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Attainment of high magnetostriction in vanadium permendur by mechanical thermal treatmeant

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Attainment of High
Magnetostriction in Vanadium
Permendur by Mechanical Thermal Treatments

by

Peter Joseph Moroz, Jr.

A Thesis

Presented to the Graduate Faculty

of Lehigh University

in Candidacy for the Degree of

Master of Science

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1964

Certificate of Approval

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

Sept 22 1969
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Abstract

Magnetostriction measurements have been made on Supermendur and Vanadium Permendur alloys at fields of 0-500 oersteds. The effect of cold rolling and of subsequent magnetic annealing and straight annealing treatments on the magnetostriction of these alloys is reported. It was found that after an initial decrease in magnetostriction, increased cold working increased the magnetostriction of Supermendur and Vanadium Permendur, and that there was a significant decrease in the magnetostriction of the as received material annealed in a magnetic field, and a definite increase in the magnetostriction of the 93.2% cold rolled material annealed in a magnetic field. The highest values of magnetostriction were obtained in Supermendur 93.2% cold rolled and annealed without a field. This alloy showed 83.6 x 10^{-6} in/in at 200 oersteds and 109 x 10^{-6} in/in at 500 oersteds. It appears from the results of this study that the magnitude of magnetostriction and crystal texture are closely related.

1. Introduction

The demand for larger payloads of scientific instruments in the rockets used to explore space has made compactness of electrical circuitry both desirable and essential. Because switching circuits and timed contact-making devices play an important role in such electrical circuitry, improved and simplified switching and contact-making devices are continually being sought. Magnetostrictive* switches have generally been ignored because either the magnitude of the magnetostriction has been too small at the required magnetic field strength, or the magnetizing coil required to produce the field to attain the desired magnetostriction has been too large. Thus, an alloy which exhibited high magnetostriction at low field strengths would be a boon in this particular area of electrical circuitry. Such a material might also be desirable in other devices such as telephone transmitters, fire alarms, electrical micrometers, or pressure and torque gages.

The goal of the work for this thesis was either a material exhibiting high magnetostriction at low fields, or a metallurgical process which would develop high magnetostriction at low fields in some material. Criteria of greater than 100 x 10^{-6} in/in for high magnetostriction and of 0-500 oersteds (preferably less than 200 oersteds) for low fields were adopted.

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*Magnetostriction will refer to linear magnetostriction throughout this thesis. The symbol λ will be used to designate the linear magnetostriction where convenient.

Reports in the literature indicate that some ferromagnetic "pure" elemental metals, binary alloys, ternary alloys, ferrites and garnets exhibit high magnetostriction, that single crystals may show evidences of higher magnetostriction than polycrystalline materials, and that certain special techniques may lead to high magnetostriction in certain alloys. The following synopsis reviews the typical magnetostrictive alloys of each group:

Some "pure" elemental metals exhibit high magnetostriction, but only at extremely high fields or at very low temperatures, or both. K. P. Belov, et. al.[1], report that dysprosium has $\lambda = 1000 \times 10^{-6}$ in/in at 87.5° K, 15,000 oersteds; $\lambda = 100 \times 10^{-6}$ in/in at 87.5° K, 5000 oersteds; and $\lambda = 0 \times 10^{-6}$ in/in at 87.5° K, 200 oersteds. Iron, cobalt, and nickel all have relatively low magnetostriction at 200 oersteds (less than 35×10^{-6} in/in) (R. M. Bozorth[2]). In contrast, A. Wolf and A. Goetz[3] report that bismuth, a diamagnetic, has $\lambda = 10^{-8}$ in/in at 20,000 oersteds. It seems probable that high magnetostriction can be obtained in pure metals only at extremely low temperatures.

Binary alloys also exhibit interesting magnetostriction properties. E. A Nesbitt and H. J. Williams[4] report $\lambda = 51 \times 10^{-6}$ in/in for 49 Fe-49 Co-2 V at 830 oersteds and $\lambda = 30 \times 10^{-6}$ in/in for Alnico V at 1600 oersteds. H. Takaki and Y. Nakamura[5] report $\lambda_{100} = 35 \times 10^{-6}$ in/in in Fe-4 S; at saturation. H. J. Williams, et. al.[6], report $\lambda = -110 \times 10^{-6}$ in/in for MnBi at 22,000 oersteds and $\lambda = -15 \times 10^{-6}$ in/in for MnBi at 500 oersteds. Of all the binary alloys that have been investigated, the Fe-Ni, Fe-Co, and Ni-Co systems appear to be the most promising, while the most promising of these three systems appears to be the Fe-Co system. Curves by Y. Masiyama[7] and by S. R Williams[8] are shown for Fe-Co in Figures 1 and 2, respectively.

Little work has been done on ternary alloy systems, but the work that has been done is not encouraging. H. E. Strauss and G. Sandoz[9] report that the magnetostriction of the Fe-Co binary alloys is higher than that of any ternary alloys of the same percentage of Co. W. A. Dean[10] reports that the only alloys in the Fe-Ni-Cr system that exhibit appreciable magnetostriction are the binary Fe-Ni and the Cr-Ni alloys, and ternary alloys containing 5-20% of the third component, and that the magnetostriction is very low (0-20 x 10^{-6} in/in at saturation).

Ferrite materials exhibit high magnetostriction in both the polycrystalline and single crystal state. R. M. Bozorth, et. al.,[11, 12] report $\lambda_{100} = -590 \times 10^{-6}$ in/in, $\lambda_{111} = 120 \times 10^{-6}$ in/in, and $\bar{\lambda} = -210 \times 10^{-6}$ in/in* at saturation for $Co_{0.8}\,Fe_{2.2}\,O_4$; $\lambda_{100} = -210 \times 10^{-6}$ in/in, $\lambda_{111} = 110 \times 10^{-6}$ in/in, and $\bar{\lambda} = -18 \times 10^{-6}$ in/in at saturation for $Co_{0.2}\,Zn_{0.2}\,Fe_{2.6}\,O_4$ $\lambda_{100} = -200 \times 10^{-6}$ in/in, $\lambda_{111} = 65 \times 10^{-6}$ in/in, and $\bar{\lambda} = -40 \times 10^{-6}$ in/in at saturation for $Co_{0.3}\,Mn_{0.4}\,Fe_{2.6}\,O_4$; and $\lambda_{100} = -19 \times 10^{-6}$ in/in, $\lambda_{111} = 81 \times 10^{-6}$ in/in., and $\bar{\lambda} = 41 \times 10^{-6}$ in/in at saturation for Fe_3O_4. However, the fields required to produce saturation in these ferrites were greater than 4000 oersteds, and at fields below 1000 oersteds, the magnetostriction generally decreased to less than 30 x 10^{-6} in/in. Thus, it appears that high magnetostriction may be obtained in ferrites only at moderately high fields.

Garnets seem to have low magnetostriction. K. P. Belov and A. V. Pedko[13] report less than $\pm 10^{-6}$ in/in for 3 Gd_2O_3 .5 Fe_2O_3 .0.2 Gd_2O_3 .4.8 Fe_2O_3 and 3 Gd_2O_3 .0.2 $Y_2\,O_3$ .4.8 Fe_2O_3. Thus, it would appear

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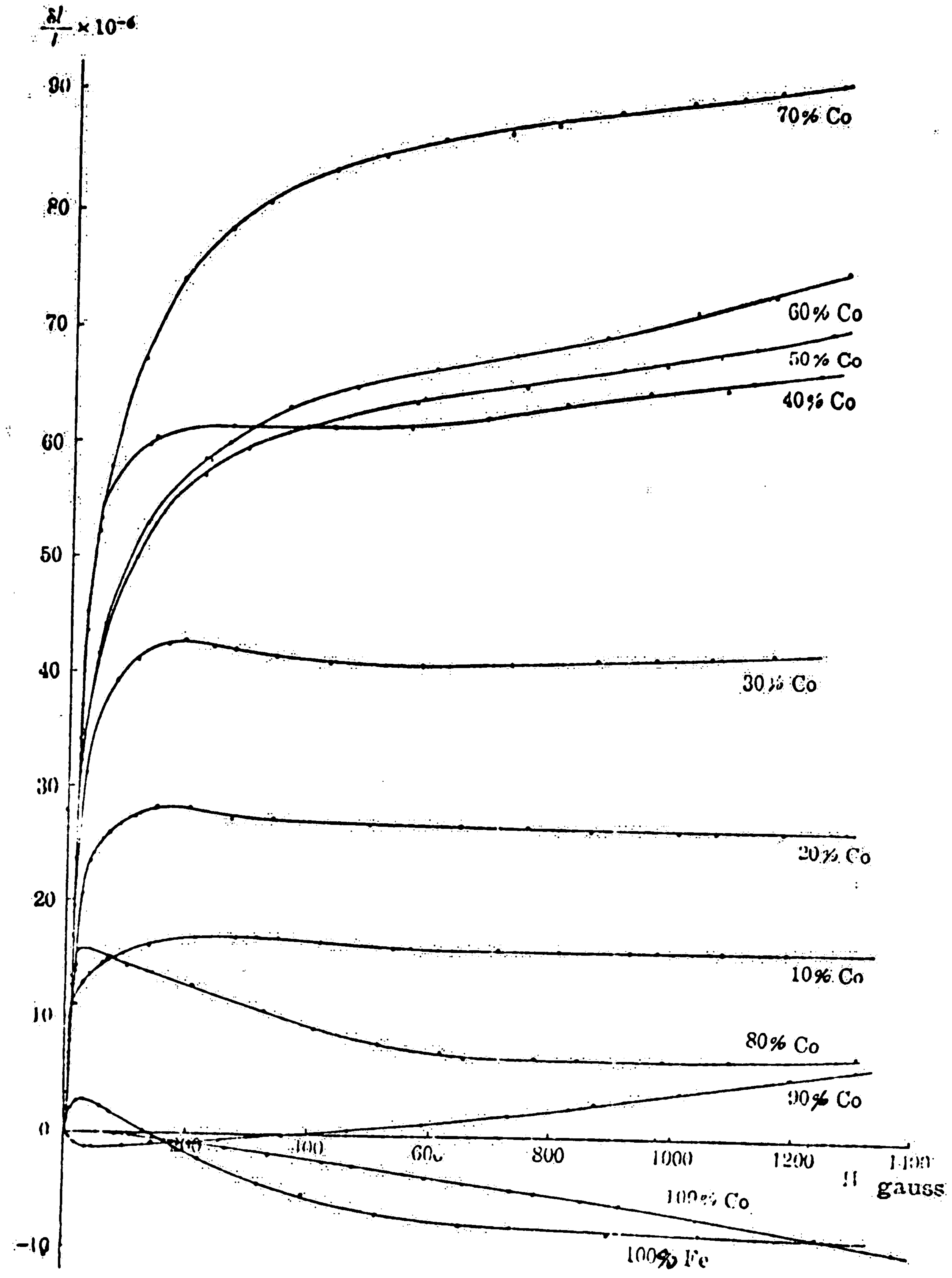
* $\bar{\lambda} = (2\,\lambda_{100} + 3\,\lambda_{111})\,/5$



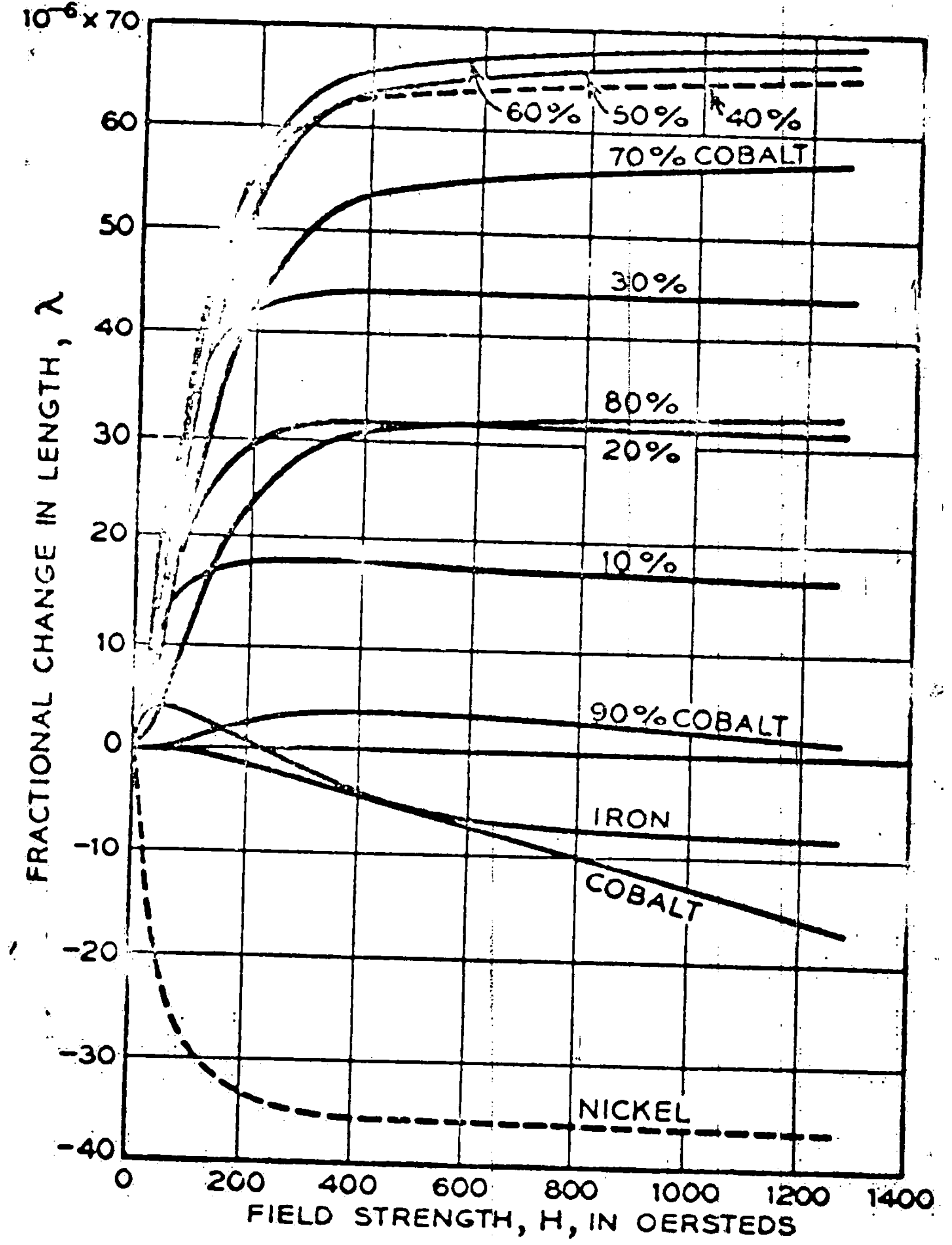


Figure 2 - Magnetostriction of Fe-Co Alloys (after Williams (8)).

Figure 1 - Magnetostriction of Fe-Co Alloys (after Masiyama (7)).

that garnets show little promise of high magnetostriction.

Single crystals, mentioned in relation to ferrites, have high magnetostriction in certain crystallographic directions, but again the high values of magnetostriction are attained only at high fields, while at low fields the magnetostriction is very low. Ferrite single crystal data are presented above. Single crystal data on single crystals other than iron, cobalt, and nickel single crystals and some ferrite single crystals, are rather limited.

Special techniques, such as ordering, cold working to develop crystalline anisotropy, and magnetic annealing to develop magnetic anisotropy tend to increase the magnetostriction of many materials. As examples, J. E. Goldman[14] reports that the magnetostriction of FeNi3 can be increased from 1.9 x 10^{-6} in/in in the unordered state to 4.15 x 10^{-6} in/in in the ordered state; G. A Nesbitt[15] reports that the magnetostriction of 70 Co-30 Fe can be raised from 85 x 10^{-6} in/in to 135 x 10^{-6} in/in by cold working; R. M. Bozorth and J. G. Walker[11] report that λ_{100} in Co_{08} $Fe_{2.1}O_4$ can be raised from -540 x 10^{-6} in/in to -720 x 10^{-6} in/in by magnetic annealing, and H. E. Strauss and G. Sandoz[16] report that the magnetostriction of 69 Co-31 Fe can be raised from 87 x 10^{-6} in/in to 107 x 10^{-6} in/in by magnetic annealing, and that the magnetostriction of 87 Fe-13 Al can be raised from 39 x 10^{-6} in/in to 45 x 10^{-6} in/in by magnetic annealing. All figures above are, however, for fields in excess of 2000 oersteds.

After careful consideration of the literature on materials exhibiting magnetostriction, and because of the dearth of theory and detailed information pertaining to magnetostriction and to the variables which affect magnetostriction, it was decided that alloy development was feasible only in a long-range program, and that the most promising approach for attaining high magnetostriction at low fields in a short-range program would be to develop either a crystallographic anisotropy by cold working or a magnetic anisotropy by magnetic annealing in Vanadium Permendur (49 Fe 49 Co 2V) or in Supermendur, an ultra-pure Vanadium Permendur produced by vacuum melting and casting by the Allegheny Ludlum Steel Company.

Investigation of Vanadium Permendur and Supermendur appeared promising for the following reasons:

(1) Supermendur and Vanadium Permendur are commercially available alloys.

(2) Vanadium Permendur in the fully annealed condition has a relatively high magnetostriction of 51×10^{-6} in/in at 830 oersteds (G. A. Nesbitt and H. J. Williams[4]).

(3) Several alloys in the Fe-Co binary system are known to be responsive to cold working (Nesbitt[15]) and magnetic annealing (Strauss and Sandoz[16]), and the effect of these processes may be greater in Supermendur since the Vanadium addition makes it extremely amenable to cold reduction.

(4) Ordering has been reported in Permendur (S. Siegel and C. G. Shull[17]) and may also occur in Vanadium Permendur and Supermendur.

2. Theoretical Background

2.1 Origin of Magnetostriction

Magnetic or quasi-magnetic forces between atoms give rise to magnetostriction by opposing the purely elastic forces between atoms in a lattice. Magnetostriction produces a change of separation between atoms such that the sum of the two corresponding energies is a minimum, and thus corresponds to an equilibrium distortion.

N. S. Akulov[18] and R. Becker[19] both ascribed the magnetostriction produced in cubic crystal structures to magnetic dipole interactions, but their theories predicted magnetostriction an order of magnitude too small in the alloys they studied. F. C. Powell[20] also attributed the magnetostriction produced in cubic crystal structures to magnetic dipole interactions, but he also considered elastic anisotropy of crystals and the surfaces of crystals in his analysis. However, his theory did not predict magnetostriction satisfactorily either. J. H. Van Vleck[21] later showed that the spin-orbital coupling that accounts in order of magnitude for crystal anisotropy also gives rise to quasi-magnetic interactions of the correct order of magnitude. S V. Vonsovsky[22] also assumed a spin-orbit coupling mechanism, and found through calculations that spin-orbital coupling could account for the observed magnetostriction.

Thus, it appears that spin-orbit coupling, crystal anisotropy, and magnetostriction are closely related, but at this time there are no generally accepted theories which explain their interrelation.

2.2 Domain Theory[2]

Magnetostriction is also associated with domain orientation. As a good first approximation, by assuming that the magnetostriction is independent of the crystallographic direction of magnetization, and that the change in volume is zero, the change in dimension of a single domain can be related to a change in the direction of magnetization in the domain by the relationship

$$\lambda = 3/2\,\lambda_s\,(\cos^2\theta - 1/3)$$

where θ is the angle between the direction of magnetization and the direction in which the change in length is measured. The origin of λ is chosen such that magnetostriction is equal to the longitudinal change in length at saturation, λ_s $(\theta = 0)$.

When the direction of magnetization in a domain is changed, the length of the domain, measured in any given direction, changes, and the total change in length of the material is the sum of the changes in length in all the domains.

In an assembly of domains initially oriented at random, the same relationship is applicable if the average value of $\cos^2 \theta$ over all domains is used. Thus, when the material is unmagnetized, $(\cos^2 \theta)$ ave = 1/3 and $\lambda = 0$, and upon application of a strong field, $\theta = 0$ and $\lambda = \lambda_s$.

If the domains are not initially at random, the relationship

$$\lambda = 3/2 \lambda_s \left(\langle \cos^2 \theta \rangle_{ave} - 1/3\right) - 3/2 \lambda_s \left(\langle \cos^2 \theta \rangle_o - 1/3\right)$$

or

$$\lambda = 3/2 \lambda_s \left(\langle \cos^2 \theta \rangle_{ave} - \langle \cos^2 \theta \rangle_o\right)$$

where $\langle \cos^2 \theta \rangle_o$ refers to the initial domain distribution and $\langle \cos^2 \theta \rangle_{ave}$ refers to the distribution at any time, holds as a good initial approximation. Now, if the domains are initially oriented so that $\theta = 0$ for one-half of them, and $\theta = 180$ degrees for the other half, $\langle \cos^2 \theta \rangle_o = \langle \cos^2 \theta \rangle_{ave} = 0$ and $\lambda = 0$; and in a strong field, $\theta = 0$ and $\cos^2 \theta$ remains unchanged, so again $\lambda = 0$. When used in this sense, magnetostriction depends on the initial domain distribution, while λ_s is a constant of the material. (The constant λ_s can be determined in any material by measuring λ when a saturating field is applied parallel and then perpendicular to the direction of magnetostriction measurement. The total change in length caused by the changes in field is then $3\lambda s/2$, independent of the initial domain distribution.)

For a more rigorous relationship for λ, the crystallographic direction of magnetization and the volume change must also be taken into account. This involves a study of crystal anisotropy and the calculation of anisotropy and magnetostriction constants.

2.3. Cold Working

A direction of easy magnetization is often found in cold-rolled sheet because of the crystal textures usually produced by the cold working. The domains are aligned along the direction of easy magnetization in the unmagnetized material, and so it would be expected that this non-random distribution of domain orientation would markedly affect the magnetostriction. This appears to be the case in some alloys. For example, E. A. Nesbitt[15] obtained magnetostriction data on 0.002 inches thick tape specimens of Fe-Co alloys with 65, 70, and 75 per cent cobalt. The specimens had been cold reduced in thickness by 95%. Nesbitt found that the domains had been ordered transversely by the drastic cold working and observed that the magnetostriction of the 70 per cent cobalt alloy had increased from 55 x 10^{-6} in/in at saturation to 130 x 10^{-6} in/in at saturation.

It should be noted that very little quantitative work on the effect of cold working on magnetostriction has been done and that most of the references to cold working and magnetostriction are for a very high reduction. No general theory concerning the effect of cold work on magnetostriction has been proposed.

2.4 Magnetic Annealing

Magnetic annealing is defined as the heat treatment of a magnetic material in a magnetic field for the purpose of changing the magnetic properties of that material. A variety of magnetic materials, including hard magnet materials, ferrites, and thin films, as well as soft magnet materials, when heat treated and cooled in the presence of a magnetic field are found to have developed a direction of easy magnetization parallel to the direction in which the field was applied during the heat treatment. This discussion is concerned with magnetic annealing in soft magnet materials only.

Magnetic annealing, when effective in soft magnet materials, tends to increase the residual induction and the maximum permeability; to decrease the coercive force; to make the hysteresis loop more upright and rectangular in the direction in which the field was applied; and to "worsen" the transverse magnetic properties of the soft magnet material.

