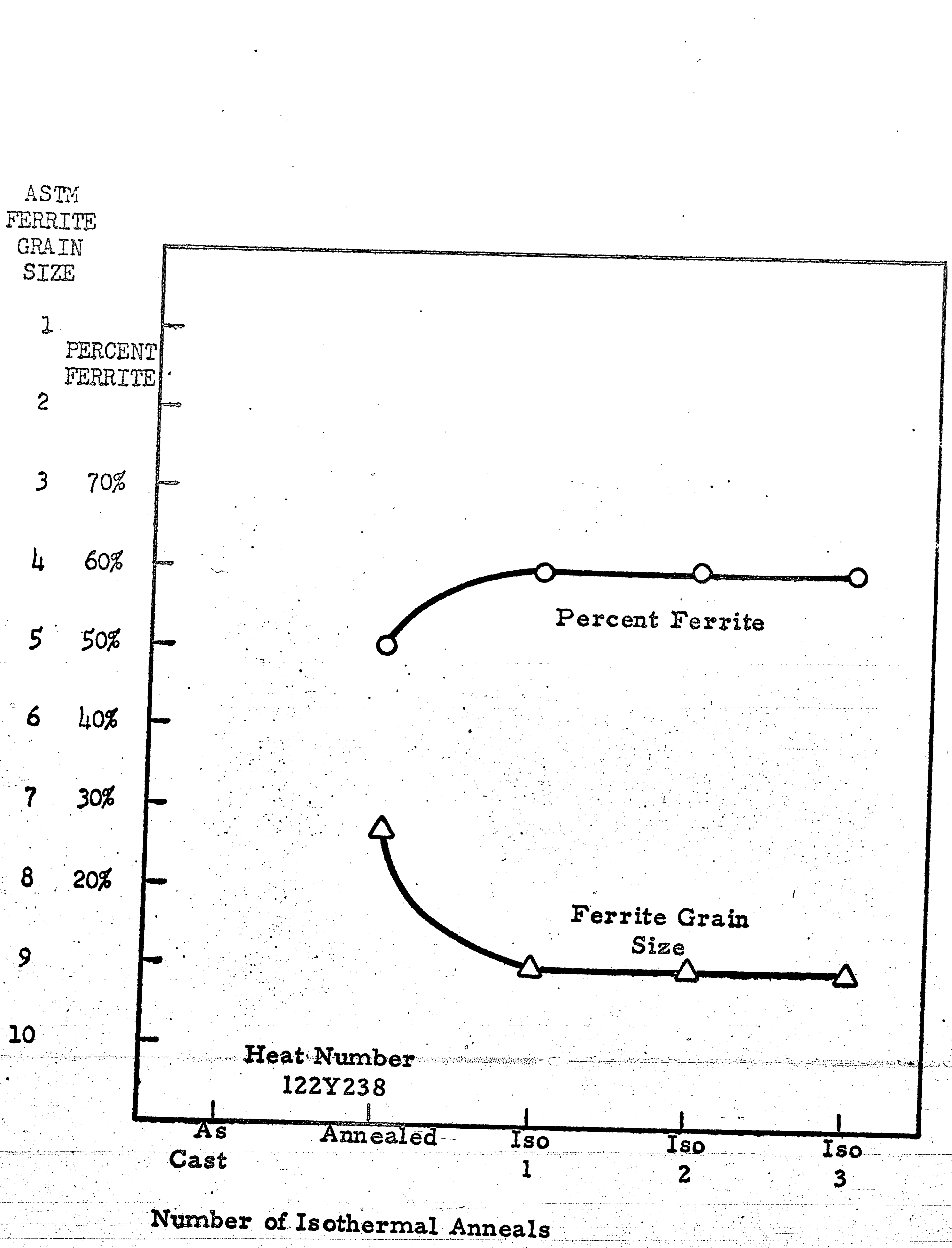

FIGURE 56: Microstructural Features of Cast .35 C .75 Mn "Keel" Blocks

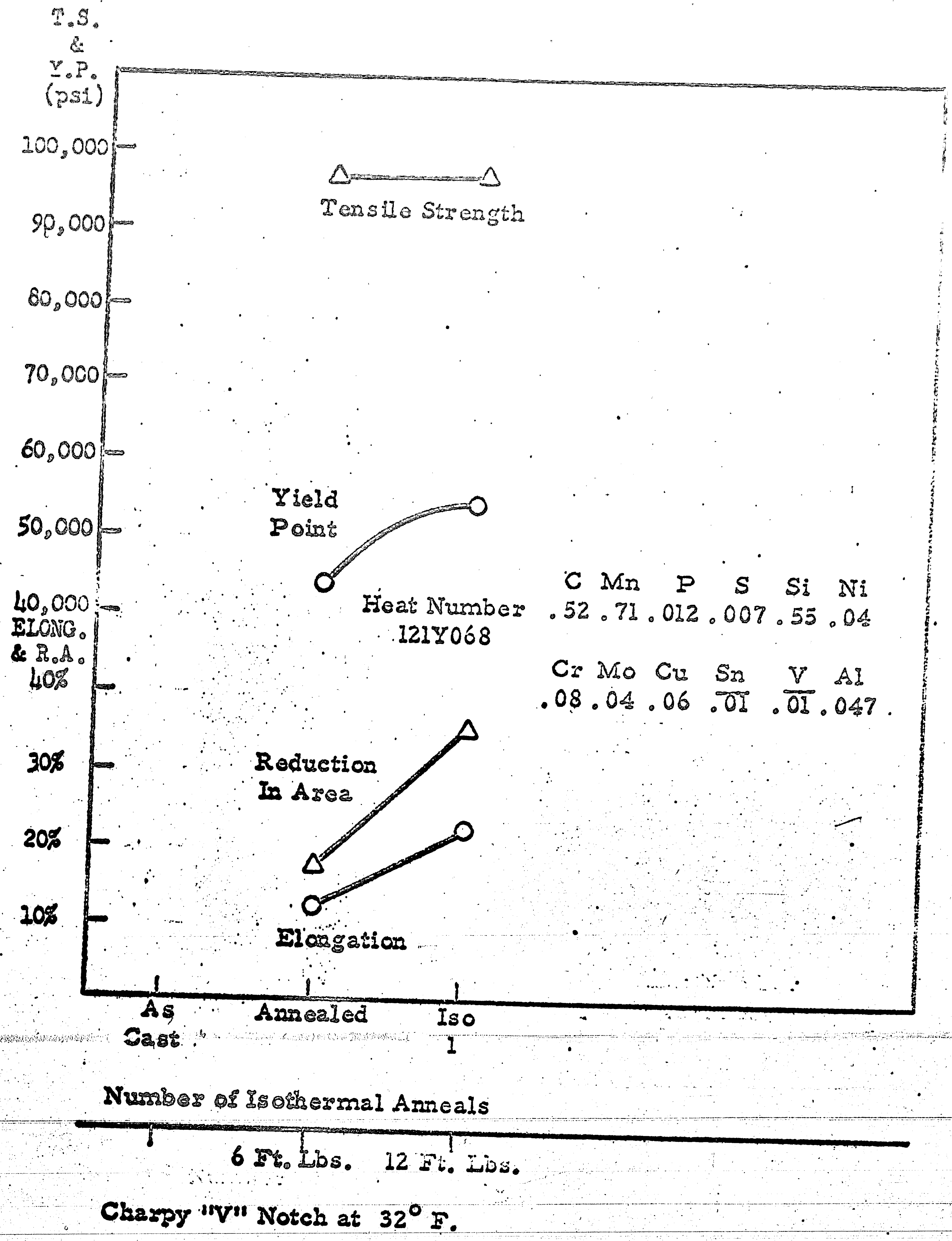

FIGURE 57: Mechanical Properties of Cast

.52 C .71 Mn 5" x 5" x 10" Test Blocks

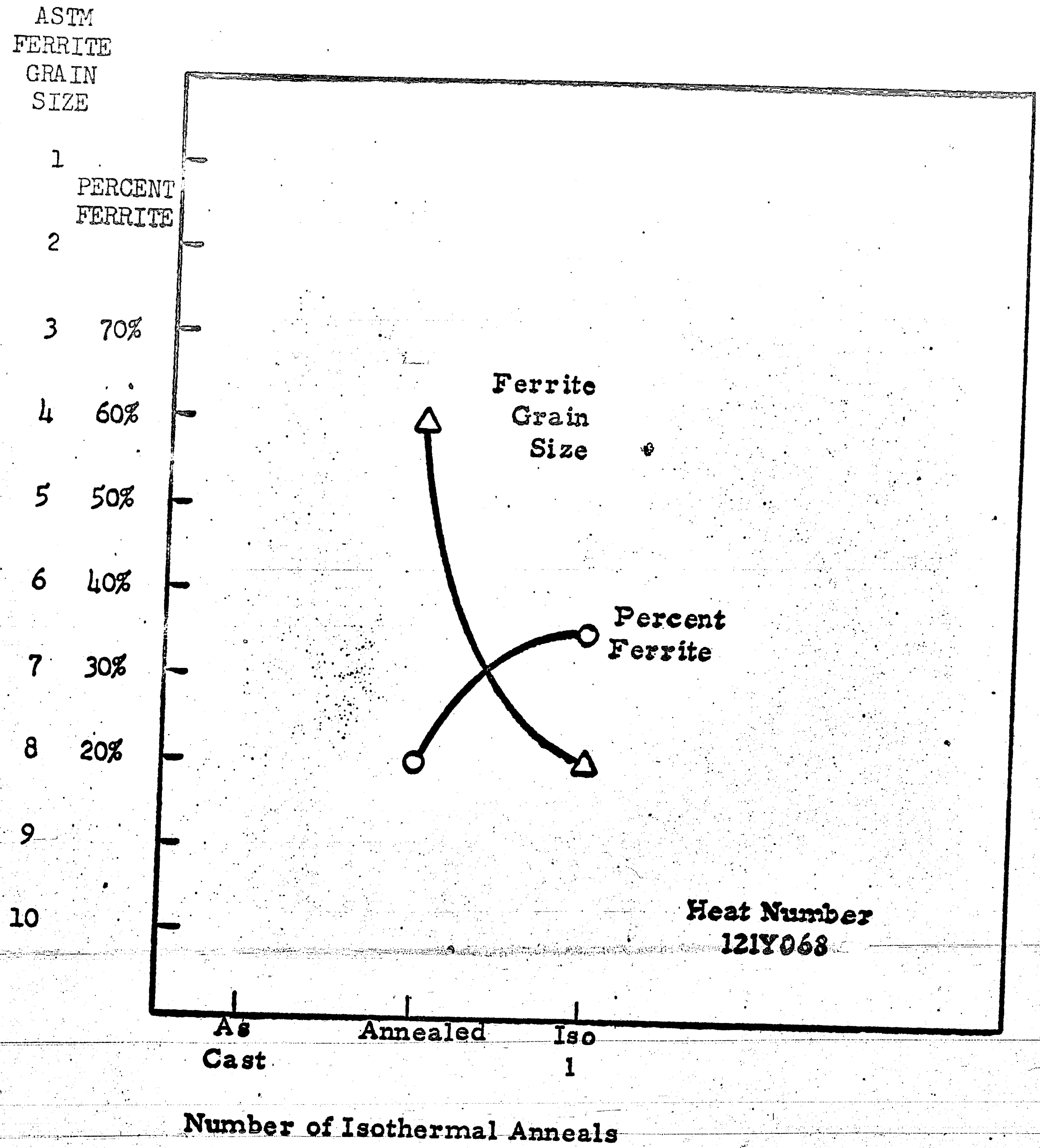

FIGURE 58: Microstructural Features of Cast

.52 C .71 Mn 5" x 5" x 10" Test Blocks

VITA

Raymond M. Hemphill, son of Constance and Raymond Hemphill, was born in Phillipsburg, New Jersey on July 6, 1944. He graduated from Montclair Academy in 1962 and received a Bachelor of Science degree in Metallurgy and Materials Science from Lehigh University in June, 1967. In July of that year, he entered the employ of Bethlehem Steel Corporation as a Looper Trainee and was assigned to the Foundry Division of the Bethlehem Plant.

Mr. Hemphill entered Lehigh University in September of 1967 as an industrial graduate student. While pursuing graduate studies in Metallurgy and Materials Science, Mr. Hemphill studied roll fracture, porosity in large high carbon steel roll necks, welded work surfaces for rolls, and developed a new material to overcome the wear/toughness conflict in small mill rolls. He also developed a method to predict the riser sizes necessary to feed large steel castings and identified the basic variables controlling sand penetration. He is a member of the American Society for Metals.