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Alpha-Gamma Transformations in Iron Alloys--Calibration of Pressure by Duplex Differential Thermal Conductivity Analysis

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By differential thermal conductivity analysis one may consecutively observe with rising temperature certain transitions in two materials. By considering one as a standard whose pressure-temperature curve for the transition is known, one may infer the pressure within the cell, and hence one may develop a pressure-temperature curve for the transition in the second material. This technique is applied to the alpha - gamma transitions in iron, as reference standard, and in binary alloys of iron with Ni, Cr, Mn, Al, Co and C, as unknowns, at pressures up to 70 kb.

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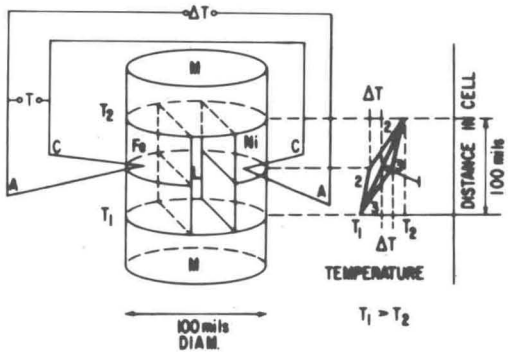

THERMOCOUPLES: C = CHROMEL A = ALUMEL
ΔT READ FROM THE TWO A LEADS, WITH THE TWO C LEADS TIED TOGETHER.
T READ FROM "Fe" PAIR OF C-A LEADS.
M = METAL PILLS FOR TEMPERATURE EQUALIZATION.
L = LAVA SEPARATOR

Fig. 1 Differential thermal-conductivity cell with temperature gradient

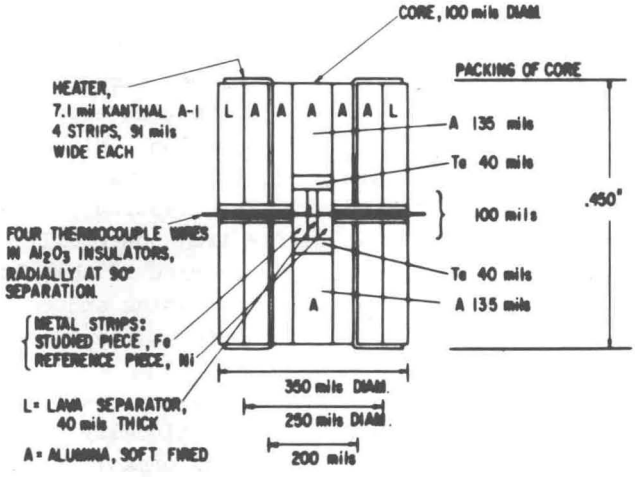

Fig. 2 Differential thermal-conductivity cell. Plan as used in superpressure apparatus

The effect of pressure on the α-γ transformation temperature in iron and iron binary alloys was studied in order to seek the general trends in the pressure-temperature curves as well as to observe possibly abnormal effects in these curves. The availability of the "belt" apparatus (1)[1] permits work up to 90 kb and upwards of 1000 C for long sustained times. The invention of differential thermal-conductivity analysis (DTCA) (2) permits one to observe phase changes in materials with slowly changing temperatures in a medium which is far from being considered as insulating. In contrast, the more common differential thermal analysis (DTA) requires much higher rates of temperature change through the transformation when in a superpressure cell, since the latent heat of the transformation is so quickly lost to the highly conducting surroundings.

The development of improved techniques with external pressure and temperature control permits one to detect phase changes with a very high precision, and the point is now reached where this precision is masked by the systematic errors of both pressure and temperature calibration.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

Belt Apparatus

These superpressure studies were carried out in the "belt" apparatus, developed at the General Electric Research Laboratory (1). This apparatus was installed in a 300-ton Elmes 3-column hydraulic press. Refinements in control of the hydraulic oil pressure were accomplished by the use of a sensitive pressure controller (Bristol, vane-type, Series 500) and a low-volume pump (Minipump by Milton Roy Company, Philadelphia, Pa.) for delivering small, controlled amounts of oil to the hydraulic system. These two devices permitted control over the hydraulic oil pressure to $\pm$ 5 psi; this corresponds to $\pm$ 0.15 kb pressure within the superpressure cell. It should be noted that this constancy in cell pressure is not realized over long periods of time, since the gasket does not remain perfectly uniform.

The DTCA Technique

The DTCA technique (2) for observing phase

[1] Numbers in parentheses designate References at the end of the paper.

changes may be understood by considering the temperature gradients which may be imposed upon a sample of metal, Fig.1. A homogeneous iron sample would, in the ideal case, possess a linear gradient (curve 1). A nonhomogeneous sample, with the hotter half transformed to gamma iron would now possess a broken line gradient (curve 3). This results because the thermal conductivities of the two forms, alpha and gamma, are not identical. By subjecting this sample of iron and a second sample of a nontransformable material (e.g., nickel) to the same temperature gradient, one may compare the midpoint temperatures of these two materials. These two temperatures would be identical in all cases except during the time the iron sample was in the process of transforming from one phase to another. Thus, by raising (or lowering) the temperature of this pair of metals through the transformation temperature of iron, one may observe a difference in temperature ΔT which is first zero, then departs from zero and reaches a maximum when one half of the iron has transformed, and finally returns to zero when the transformation is completed.

For infinitesimally low rates of heating or cooling of single-component materials, the midpoint temperature when the difference temperature, ΔT, is a maximum corresponds to the true equilibrium temperature of the transformation. With heating and cooling rates that are too rapid to allow equilibrium to prevail, the midpoint temperature at maximum ΔT will differ from the equilibrium temperature; however, the average of the midpoint temperatures obtained from heating and cooling cycles may be expected to approach the equilibrium temperature.

The analysis of data from multi-component systems with two-phase regions is additionally complicated by the fact that the transformations may take place over a range of temperatures. In this case, it is expected that there will be an even greater hysteresis in the transformation temperature obtained by heating and cooling, and the average transformation temperature here has no clear physical significance. Nevertheless, a plot of average temperature versus pressure still provides a convenient method for searching for the existence of new phases, which would be revealed by discontinuous changes in slope of the P-T curve.

A Speedomax Model G X_1-X_2 recorder permits the continuous recording of the two separate DTCA variable; (a) temperature of the cell, and (b) difference temperature between the sample and the reference material. A Rubicon potentiometer is used to buck out a large portion of the voltage from the temperature thermocouple, while a Beckman Model 14 dc breaker amplifier is used to amplify the difference voltage from the ΔT thermocouples.

In order to minimize uncertainties in the pressure measurements, it was advantageous to use a modified (duplex) DTCA technique in which the nontransforming material was replaced by a material that, for a given pressure, undergoes a transformation at a known temperature slightly different from that of the material under investigation. The additional maximum in the ΔT trace generated by the transformation of the standard material provides a convenient "built-in" pressure calibration. The ΔT trace from such a cell shows either positive and negative ΔT maxima, or two positive ΔT maxima, or two negative ΔT maxima, depending on the relative senses of the thermal conductivity changes in the two transformations. Fig.3 shows a typical ΔT versus T trace obtained with a duplex cell. The first part of the present work, described under "Experimental Results," relates to the establishment of the pressure dependence of the α-γ transformation in pure iron by the simple DTCA technique. Once these data were available, pure iron could be used as the reference standard in the duplex method.

The Superpressure Cell

The superpressure cell used in most of these investigations follows the pattern of Fig.2. An outer lava sleeve encloses a pair of concentric alumina sleeves between which are encased the heaters. The heater strips shown in the drawing were constructed from Kanthal A-1, because of its constant temperature coefficient of resistance and because of its high safe operating temperature of around 1200 C. The development of a satisfactory temperature gradient along the length of the iron sample was accomplished either by the use of 15-mil-deep symmetrical notches in the strip heaters 340 mils from the top, or by shorting out the heater tabs at the top of the cell by means of a 5-mil copper disk.