The first deliberate attempt to alter the magnetic properties of a metal by annealing in a magnetic field was made by H. Pender and R. C. Jones[23] in 1913. However, no investigators attempted to explain the effects of magnetic annealing until 1934, when R. M. Bozorth[24] presented a strain-magnetostriction picture. He proposed that when the material was heat treated in a magnetic field, the domains, normally randomly oriented in one of the $\langle 100 \rangle$ directions of the crystal, all became magnetized in the $\langle 100 \rangle$ direction nearest that of the field. When the material was magnetized at a high temperature, magnetostriction deformations set up local stresses which were removed by plastic flow, but below the minimum temperature for plastic flow under these stresses, the stresses were "frozen in", resulting in a slight permanent deformation which, because of magnetostriction, favored magnetization in the direction in which the field had been applied during the magnetic annealing treatment.

Quantitative objections to the strain-magnetostriction theory were raised on the basis that the predicted energy change associated with the domain rotation in the theory was only about one-tenth of that observed, and because studies of the initial permeabilities in iron-nickel alloys revealed that the initial permeabilities predicted by the theory were nearly 8 times the observed initial permeabilities. There were also qualitative objections to the theory, and thus another explanation was sought.

Later work seemed to indicate that there was some connection between the response to magnetic annealing and the order-disorder transformation in some alloys. So it was that S. Kaya[25] proposed a mechanism that related atomic ordering to the uniaxial anisotropy caused by a magnetic field during magnetic annealing. He felt that if non-uniform locally developed atomic ordering (i.e., a partially ordered state consisting of a two-phase mixture of ordered and disordered material) occurred in a magnetic alloy and that if the atomic ordering developed in a needle shape (i.e., if one of the phases formed in elongated regions), then each needle-like region would have a magnetic anisotropy as a result of its shape. A field applied during ordering could cause the needles to form with their long axes parallel to the field, thus producing the uniaxial anisotropy.

Many other investigators also concluded that the presence of crystal ordering was an essential part of magnetic annealing. However, two major objections arose to this ordering theory. The first was that some nickel-cobalt alloys which were not known to order were strongly affected by magnetic annealing[26], and the second, that some alloys responded to magnetic annealing at temperatures above their ordering temperatures[27]. These findings indicated that ordering and magnetic annealing were not necessarily related.

Shortly after these questionable aspects of Kaya's ordering theory were raised, several investigators proposed a directional-ordering theory. This idea seems to have has its origin in work done on the time decay of permeability in iron, which was concerned largely with the behavior of carbon and nitrogen in iron. These two interstitials are found in the centers of ⟨100⟩ axes in the iron lattice, and if most of them lie along a particular ⟨100⟩ axis, they define a direction of uniaxial anisotropy. This direction of uniaxial anisotropy as defined by groups of atoms is the basis of the directional order theory.

S. Chikazumi[28,29] applied this idea to substitutional alloys, reasoning that any two like-atom pairs define a particular axis. In a normal randomly oriented material, these pairs would be directed at random, while in a perfectly ordered structure, no pairs at all would exist; and it is certainly conceivable that alloys in which most of the pairs are aligned in one direction also exist. This latter case is known as directional-order.

S. Taniguchi and M. Yamamoto[30] (1954) used Chikazumi's idea of directional-order and reasoned that each atom pair could be considered to have an energy that depended on the angle between the local magnetization and the axis of the pair. Their proposal was that like-atom pairs tend to be aligned in the direction of the local magnetization. This tendency is opposed by thermal fluctuations which tend to randomize the directions of the pairs. If, however, an applied field aligns the magnetization throughout the sample, the like-atom pairs also tend to be parallel throughout the materials. When the temperature drops so low that diffusion can no longer occur at an appreciable rate, the like-atom pairs are frozen in place, and produce a uniaxial anisotropy in the material[31].

This directional order theory appears to work well for most alloys that do respond to a magnetic anneal.

Recently (1959), however, R. D. Heidenrich, E. A. Nesbitt and R. D. Burbank[32] proposed, based on an electron diffraction investigation of the structure of soft magnet materials containing iron, cobalt, and nickel, that the response of these soft magnet alloys to magnetic annealing is due to oxygen present in them as an impurity. They found that oxygen condensed in the (111) planes of the crystal lattice, giving rise to a stacking disorder or fault, and they attributed the response to magnetic annealing to the alignment of these oxygen impurity faults by the applied field.

This oxygen fault theory of magnetic annealing was reinforced by the observation that a perminvar containing 0.0001% oxygen did not respond to a magnetic anneal, while the same alloy containing 0.0014% oxygen did respond to magnetic annealing.

Nesbitt and Heindenrich also suggested the possibility of short range order between faults, and the possibility of a superexchange mechanism acting through the oxygen atoms since there are layers of metal atoms separated by a layer of oxygen[33].

The oxygen fault theory appears to work well for alloys of Fe, Ni, and Co that respond to magnetic annealing.

At the present time, the strain-magnetostriction theory has been completely abandoned, and few investigators accept the theories based solely on normal ordering. The directional order theory works rather well for most soft magnet materials, and was the generally accepted theory until the oxygen fault theory was advanced. The discovery of the importance of oxygen in magnetic annealing very definitely requires a modification of the existing directional-order ideas of magnetic annealing. It is possible that the alignment of the oxygen stacking faults in an applied field is a type of directional-order, but additional work must be done to determine whether oxygen is required for magnetic annealing in all materials, and to determine the exact mechanism by which oxygen affects magnetic annealing.

One example of the effect of magnetic annealing on magnetostriction is given by Strauss and Sandoz[16] who magnetically annealed a 69 Co-31 Fe alloy. They found that the saturation magnetostriction of 87×10^{-6} in/in for this alloy decreased to 37×10^{-6} in/in when measured in a direction parallel to the direction of the field, and increased to 107×10^{-6} in/in when measured in a direction normal to the direction of the field. No magnetostriction-magnetic annealing data for Vanadium Permendur was found in the literature.

It also appears that there is a connection between magnetostriction, crystal anisotropy, and the response of an alloy to the magnetic annealing process, but it is not clear from the literature just what this connection is.

Thus, although considerable experimental evidence is available as to the effectiveness of the magnetic anneal process for certain materials, no theory has been universally accepted to explain the mechanism of the magnetic anneal process and its relationship to magnetostriction.

3. Procedure

3.1.1 Specimen Description

The specimens for the magnetostriction tests consisted of strips of Vanadium Permendur and Supermendur, each approximately 2" x 3/8" x gage. These alloys had the following compositions:

Material	Chemistry								
	C	Mn	P	S	Si	Ni	V	Al	Co
Vanadium Permendur	.009	.013	.004	.005	.005	.22	1.75	.05	48.30
Supermendur	.003	.007	.005	.002	.047	.15	2.02	.007	48.95

(balance Fe)

The alloys were prepared and cold rolled into strips by the Allegheny Ludlum Steel Corporation Research Center (Brakenridge, Pa.), and subsequently annealed and magnetically annealed at Lehigh University.

3.1.2 Processing of Cold Rolled Strip

Experimental heats of Supermendur and Vanadium Permendur were prepared, melted and cast into 17-pound ingots. The Supermendur was melted and cast under vacuum, while the Vanadium Permendur was melted and cast in an air atmosphere. After the heats had been cast, processing proceeded identically for both alloys.

Data for the following synopsis of the processing was provided by the Allegheny Ludlum Steel Corporation Research Center:

Forging: The 17-pound ingots were preheated at 1200°F for 30 minutes, and then soaked for 30 minutes at 2200°F.

They were then press-forged into 1/2" sheet.

Hot Rolling:	The hot roll cycle was begun immediately after forging. The sheets were reheated at 200°F for 30 minutes, and rolled to a .090" gage hot rolled band.
Quenching:	The hot rolled band was soaked for 45 minutes at 1475°F, then quenched in iced brine.
Cold Rolling:	The quenched band was <u>shot blasted</u> to remove scale, and cold rolled directly to the following final nominal gages: .090", .070", .045", .015", .006". These nominal gages corresponded to, respectively, 0, 24.0 ± 0.5, 49.7 ± 0.6, 81.6 ± 0.8, and 93.2 ± 0.1 per cent reduction in thickness, as determined for a 95% confidence interval, for the specimens used for testing.
Shearing:	Twelve longitudinal (long axis parallel to the direction of rolling) and twelve transverse (long axis normal to the direction of rolling) specimens, each 2" x 3/8" x gage, were sheared from each strip.

Two longitudinal and two transverse specimens of the Supermendur at each cold rolled gage, and two longitudinal and two transverse specimens of the Vanadium Permendur at the .090" and the .006" gages, were used as specimens for the magnetostriction measurements on the cold rolled alloys.

3.1.3 Annealing and Magnetic Annealing

The annealing furnace consisted of a non-inductively-wound ceramic tube 26" long with a 2" inside diameter. A.C. power was used for heating. The furnace windings and ceramic tube were embedded in bakelite, and water coils were wrapped around the bakelite to keep the bakelite from overheating. Copper solenoids, separated by copper water cooling fins, were placed around this central core. D.C. power was used to provide a D.C. magnetic field when the furnace was used as a magnetic annealing furnace.

The magnetic field supplied by the magnetizing solenoid was an axial field, and was calibrated with a Dyna-Empire Gaussmeter (Model D-855). The Gaussmeter was also used to probe the tube. The D.C. magnetic field was found to be constant (for a given current) at every point checked in the tube and to be unaffected by A.C. power in the furnace coils.

One magnetic anneal and two straight anneals were made. Each anneal was performed in identical manner, except that a D.C. magnetic field of 100 oersteds was used during the magnetic anneal and no magnetic field was used during the straight anneals. Specimens for each anneal consisted of cold rolled material. They were placed between copper strips which were used to hold them in a fixed position in the furnace tube. The binding by the copper strips kept the specimens used in magnetic annealing from rotating and twisting in the magnetic field, and permitted duplication of technique during the straight anneals. According to electromagnetic theory, copper strips would not hinder the D.C. magnetic field from passing through the samples[33]. The specimens were then placed in a Vycor tube in the furnace core, and sealed at both ends by gaskets. An argon atmosphere was introduced into this tube before annealing, and 6 cubic feet of argon per hour were passed through the tube during the annealing cycle. The specimens were placed in an 8" zone of the furnace that had constant temperature as measured with a Leeds and Northrup Potentiometer Indicator and a Chromel-Alumel thermocouple. The temperature in the furnace during the annealing cycle was measured with the thermocouple at the center of the constant heat zone. The annealing cycle in all anneals was the same: the specimens were heated from room temperature to 1600°F in one hour, cooled from 1600°F to 1300°F in 30 minutes, held at 1300°F for 80 minutes, and finally cooled to room temperature in 30 minutes by a blast of cool air. During the magnetic anneal, the magnetic field was applied when the specimens reached 1300°, and remained on until the specimens had been cooled to room temperature. The temperatures used were chosen on the basis of a favorable response to magnetic annealing shown by 50 Fe - 50 Co alloys in studies done at Lehigh University[34]. Specimens used in each of the three anneals are described below, and the interval cooling curve for each anneal is shown in Figure 3.

Anneal A: Magnetic Anneal

Four longitudinal and four transverse specimens of Supermendur at the .090" and the .006" gages, and four longitudinal and four transverse specimens of Vanadium Permendur at the .090" and the .006" gages, were used as specimens for magnetic annealing. Two specimens from each set were placed in the furnace with their long axes parallel to the direction of the magnetic field, while the other two specimens in each set were placed with their long axes normal to the direction of the magnetic field. Two specimens each for X-ray studies from the .090" and the .006" gage were placed in the furnace, one with the direction of rolling parallel to the direction of the field and the other with the direction of rolling normal to the direction of the field.

Anneal B: Straight Anneal

Two longitudinal and two transverse specimens of Supermendur at the .090" and the .006" gages were used as specimens for straight annealing. One .090" and one .006" gage X-ray specimen of Supermendur was also annealed at this time.

Anneal C: Straight Anneal

Two longitudinal and two transverse specimens of Supermendur at

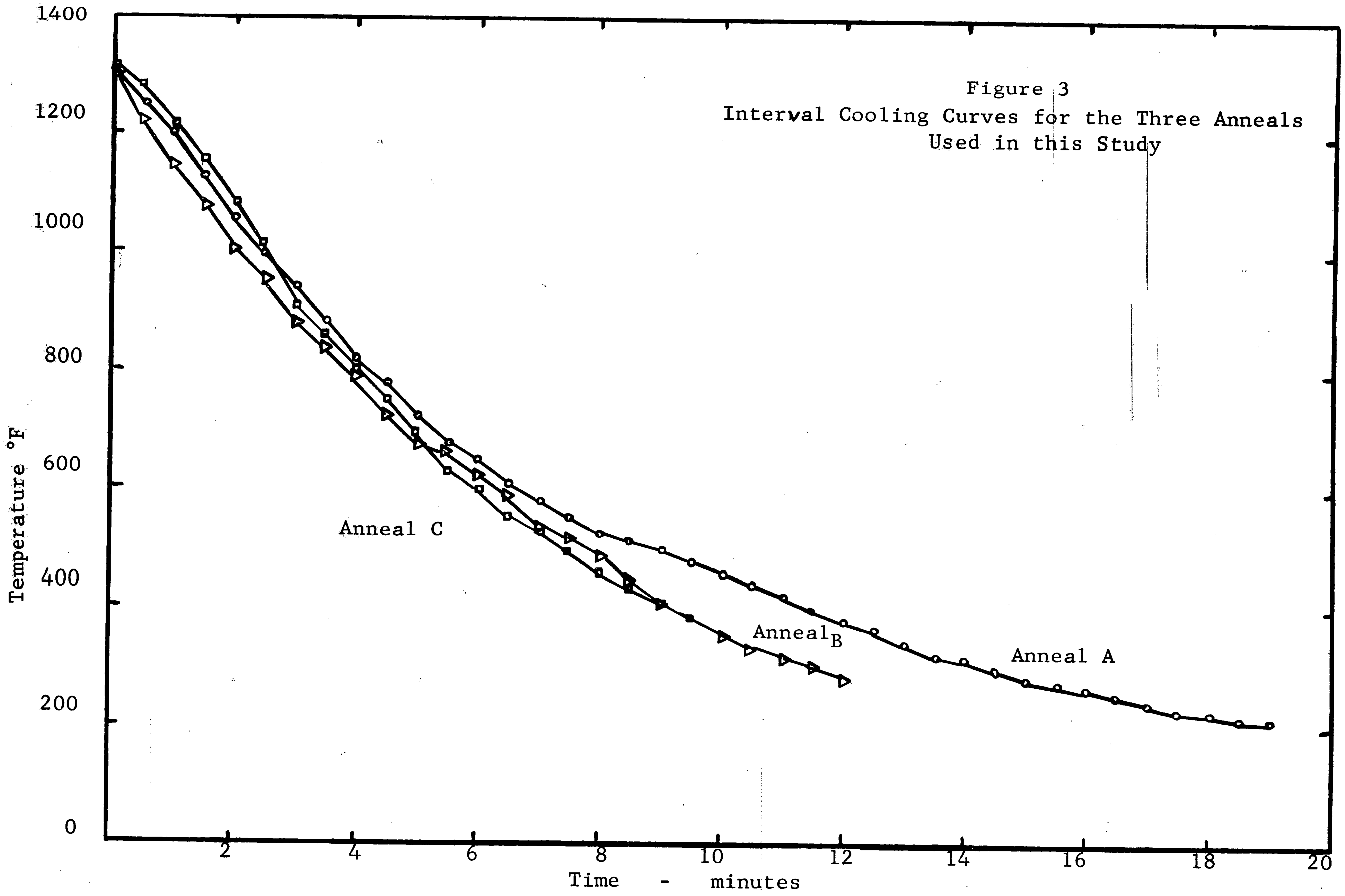


Figure 3
Interval Cooling Curves for the Three Anneals Used in this Study

the .070", .045", and the .015" gages were used as specimens in this straight anneal. One X-ray specimen of Supermendur from each gage was also annealed at this time.

3.2 Description of Apparatus

3.2.1 Magnetostriction Measuring Equipment

The magnetostriction measurements were performed using a strain-gage technique. Budd Metalfilm strain gages (type C5-121) formed adjacent arms of a Wheatstome bridge in an SR-4 Type K Strain Indicator (Baldwin-Lima-Hamilton Corp.). An "active" gage was cemented to the specimen, and a "dummy" gage, mounted on thin cardboard, was taped to the specimen near the active gage. This arrangement minimized and compensated for temperature, magnetic field, and stray effects in the active gage. The specimen was insulated in asbestos board and placed in the center of a magnetizing coil. Temperature effects in the specimen itself were nullified by balancing the bridge immediately before applying the magnetic field. D.C. demagnetization was performed on each sample at each field to insure that all measurements were based on the same initial state. It was also assumed that temperature fluctuation due to magnetothermal effects were small since the measurements were performed at low fields at room temperature.

The SR-4 Type L Strain Indicator, as sold commercially, is a direct reading instrument. The indicator consists of the two upper arms of a Wheatstone bridge, an oscillator as a power source for the bridge, an amplifier, rectifier, phase descriminator, and a galvanometer which is used as a null indicator. The dial from which strains were read was sub-divided into 10 μ-in/in units; however, use of a magnifying glass mounted above the dial, and a small scale divided into 2 μin/in units, enabled readings within plus or minus 1 μin/in to be taken. It was felt that this range was well within the normal error range inherent in the strain gages used.

3.2.2 Calibration of Strain Indicator

As a check on the accuracy of the indicator, the indicator was calibrated by observing the $\frac{\Delta L}{L}$ indicated by the instrument caused by a known change in resistance in series with the Temperature Compensating Gage. The known change in resistance was produced by shunting various resistances across a one ohm resistor in series with the Temperature Compensating Gage. This produced a decrease in the resistance in that arm of the bridge and corresponded to an expansion of the specimen since the test gage was in the adjacent arm. The circuit arrangement for the calibration is shown below in Figure 4.

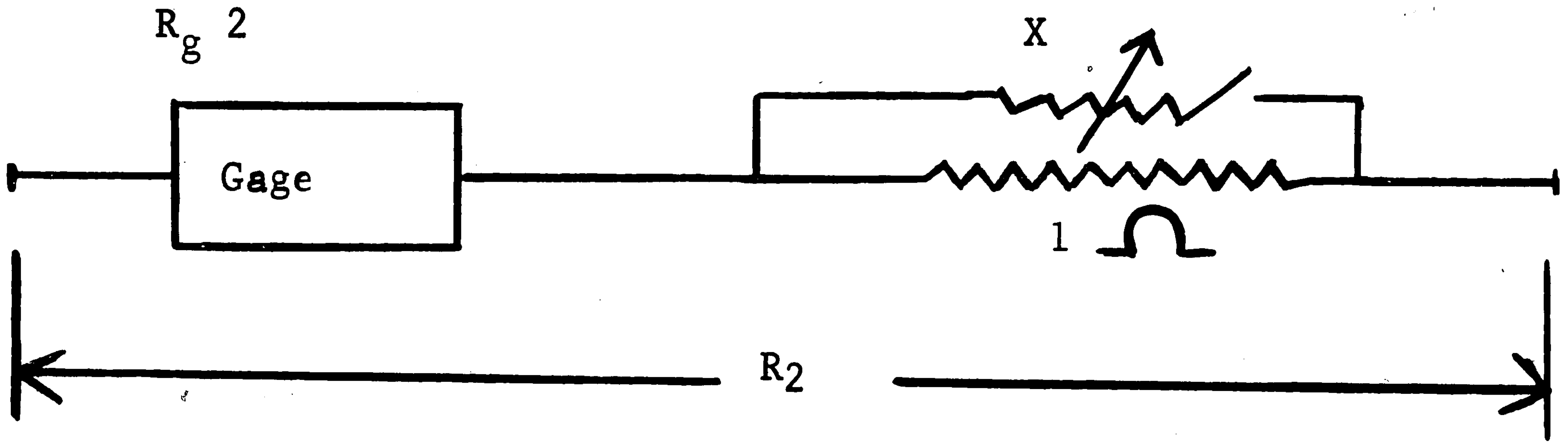


Figure 4 - Temperature Compensating Arm of the Bridge

The sketch shows the temperature compensating arm of the bridge. When a resistance is shunted across the one ohm resistor, the resistance of the arm changes by an amount $\Delta R_2 = (Rg + 1) - (Rg + \frac{x}{1+x})$ or

$\Delta R_2 = \frac{1}{1+x}$

This ΔR_2 causes the null balancing galvanometer to deflect and thus a $\frac{\Delta L}{L}$ is indicated by the instrument. Since $\frac{\Delta L}{L} = \frac{\Delta Rg}{KRg}$ for the gage (K is the gage factor), $\frac{\Delta L}{L}$ could be obtained by multiplying the value of ΔRg for the given resistance x used, by $\frac{1}{KRg}$. However, $\frac{1}{KRg}$ is a constant, so $\frac{\Delta L}{L}$ could be found directly my multiplying the value of $\frac{1}{1+x}$ by $\frac{1}{KRg}$. This calculated $\frac{\Delta L}{L}$ could then be checked against that measured by the indicator, and a calibration curve made, if necessary. To further increase precision, all gages used were from the same lot, having a resistance of 120 ohms and a gage factor of 2.05.

The calibration curve for the SR-4 Strain Indicator used for the magnetostriction measurements is shown in Figure 5. The shunting resistances (x) used in the calibration ranged from 30-900 ohms and corresponded to strains of 131.5 - 4.51 -in/in. The equations

$$\left(\frac{\Delta L}{L}\right)\text{calc.} = 1.05 \left(\frac{\Delta L}{L}\right) \text{record.} \pm 3.02\%$$

for $\left(\frac{\Delta L}{L}\right)$ calc. from 0-131.5 μ-in/in and

$$\left(\frac{\Delta L}{L}\right) \text{calc.} = 1.05 \left(\frac{\Delta L}{L}\right) \text{record} \pm 1.13\% \text{ for}$$

$\left(\frac{\Delta L}{L}\right)$ calc. from 10 - 131.5 μ-in/in

represent a best straight line fit by the average point method to the calibration curve, and were used to determine the actual magnetostriction of each specimen tested. The SR-4 Strain Indicator used was recalibrated periodically, and in each case, the above equations represent the best fit to each calibration curve. The divergence from a one-to-one correspondence was probably due to the fact that the circuit used was more complex than just the SR-4 Indicator circuit.

