

ISOTHERMAL NUCLEATION OF MARTENSITE IN AN IRON-
NICKEL-MANGANESE ALLOY.

by

SATYA RANJAN PATI

B.E.(Met), University of Calcutta,
West Bengal, INDIA (1961)

Submitted in Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

at the

Massachusetts Institute of Technology

1964

Signature of Author
Department of Metallurgy
August, 1964

Signature of Professor
in Charge of Research

Signature of Chairman
Department Committee
on Graduate Students

ISOTHERMAL NUCLEATION OF MARTENSITE IN AN IRON-
NICKEL-MANGANESE ALLOY.

by

Satya Ranjan Pati

SUBMITTED TO THE DEPARTMENT OF METALLURGY ON
AUGUST 31, 1964 IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

ABSTRACT

The effects of austenitizing treatment on the incubation period and the initial nucleation rate of the isothermal martensitic transformation at subzero reaction temperatures were determined in an iron-24 per cent nickel-3 per cent manganese alloy.

The incubation period shows a U-shaped behavior as a function of austenitizing temperature at all reaction temperatures, with the minimum of the curve occurring in the temperature range of 900° to 950°C. This trend appears to result from a compromise between a grain-size effect (dominant at low austenitizing temperatures) and an embryo effect (dominant at high austenitizing temperatures).

For all austenitizing conditions, the incubation period is shorter at -125°C than at -140° or -115°C , indicating a C-curve behavior of the isothermal nucleation kinetics.

The initial nucleation rate, calculated by two different methods, increases with increasing austenitizing temperature up to about 850° or 900°C , beyond which it decreases rapidly. The nucleation rate in preferentially transformed regions behaves like the average nucleation rate, but is approximately 15 to 100 times faster.

These results are interpreted as an interplay between changes in the configuration of embryos, dominant at low austenitizing temperatures, and the annealing out of embryos, dominant at high austenitizing temperatures.

The activation free energy of nucleation, obtained on the basis of preferred nucleation sites, is of the order of 11,000 calories per mole, and shows some tendency to decrease with increasing austenitizing temperature.

Thesis Supervisor: Morris Cohen
Ford Professor of
Material Science and
Engineering

TABLE OF CONTENTS

	<u>Page Number</u>
ABSTRACT	ii
TABLE OF CONTENTS	iv
LIST OF FIGURES	v
LIST OF TABLES	vi
ACKNOWLEDGMENTS	vii
I. INTRODUCTION	1
A. Previous Work	1
B. Present Investigation ,	5
II. EXPERIMENTAL PROCEDURE	7
III. METHODS OF CALCULATION OF INITIAL NUCLEATION RATE	16
IV. EXPERIMENTAL RESULTS	20
V. DISCUSSION OF RESULTS	28
VI. CONCLUSIONS	42
VII. SUGGESTIONS FOR FUTURE WORK	44
BIBLIOGRAPHY	46
APPENDIX: Incubation Periods, Time of Transformation and the Fraction of Isothermal Martensite Formed at Different Transformation Temperatures for Various Austenitizing Treatments.	47

LIST OF FIGURES

<u>Number</u>	<u>Title</u>	<u>Page</u>
1.	Electrical Resistance versus time for Fe-Ni-Mn Alloy Austenitized at 1150°C (one hour) and reacted at -115°C	21
2.	Incubation period as a function of austenitizing temperature, reacted at indicated temperatures. . .	22
3.	Initial nucleation rate at -140°C, as a function of austenitizing temperature.	24
4.	Initial nucleation rate at -125°C, as a function of austenitizing temperature.	25
5.	Initial nucleation rate in preferentially transformed regions at indicated temperatures, as a function of austenitizing temperature	26
6.	Volume of an initial martensitic plate as a function of austenitizing temperature	29

LIST OF TABLES

<u>Table Number</u>		<u>Page Number</u>
I	Composition of Alloy Z-551	8
II	Initial nucleation rates and activation energies for isothermal martensite formation at -140°C , for various austenitizing temperatures	35
III	Initial nucleation rates and activation energies for isothermal martensite formation at -125°C for various austenitizing temperatures	36
IV	Incubation periods, time of transformation and the fraction of isothermal martensite formed at different transformation temperatures for various austeniti- zing treatments.	47

ACKNOWLEDGMENTS

The author wishes to thank Professor Morris Cohen for suggesting this investigation and for his constant guidance and encouragement.

He thanks Mr. Hugh Morrow III who helped the author through many of the initial phases of the investigation.

The author acknowledges the help of Mr. Phillip Dellori and Mr. P. K. K. Nayar for their assistance in the experimental work.