The thermocouple used in this work was chromel-alumel. This couple gives a very high response, and according to Bundy (3) the pressure correction may amount to only several degrees. No attempt was made to apply a pressure correction.

The core of the superpressure cell is 100 mils dia, and contains in its center two partially cylindrical pieces of the metal under investigation and two like-sized pieces of the reference material. These are shown in perspective in Fig.1. Between the two pieces of each of the materials lies a thermocouple junction, and between the two pairs of metals is located a spacer, 40 mils thick, composed of either lava or alumina. Immediately above and below the metal pieces are tantalum

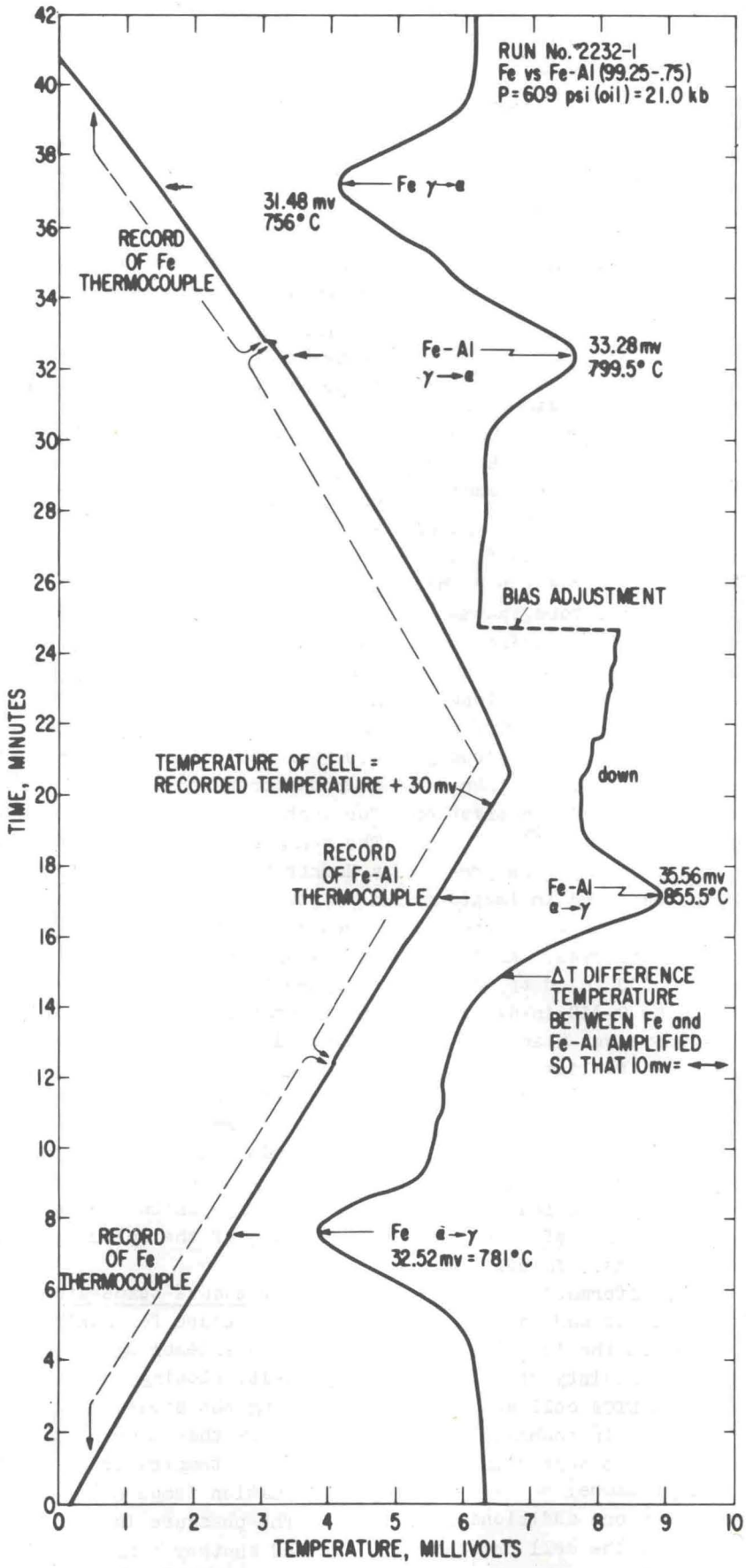

Fig. 3 Temperature versus ΔT trace from an actual duplex DTCA run

pills, the purpose of which is to provide good thermal conduction at the top and at the bottom between the metal being investigated and the reference pieces.

The electrical heating current is carried from the strips to current rings via the heater tabs or ears, shown in Fig.2. The current rings make direct contact with the punches of the punch-belt-punch superpressure apparatus, and the electrical leads are connected to these punches which are electrically insulated from one another with respect to the body of the press.

Pressure Calibration of Cell

The pressure within the DTCA cell was determined by observing the room temperature transformations of Bi wire (25.3 and 89 kb) and of Ba wire (59 kb). Two methods of calibration were used:

(a) The center 0.100-in-dia core of a typical DTCA sample holder, as shown in Fig.2, was filled with AgCl, into which was placed a hole for either a Bi or a Ba wire. With the heater tabs incomplete one could read the wire resistance from punch to punch, and hence could observe the ram loading required for these wire transformations. A second cell was then constructed for a DTCA run, loaded to a ram pressure close to that previously observed for the wire transformation, and then heated through the temperature for the observation of the iron transformation.

(b) An alternative, and probably more precise, method of calibration consisted in locating the Bi wire in the same DTCA cell in which the iron transformation was to be observed. An annular ring 0.100 in. wide and 0.030 in. deep was grooved into the outside of the 0.350-in-dia sample holder, and into this groove was placed 3/4 turn of 0.019-in. Bi wire and a filling of NaCl paste containing glyptal resin and acetone. The ends of the Bi wire were attached to platinum leads going through the gasket area in a manner similar to that used for the thermocouple leads. Values of the resistance across these leads were recorded, permitting the observation of both the 25.3 and the 89 kb transformations. Immediately after the room-temperature transformation was observed at 89 kb, the DTCA cell was warmed to observe the iron transformation in the identical cell, thus eliminating the uncertainty of cell-pressure variation between the DTCA cell and a second calibrating cell, as used in technique (1). The 25.3-kb points for iron were observed later in each run after lowering the pressure.

Both techniques suffer from one additional calibrating deficiency; namely, the cell pressure may change appreciably in warming up the DTCA cell to observe the iron transformation. For the present, this possible error is believed to be less than 1-2 kb, but it remains uncertain.

Reproducibility of DTCA Data

The observed transformation temperatures from successive temperature cycles at a fixed pressure generally varied less than 3 deg C. The first transformation of a run was generally low by a few more degrees and these data were not used. Successive runs on the same alloy usually reproduced to around 5 deg or less.

The reference curve for iron may possess an error of 5-10 deg, which corresponds to an error in pressure of about 2 kb. This estimate is based on the degree of agreement between the various sets of data, on the reproducibility of successive DTCA runs, and on the consideration of possible changes in pressure which might occur in the cell as it is warmed up.