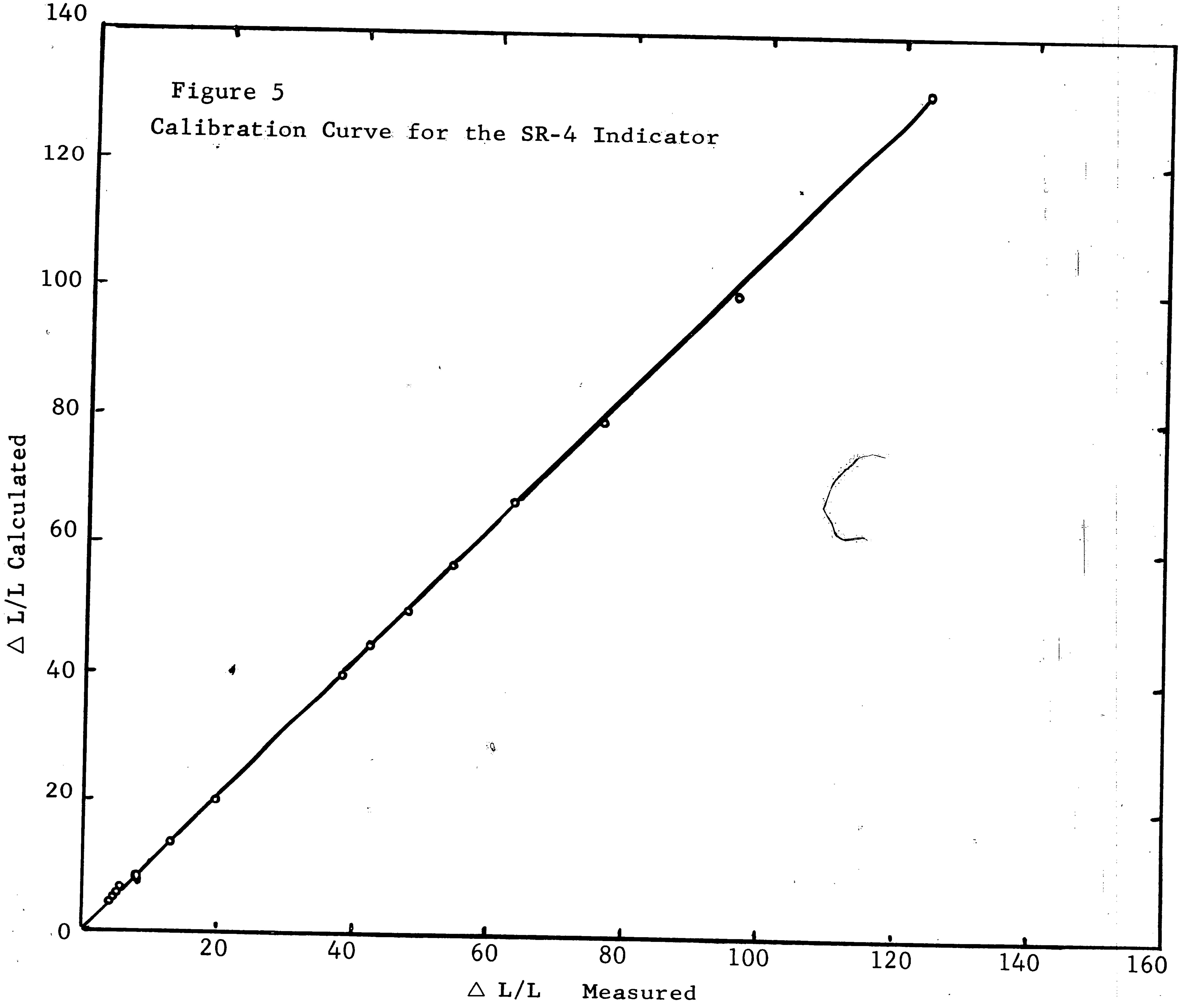


Figure 5
Calibration Curve for the SR-4 Indicator

3.2.3 Magnetizing Coil

The magnetizing coil was a solenoid 6 inches long wrapped with AWG #16 insulated copper wire at 52.5 turns per inch. It was calibrated with a Dyna-Empire Gaussmeter (Model D-855). The equation

$$H \text{ (field strength in oersteds)} = 25.96\ I \text{ (current in amperes)} \pm 3.22\%$$

represents a best straight line fit by the average point method to the calibration curve, and was used to determine the field strength of the coil for each current used.

3.2.4 Magnetizing Current Circuit

The power for the magnetizing current was supplied by twenty 6-volt storage batteries connected in two banks wired in parallel, with each bank composed of ten batteries joined in series. The magnitude of the coil current was varied by passing the current through a series of ohmite rheostats. Shorting switches across each rheostat were used to divert the current around the rheostat when the circuit current was too high for the capacity of that rheostat. Each rheostat was also protected by a fuse. The circuit could handle currents up to 50 amperes, but field strengths of 0-500 oersteds were attained by varying the current in the coil between 0-20 amperes. (See Figure 6).

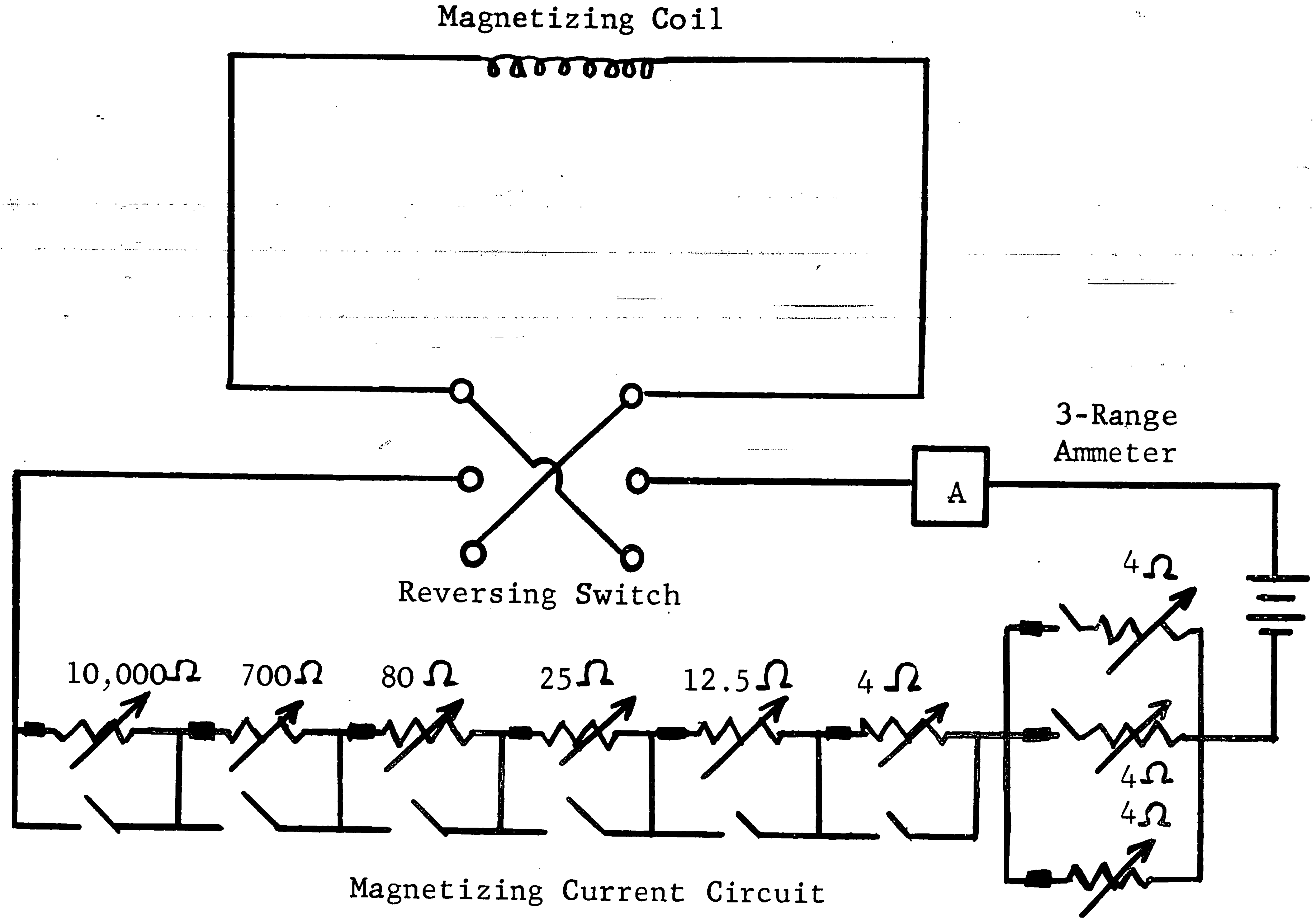


Figure 6

3.3 Texture Analysis

Texture studies of cold rolled Supermendur at each gage, of cold rolled and magnetically annealed Supermendur at the .090" and .006" gages, and of cold rolled and annealed Supermendur at the .090", .045", and .006" gages, were made, using a Siemens and Halske Aktiengesellschaft texture diffractometer and X-ray equipment.

Molybdenum K_α -radiation - excited with 40 kv and 18 ma, and filtered with a zirconium filter - was used to determine a (110) pole figure ($2\theta = 20.14^o$) from 0-70^o for each of these specimens. An integrated proportional counter was used to receive the reflections, and the impulses were recorded on a strip chart (full scale = 4×10^4 counts per minute).

The same full-scale deflection was used for each sample so that a general comparison could be made. The relative values of the intensities were transferred from the strip chart to a Siemens 20 cm. Registrierspirale to obtain the pole figures.

3.4 Determination of Order

A back-reflection pinhole camera technique was used to detect evidences of ordering in cold rolled, cold rolled and magnetically annealed, and cold rolled and annealed Supermendur, all at 93.2% reduction in thickness. Cobalt K_α -radiation - excited with 35 kv and 9 ma, and filtered with an iron oxide filter - was used to obtain the reflections. The specimen - to - film distance employed was 3 cm. At this distance, the 220 reflection and the 310 reflections are the only ones that should appear: planes of lower indices are not in the back reflection region, while planes of higher indices do not diffract. The 300 line will appear as a super lattice line, if it appears at all. Exposure times of 4 to 10 hours were used for each specimen.

3.5 Metallographic Studies

Representative longitudinal specimens of Supermendur of .090" and .006" gages for each of the four treatments used in this study were mounted in Quickmount (Princeton Photo Co.). The surface to be examined was the cross-section whose normal was parallel to the direction of rolling. All specimens were rough polished on belt sanders, successively smoothed on 100 to 400 sandpapers, and polished on wet laps with successively finer powders, from 800 mesh to Linde "B" powder. The samples were etched with a 5% Nital solution.

4. Presentation and Discussion of Results

4.1 General

Each magnetostriction curve shown in Figures 7-23 represents the average curve for two samples treated in the same manner. The maximum deviation between such samples at any field was 3μ-in/in, or ± 1.5μ-in/in from the average curve. Successive readings for any given sample at any field were always within ± 1μ-in/in of the average of a number of readings taken at the given field.

The magnetostriction of every sample tested increased as the magnetic field was increased, or, in other words, Vanadium Permendur has a positive linear magnetostriction at all fields used.

The magnetostriction values for Vanadium Permendur and Supermendur were found to be approximately the same for identical treatments. For this reason, only the Supermendur was tested completely.

4.2 Cold Rolled Alloys

The magnetostriction in transverse and longitudinal specimens of as received Vanadium Permendur and Supermendur (Figure 7) varied considerably at all fields. The magnetostriction in the transverse specimens was higher than the magnetostriction in the longitudinal specimens for both alloys.

After an initial abrupt decrease from the as received material, cold rolling was found to increase the magnetostriction in the direction parallel to the direction of rolling, and in the direction normal to the direction of rolling, in both Supermendur (Figures 8,9) and Vanadium Permendur (Figure 10) in an orderly manner: as the amount of cold rolling as measured by the per cent reduction of thickness increased, the

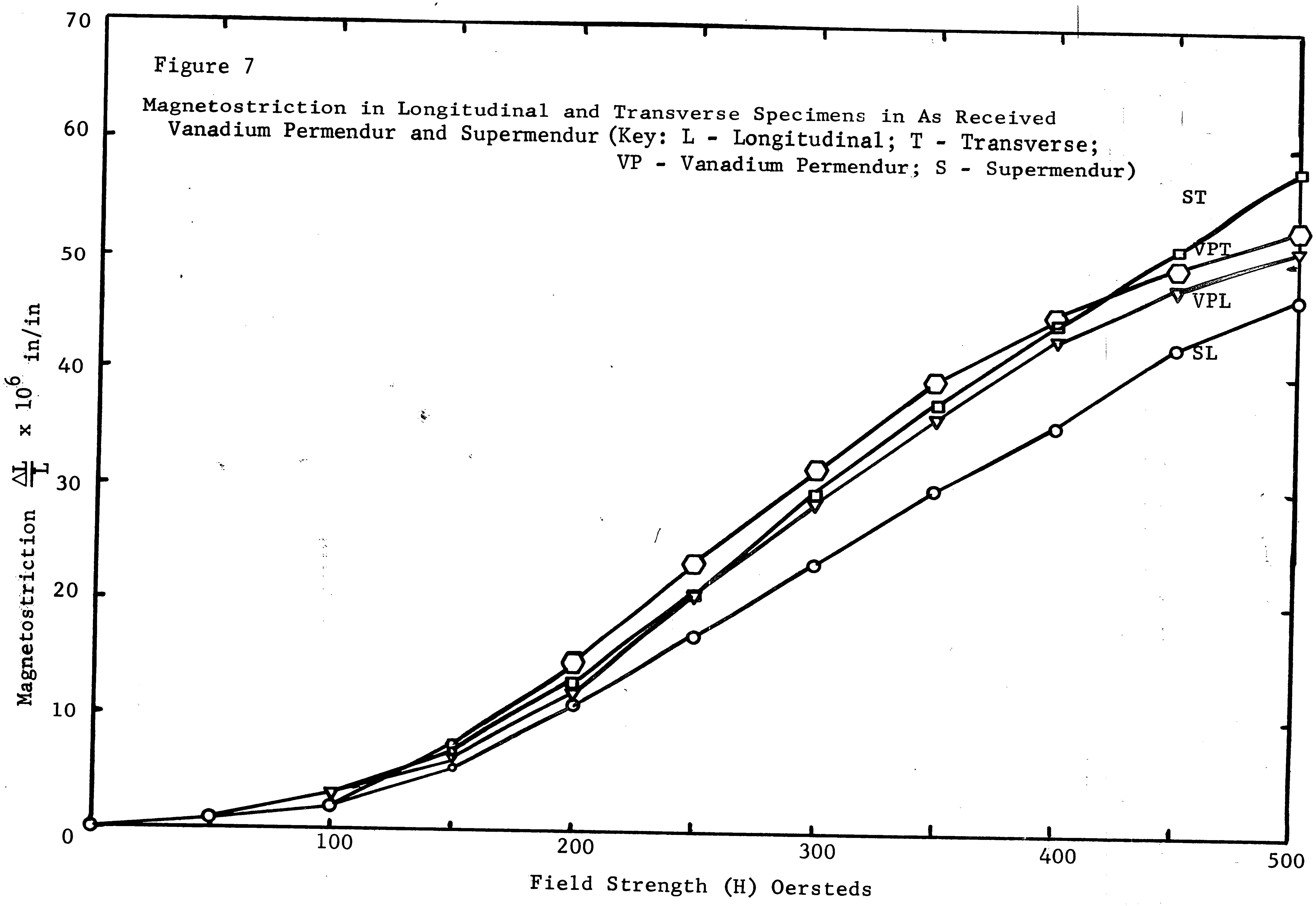


Figure 7

Magnetostriction in Longitudinal and Transverse Specimens in As Received Vanadium Permendur and Supermendur (Key: L - Longitudinal; T - Transverse; VP - Vanadium Permendur; S - Supermendur)

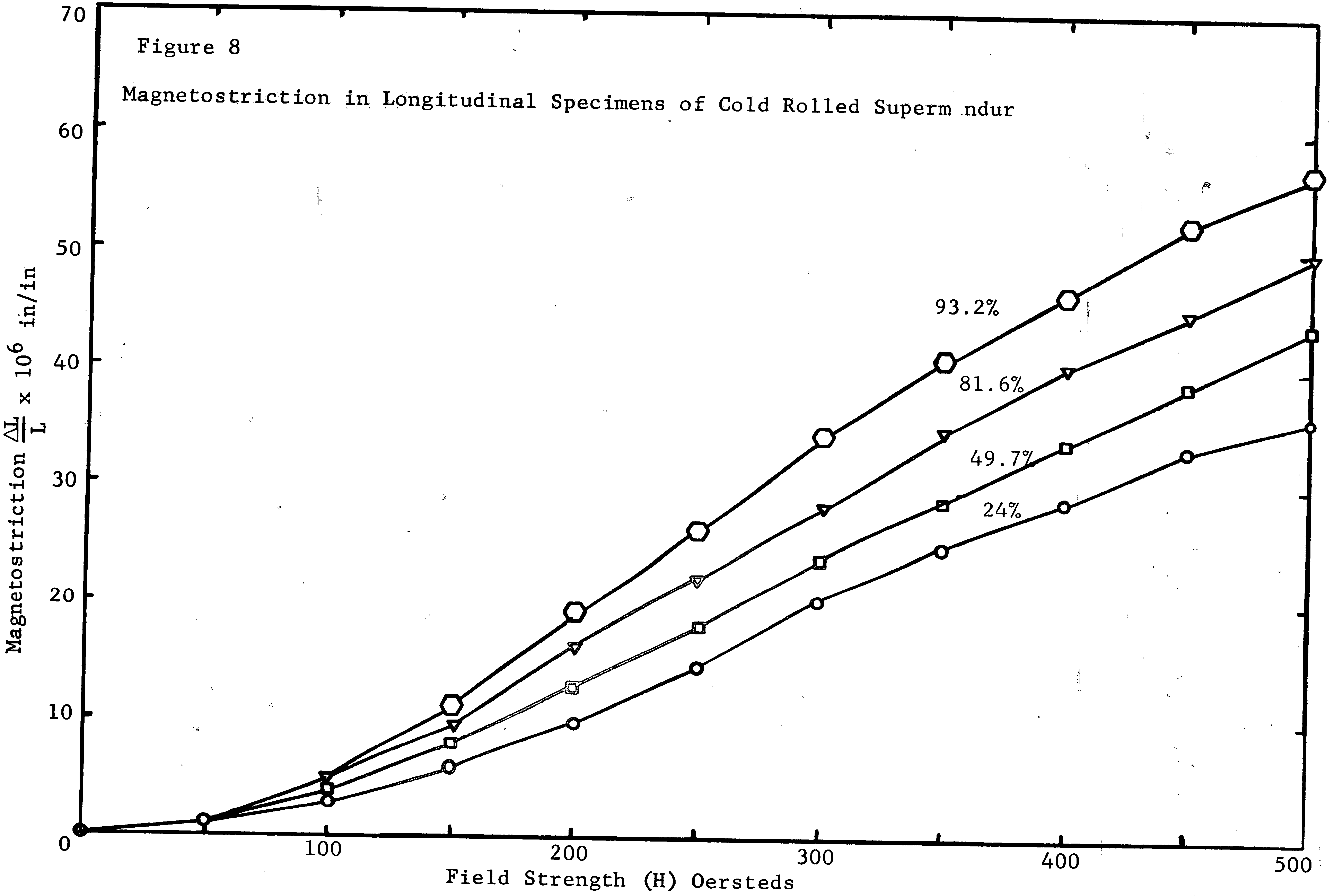


Figure 8

Magnetostriction in Longitudinal Specimens of Cold Rolled Supermendur

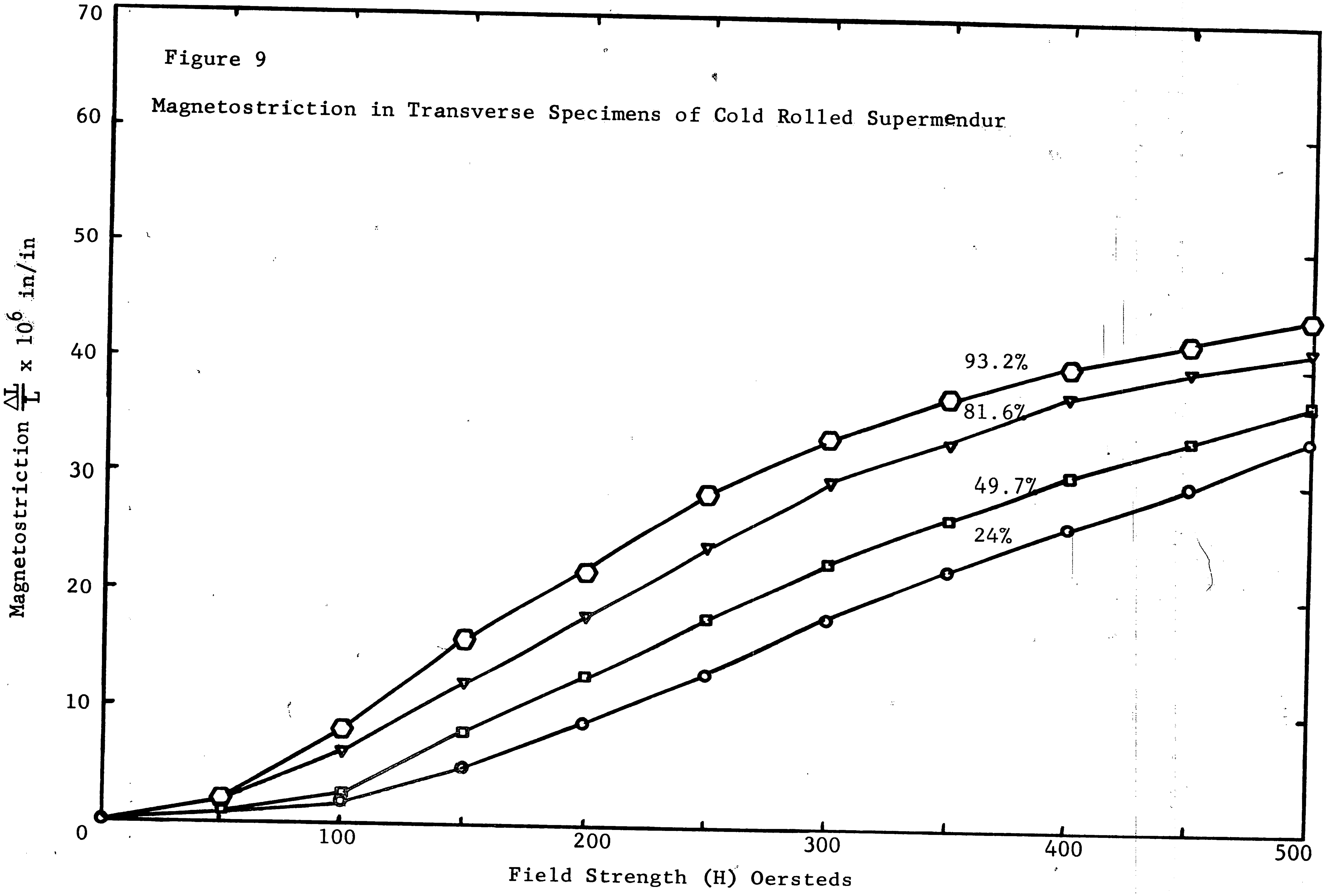


Figure 9

Magnetostriction in Transverse Specimens of Cold Rolled Supermendur

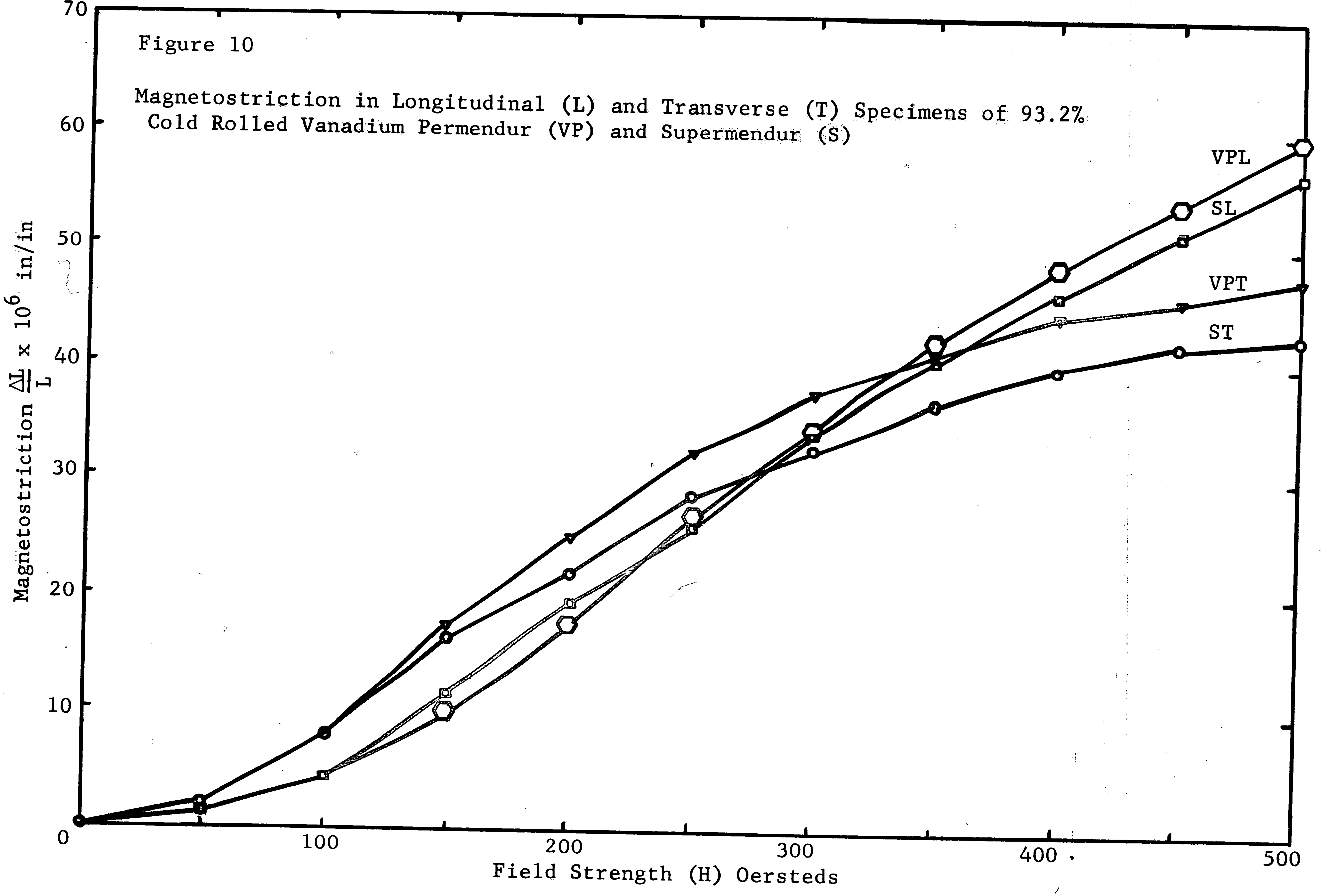


Figure 10

Magnetostriction in Longitudinal (L) and Transverse (T) Specimens of 93.2% Cold Rolled Vanadium Permendur (VP) and Supermendur (S) magnetostriction also increased at any given field. The increase in magnetostriction in the rolling direction was greater than the increase in magnetostriction in the transverse direction of rolling at fields greater than 200 oersteds, while the reverse was true at lower fields. This difference in the increase indicates that the mode of deformation was not symmetrical, as might be expected, and that magnetostriction is a structure sensitive property that may be strongly affected by the degree of anisotropy in a material.