I. INTRODUCTION

The phenomenon of isothermal martensitic transformations has an important bearing on the understanding of the mechanism of martensitic reactions in general. The kinetics of such transformations if it can be followed without interference by athermal reactions, is much simpler to treat theoretically and helps, thereby, towards a theoretical understanding of martensitic transformation kinetics. Effects of variables such as grain size and austenitizing conditions on the kinetics of such transformations are likewise important.

A. Previous Work.

The phenomenon of isothermal martensitic transformations is now well established⁽¹⁻⁶⁾. However, some of the early investigators^(1,2,3) made the observations in the presence of varying quantities of athermal martensite. Kurdjumov and Maksimova⁽²⁾ first reported the formation of isothermal martensite in an iron-nickel-manganese alloy (23 per cent nickel, 3-4 per cent manganese, balance iron) where the athermal martensite was reported to be completely avoided. However, later work of Cech and Hollomon in a similar alloy showed that up to 3 per cent martensite did form on cooling in their samples, and thus was present at the initiation

of the isothermal transformation. They reported the results obtained on the isothermal transformation over the temperature range of -196° to -79°C and found that the reaction rate was a maximum at -128°C .

Shih, Averbach and Cohen⁽⁴⁾ studied the isothermal formation of martensite in an iron-nickel-manganese alloy (23.2 per cent nickel, 3.62 per cent manganese, balance iron) and an iron-manganese-carbon alloy (5.24 per cent manganese, 1.10 per cent carbon, balance iron) at a series of reaction temperatures in the range of -196° to -90°C . In both cases, athermal martensite was completely avoided. Their results showed that the reaction rate at the beginning of the strictly isothermal reaction was relatively slow, but as soon as some detectable amount of martensite was produced, the transformation rate increased rapidly. They reported that in the absence of initial martensite produced on cooling, there was an incubation period in the isothermal transformation wherein no martensite (within a sensitivity of 0.2 per cent transformation) was observed. On the other hand, in the presence of 1 to 2 per cent prior martensite, the reaction rate was maximum at the beginning. This explained why the previous investigators^(2,3) reported that the isothermal transformation rate was a maximum at the beginning of such transformations.

Shih et al.⁽⁴⁾ also studied the effect of internal strain on the incubation period and the subsequent rate of transformation. They found that the samples which were stress relieved after quenching from austenitizing temperature had longer incubation periods and

slower transformation rates than the as-quenched ones. Machlin and Cohen⁽⁷⁾ found for an iron-nickel-alloy (29 per cent nickel, balance iron) in presence of athermal martensite that the state of internal strain affects the rate of isothermal martensite formation. Hence, the rate of cooling from austenitizing temperature and the resulting residual stresses may be quite important in determining the initial kinetics of isothermal martensite formation.

Cech and Hollomon⁽³⁾ included in their investigation the effect of delayed quenching on the kinetics of isothermal transformation. They found that partial stabilization (slowing of isothermal transformation) could be brought about by holding a sample at room temperature either prior to subcooling or after some isothermal martensite transformation. However, their alloy contained 0.05 per cent carbon, and Yeo⁽⁸⁾ has suggested that carbon has a stabilizing effect on the kinetics of isothermal martensite formation. He investigated the stabilizing effect of carbon on the isothermal martensitic transformation in an iron-nickel-aluminum-titanium-columbium (24.9 per cent nickel, 0.26 per cent aluminum, 1.58 per cent titanium, 0.15 per cent columbium and 0.01 per cent carbon) alloy. The alloy showed isothermal martensitic transformation when held for several hours at room temperature. Practically no carbon was there in solid solution in the alloy in presence titanium and columbium. This demonstrated that martensite could form isothermally at comparatively high temperatures if stabilization of austenite-martensite transformation was eliminated by removal of carbon.

Morrow⁽⁶⁾ has studied recently the effect of austenitizing treatment on the incubation period of isothermal martensite formation in two iron-nickel-manganese alloys, one of them being the same alloy as is used in the present investigation. He used reaction temperatures of -150° , -140° , and -120°C . The incubation periods in these alloys showed a U-shaped behavior as a function of austenitizing temperature, with the minimum occurring in the temperature range of 900 to 950°C . This dependence of the incubation period on the austenitizing temperature has been interpreted as a compromise between a grain-size effect (dominant at low austenitizing temperatures) and the annealing out of embryos (dominant at high austenitizing temperatures).