Temperature Control

Temperature control depends upon the maintenance of constant voltage across the heater elements, and is accomplished by means of a Sorensen Model 2501, 115-volt, 2.5-kva voltage regulator, capable of holding the output voltage to within $\pm$ 0.01 percent. This constant voltage is fed to a stepdown transformer, with a reactor interposed for controlling the voltage to the transformer. The control winding of the reactor is energized by a Hamner Model H-108 power supply, which provides a constancy in voltage comparable with that of the Sorensen regulator; interposed between the Hamner supply and the reactor is a 25,000-turn Helipot, designed to give a variable and almost completely smooth change in voltage to the reactor. The Helipot is motor-driven and the speed can be varied stepwise in either direction 1000-fold by means of an Insco Model 00140 speed changer. This equipment permits the rate of temperature rise or fall within the superpressure cell to be controlled in the range from 500 to 0.5 deg C/min, with a fairly constant rate being observed at any one setting of the speed changer.

Making a Pressure-temperature Run

The procedure for making a superpressure run consists in assembling the cell and gasket parts in the belt, closing the punch-belt-punch assembly and raising the pressure to the desired value. A DTCA pass is then made by slowly raising and then lowering the temperature of the cell through the transformation temperature and difference temperature. The pressure is then changed to a different value and another temperature cycle is made. In this way, the entire P-T curve may be established for any one sample assembly.

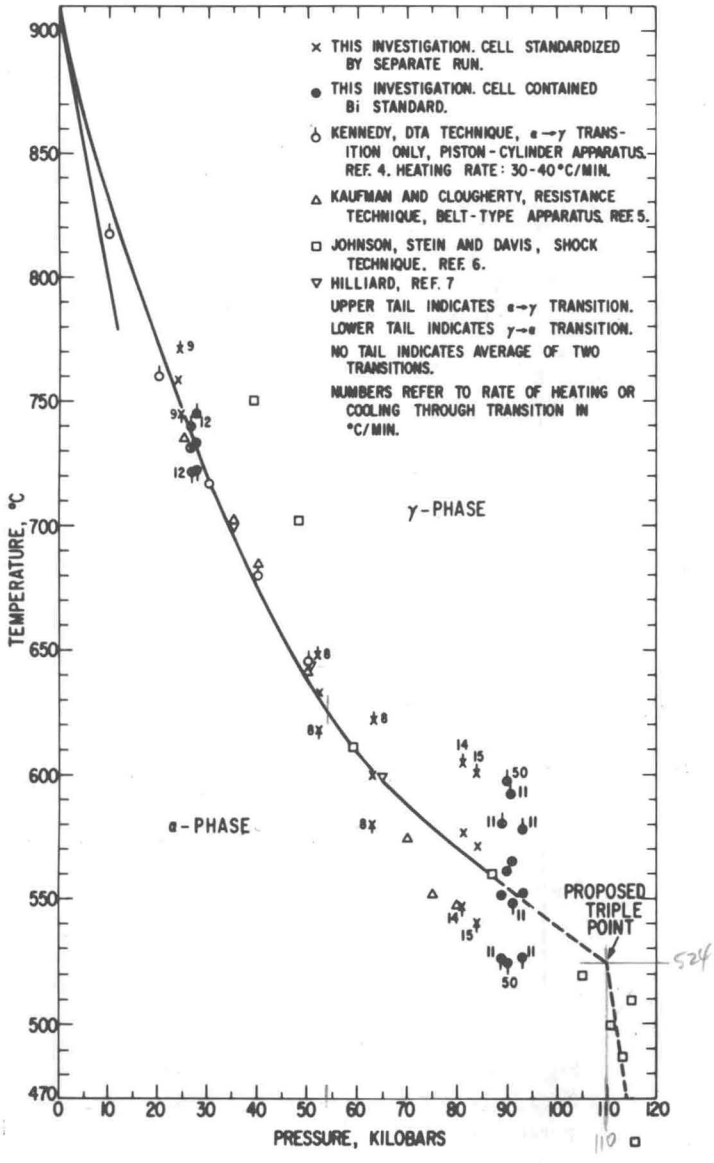

Fig. 4 Pressure-temperature curve for α - γ transformation in iron

Preparation of Alloys

The pure-iron reference samples used were Johnson-Matthey spectroscopic grade.

The iron alloys used in this study were vacuum-induction-melted from electrolytic iron and from a second component of comparable or higher purity. The ingot was hot-forged to 150 mils dia, decarburized in wet hydrogen at 700 C for 16 hr, and centerless ground to 100 mils diameter. The specimens were machined from these rods.

EXPERIMENTAL RESULTS

The α-γ Transformation in Iron--The Development of a Standard Reference Curve

The success of the duplex DTCA technique, in describing an accurate pressure-temperature transformation curve for any given material, depends upon the accuracy with which the pressure-temperature curve of a reference material is known. The data on the α-γ transformation of pure iron serve to define such a standard reference curve, shown in Fig.4, and all of the subsequent data presented in this paper will be related (directly or indirectly) to this reference P-T curve. The data used to develop this iron curve were derived from simple DTCA runs, where iron was compared with a nontransforming material. The temperatures in the plot are averages of the forward and the reverse transformations.

Other available data on the α-γ iron transformation are included in the curve in Fig.4. The data by Kennedy (4) taken by a DTA technique, are for the forward, α→γ, transformation only, and hence would be somewhat higher than the average of the forward and the reverse transformation temperatures. Advantageously, these data were obtained with a piston-cylinder apparatus, which one might expect to be a primary pressure-calibrating apparatus.

The data of Kaufman and Clougherty (5) were obtained with a belt-type apparatus similar in design to that used in this investigation. The iron transformations were observed by resistance changes in a wire, a thermocouple being located near the midpoint of the wire. There may be some question whether the location of the thermocouple always permits a precise observation of the transformation temperature, since the temperature gradient in the wire might permit a transformation to take place initially at the ends away from the thermocouple in some circumstances. The data of Johnson, Stein and Davis (6) were obtained by a shock technique. These data agree well in the 85-115 kb region with those of this investigation, which extend to 90 kb. The triple point at 115 kb and 503 C, proposed as the result of the shock experiments, lies close to an extrapolation of the present static data. However, the low-pressure shock data are much higher than the data from static apparatuses. At present it is not understood why at the higher pressures the shock data agree with the static data and at low pressures large deviations occur. The iron-transformation studies at 35-65 kb by Hilliard (7) agree well with the present iron curve. Here, the method of detection of the phase transformation was metallographic observation of recrystallization of that part of the α- iron which had been transformed to γ-iron.

The slope of the iron curve at atmospheric pressure was adjusted in agreement with that calculated from the heat of the α-γ transformation, 215 cal per g atom (8) and the volume change,

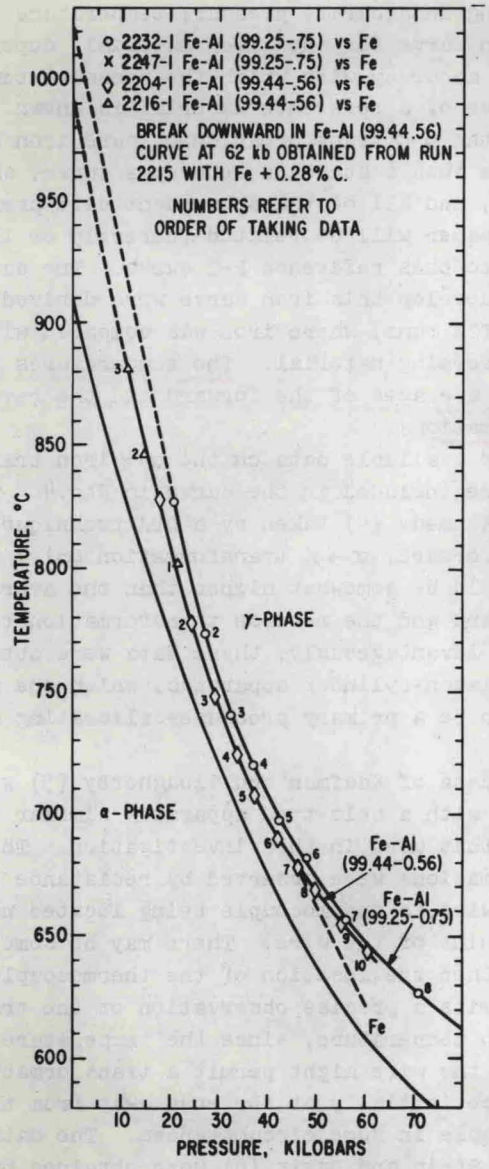

Fig. 5 P-T plots for α - γ transformations in Fe-Al alloys. Average temperature curves