The effect of cold rolling on the magnetostriction of Supermendur is graphically illustrated in Figure 11. It should be noted that the magnetostriction in the as received transverse specimens of Supermendur is higher than the magnetostriction in longitudinal specimens cold rolled to 93.2% reduction in thickness. The drop in magnetostriction between the as received and 24% cold rolled material is probably not a true picture of the effect of small amounts of cold rolling or magnetostriction because of lack of data at lower reductions.

Comparison of the (110) pole figures (Figures 12-16) with each other and with the corresponding magnetostriction curves indicated that crystal texture has a large effect on magnetostriction in Supermendur.

The pole figure for the as received Supermendur (Figure 12) proved extremely difficult to index and may be a complex texture brought about by a phase change which may have occurred during the hot rolling of this alloy. The hot rolling cycle was begun at 2200°F, and at this temperature the Supermendur was completely in the γ (FCC) region[4,35]. The temperature at the end of the hot rolling cycle is unknown, but the soak at the end of the cycle at 1475°F put the alloy completely in the α (BCC) region. Thus, if the transformation of γ to α occurred

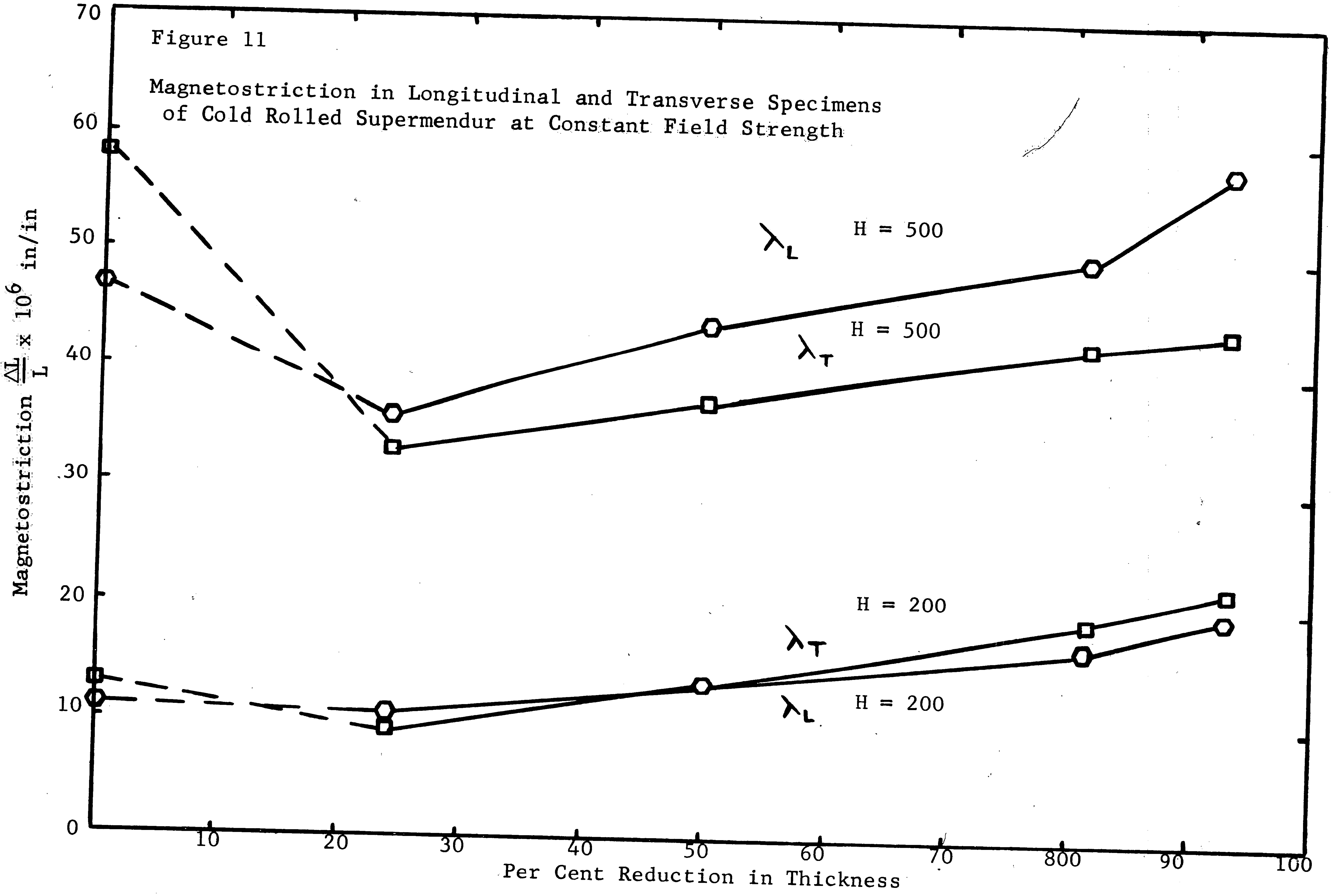


Figure 11

Magnetostriction in Longitudinal and Transverse Specimens of Cold Rolled Supermendur at Constant Field Strength