The initial nucleation rate for isothermal martensite formation has been derived by a number of investigators^(4,6,9). A detailed account of their result will be reserved for a later section. Only the outline of their method will be presented at this point. Fisher⁽⁹⁾ used the initial transformation rates (maximum rate, due to presence of 1 to 2 per cent athermal martensite) of Cech and Hollomon⁽³⁾ for the confirmation of calculated nucleation rates based on classical nucleation theory extended to include the effect of elastic strain energy. Shih et al.⁽⁴⁾ calculated the initial nucleation rate by noting the time required to detect the formation of 0.2 per cent martensite, the volume of each initial martensitic plate being known from the metallographic measurements of their radii and thickness. The initial nucleation rate was assumed to remain

constant during the incubation period. In both of the above papers the nucleation rate was calculated for a particular austenitizing condition. On the other hand, Morrow⁽⁸⁾ calculated the initial nucleation rate with varying austenitizing conditions. He used the same approach as Shih et al, but he calculated the volume of each initial martensitic plate from a measured ratio of its radius and thickness, and he expressed the radius in terms of the austenitic grain diameter.

B. Present Investigation.

The purpose of this investigation is to study the effect of austenitizing treatments on the nucleation of isothermal martensite in an iron-nickel-manganese (24.2 per cent nickel, 2.98 per cent manganese, balance iron) alloy. This alloy undergoes isothermal transformation without complications by the athermal reaction. Therefore, the possible accelerating effect of athermal martensite does not affect the determination of either the incubation period or the subsequent progress of the isothermal reaction.

The effect of austenitizing treatment on this iron-nickel-manganese alloy (initially cold worked) was studied by varying the austenitizing temperature at a constant time of one hour. The incubation period for isothermal transformation as well as the time for small fractions of transformation were measured as a function of austenitizing temperature using reaction temperatures of -140° , -125° , and -115°C . The initial nucleation rate was calculated by two different

methods: (a) by counting the number of martensitic plates per unit area and per unit length of traverse on a polished specimen, transformed to a small fraction of martensite and noting the time for that transformation, and (b) by following the approach of Shih et al.⁽⁴⁾ and of Morrow⁽⁶⁾.

In each instance, the incubation period for isothermal martensite formation and the nucleation rate calculated by the above two methods were used as indices of the effects produced by the austenitizing treatment.

The result of these studies have been interpreted as an interplay between relaxation effects (dominant at low austenitizing temperatures) and the annealing out of embryos (dominant at high austenitizing temperatures).

II. EXPERIMENTAL PROCEDURE

The alloy used in this investigation was provided by the Ford Scientific Laboratory of Dearborn, Michigan. The alloy was melted in an induction arc furnace. The ingot was then forged into rods approximately five feet long and 0.5 inches in diameter; this was the condition in which the stock was received.

The as-received rods were examined for flaws, such as pipes and seams, and one-inch samples were cut from each end of these rods to remove pipes and cracks existing therein. The remainder of each rod was cut up according to the following scheme: one inch for macroscopic examination, three inches for chemical analysis, one-half inch for another macroscopic examination, six inches for swaging into test specimens, one-half inch for a third macroscopic examination, six inches for a second swaging sample, one-half inch for a fourth macroscopic examination, and three inches for a second chemical analysis.

The rods were examined macroscopically to check for cracks, flaws and flow patterns. The ends of the pieces for metallographic examination were polished through the 240, 320, and 600 grit papers, and then immersed in an acid solution of 50cc hydrochloric acid, 7cc sulphuric acid, and 18cc water for at least 12 hours. Flaws became obvious and inhomogeneities could be readily detected after such a treatment. This also revealed a thin region at the surface which was

clearly different from the bulk of the rod. This thin layer was removed by turning down the samples on a lathe from 0.500 to 0.404 inches in diameter.

The two three-inch analysis samples were milled into small chips for wet chemical analysis, and then degreased with acetone to remove any carbon pick up from machining operation. The composition of the alloy (Z-551) is given in Table I below.

TABLE I

Composition of Alloy Z-551

<u>Sample</u>	<u>%Ni</u>	<u>%Mn</u>	<u>%C</u>	<u>%Fe</u>
Z-551, No. 1	24.2	2.98	0.017	Balance
Z-551, No. 2	24.2	2.98	0.016	Balance

Two six-inch swaging samples were then sealed in evacuated quartz tubes and homogenized at 1250°C for 10 days. The quartz tubing collapsed during this long anneal, but vacuum remained intact. Upon air cooling to room temperature, the quartz tubing cracked resulting in surface oxidation. This oxidized layer was removed partially by scraping with steel wool. In addition, the depleted manganese layer was removed by grinding the swaging rods from 0.404 to 0.343 inches in diameter.

The rods were then swaged through the following dies: 0.312, 0.281, 0.265, 0.250, and 0.225 inches. Swaging was accomplished easily at each of these steps. The dies readily accepted the rods and no

flashing occurred. No cracking was visible, even at the ends of the rods. Each swaging sample, originally six inches long, was now in the form of six rods ranging in length from five to eight inches. These rods were annealed at 800°C for 30 minutes, sealed in evacuated vycor tubes, and then air cooled to room temperature.