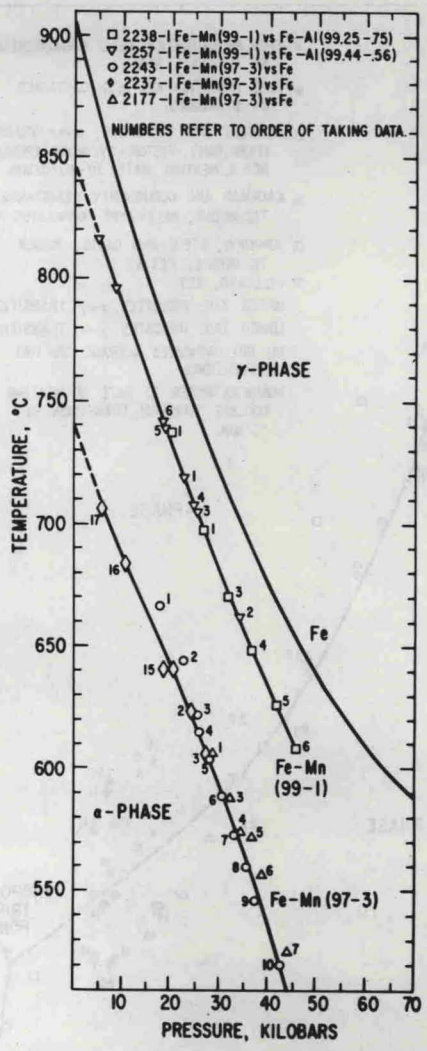

Fig. 6 P-T plots for α - γ transformations in Fe-Mn alloys. Average temperature curves

0.0746 cc per g. atom (9), in going from α to γ; this slope is 9.85 deg per kb.

Certain α-γ transformation data had shown discontinuities in the region of 30 kb. However, the averaged data generally were much smoother, and this break may be related to a general increase in sluggishness in the transformations in both the forward and the reverse directions. The P-T curve for pure iron, as shown in Fig.4, is reproduced in subsequent figures for reference purposes.

α-γ Transformations in Iron Binary Alloys

The average temperature-pressure curves for the alloy transformations are shown in Figs.5-9. The average temperature data were generally smooth, with few exceptions, over the entire pressure region indicating no new phases in either the alpha or the gamma fields. Numbers beside data points refer to the order of taking data.

Both the actual transformation temperatures and the average temperatures for the binary alloys are summarized in Table 1. The data were smoothed at the three indicated pressures. When the iron P-T curve is known with greater precision, the heading pressures in this table can simply be revised accordingly.

(a) Iron-Aluminum Alloys. The data for two Fe-Al alloys containing 0.56 and 0.75 percent Al, are shown in Fig.5 and Table 1. The 0.75 percent Al alloy is characterized by a smooth plot up to 71 kb. A change in slope at about 46 kb appeared in one run with Fe-Al (0.56 percent) measured against Fe-C (0.28 percent) standard, while a second run with the same Fe-Al alloy measured against

TABLE 1

α-γ TRANSFORMATION TEMPERATURES OF IRON AND IRON ALLOYS AT 20, 40 and 60 kb

Pressure		20 kb			40 kb			60 kb		
Temperature change during transformation	direction up-down average rate °C/min.	↑	↓	av	↑	↓	av	↑	↓	av
		α-γ Transformation Temperatures, °C								
Alloy Fe-X(weight per cent of minor element)										
Fe(pure)	8-12	786	761	773	691	657	674	636	581	609
Fe-Al (0.54)	8-12	836	793	814	721	676	699	669	618	644
Fe-Al (0.75)	8-12	865	807	836	733	683	708	676	618	648
Fe-Cr (1.09)	8-11	770	750	760	687	640	663	631	566	598
Fe-Cr (2.95)	8-12	766	728	747	676	606	641	---	---	---
Fe-Cr (9.49)	30-50	742	642	692	667	429	548	640	391	490
Fe-Mn (1.07)	9-16	765	708	736	676	592	634	---	---	---
Fe-Mn (2.85)	9-12	576	715	645	638	433	536	---	---	---
Fe-Co (10.2)	30-50	810	781	796	726	694	710	683	630	656(a)
Fe-Co (19.9)	8-12	891	876	883	837	816	827	805	778	792
Fe-Co (39.6)	15-25	945	933	939	902	885	893	870	846	858
Fe-Ni (1.07)	8-12	766	724	745	681	629	655	627	545	585
Fe-Ni (3.06)	8-16	736	662	698	655	564	610	---	---	---
Fe-Ni (10.0)	22-31	641	460	550	577	327	452	520	168	344(b)

(a) Extrapolated from 52 kb.
(b) Extrapolated from 53 kb.

a pure iron standard showed a very much smaller change in slope. This apparent discrepancy needs further investigation.

Both of these Fe-Al alloys were utilized as secondary standards in later duplex DTCA runs, where the use of iron would have resulted in the standard transition being too close to that of the second material. Particularly, Fe-Al was used with the 1 percent alloys of Mn, Cr and Ni in iron, and with certain Fe-C runs at the higher pressure.

(b) Iron-Manganese Alloys. The data for two Fe-Mn alloys containing 1.0 and 3.0 percent Mn are shown in Fig.6 and Table 1. The average temperature curves for both alloys appear to be smooth in the region up to 45 kb, except for the scatter from different runs on the 3 percent alloy. However, because of the very large hysteresis in the temperature in these latter data, the average temperature data may not be very accurate; it would seem inadvisable to attribute any significance to apparent changes in slope.

(c) Iron-Chromium Alloys. The data for three Fe-Cr alloys containing 1, 3 and 10 percent Cr are shown in Fig.7 and Table 1. All of the average temperature curves appear smooth, with no significant changes in slope at any point. The 1 percent curve follows closely parallel to the curve for pure iron. The 3 percent curve departs downward at the higher pressures while the 10 percent curve veers upward at these pressures. This behavior may be related to the expansion of the gamma loop at higher pressures; with more data, particularly with a 20 percent alloy, a more complete analysis could be made in this direction.

(d) Iron-Nickel Alloys. The data for three Fe-Ni alloys containing 1, 3 and 10 percent Ni are shown in Fig.8 and in Table 1. All of the average temperature curves appear smooth, with no significant changes in slope at any point. In comparison to the corresponding Fe-Cr alloys, the Fe-Ni alloys transform at lower temperatures and with larger hystereses. Both kinetics and the width of the respective two-phase regions probably make this difference.

(e) Iron-Cobalt Alloys. The data for three Fe-Co alloys containing 10, 20 and 50 percent cobalt are shown in Fig.9 and Table 1. All of these average temperature Fe-Co curves appear smooth with no significant changes in slope. However, the 20 percent data require some additional comment. At 26 kb and at 28 kb, a second transformation was observed at 796 and 788 C, about 70 deg lower than the α-γ transformation. The origin and nature of this additional apparent transformation is unknown, and warrants further investigation.