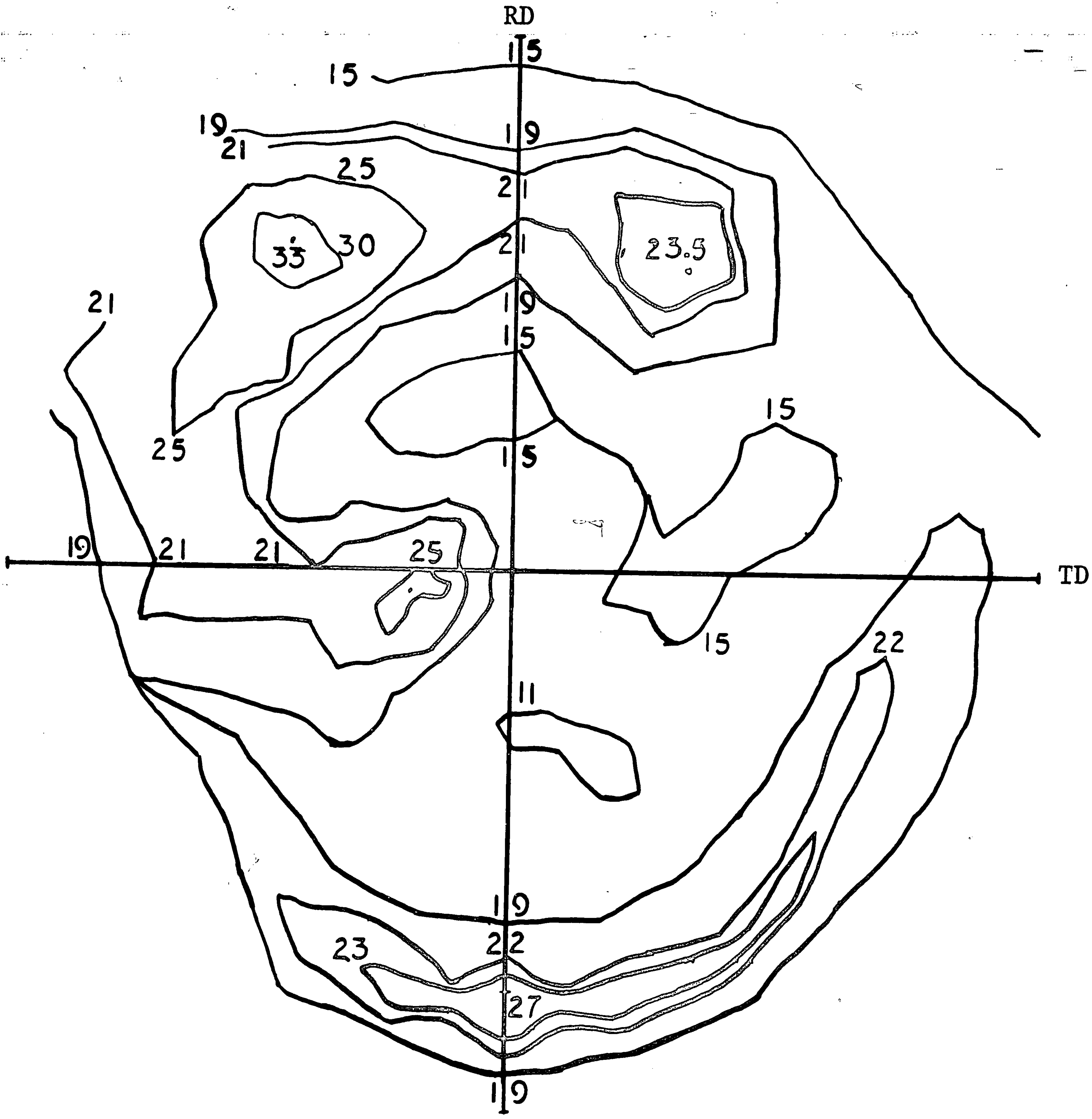


Figure 12

(110) Pole Figure from 0-70° for
As Received Supermendur

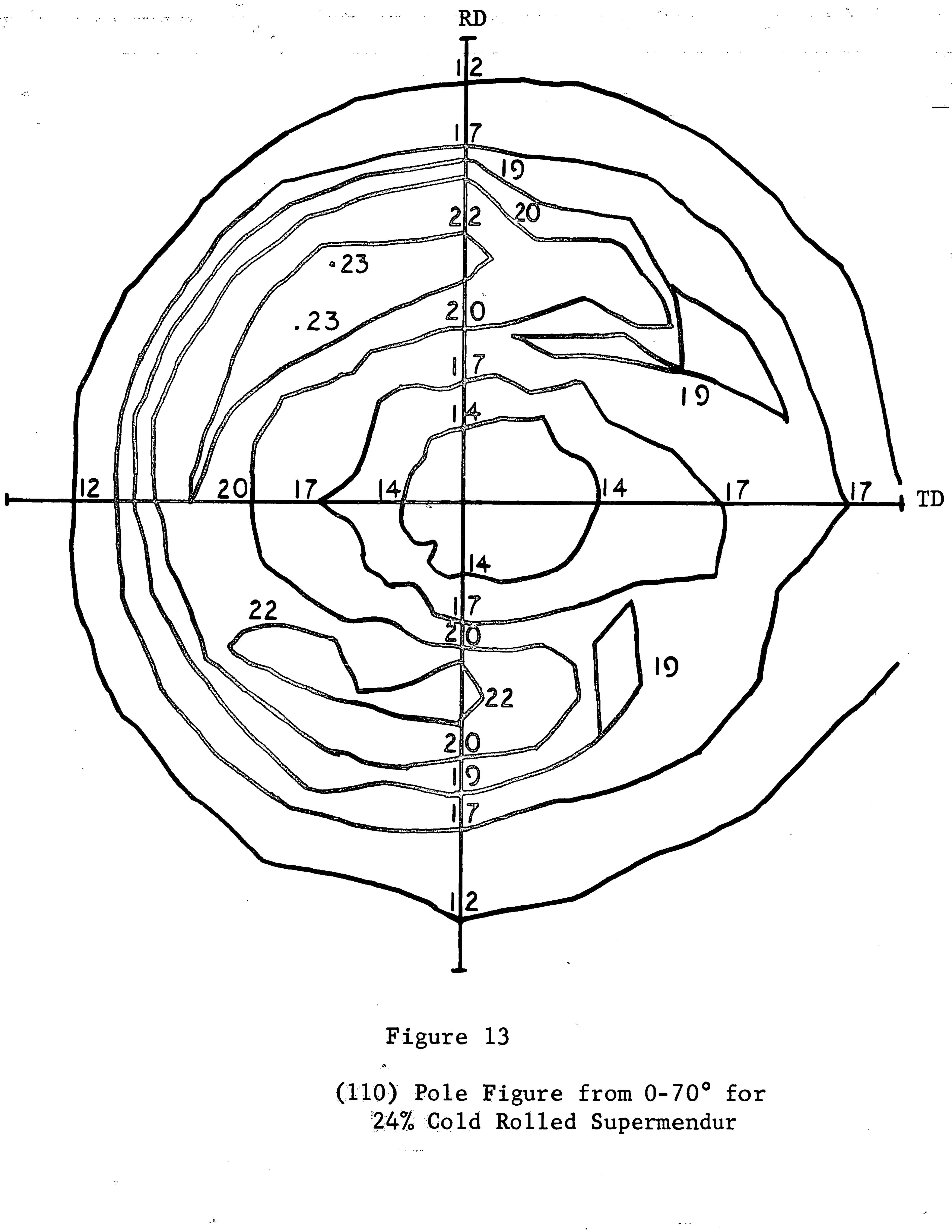


Figure 13

(110) Pole Figure from 0-70° for
24% Cold Rolled Supermendur

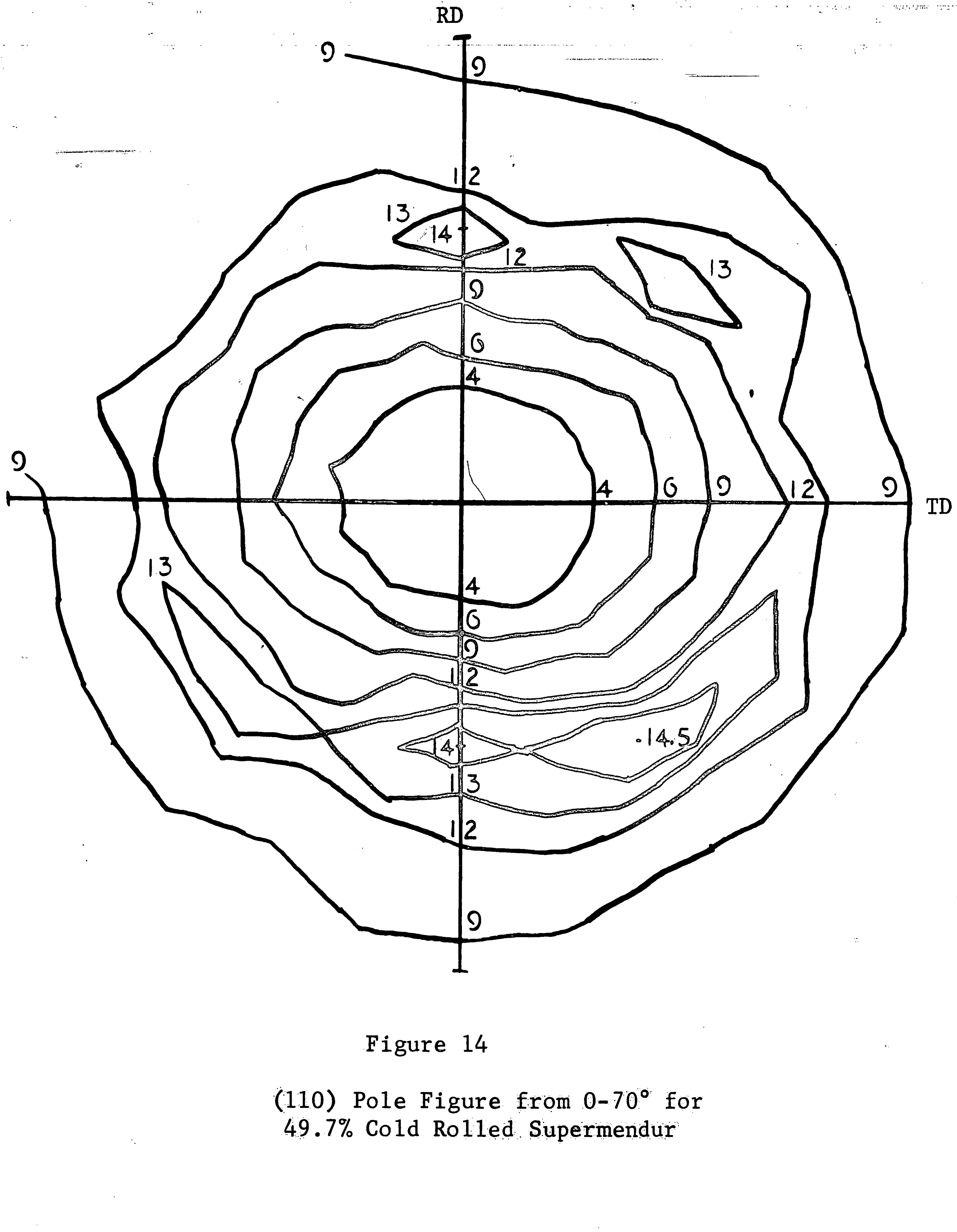


Figure 14

(110) Pole Figure from 0-70° for
49.7% Cold Rolled Supermendur

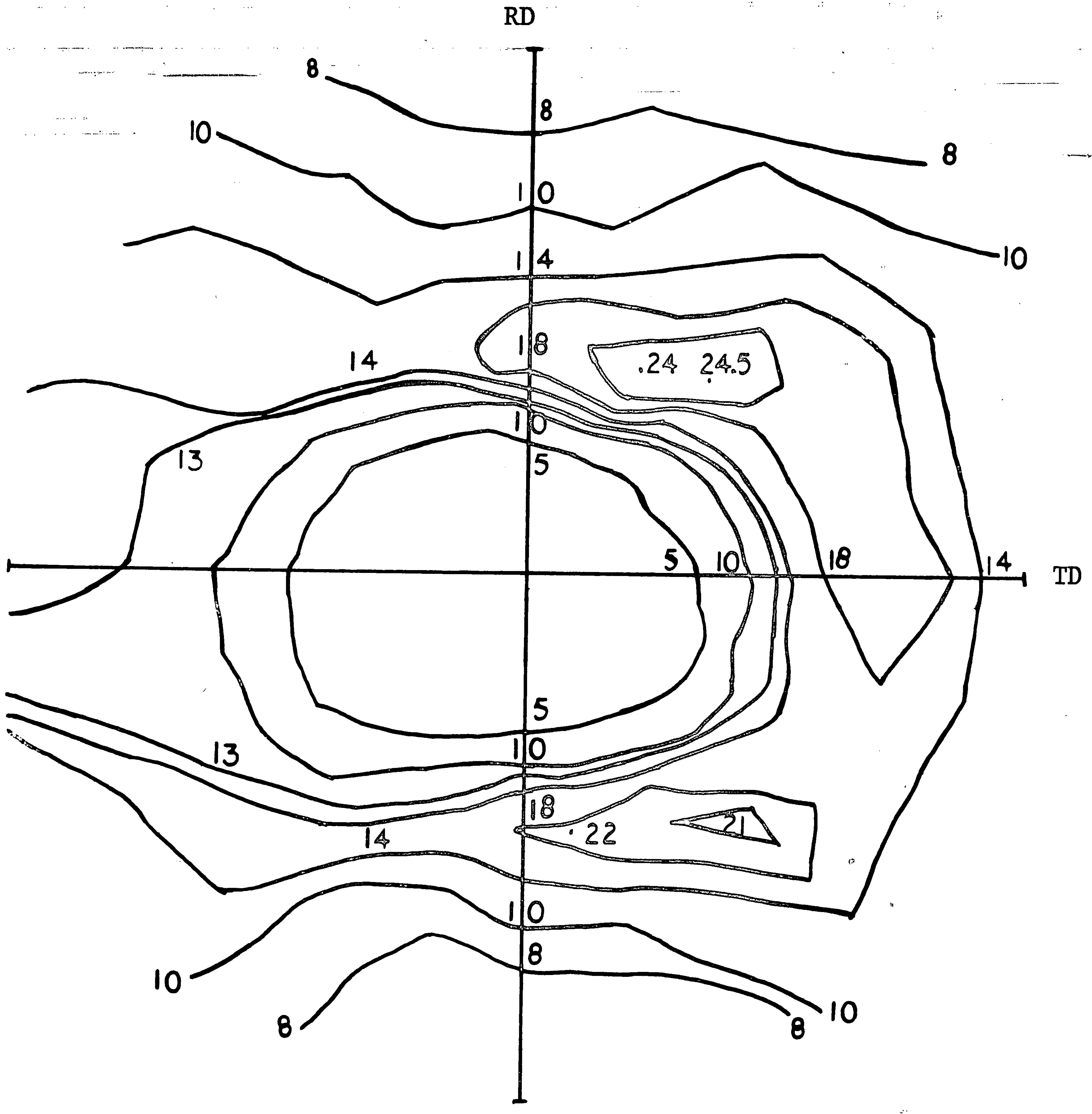


Figure 15

(110) Pole Figure from 0-70° for
81.6% Cold Rolled Supermendur

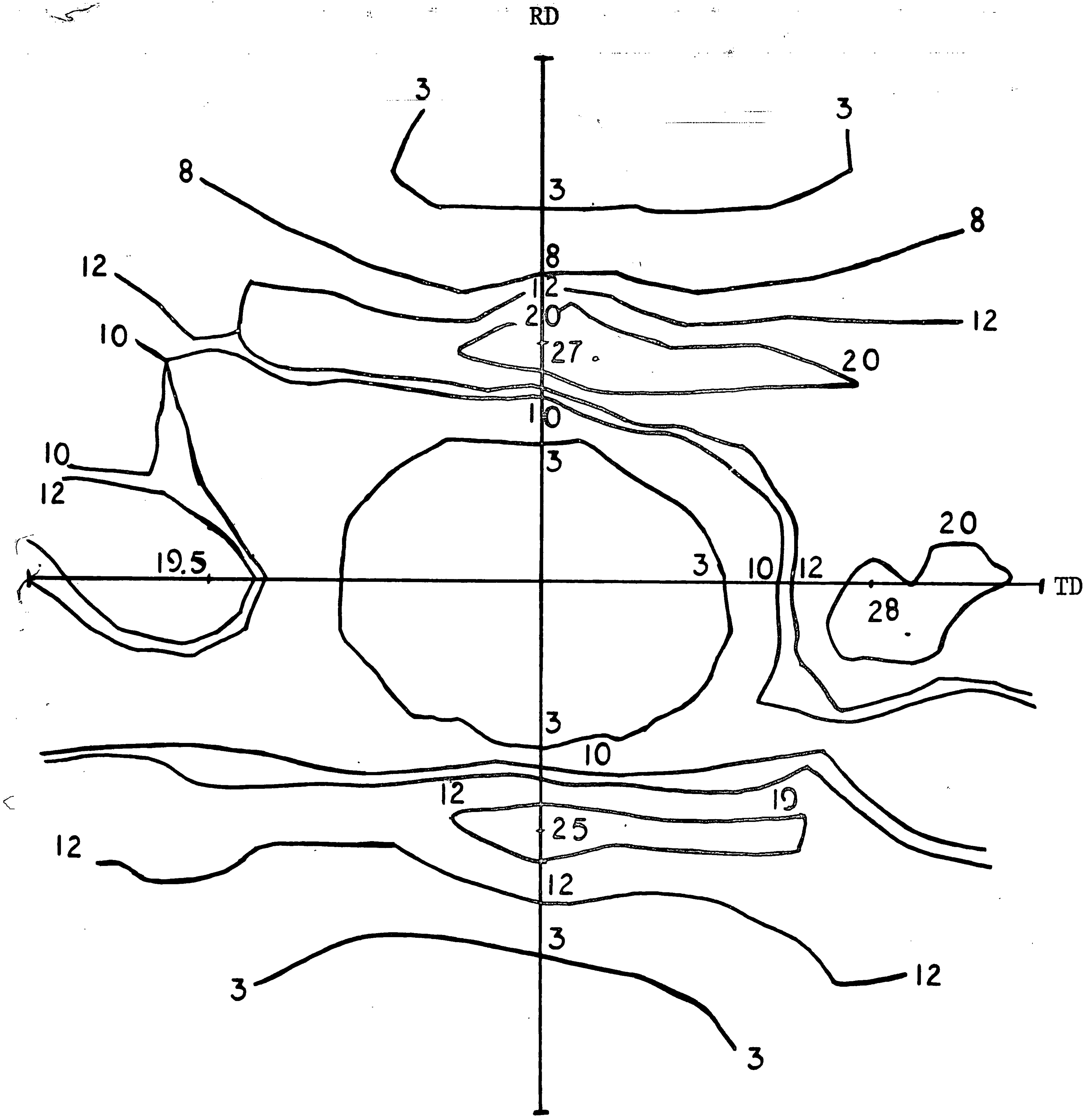


Figure 16

(110) Pole Figure from 0-70° for
93.2% Cold Rolled Supermendur

during rolling, the orientations from phase transformations, hot rolling of two entirely different phases, and recrystallization may have combined to form the complex texture of this alloy. This explanation accounts for the odd angles ($\measuredangle \nless 60^{\circ} \nless 90^{\circ}$) between (110) poles found on the figure. This unusual texture may also be the reason for the unexpected high magnetostriction values of the as received alloy.

The pole figure for the Supermendur specimen reduced to 93.2% (Figure 16) appears to be a typical cold rolled texture for a BCC material. It seems to be composed of two components, a (111) $[11\bar{2}]$ component, which, according to G. Kurdjumow and G. Sachs[36] is not unusual in a cold rolled BCC metal, and a (210) $[1\bar{2}1]$ component, an orientation that is quite conceivable in a cold rolled BCC metal[37]. Perhaps more rolling would bring the specimen even closer to its ideal texture, (100) $[011]$. The strong texture of the Supermendur in this cold rolled form may account for the high values of magnetostriction in both the longitudinal and transverse specimens.

The pole figures for the intermediate reductions (Figures 13-15) seem to show intermediate steps leading from the breakdown of the hot rolled texture to the build-up of the cold rolled texture. The change in the magnetostriction can be followed along with the change in texture in that as the hot rolled texture disappears (Figure 13), the magnetostriction drops drastically, and as the cold rolled texture begins to form (Figures 14-16), the magnetostriction increases.

Work done on single crystals of iron-cobalt alloys by H. Urquhart and J. E. Goldman[38] indicates that a magnetostriction of over 100 μ in/in can theoretically be obtained in 50 Fe-50 Co, so, based on this figure, cold working alone is not the ideal way to increase magnetostriction. However, little work has been done on λ_{110} in 50 Fe-50 Co alloys, so a comparison cannot be made with single crystals.

Ordering probably did not occur in the cold worked alloys since all temperatures used in treating the Supermendur were above the ordering temperature for Supermendur[35]. No superlattice line was found in the X-ray study (Table I). Though this also indicates lack of order, it is not conclusive in that preferred orientation may increase normally appearing lattice lines at the expense of super-lattice lines.

Ordering may actually be somewhat detrimental to increasing magnetostriction. R. C. Hall[39] found that λ_{100} was slightly lower and λ_{111} slightly higher in 50 Fe-50 Co in the ordered lattice than in the disordered lattice.

The microstructure of the as received Supermendur (Figure 17) shows evidences of slip lines or mechanical twins, even though it appears to have recrystallized. The microstructure of the 93.2% cold rolled Supermendur (Figure 18) shows highly distorted grains typical of a cold rolled alloy.

Domain configuration coupled with texture could also have an effect on magnetostriction, but no work was done on this phase.

4.3 Magnetically Annealed Alloys

Magnetic annealing was found to drastically decrease the magnetostriction in as received Supermendur and Vanadium Permendur in both longitudinal and transverse specimens, regardless of the orientation (parallel or normal) of the magnetic annealing field with respect to

Table I

Results of Ordering Studies

Alloy	Lines Appearing 220	Lines Appearing 300	Lines Appearing 310
93.2% CR Supermendur	yes	no	yes
93.2% CR and Magnetically Annealed Supermendur	yes	no	yes
93.2% CR and Annealed without a field Supermendur	yes	no	yes

Figure 17 Photomicrograph of As-Received Supermendur Showing Slip Bands or Deformation Twins

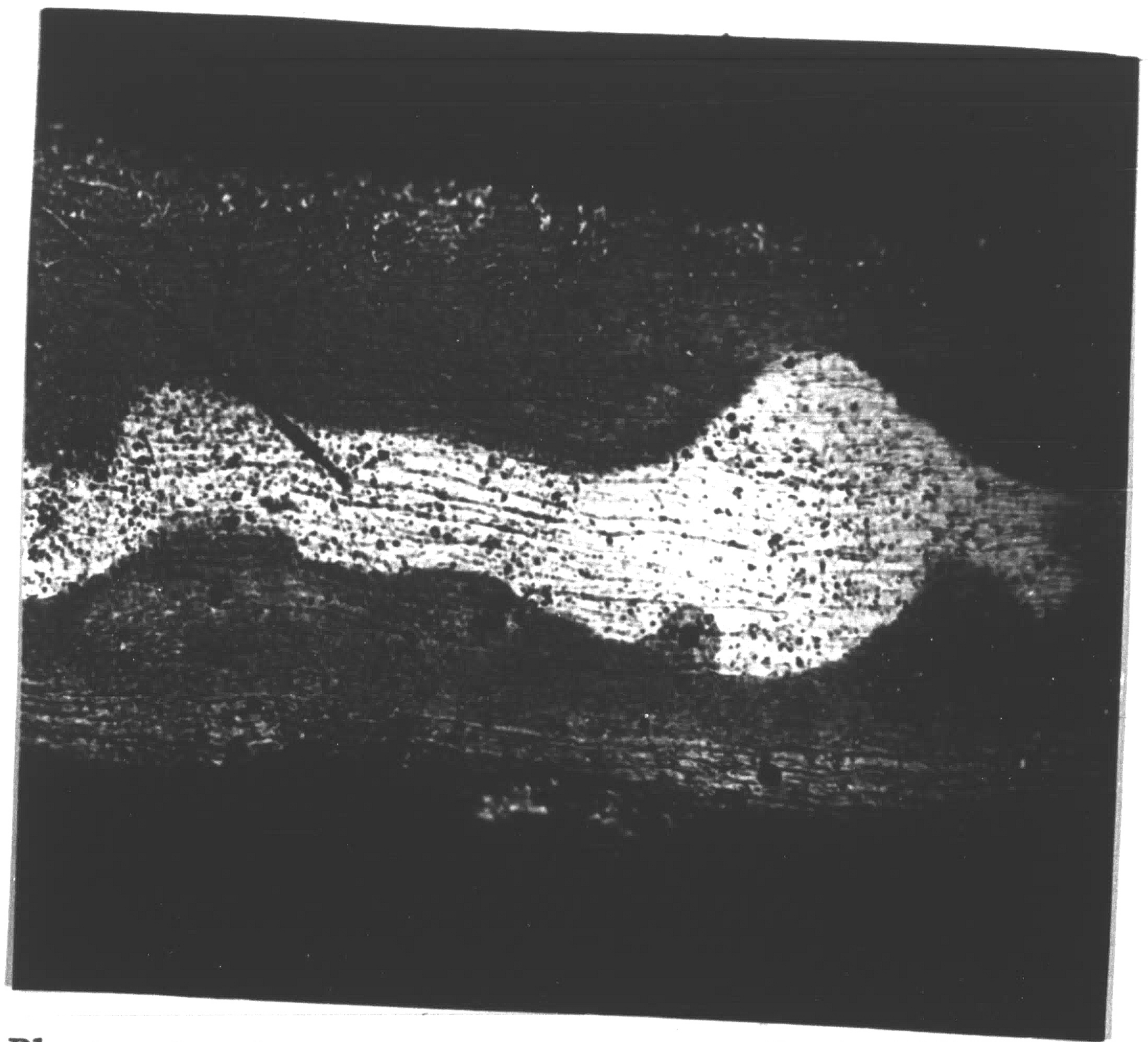


Figure 18 Photomicrograph of 93.2% Cold Rolled Supermendur. Etching Phenomenon is present in this sample.

the axes of the specimens (Figures 19-21 for Supermendur and Figures 22-24 for Vanadium Permendur).

Magnetic annealing was also found to increase the magnetostriction somewhat at 500 oersteds and to markedly increase the magnetostriction at 200 oersteds (up to 2 1/2 times) in the 93.2% cold rolled Supermendur and Vanadium Permendur in both longitudinal and transverse specimens, regardless of the orientation (parallel or normal) of the magnetic annealing field with respect to the axes of the specimens. In these specimens, however, the magnetostriction in the transverse specimens was slightly lower than that in the longitudinal specimens for identical magnetic anneals, and the magnetostriction of the specimens in which the annealing field was parallel to the axes of the specimens was somewhat higher than the magnetostriction of the specimens in which the annealing field was normal to the axes of the specimens, although the difference was not great (Figures 19-24).

The magnetostriction of the Vanadium Permendur for a given treatment was slightly higher than the magnetostriction of Supermendur for the same treatment (Figure 25).

The effect of cold rolling and subsequent magnetic annealing on the magnetostriction of Supermendur is graphically illustrated in Figure 26.

Because texture seemed to play an important role in the magnetostriction of cold rolled alloys, it might also be expected to play an important part in magnetically annealed material.

The (110) pole figures for the as received Supermendur, magnetically annealed with the annealing field parallel to the direction of rolling and parallel to the transverse rolling direction were identical, and

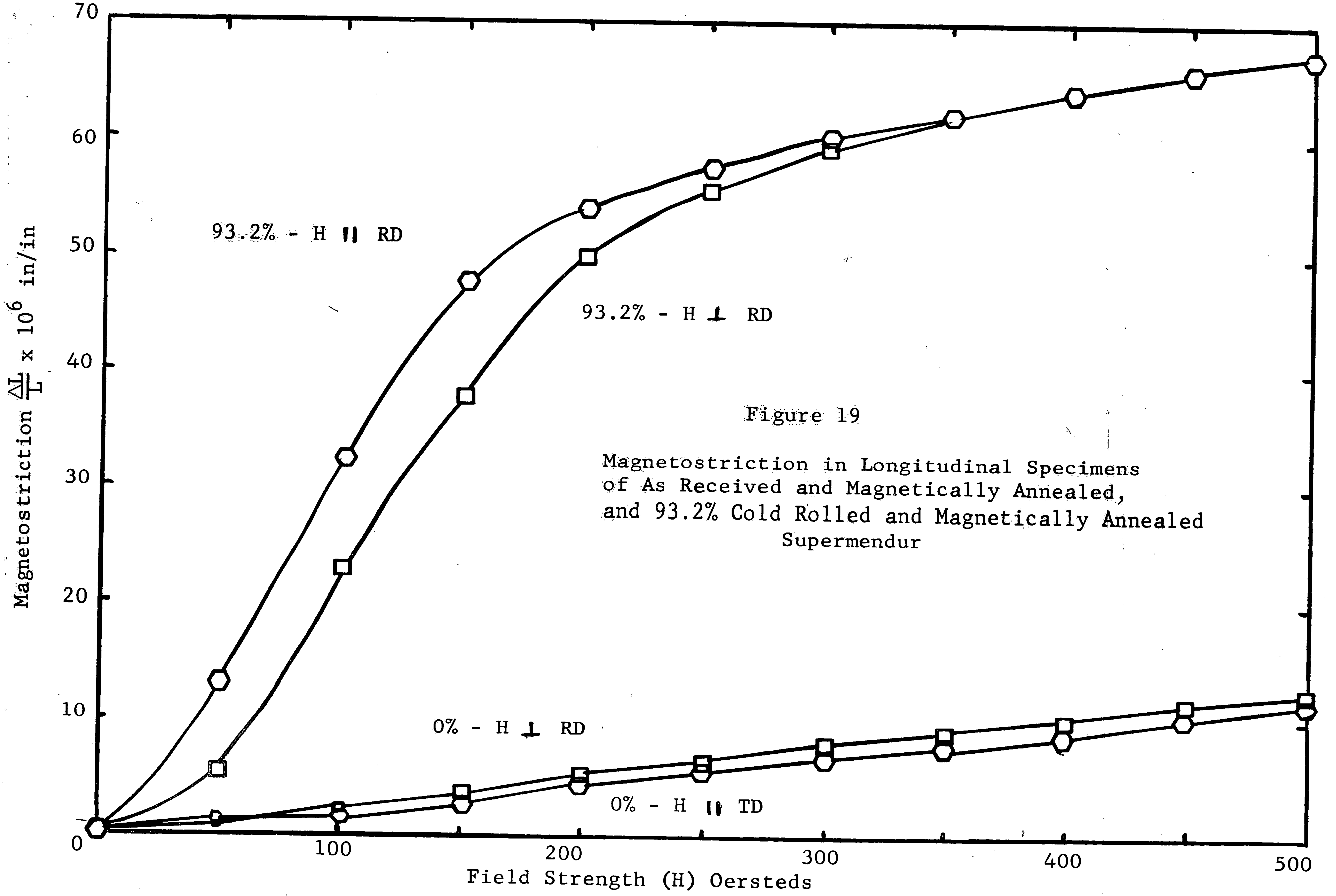


Figure 19

Magnetostriction in Longitudinal Specimens of As Received and Magnetically Annealed, and 93.2% Cold Rolled and Magnetically Annealed Supermendur

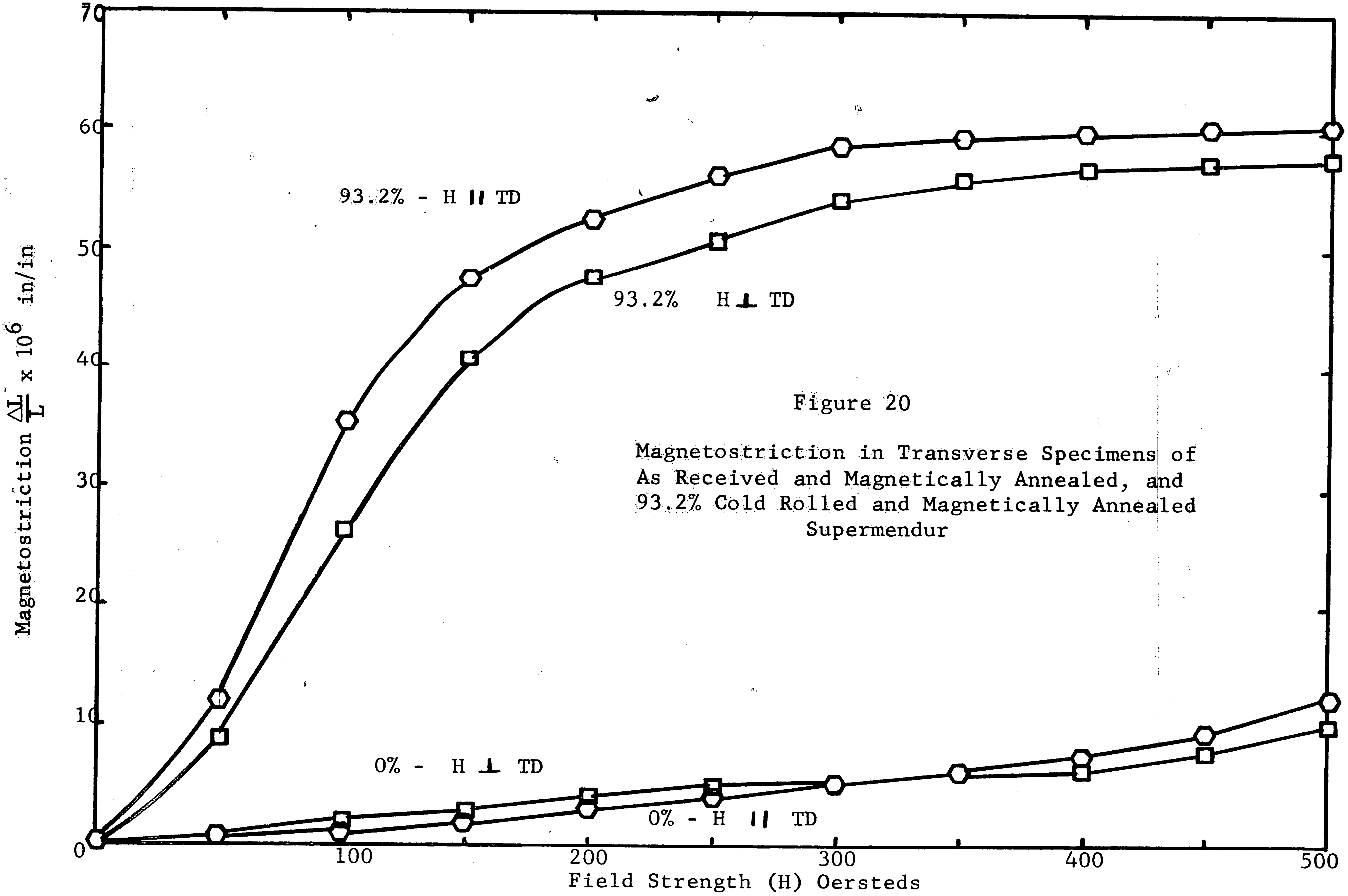


Figure 20

Magnetostriction in Transverse Specimens of As Received and Magnetically Annealed, and 93.2% Cold Rolled and Magnetically Annealed Supermendur

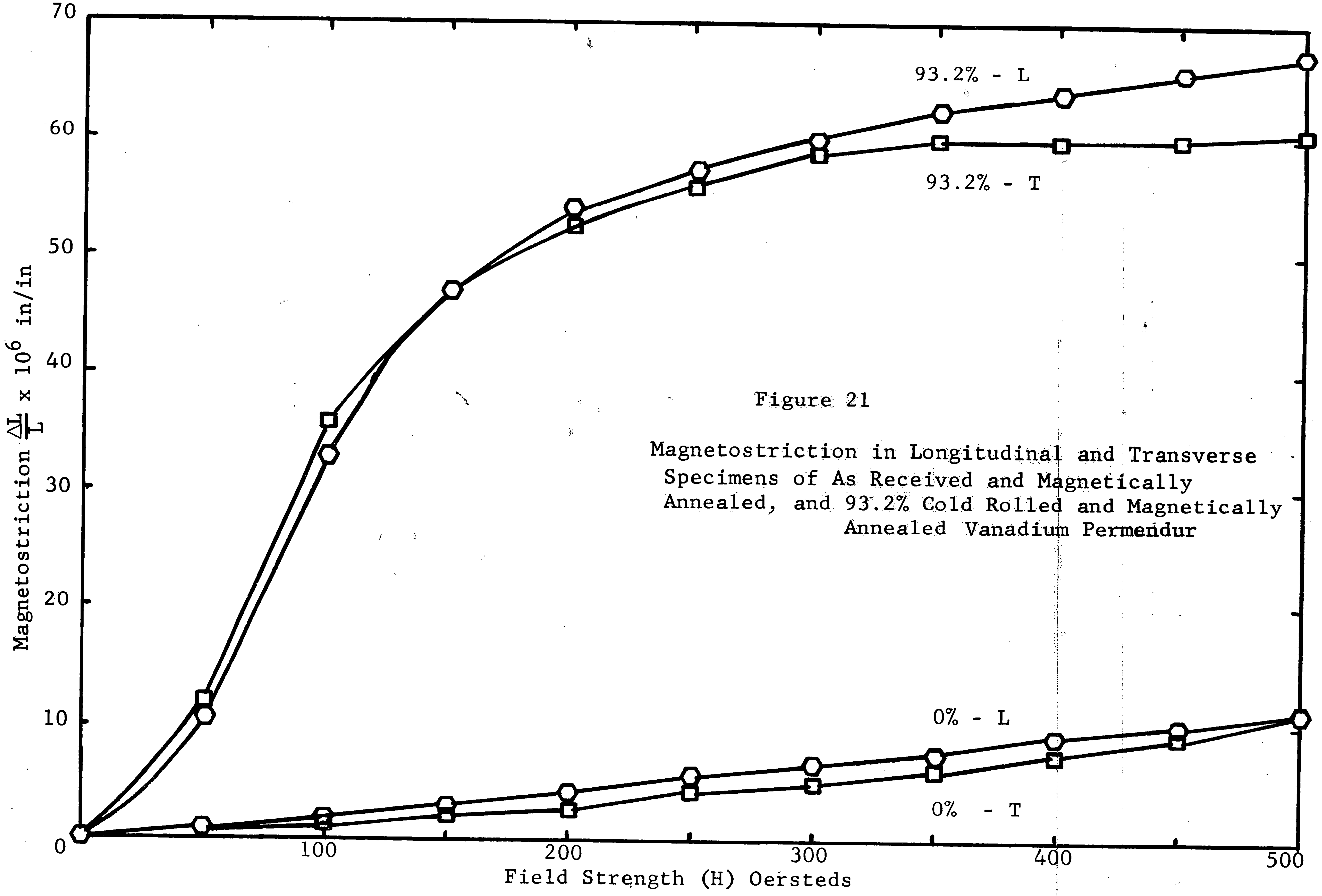


Figure 21

Magnetostriction in Longitudinal and Transverse Specimens of As Received and Magnetically Annealed, and 93.2% Cold Rolled and Magnetically Annealed Vanadium Permendur