The annealed rods were next swaged through the following dies: 0.223, 0.186, 0.115, and 0.129 inches. In this series also, swaging was accomplished easily without any flashing or cracking. The starting six rods were now in the form of twelve rods ranging in length from five to eight inches. These rods were sealed in evacuated vycor tubes, as before, and annealed at 800°C for 40 minutes. The appearance of the rods after recrystallization was, in most cases, free from oxidation and tarnish.

The rods were next swaged through 0.108 and 0.090 inch dies. Some flashing was observed, and cracks occurred at the ends of some of the rods. These ends were cut off. The samples were now in the form of twelve rods, 0.090 inches in diameter and 10 to 17 inches in length.

The rods were then given some identification number and were centerless ground by the Centerless Grinding Company in Waltham, Massachusetts, from 0.090 to 0.060 inches in diameter. The centerless ground rods were cut into 2.50 inch lengths, cleaned with soap and water, and rinsed in alcohol. These were then sent to the Research Electronic Tube Laboratories at M.I.T. to have nickel wire leads spot welded on. Pure nickel wire of B and S 24 gauge was used for leads

(8 inches long). The two current leads were positioned at the ends of the sample, 2.50 inches apart, and the two voltage leads were positioned 0.25 inches in from each end, or 2.00 inches apart.

These samples were then electropolished in a solution of 95 per cent glacial acetic acid and 5 per cent of a 60 per cent strength perchloric acid solution. The solution was surrounded by an ice-water bath and was stirred constantly with a magnetic stirrer. A sheet of pure nickel was used for the cathode, completely surrounding the sample, to obtain a uniform removal of material from the sample. 105-110 volts and a current of 4 to 5 amperes (depending on the depth of immersion) were used for electropolishing.

The total time of electropolishing was 60 seconds. After each 30 second polish the sample was withdrawn from the bath, rinsed in alcohol, and dried in a forced hot-air stream. The diameter of the resistivity samples were reduced from 0.060 to 0.058 inches as a result of the electropolishing treatment.

The resistivity leads were then folded and the samples were placed inside 9 mm vycor tubing. The tubing was cleaned with hot soap solution, water, rinsed with alcohol, and dried before inserting the samples. During evacuating, the tube was gently heated to drive off any excess moisture. After being pumped down for at least 20 minutes, the tube was sealed at a point away from the sample to avoid heating the latter. Some samples, used for the high-temperature austenitizing treatments, were sealed off in one-half atmosphere of argon in an attempt

to minimize the manganese loss. In some cases, electrolytic manganese chips were placed at both ends of the tubes, but contact with the sample was avoided by putting constrictions in the tube. This was tried with the expectation that manganese would evaporate preferentially from the pure manganese chips and inhibit its loss from the samples. But at high temperatures, there was enough manganese evaporation from the manganese chips to fuse the resistivity leads, thereby rendering the sample unusable for resistivity measurements.

These resistivity specimens were austenitized at a series of temperatures ranging from 750°C to 1150°C for one hour. The temperature control was $\pm 3^{\circ}\text{C}$. After austenitizing, the specimen in its tube was removed slowly from the furnace, held in front of the door of the furnace for one minute to prevent drastic air cooling, and finally allowed to air cool in 15 minutes to room temperature. This slow rate of cooling was adopted to reduce the residual internal stresses. However, this slow cooling rate did not affect the austenitic state of the alloy at room temperature. The tube was then carefully broken away from the sample to prevent scratching and the sample removed. The nickel wire leads were then straightened and the specimen was electropolished as before reducing the diameter by another 0.002 inches. For the high-temperature austenitizing treatments, the samples were electropolished an extra 30 to 60 seconds in an attempt to remove the manganese-depleted layer from the surface. Although in a number of cases during the course of transformation, it was realized that removal of the manganese-depleted layer was not complete even with this longer

electropolishing, the time of polishing could not be increased any further because the leads became very thin and tended to break off the sample. This manganese-depleted layer, when present, caused the premature initiation of some martensite near the surface on cooling below room temperature. This was the reason that a number of high-temperature treated samples showed unduly short incubation periods (practically undetectable experimentally). However, those runs which showed regular incubation periods were accepted as representative of the true isothermal reaction.

The resistance of the sample was measured with a Kelvin double bridge at 20°C in a water bath. Resistance measurements were then conducted as a function of time at the subzero reaction temperature. After isothermal transformation at the reaction temperature, the sample was upquenched to 20°C and resistance was again measured. A change in resistance of one unit out of approximately 2000 to 2400 units corresponded to 0.2 per cent isothermal martensite, (this amounted to a change in resistance of 1×10^{-5} ohms. for 0.2 per cent isothermal martensite formation compared to a resistance of about 2×10^{-2} ohms. for the austenitic specimen) according to a calibration by Entwisle⁽⁵⁾ who used the same type of equipment on similar alloys. This calibration was also checked in the present investigation by estimating the amount of transformation metallographically by point counting. This procedure will be discussed later. The fraction of isothermal martensite formed during the transformation was thus noted. The sample was further checked with a magnet after transformation to make sure that it had or had not transformed.