The α-γ transformations in all of the Fe-Co alloys proceeded with the lowest hystereses of any of the materials studied. The reason for the low hysteresis may be surmised by inspection of the Fe-Co phase diagram. A maximum temperature for the transformation is recorded at 45 percent Co, and at this point the vertical (along the temperature axis) distance separating the two phases, alpha and gamma, should be nil, with a congruent

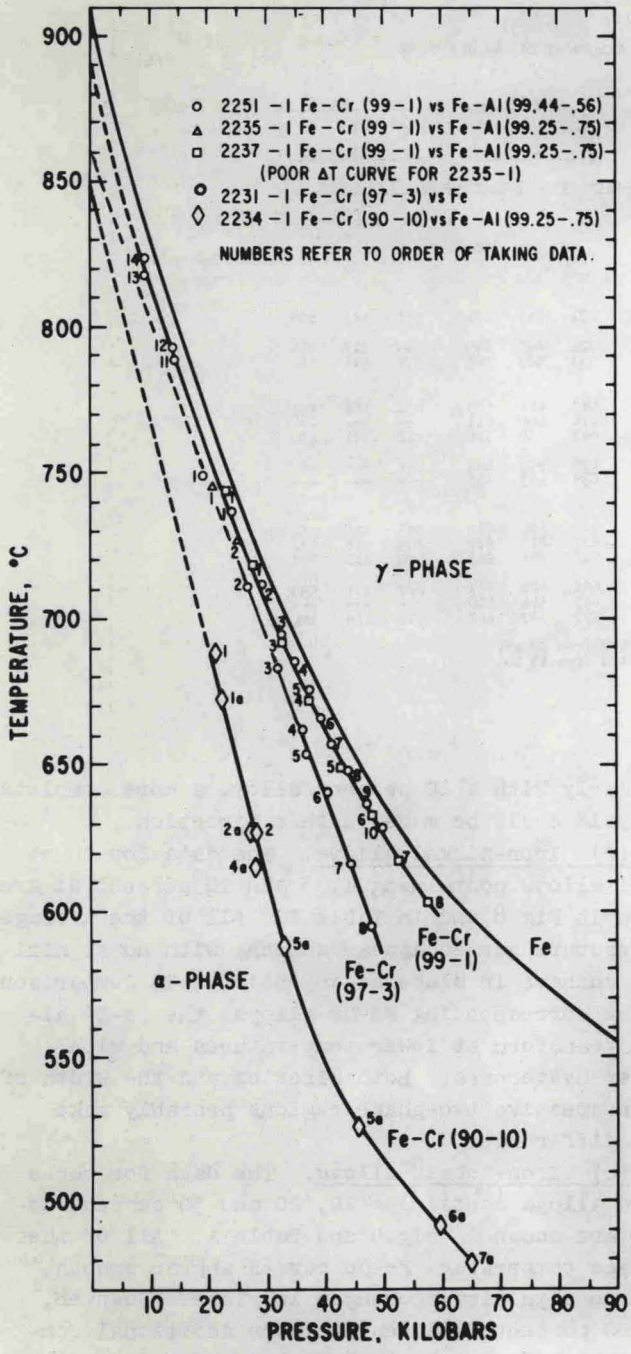

Fig. 7 P-T plots for α - γ transformations in Fe-Cr alloys. Average temperature curves

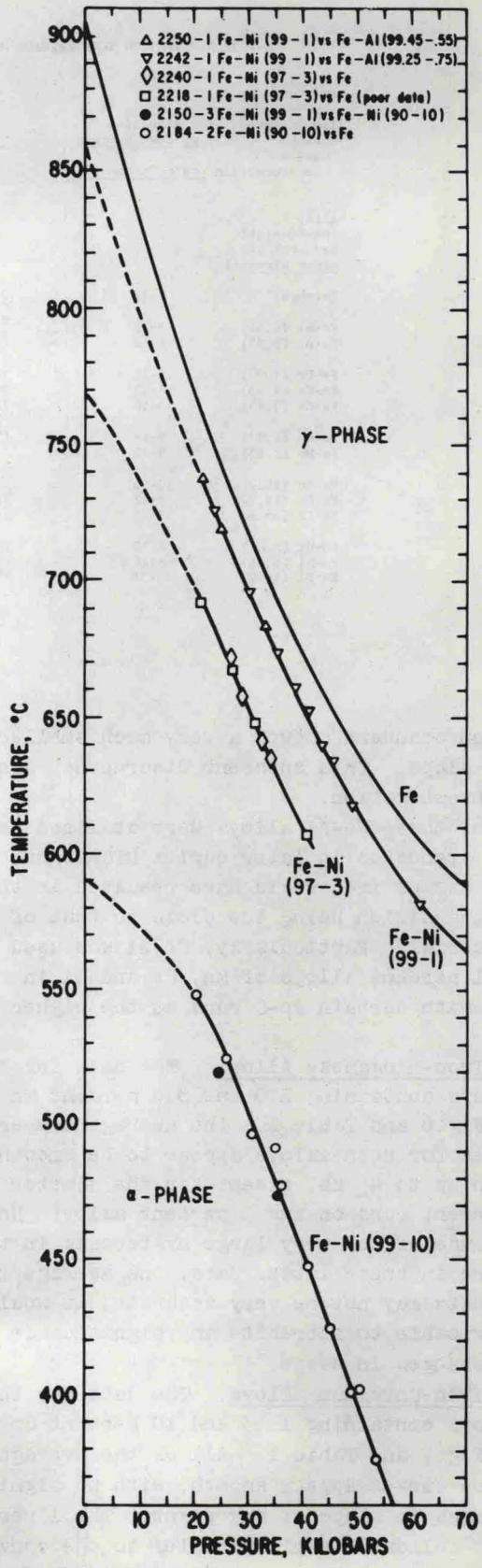

Fig. 8 P-T plots for α - γ transformations in Fe-Ni alloys. Average temperature curves

change in phase. The observation of the lowest hysteresis with the 60-40 alloy agrees with this concept.

The extrapolation of the high-pressure α-γ data usually fits in reasonably well with the atmospheric-pressure data. For the Fe-Co (60-40) alloy, however, where some of the best low-pressure data were obtained, the extrapolation to 972 C was 14 deg lower than that recorded in the literature. A second discrepancy appeared later

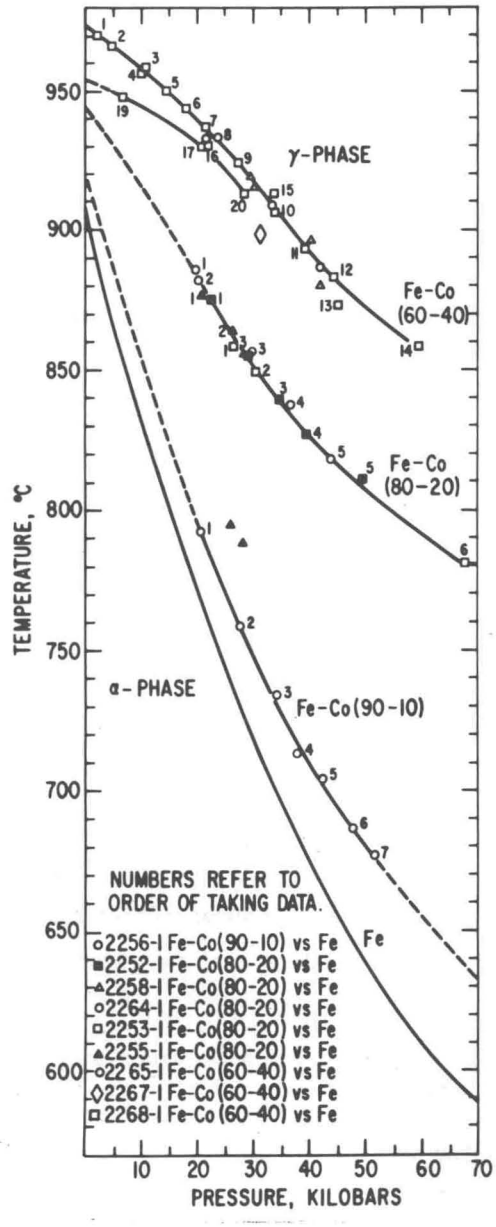

Fig. 9 P-T plots for α - γ transformations in Fe Co alloys. Average temperature curves