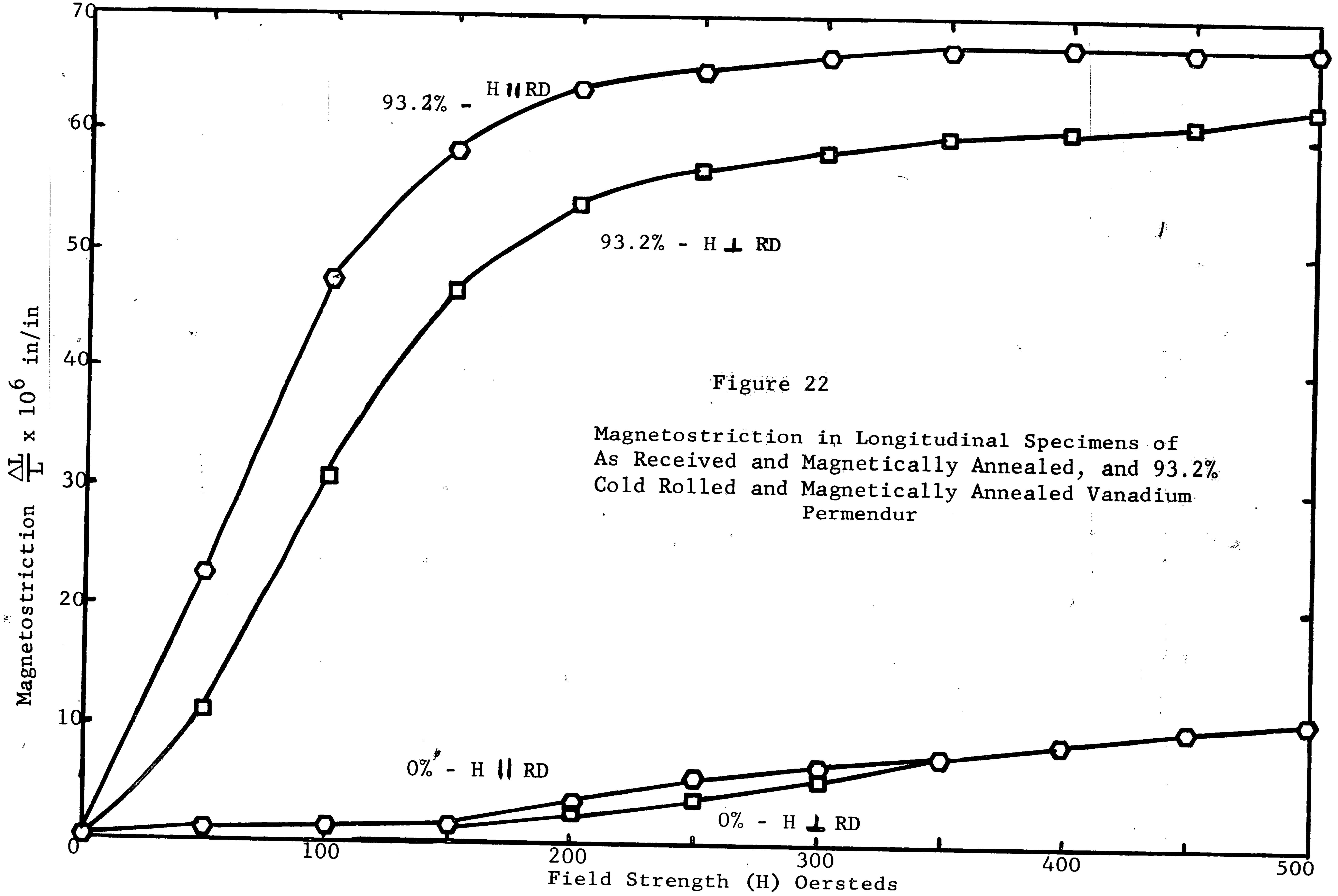


Figure 22

Magnetostriction in Longitudinal Specimens of As Received and Magnetically Annealed, and 93.2% Cold Rolled and Magnetically Annealed Vanadium Permendur

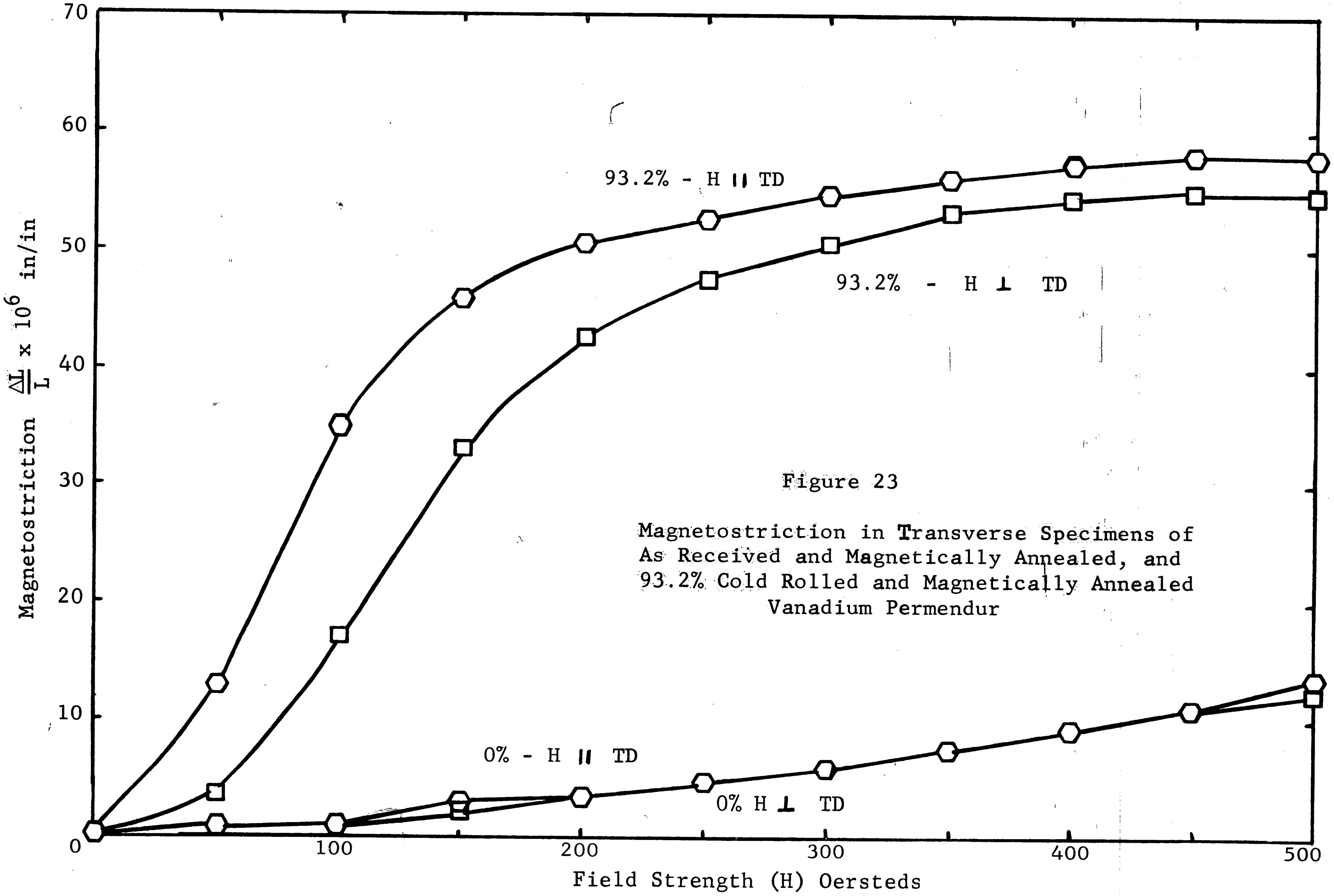


Figure 23

Magnetostriction in Transverse Specimens of As Received and Magnetically Annealed, and 93.2% Cold Rolled and Magnetically Annealed Vanadium Permendur

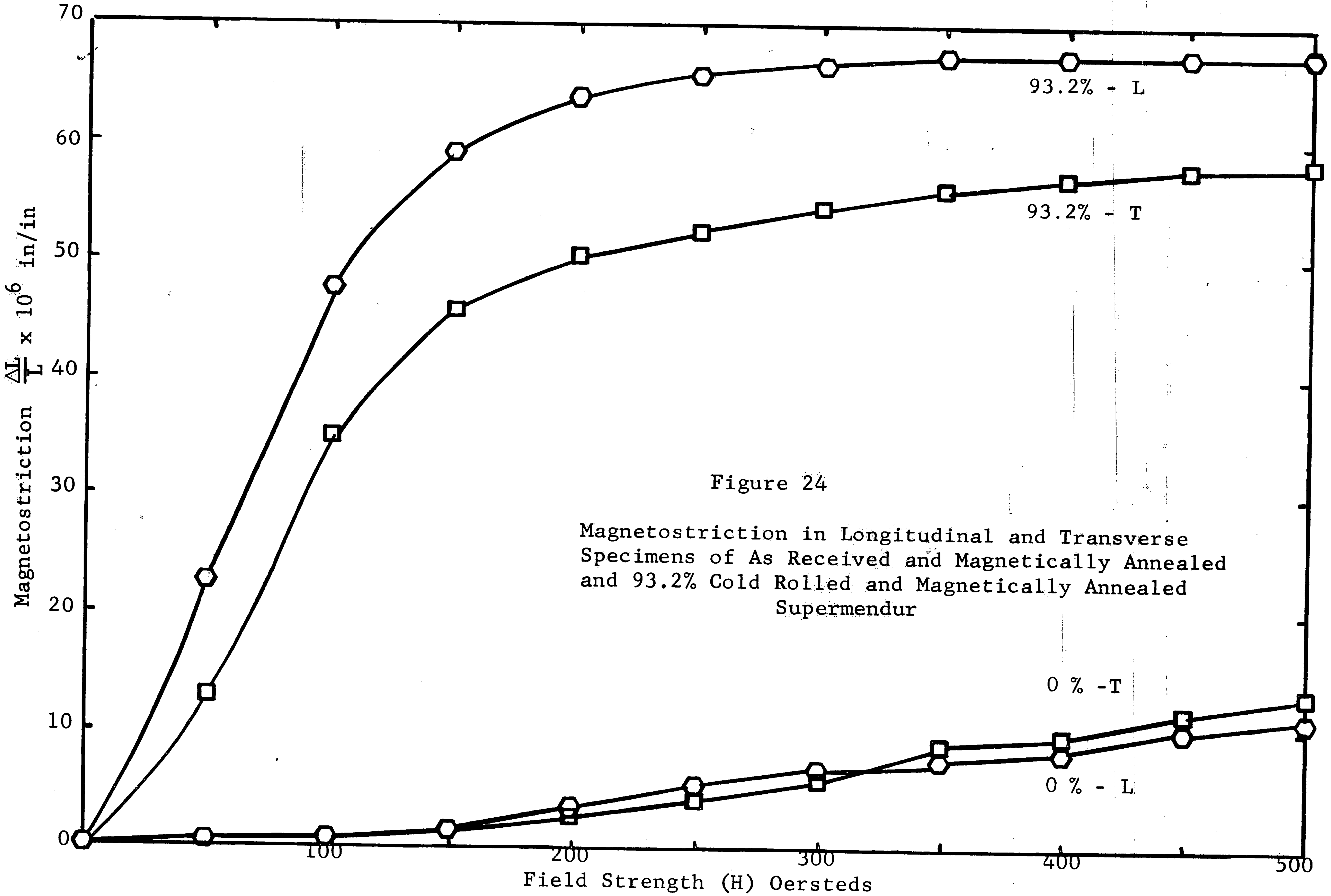


Figure 24

Magnetostriction in Longitudinal and Transverse Specimens of As Received and Magnetically Annealed and 93.2% Cold Rolled and Magnetically Annealed Supermendur

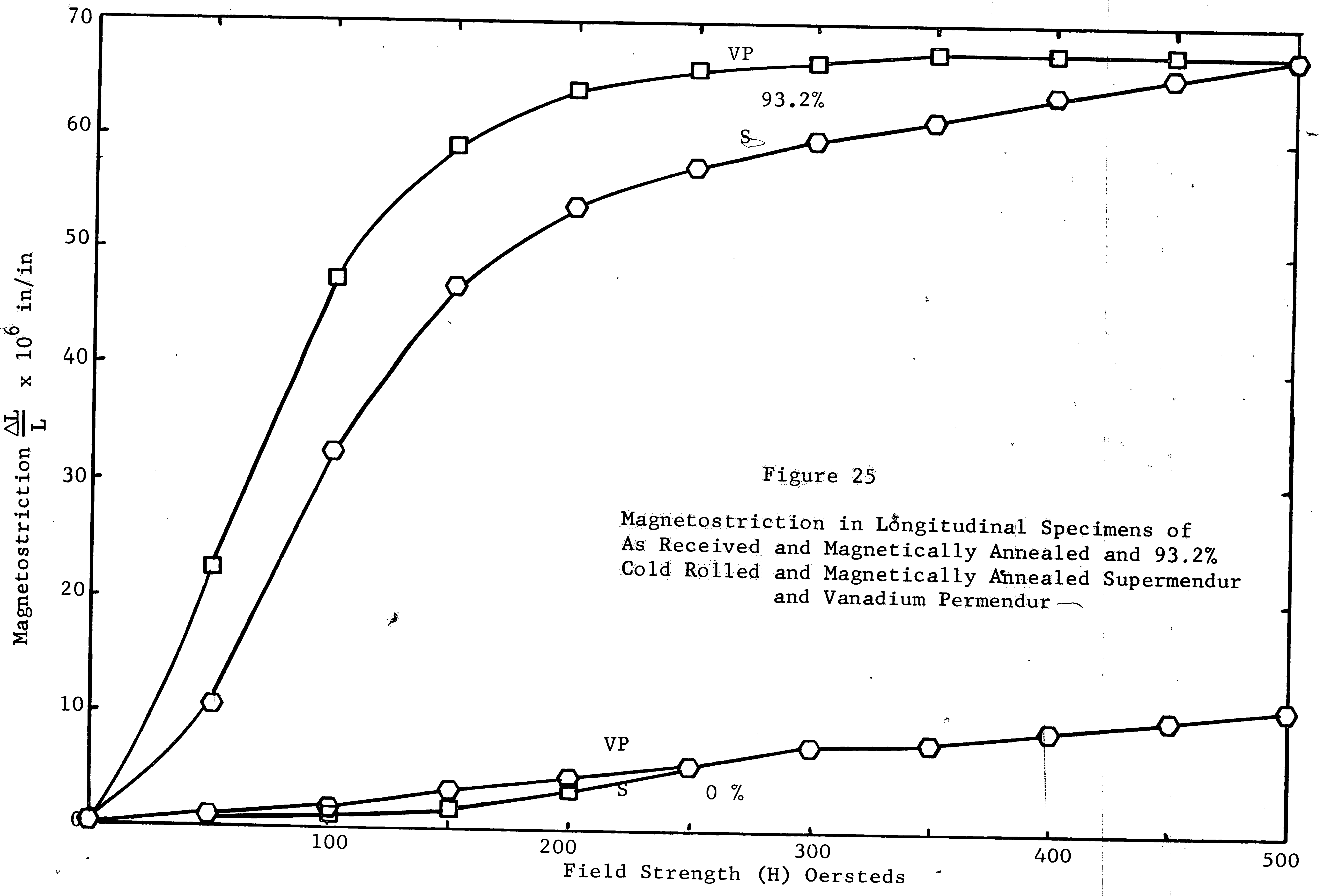


Figure 25

Magnetostriction in Longitudinal Specimens of As Received and Magnetically Annealed and 93.2% Cold Rolled and Magnetically Annealed Supermendur and Vanadium Permendur

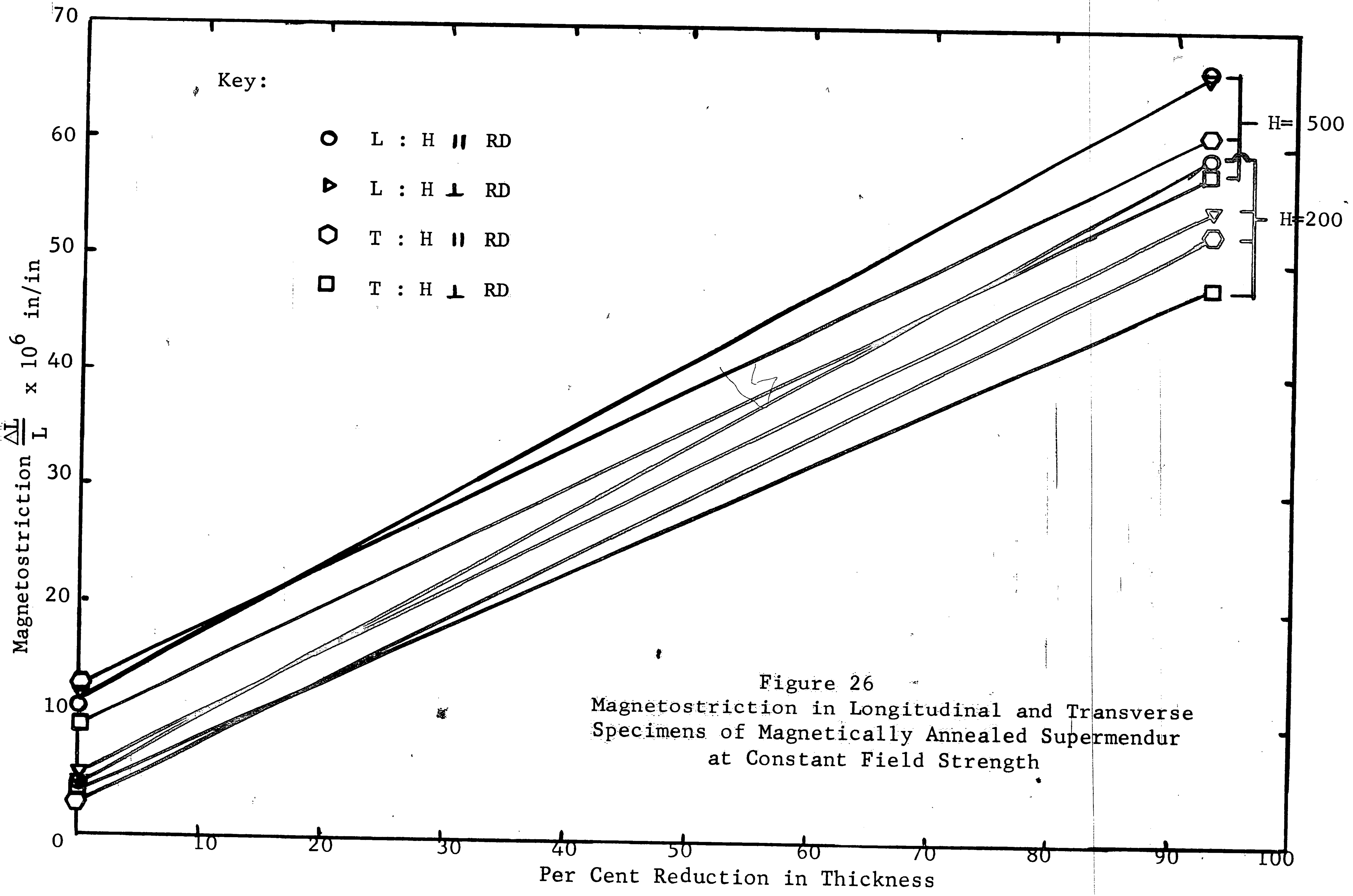


Figure 26
Magnetostriction in Longitudinal and Transverse Specimens of Magnetically Annealed Supermendur at Constant Field Strength

completely different from any others encountered in this study. (Figures 27,28). These pole figures had a (110) pole at 0°, but had no other maxima. This means that the rolling plane is a (110) type, but the rolling direction in this case could by any direction. This texture is roughly analagous to a compression axis in a block of metal in which the compression axis is perpendicular to the surface. The magnetostriction of these alloys was very low, so perhaps this particular texture is a very detrimental one for magnetostriction.

The pole figures for 93.2% cold rolled Supermendur (Figures 29,30), magnetically annealed with the annealing field parallel to the direction of rolling and parallel to the transverse direction were also identical. These pole figures index to (100) ~ 15° [011] and with a component (111) [11$\bar{2}$] . Both of these textures are typical of a cold rolled BCC metal annealed at 1300°F[37]. The positions of two peaks in this figure are similar to those in the corresponding cold rolled specimens, and thus this texture may be one that yields high magnetostriction.

Metallographic studies indicated that the .006 gage specimens were completely recrystallized by the magnetic anneal treatment (Figure 31,32). No evidence of ordering was detected in this alloy (Table I). Domain configurations may also be playing an influencing role as far as magnetostriction is concerned.