The isothermal runs were started in all cases within 30 to 45 minutes after completion of austenitizing treatment in order to obtain a uniform stabilizing effect, if any, on the transformation.

In following the resistance as a function of time at the isothermal transformation temperature, readings were taken as often as possible, generally at intervals of 0.30 minutes when short incubation periods were expected. For samples with long incubations, readings were taken at intervals of one minute, until the incubation period had elapsed. However, these intervals were reduced when prior evidence indicated that the specimen was about to transform. This was necessary in order to be able (a) to detect the initiation of transformation as closely as possible, and (b) to discontinue the run for metallographic measurements after only a very small fraction of martensite had been formed.

The isothermal transformations were conducted at -140° , -125° , and -115°C . A mixture of 75 per cent petroleum ether and 25 per cent methyl cyclohexane was used for the isothermal baths. The bath temperature was maintained by small additions of liquid nitrogen, and was monitored constantly with a calibrated copper-constantan thermocouple. Resistance readings were taken when the bath temperature was correct. The bath was stirred vigorously to maintain uniformity of temperature inside the bath. The potentiometer was standardized before each resistance reading, and the liquid-nitrogen additions to the bath were made in between the resistance readings.

After each isothermal-transformation run, the resistance specimen was mounted in a cold-setting compound and polished mechanically. The sample was ground longitudinally to the plane of maximum cross section and polished on the 240, 320, and 600 grit paper wheels, followed by Linde "A" and "B" aluminum oxide suspension laps. Such

polished surfaces were etched with 6 per cent nital and examined optically to check the location of isothermal martensite in the samples.

The fraction of martensite formed in each sample was then determined by point counting, using an 8×8 grid of dimensions 6.84×6.84 cm superimposed on the specimen image. Since the martensitic transformation was not uniform across the section of the specimen, point counting was done at 200 to 250 grid positions in each sample, to obtain the average value of fraction of martensite formed over the entire specimen. A magnification of either 200X or 500X was adopted depending on the austenitic grain size.

At each of the above grid positions, the number of martensitic plates falling within the area of the grid was counted, from which the average number of plates per unit area of the specimen could be calculated. The average number of plates per unit length of the specimen was determined by the linear intercept method. Usually 3 to 4 traverses were made along the length of the sample. The total number of intercepts was recorded on a mechanical counter, and the distance traversed was determined by a calibrated, movable stage. For each sample, the magnification employed for the determination of the planar and the lineal parameters was the same as that for the determination of the fraction transformed.

During traversing of the specimen under the optical microscope, the regions having highest density of martensitic plates were also located. Measurements were made, as before, to obtain the number of plates per unit area and per unit length corresponding to these preferentially transformed regions. Usually the grid could be placed in 4

to 5 positions within each one of these regions at a magnification of 500X. Counting was repeated in 2 to 3 such regions for each sample.

Samples used to determine the austenitic grain sizes were then etched further with 12 per cent nital for about two minutes to bring out the austenite grain boundaries. The grain size measurements were made by the linear intercept method, at 100X or 500X depending on the grain size. At least 200 intercepts were counted for each sample. Since the twin boundaries as well as the grain boundaries restricted the size of the initial martensitic plates, large twins were counted as contributing two boundaries and small twins counted as contributing one boundary. The total number of intercepts was recorded on a mechanical counter and the distance traversed was known from the calibrated microscopic stage. The twin grain size linear intercepts were measured for austenitizing temperatures of 750°, 1100°, and 1150°C. For other austenitizing temperatures, values measured by Morrow⁽⁶⁾ for the same alloy were accepted.

Since martensite formed nonuniformly across the section of the specimen, a sample was examined by electron microanalyser to check the compositional homogeneity. After isothermal transformation, a resistance specimen was cut into 6 pieces and mounted in bakelite for this purpose. It was polished in the same way as for optical examination. An A.R.L. (Applied Research Laboratories) electron microanalyser operated at 30KV was used. The mount was traversed both parallel and normal to the axis of the specimen while the intensity of the Mn_K line fluoresced by the specimen was continuously recorded on a chart.

III. METHODS OF CALCULATION OF INITIAL NUCLEATION RATE.

The initial nucleation rate for isothermal martensite formation has been calculated by two different methods as discussed below:

(A). This is based on measurement of the time for a specific fraction of martensite transformed and counting the number of plates per unit area and the number of plates per unit length for that amount of transformation.