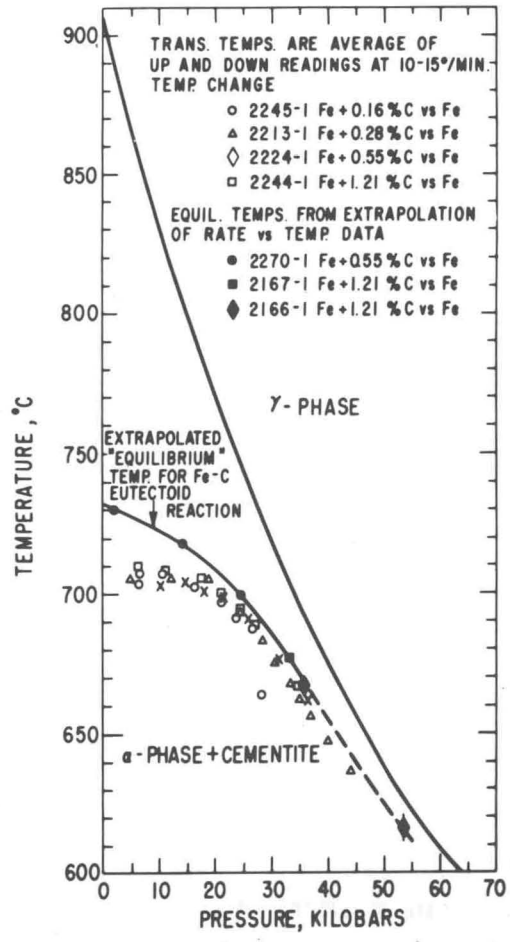

Fig. 10 P-T plots for Fe-C eutectoid reaction

in the same run (2268-1), when, after going up to 60 kb in a series of steps, the pressure was lowered to 20 kb; the value for the transformation now appeared 8 deg lower than originally at this pressure. Lowering the pressure still further resulted in an extrapolated value at atmospheric pressure about 20 deg lower than observed at the beginning of the run. Since this was a fairly long run involving many passes through the α-γ transformation, it is very likely that this shift is due to deterioration in the chromel-alumel thermocouple.

(f) The Fe-C Eutectoid Reaction. Four Fe-C alloys, containing 0.16, 0.28, 0.55 and 1.21 percent carbon, respectively, were studied by the duplex DTCA technique. The P-T plots presented in Fig.10 show two types of temperature: (a) Average temperatures, obtained by averaging the transformation temperatures for $\alpha \rightarrow \gamma$ and $\gamma \rightarrow \alpha$ transformations. (b) "Extrapolated" temperatures, obtained by plotting the observed temperature for the forward or reverse transformation against the logarithm of the rate of change of temperature during the transformation and extrapolating these curves to the point of intersection, as shown in Figs. 11(a-d).

These extrapolated temperatures form a smooth, continuous curve and approach the equilibrium eutectoid temperature at atmospheric pressure. Therefore, it is believed that the "extrapolated" temperatures more nearly represent the equilibrium eutectoid temperatures than do the average temperatures.

A large amount of data on the pressure dependence of the average temperatures for the eutectoid reaction were obtained, particularly at higher pressures. However, because they appear not to be easily relatable to equilibrium data, the signifi-

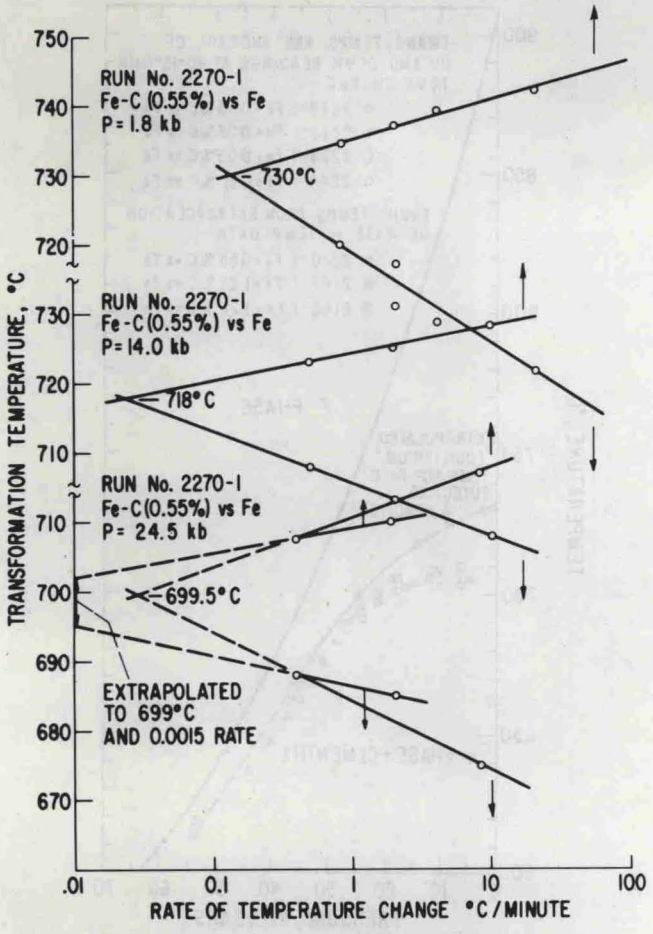

Fig. 11 (a) Kinetic data on Fe-C eutectoid reaction

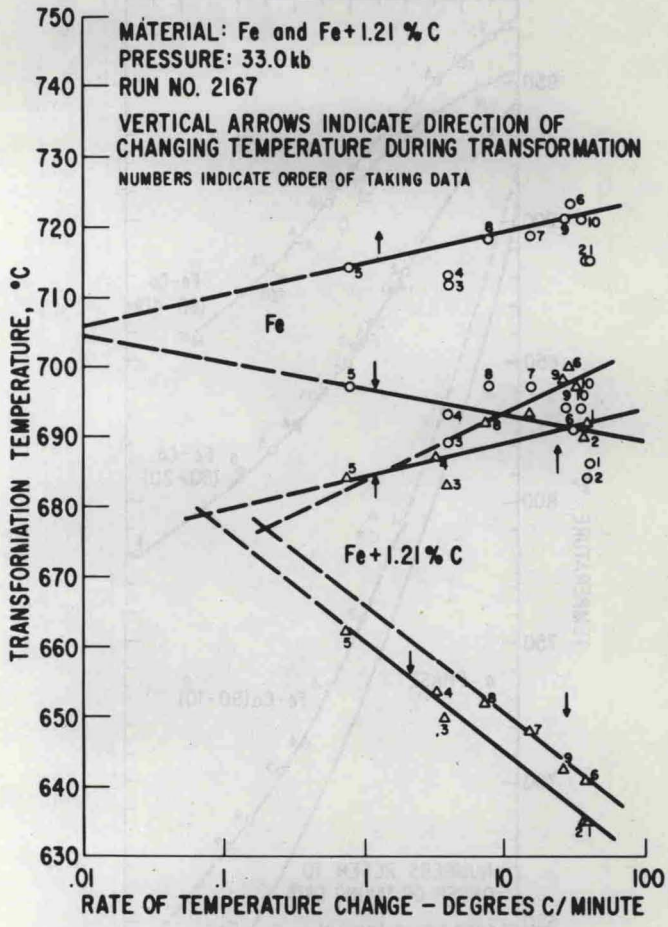

Fig. 11(b) Kinetic data on Fe-C eutectoid reaction

cance must remain questionable until additional kinetic measurements have been made.