The effect of magnetic annealing on the magnetostriction of Supermendur and Vanadium Permendur was different from that found in 69 Co - 31 Fe by Strauss and Sandoz[16]. While Permendur is known to respond to magnetic annealing as far as other magnetic properties are concerned[40], the literature does not seem to contain information on the effect of magnetic annealing in magnetostriction in Permendur or Vanadium Permendur

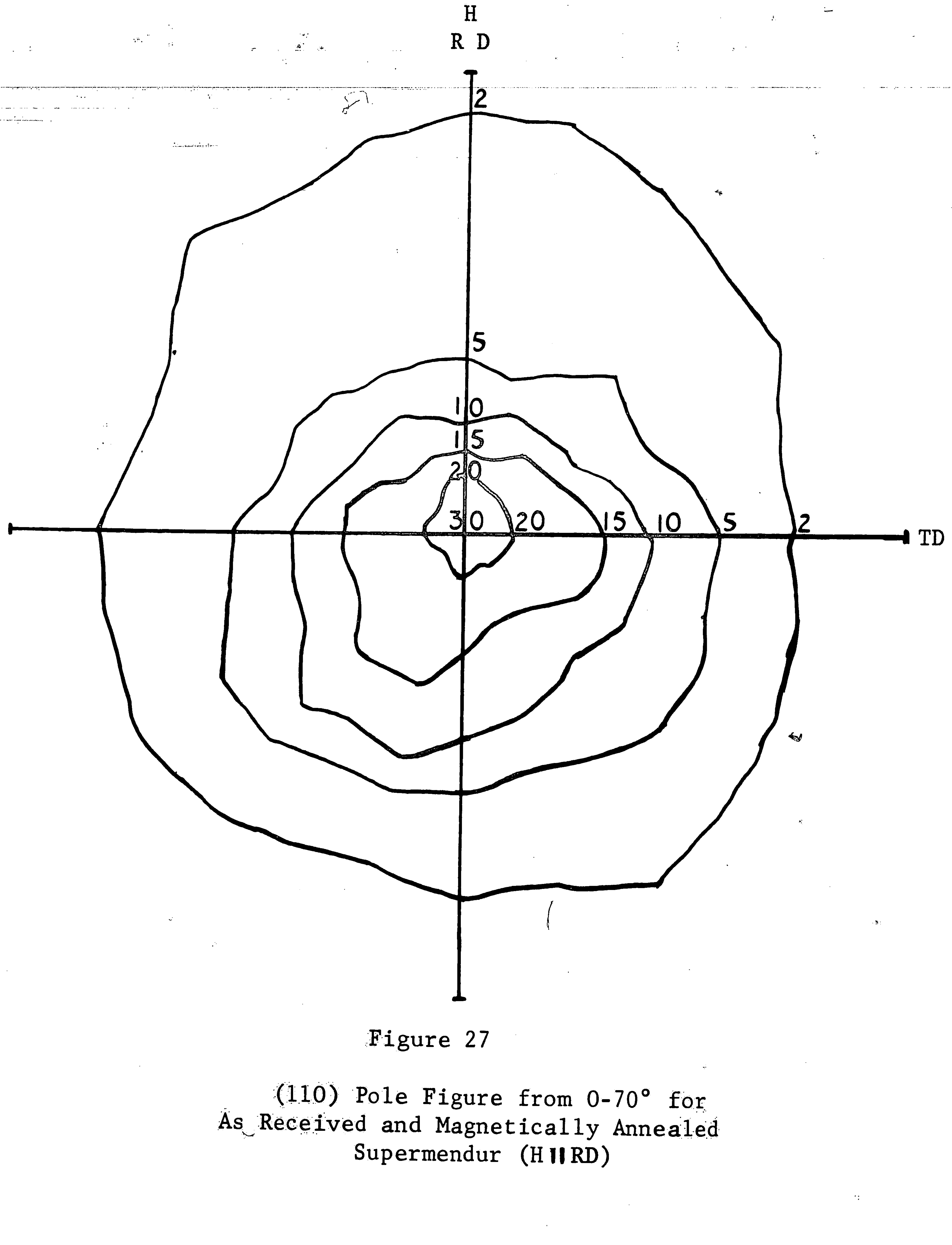


Figure 27

(110) Pole Figure from 0-70° for
As Received and Magnetically Annealed
Supermendur (H || RD)

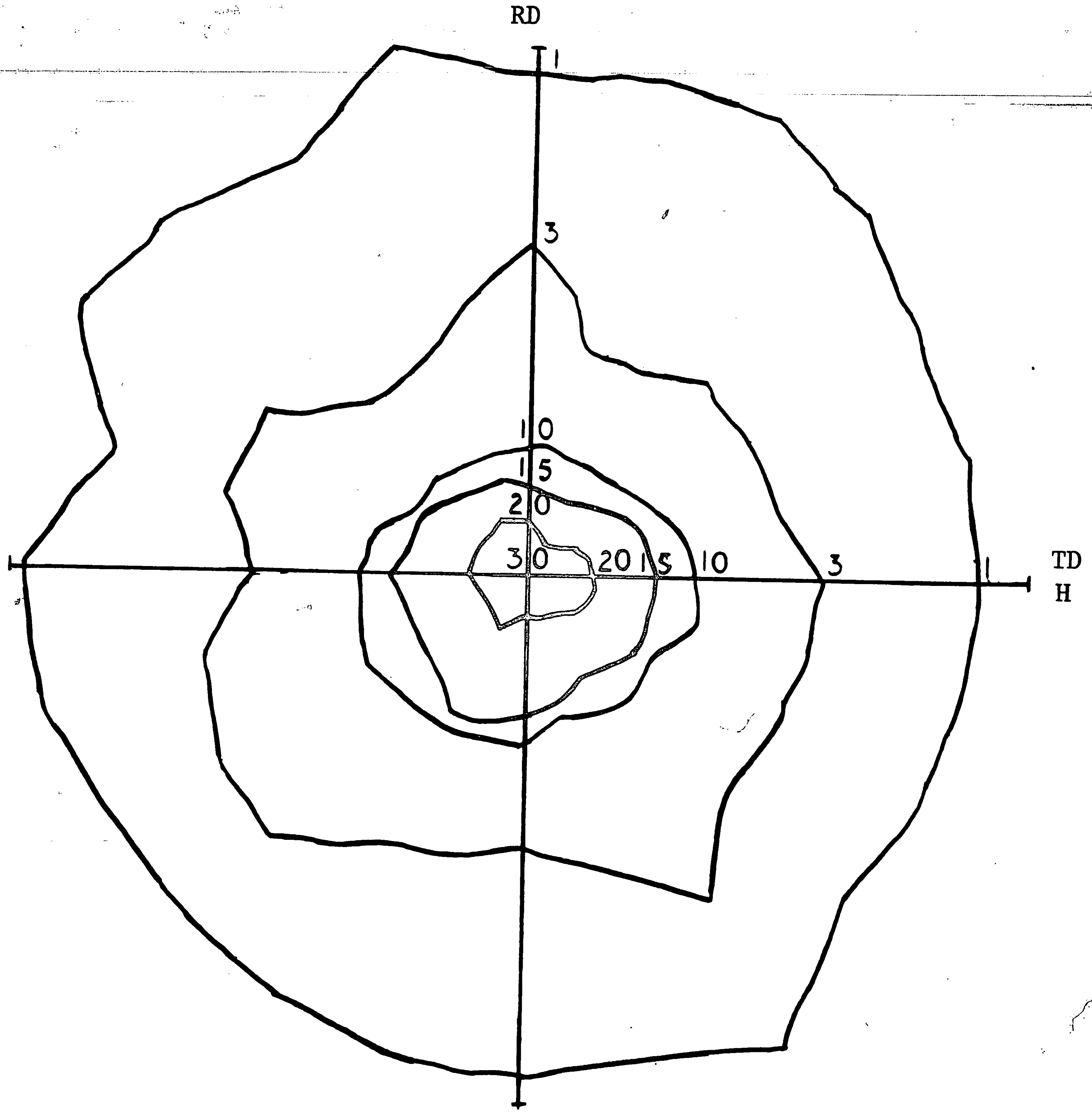


Figure 28

(110) Pole Figure from 0-70° for
As Received and Magnetically Annealed
Supermendur (H⊥RD)

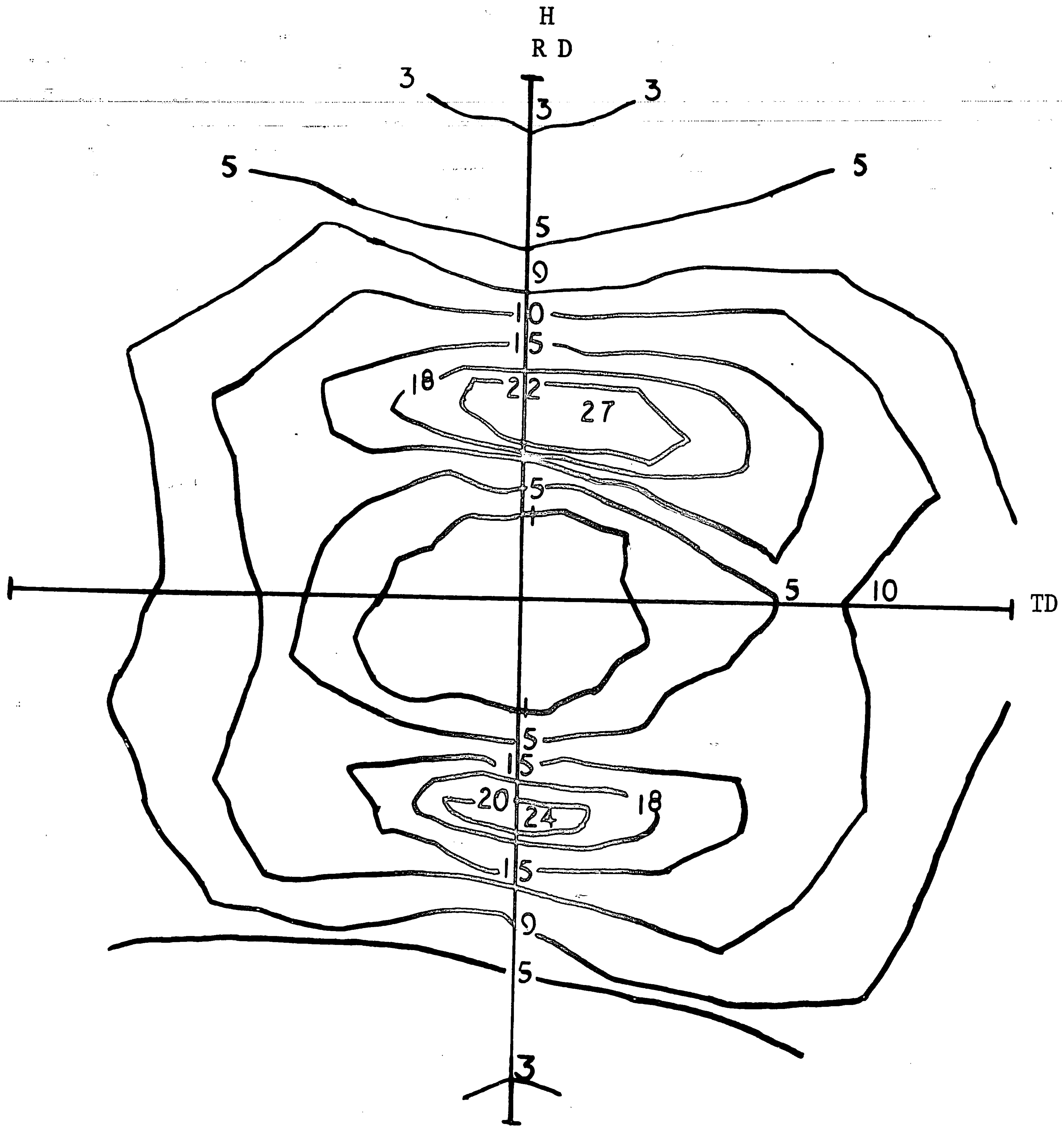


Figure 29

(110) Pole Figure from 0-70° for
As Received and Magnetically Annealed
Supermendur (H || RD)

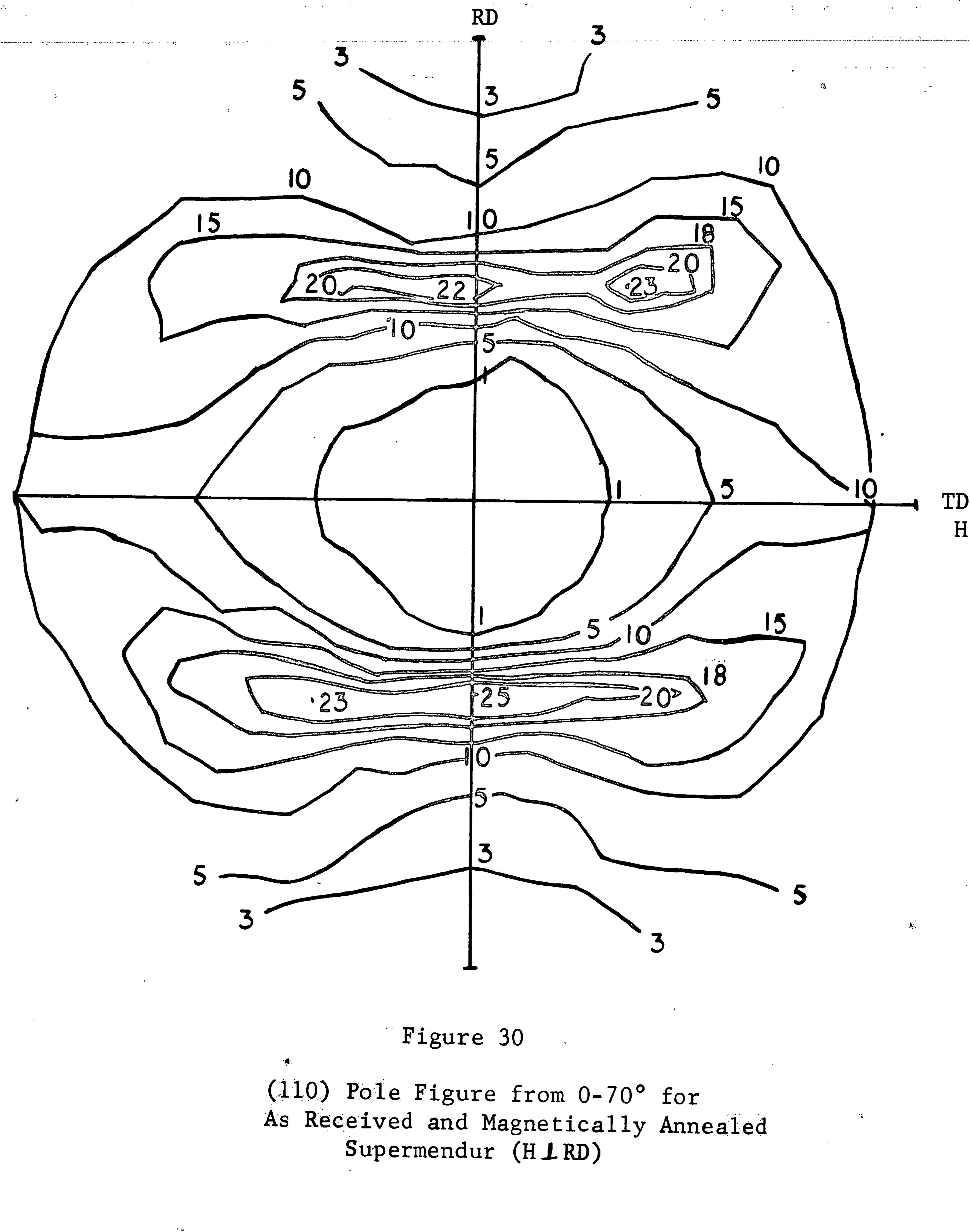


Figure 30

(110) Pole Figure from 0-70° for
As Received and Magnetically Annealed
Supermendur (H ⊥ RD)

Figure 31 Photomicrograph Typical of As Received and Annealed and Magnetically Annealed Supermendur.

Figure 32 Photomicrograph Typical of 93.2% Cold Rolled and Annealed and Magnetically Annealed Supermendur.

alloys. The response obtained here is undoubtedly strongly connected to the anisotropy of the specimens.

4.4 Annealed Alloys

Annealing without an applied magnetic field was found to greatly increase the magnetostriction in longitudinal and transverse specimens (Figures 33,34) of Supermendur as received, cold rolled to 49% reduction, and cold rolled to 93.2% reduction, with the most drastic change occurring in a longitudinal specimen cold rolled 93.2%. This alloy attained a magnetostriction of 84μ in/in at 200 oersteds, and $\lambda = 109\mu$-in/in at 500 oersteds. These values are believed to be the highest ever reported for Supermendur at fields less than 500 oersteds.

The effect of annealing on the magnetostriction of cold rolled Supermendur is graphically illustrated in Figure 35.

Texture again appears to play an important role in the magnetostriction of the cold rolled and annealed alloys.

The pole figures for the as received and annealed Supermendur (Figure 36) seems to be a (011) $[01\bar{1}]$ or (011) $[0\bar{1}1]$ texture. This texture is different from the corresponding magnetically annealed specimens, and appears to be a texture that is more favorable for high magnetostriction.

The pole figure for the cold rolled 49.6% and annealed Supermendur (Figure 37) is similar to the previous one but the center peak has decreased and the other two maxima have increased. The pole figure is very similar to that of the 93.2% cold rolled and magnetically annealed specimens, which also exhibited rather high magnetostriction. It indexes to be (112) $\sim$10° $[110]$.

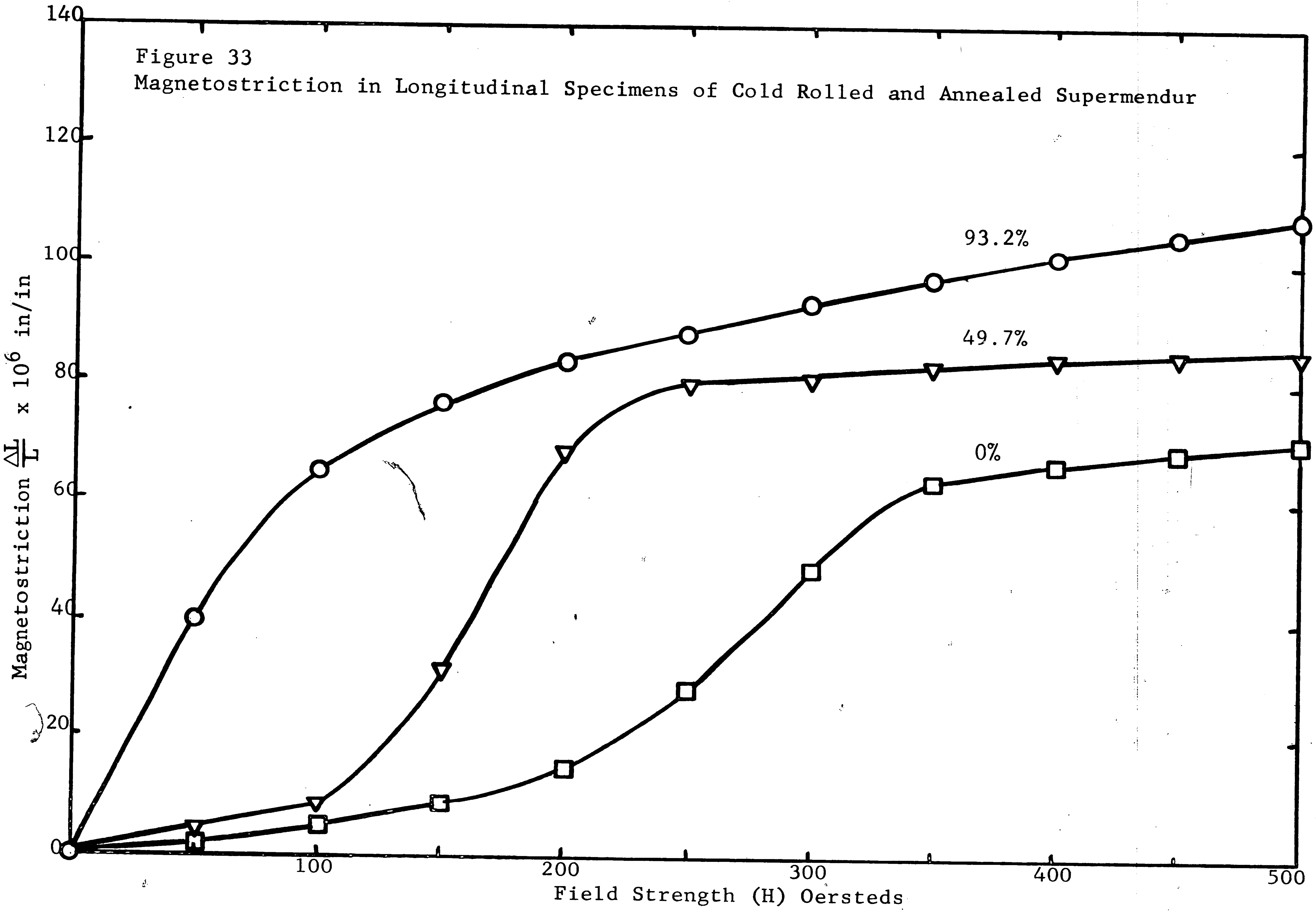


Figure 33
Magnetostriction in Longitudinal Specimens of Cold Rolled and Annealed Supermendur

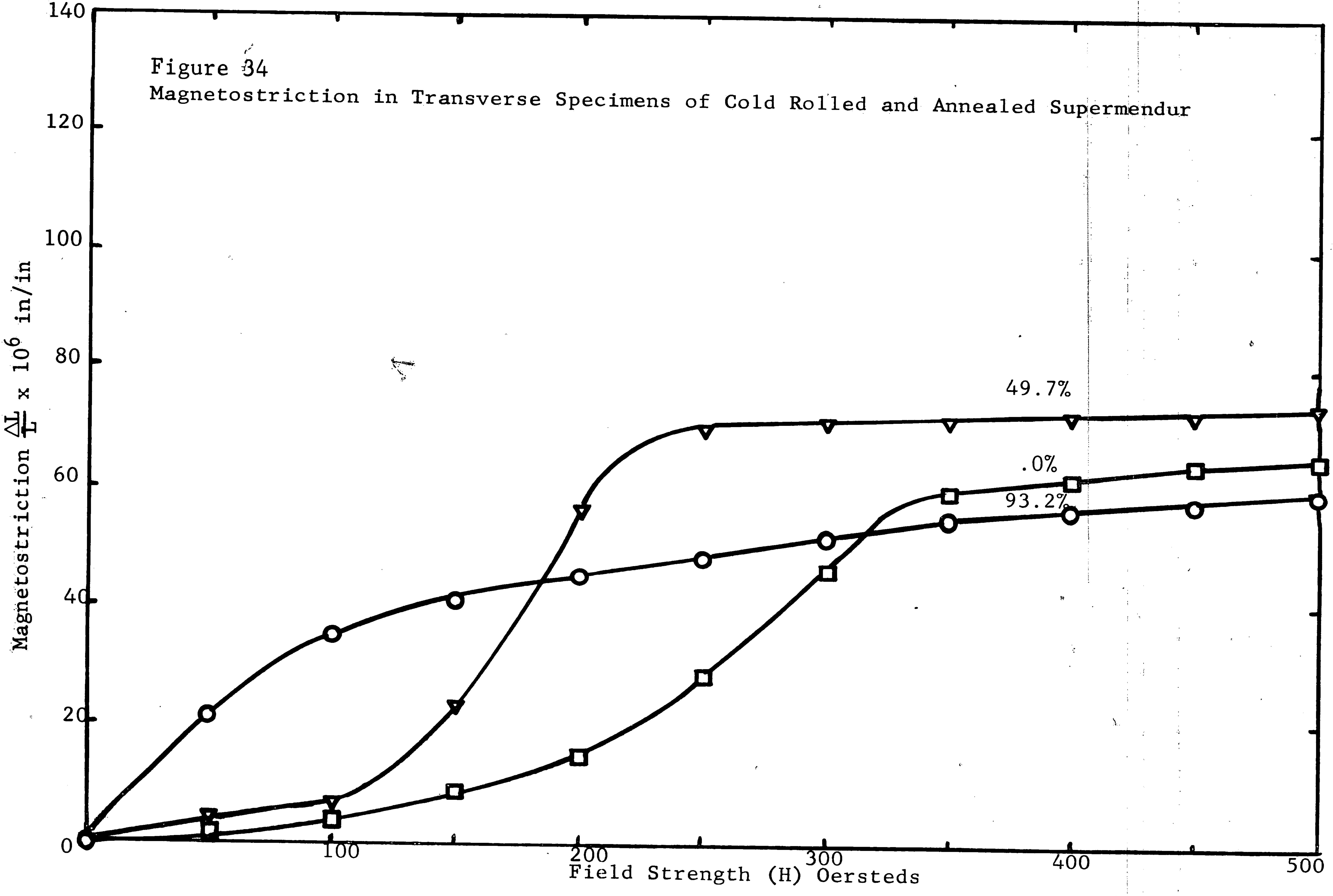


Figure 34
Magnetostriction in Transverse Specimens of Cold Rolled and Annealed Supermendur