Nucleation rate, \dot{N} (number of nuclei per cubic centimeter per second) can be expressed as

$$\dot{N} = \frac{N}{t} \quad (1)$$

where N_V is the number of plates formed per unit volume within the time of transformation and t is the time in seconds. Fullman⁽¹⁰⁾ has shown by statistical analysis that for a sample containing particles of a phase distributed in the form of circular plates of uniform radius r , and thickness h , where $r \gg h$, the following relations hold:

$$N_A = \frac{\pi}{2} r N_V \quad (2)$$

$$N_L = \frac{\pi}{2} r^2 N_V \quad (3)$$

where N_A is the number of plates per unit area and N_L is the number of plates per unit length. Combining equations (2) and (3), the radius

of the plates can be expressed as

$$r = \frac{N_L}{N_A} \quad (4)$$

The volume fraction of martensite formed within the time t is related to the volume of each plate and number of plates formed:

$$f = N_V V \quad (5)$$

where f is the fraction transformed, and V is the volume of each initial martensitic plate $= \pi r^2 h$. Putting the expression of volume in equation (5), rearranging the terms and using equation (3), we have

$$h = \frac{f}{2N_L} \quad (6)$$

Substituting this value of h in equation (5) and using equations (2) and (3), the desired expression for N_V is obtained

$$N_V = \frac{f}{\pi r^2 h} = \frac{2 h (N_L)}{\pi \left(\frac{N_L}{N_A}\right)^2 h} = \frac{2 (N_A)^2}{\pi N_L} \quad (7)$$

Expressing N_V in equation (1) in terms of equation (7), we get

$$\dot{N} = \frac{2}{\pi t} \frac{(N_A)^2}{N_L} \quad (8)$$

The initial nucleation rate (averaged over the whole specimen) was calculated from the above equation using the average N_A and N_L . The high rate of nucleation in the heavily transformed regions was also calculated using N_A and N_L values confined to these regions only. This method of calculation for the whole specimen as well as for the

preferentially transformed regions is referred as method A in the text.

(B). This method is based on the measurement of the incubation period for formation of isothermal martensite, and volume of the martensitic plates initially formed.

If it is assumed that at each reaction temperature the rate of nucleation is constant during the incubation period, at least up to time (τ_i) of the first detectable amount of martensite (0.2 per cent), then according to the relation proposed by Shih et al. ⁽⁴⁾

$$0.002 = \dot{N} V \tau_i \quad (9)$$

Entwisle ⁽⁵⁾ considered each initial martensitic plate as an oblate spheroid of volume $V = 4/3 \pi r^2 c$, where c is the semi thickness of the martensitic plate. Entwisle found a r/c ratio of 35 in iron-nickel-manganese alloys of composition similar to the alloy under investigation, for an austenitizing treatment at 900°C . Morrow ⁽⁶⁾ found a r/c ratio of 12 and 40 for one hour austenitizing at 775°C and 950°C respectively. Assuming a linear variation of r/c ratio over the range of austenitizing temperature under investigation, the volume of an initially formed martensitic plate can be calculated if r is known. Entwisle has further shown that the average martensitic plate radius r in austenite grains of mean linear intercept L is given by

$$r = 0.6720 L \quad (10)$$

As already mentioned, the twin boundaries as well as the grain boundaries restrict the size of the initial martensitic plate in this alloy. Therefore, the twin grain size linear intercept should

be used rather than the grain size linear intercept to calculate the radius. Using this relation for r , the volume of an initially formed martensitic plate can be expressed as

$$V = \frac{4\pi (0.6720L)^3}{3 (r/c)} = 1.272 \frac{L^3}{(r/c)} \quad (11)$$

The volume of an initially formed martensitic plate was calculated for each austenitizing temperature from the measured twin grain size mean linear intercept of the austenite grains. The initial nucleation rate was then calculated as a function of austenitizing temperature using equation (9). This method of calculation is referred to as method B in the text.

IV. EXPERIMENTAL RESULTS

Fig. 1 shows a typical curve of electrical resistance versus time for a sample austenitized for one hour at 1150°C and reacted at -115°C . The incubation period for this sample was 6.0 minutes as shown in the figure. All specimens which were reacted isothermally in the range of -115° to 140°C showed incubation periods from 0.20 to 32 minutes.

The incubation period of the samples isothermally transformed and the time of continuation of isothermal runs are listed in Table IV in the appendix. This also shows the fraction of isothermal martensite formed within that time of transformation, measured by two different methods, namely resistivity and point counting.

Fig. 2 summarizes the incubation periods as a function of austenitizing temperature for samples reacted at -140° , -125° and -115°C . Samples reacted at all of these reaction temperatures showed similar behavior. In all cases, the incubation period was a minimum at an intermediate austenitizing temperature and increased rapidly with increasing or decreasing austenitizing temperature. The minimum incubation period occurred in the austenitizing temperature range of 900° to 950°C . For all austenitizing conditions, the incubation period was shorter at -125°C than that at -140°C or -115°C .