(g) The Fe-Mn-C Eutectoid Reaction. The duplex DTCA technique was applied to the measurement of eutectoid transformation temperatures for Fe-Mn-C (98.7-1.0-0.33) versus Fe-Mn (99-1). The application of DTCA to a ternary system proved successful, with very good ΔT-maximum curves resulting. The interpretation of the results for this eutectoid reaction are more complicated than for the Fe-C eutectoid reaction, because the presence of the manganese causes an additional hysteresis in the transformation temperatures. As in the case of the binary alloy Fe-Mn, one should expect for Fe-Mn-C that the manganese would not diffuse to any great extent during the course of the transformation. The equilibrium phase diagram would show a three-phase region, comparable to the two-phase region in the Fe-Mn diagram, where the alpha phase, a carbide phase and an austenite phase co-exist at various manganese concentrations in the state of the eutectoid equilibrium. This three-phase region is reported (10) at 1.0 percent Mn and 0.75 percent carbon to occur at atmospheric pressure between 695 and 720 C.

The observed DTCA transformation temperatures were plotted versus the log rate of temperature change, as shown in Figs. 12(a) and 12(b); the extrapolated temperatures, while having no physical significance beyond locating a point in the three-phase region, are plotted against pressure in Fig. 13. One set of observed transformation temperature data are also plotted against pressure in Fig. 13, showing the actual hysteresis. These data (668 and 730 C) agree fairly well with that reported for 1 atm pressure (10), but with a somewhat larger hysteresis in temperature.

(h) Significance of Breaks in Certain Transformation Curves. The earlier simple DTCA runs as well as some of the later duplex DTCA runs on 1 percent alloys of Ni, Cr and Mn gave forward α-γ transformation P-T curves which exhibited certain reproducible breaks at around 30-40 and 670-715 C. The reverse transformation curves also departed from linearity or regularity and in the opposite direction from that observed for the forward

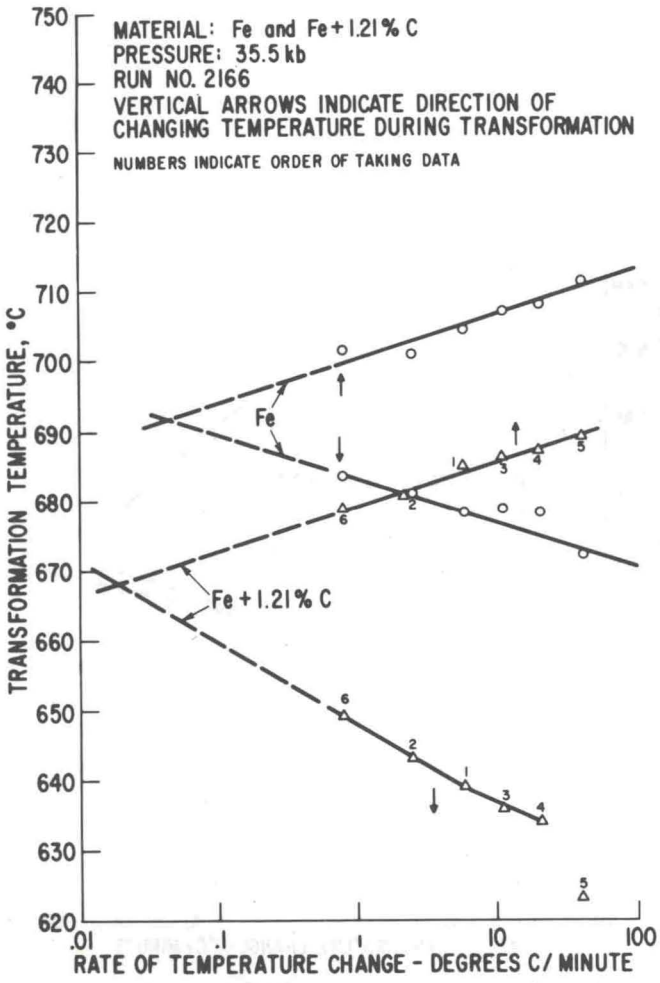

Fig. 11(c) Kinetic data on Fe-C eutectoid reaction

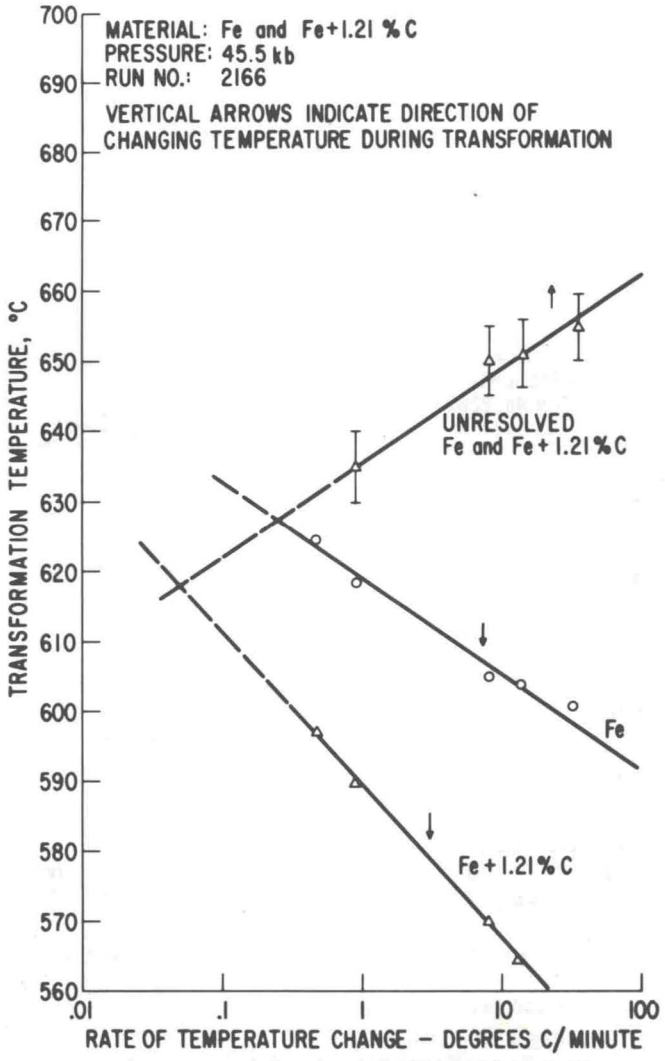

Fig. 11(d) Kinetic data on Fe-C eutectoid reaction

curves. However, the average temperature curve was essentially smooth. It was natural to presume that this effect was evidence of a kinetic phenomenon, that is, in the forward transformation one must exceed an equilibrium temperature further in order to observe the transformation, and conversely, in the reverse transformation one must lower the temperature further, beyond the equilibrium value in order to observe the transformation. In each case, these equilibrium temperatures are presumed to be those where the transformation would take place without diffusion and segregation. A possible explanation for these breaks in the transformation curves would be that beyond some pressure and temperature, the transformations become more sluggish. Some attempts were made to translate the breaks in the forward and reverse transformation curves to a change in phase in the gamma-field. Certain data indicating changes in phase within the gamma-field were tenuous and essentially unconfirmed or not reproducible.