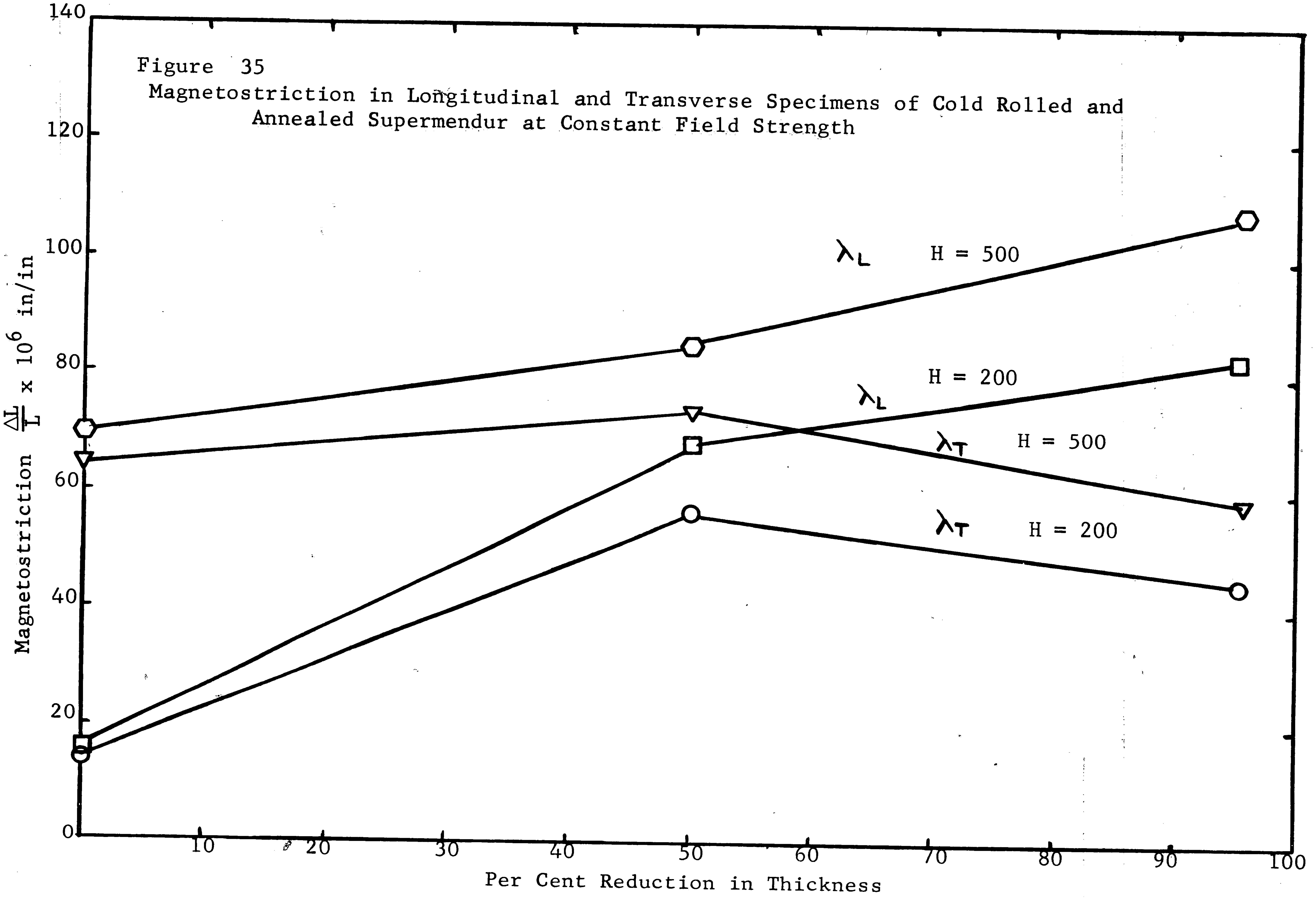


Figure 35
Magnetostriction in Longitudinal and Transverse Specimens of Cold Rolled and Annealed Supermendur at Constant Field Strength

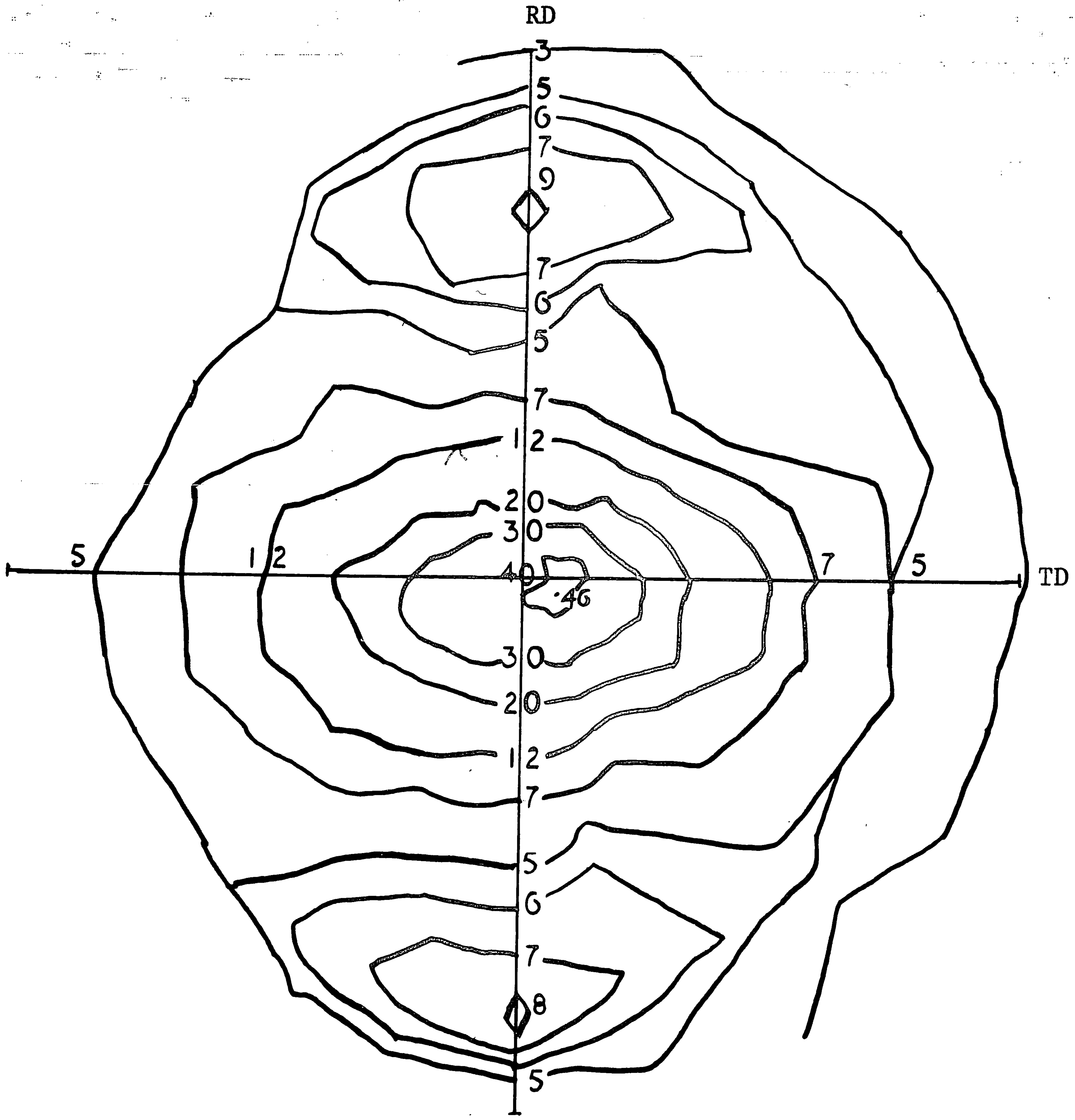


Figure 36

(110) Pole Figure from 0-70° for
As Received and Annealed Supermendur

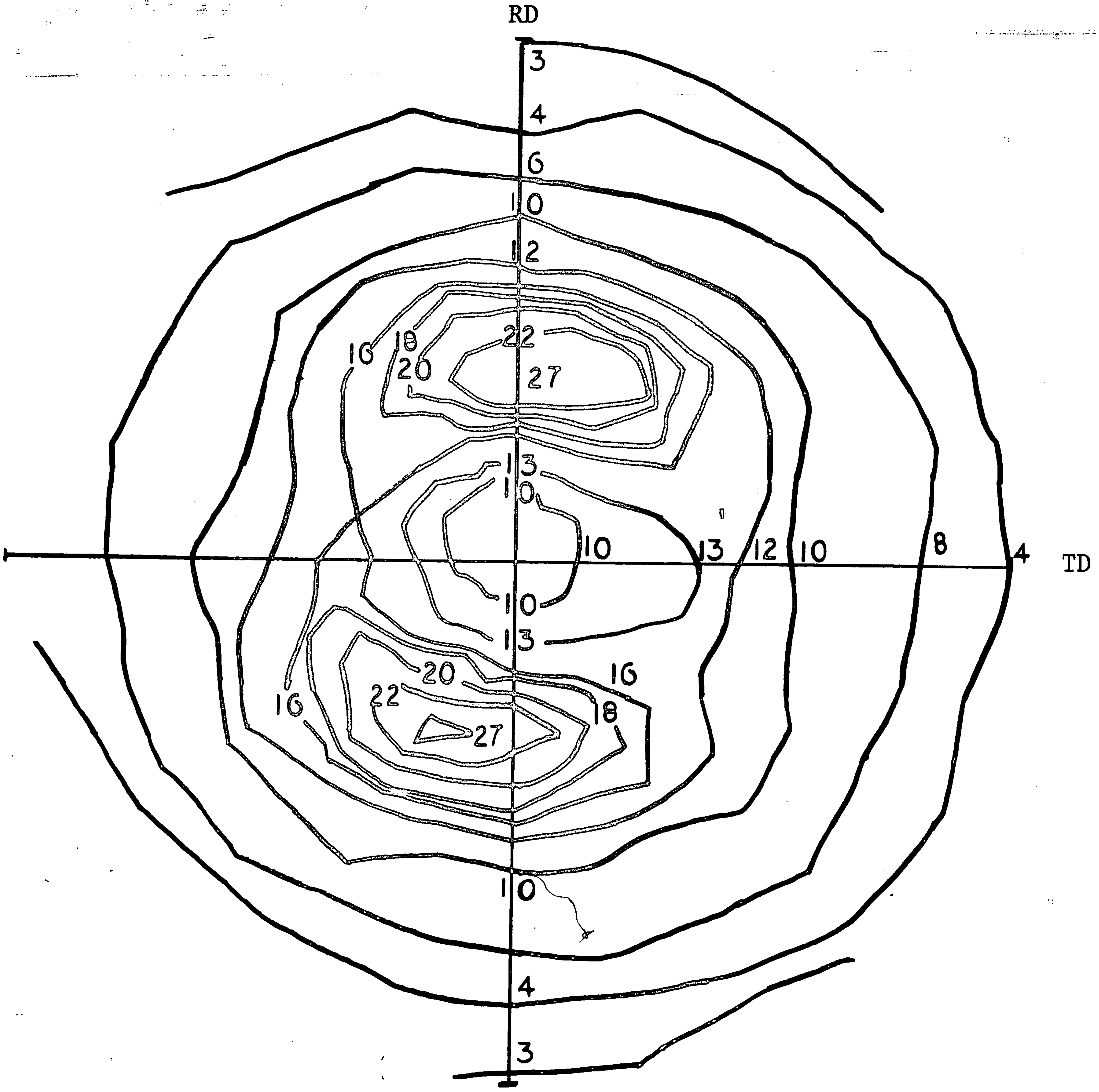


Figure 37

(110) Pole Figure from 0-70° for
49.7% Cold Rolled Supermendur

The pole figure for the cold rolled 93.2% and annealed Supermendur (Figure 38) indexes as (112)$\sim$17° [110] , which is very close to the ideal recrystallization annealing texture. The peaks on this pole figure were extremely high. This suggests that both the position and the intensity of the poles are important factors influencing the magnetostriction. The magnetostriction of 109 x 10^{-6} in/in at 500 oersteds is close to the value predicted by Urquhart and Goldman[38].

The annealed Supermendur alloys were found to have recrystallized completely (Figures 31,32), and once again no evidence of ordering was detected. Domain configurations are also probably influencing the magnetostriction.

The fact that the magnetostriction in the cold rolled and annealed alloys was greater than the magnetostriction in the cold rolled and magnetically annealed alloys suggests that the magnetic field may be detrimental--perhaps in the way it influences recrystallization and changes texture, but this is merely speculation. However, R. Smoluchowski and R. W. Turner[41] report findings that indicate that the texture of a recrystallized material can be changed somewhat by the application of a magnetic field. Little other information is reported in the literature on the effect of a magnetic field on texture. Perhaps the presence of vanadium in the structure is also a factor (the addition of 2% V to 50 Fe - 50 Co reduces its magnetostriction from 61 x 10^{-6} in/in to 51 x 10^{-6} in/in).

It is possible that the heat treated alloys are actually ordered, even though no evidence of ordering was found in this study. The presence of vanadium in the structure may change the structure factor of the ordered line just enough to render it invisible, or the high texture exhibited

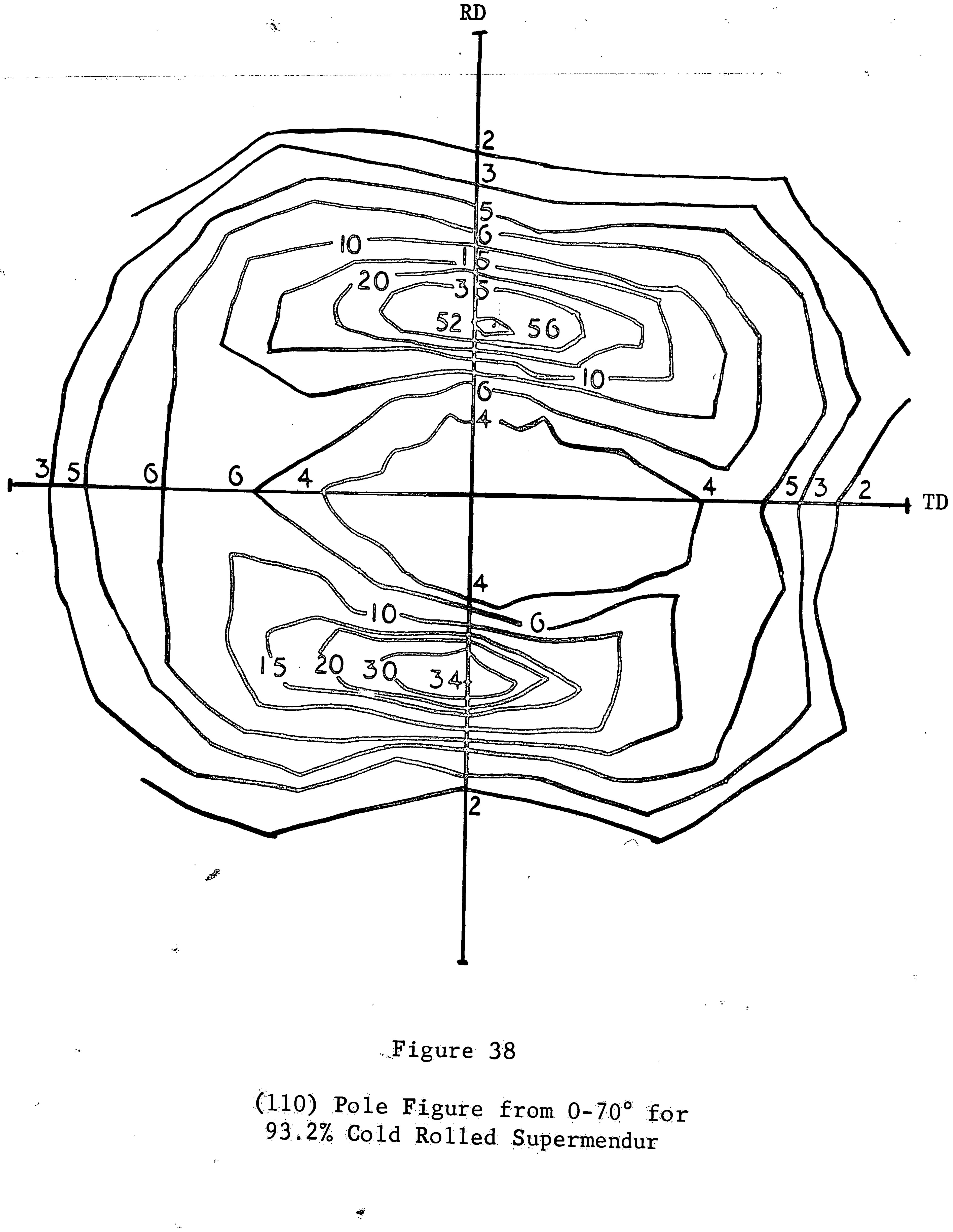


Figure 38

(110) Pole Figure from 0-70° for 93.2% Cold Rolled Supermendur

by the alloys may have weakened it, as discussed earlier. On the other hand, it may be that the alloys are truly disordered.

Magnetostriction curves for the longitudinal 93.2% specimens of Supermendur for each of the four treatments used in this study are shown in Figure 39. These curves represent the maximum effects of each treatment, and are plotted on the same scale for comparison purposes.

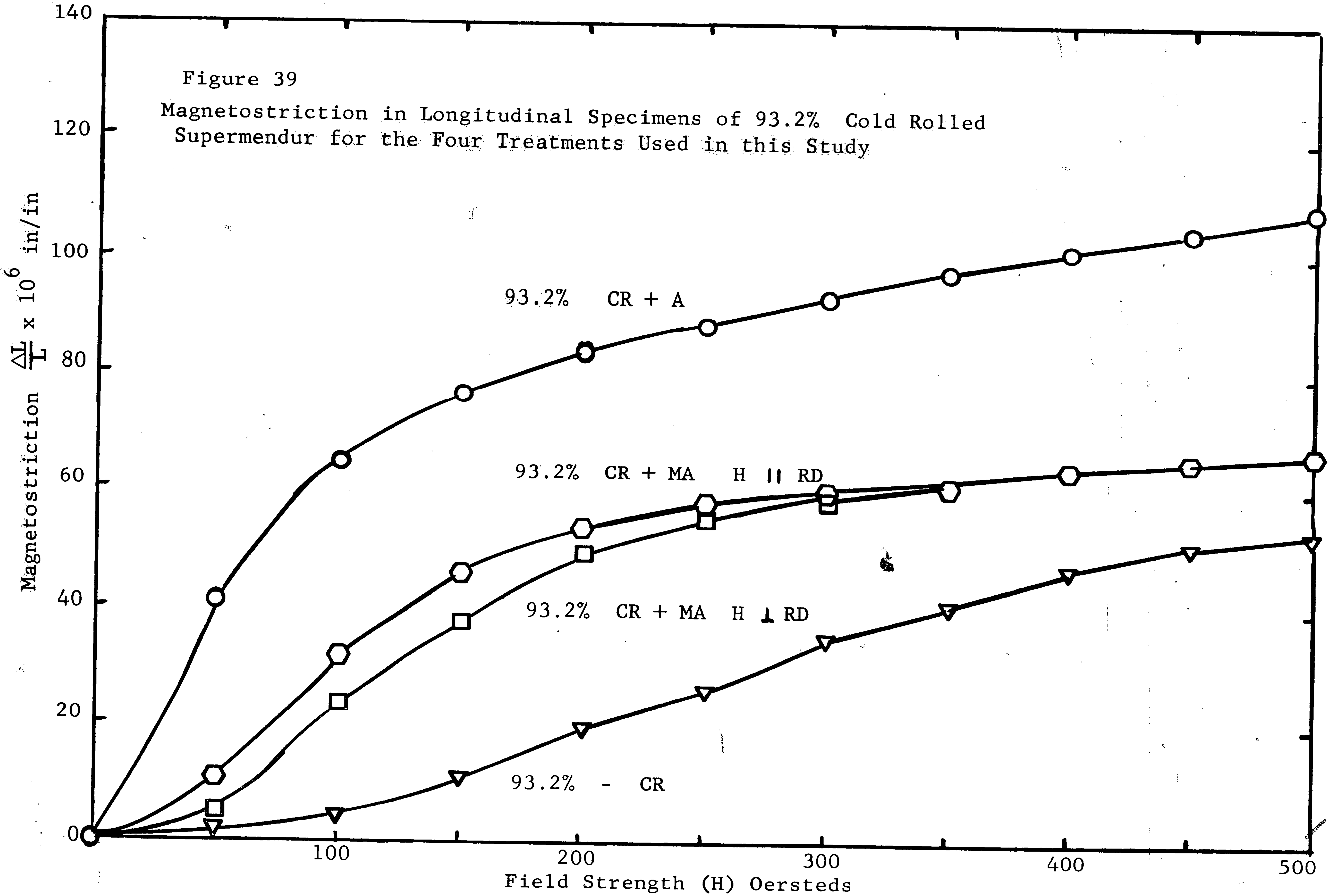


Figure 39

Magnetostriction in Longitudinal Specimens of 93.2% Cold Rolled Supermendur for the Four Treatments Used in this Study

Conclusions

The following conclusions have been obtained from the results of this study:

(1) Magnetostriction of Supermendur and Vanadium Permendur at any given field is nearly identical for identical treatments.

(2) After an initial decrease in magnetostriction, increased cold working tends to increase the magnetostriction of Supermendur and Vanadium Permendur.

(3) Cold rolling imparts a cold rolled texture to the Vanadium Permendur and the Supermendur, while annealing changes this texture to a characteristic annealing texture (approximately (100) [011]). However, annealing with a field tends to diminish the texture while annealing without a field tends to strengthen the texture.

(4) Texture and magnetostriction are closely related in both Vanadium Permendur and Supermendur. Annealing without a field leads to higher magnetostriction than annealing with a field, presumably because the magnetic field affects the texture in such a way as to be deterimental to high magnetostriction. Both straight annealing and magnetic annealing give high magnetostriction of the specimen concerned.

(6) It appears that strong texture is required to attain high values of magnetostriction in Vanadium Permendur and Supermendur.

Recommendations for Further Study

This study of magnetostriction in Vanadium Permendur and Supermendur is by no means complete--it has, in fact, opened several new avenues for investigation. Among the areas that should be studied further are:

(1) The effect of small amounts of cold work (10-20%) and the effect of high amounts of cold work (90-99%), with and without subsequent annealing, on the magnetostriction and texture of Supermendur.

(2) The effect of different annealing cycles, with and without a field, on the texture and magnetostriction of Supermendur.

(3) The effect of the magnitude of the field on annealing texture as well as on magnetostriction.

(4) The effect of Vanadium on magnetostriction.

(5) The effect of treatments similar to those used in this study on the texture and magnetostriction of 70 Co-30 Fe.

(6) Studies of domain configuration and its effect on magnetostriction.

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Vita

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