SUMMARY AND CONCLUSIONS

1 A duplex DTCA technique was used to record and compare α-γ transformation temperatures in iron alloys of aluminum, chromium, manganese, cobalt and nickel with those in pure iron, all measurements being made under various pressures up to 70 kb in the belt apparatus. A pressure-temperature curve for this transformation in iron was developed using Ba and Bi room-temperature transformations as primary standards. By relating all iron-alloy data to this iron curve, the data are placed on a self-consistent pressure scale. Future improvements in the iron curve can easily be used to improve the iron alloy data.

2 A pressure-temperature curve for the Fe-C eutectoid reaction was similarly developed. In order to bring these data in agreement with atmospheric data, a special kinetic evaluation of the data was necessary to improve the estimation of

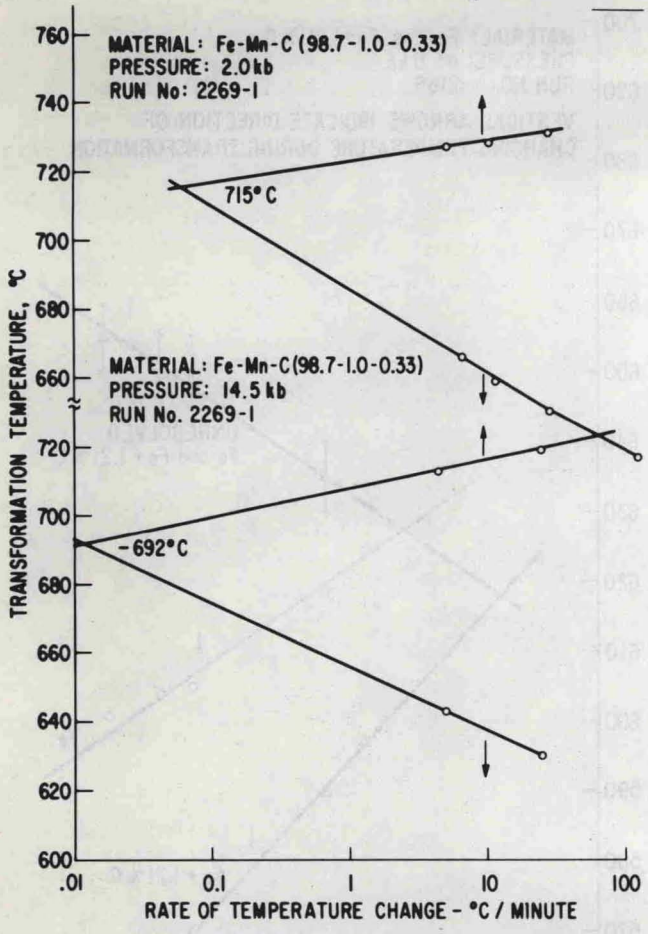

Fig. 12(a) Kinetic data on Fe-Mn-C eutectoid reaction

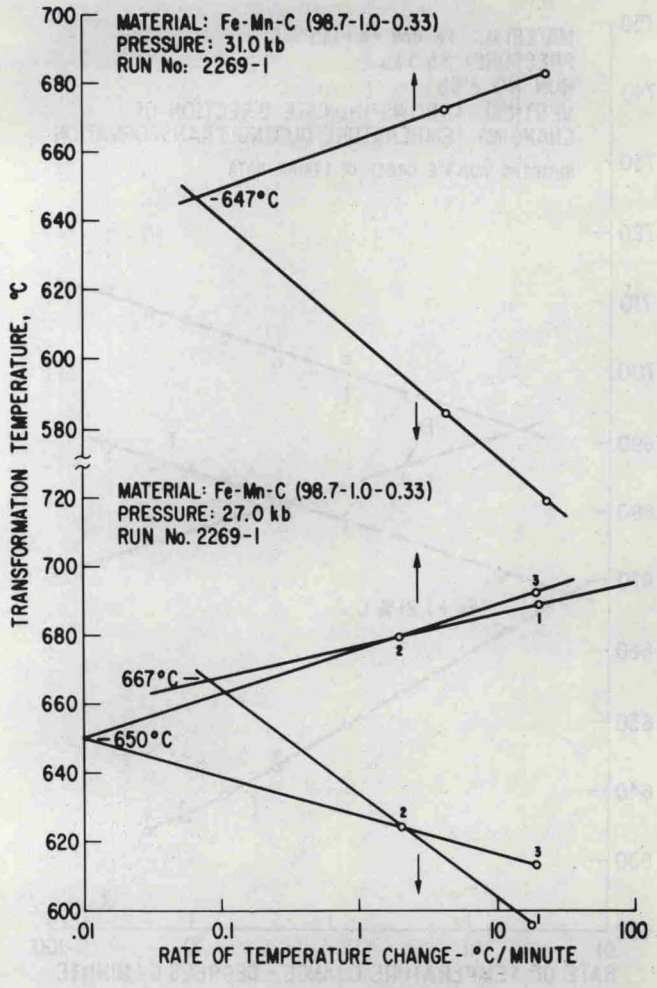

Fig. 12(b) Kinetic data on Fe-Mn-C eutectoid reaction

equilibrium transformation temperature. Similarly, the Fe-Mn-C eutectoid reaction was investigated.

3 The magnitude of hysteresis in the α-γ transformations, i.e., the difference in temperature between the forward and the reverse transformations at any one pressure, is correlated to the difference in temperatures of the alpha and gamma boundaries in the equilibrium phase diagram. Particularly, this argument would hold for Fe-Mn and Fe-Ni, which show large hystereses, and for Fe-Co, which has a very low hysteresis. The Fe-Co system gave a lower hysteresis the closer the composition was to that giving a maximum transformation temperature. All hystereses increased with increasing pressure.

4 The lack of smoothness of certain forward and reverse transformation curves is believed to be due to kinetic factors; no indisputable evidence for the existence of new phases was found within the range of experimental conditions.

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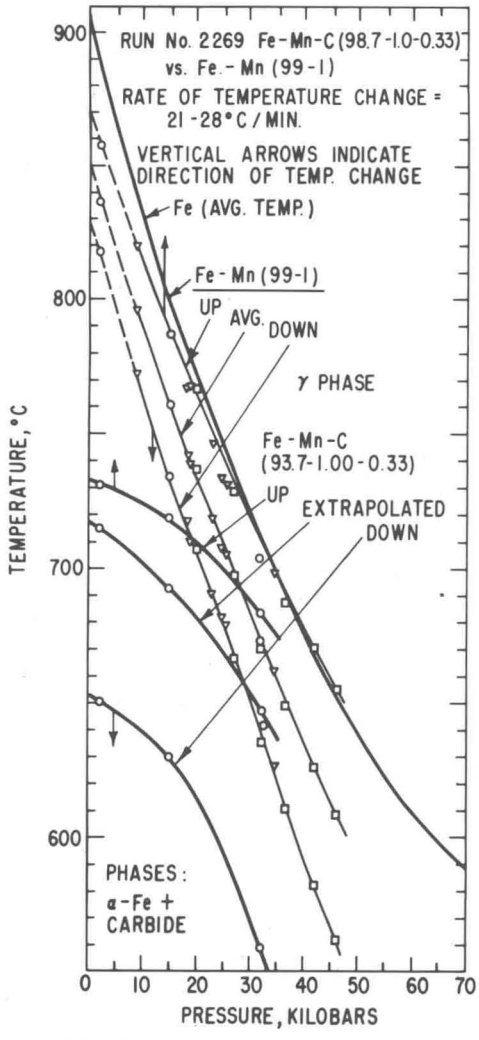

Fig. 13 P-T plots for Fe-Mn-C eutectoid reaction. Extrapolated temperatures and temperature hysteresis

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