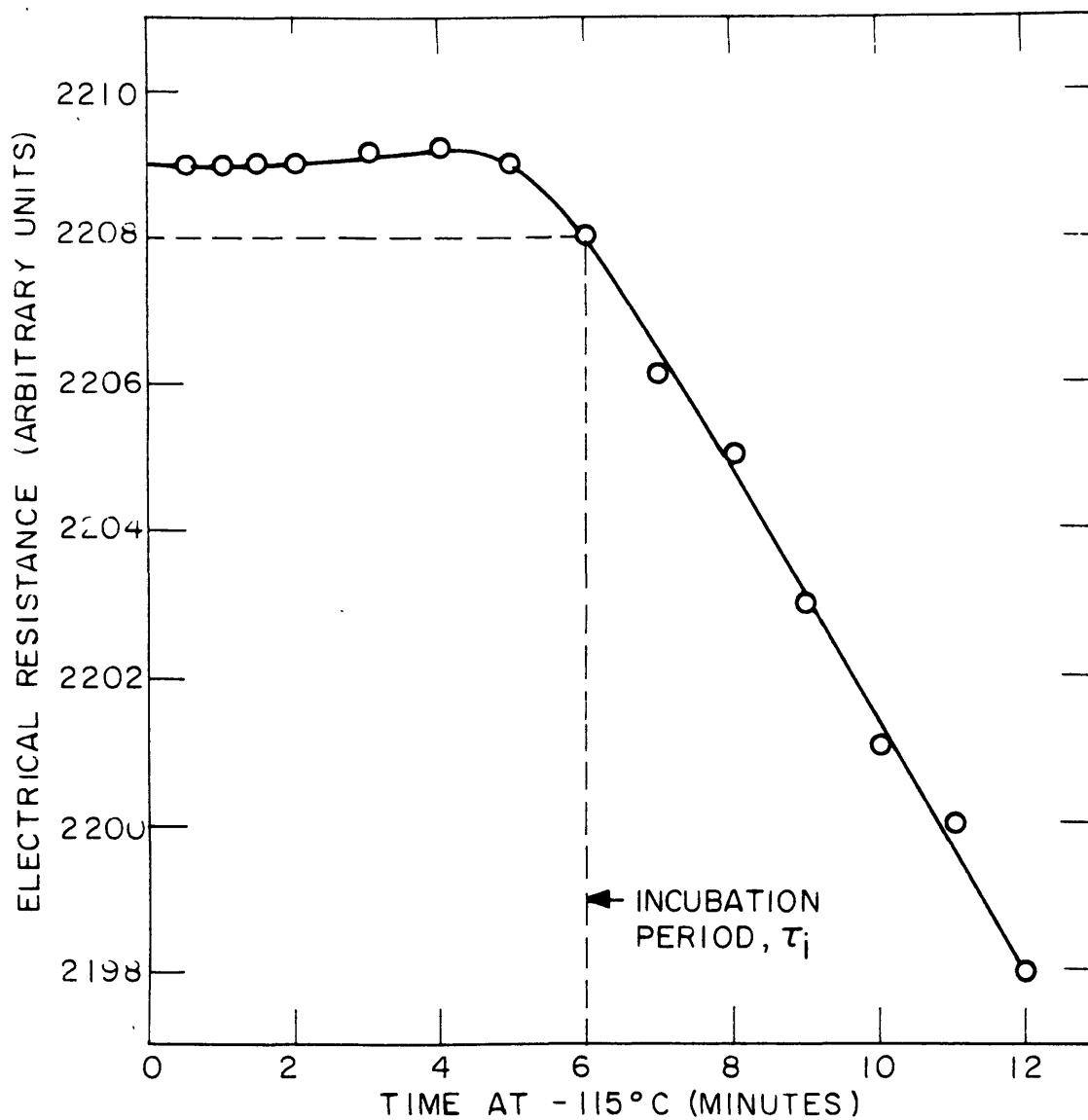


FIGURE 1 ELECTRICAL RESISTANCE VERSUS TIME FOR Fe-Ni-Mn ALLOY AUSTENITIZED AT 1150°C (ONE HOUR) AND REACTED AT -115°C

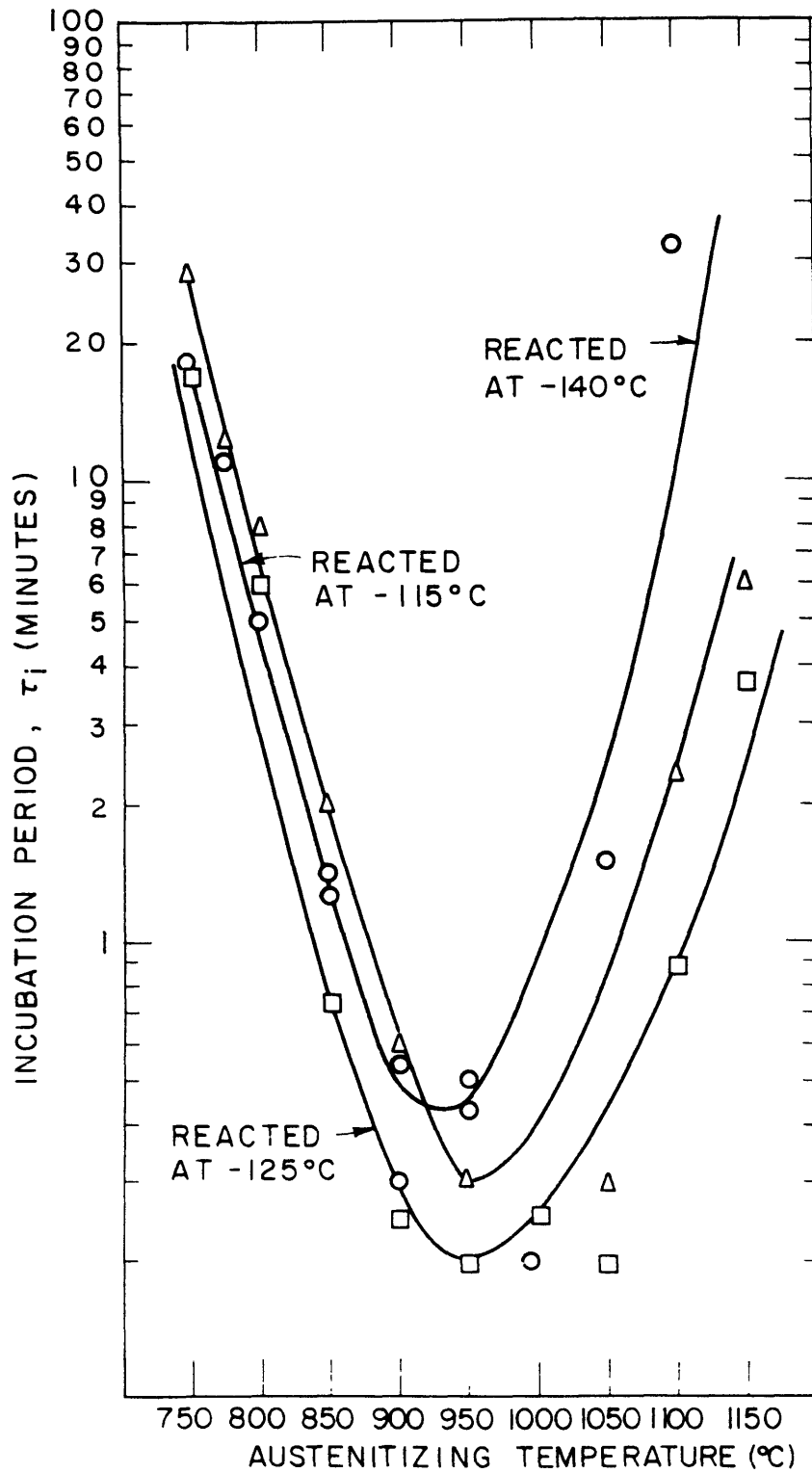


FIGURE 2 INCUBATION PERIOD AS A FUNCTION OF AUSTENITIZING TEMPERATURE, REACTED AT INDICATED TEMPERATURES

Fig. 3 shows the initial nucleation rate as a function of austenitizing temperature for samples reacted at -140°C . The initial nucleation rate exhibited similar behavior whether the calculations were made by method A or method B. The rate increased with austenitizing temperature until 900°C after which it decreased rapidly. The rate of nucleation was found to be maximum by both the methods of calculations at an austenitizing temperature of 900°C . Nucleation rates calculated by method B were higher than by method A up to an austenitizing temperature of about 850°C , beyond which the converse was true.

Fig. 4 is a plot of the initial nucleation rate as a function of austenitizing temperature for samples reacted at -125°C . The behavior was similar to that found for -140°C , with the maximum nucleation rate occurring in the austenitizing temperature range of $850^{\circ} - 900^{\circ}\text{C}$. In general, the initial nucleation rate at -125°C was faster than that at -140°C .

Fig. 5 shows the initial nucleation rate in heavily transformed regions as a function of austenitizing temperature for samples reacted at -140° and -125°C . The nucleation rate in these regions behaves like the average nucleation rate going through a maximum for 900°C austenitizing treatment, but is approximately 15 to 100 times faster than the average rate.

Observation of the microstructure of transformed samples indicated that isothermal martensite formed nonuniformly across the

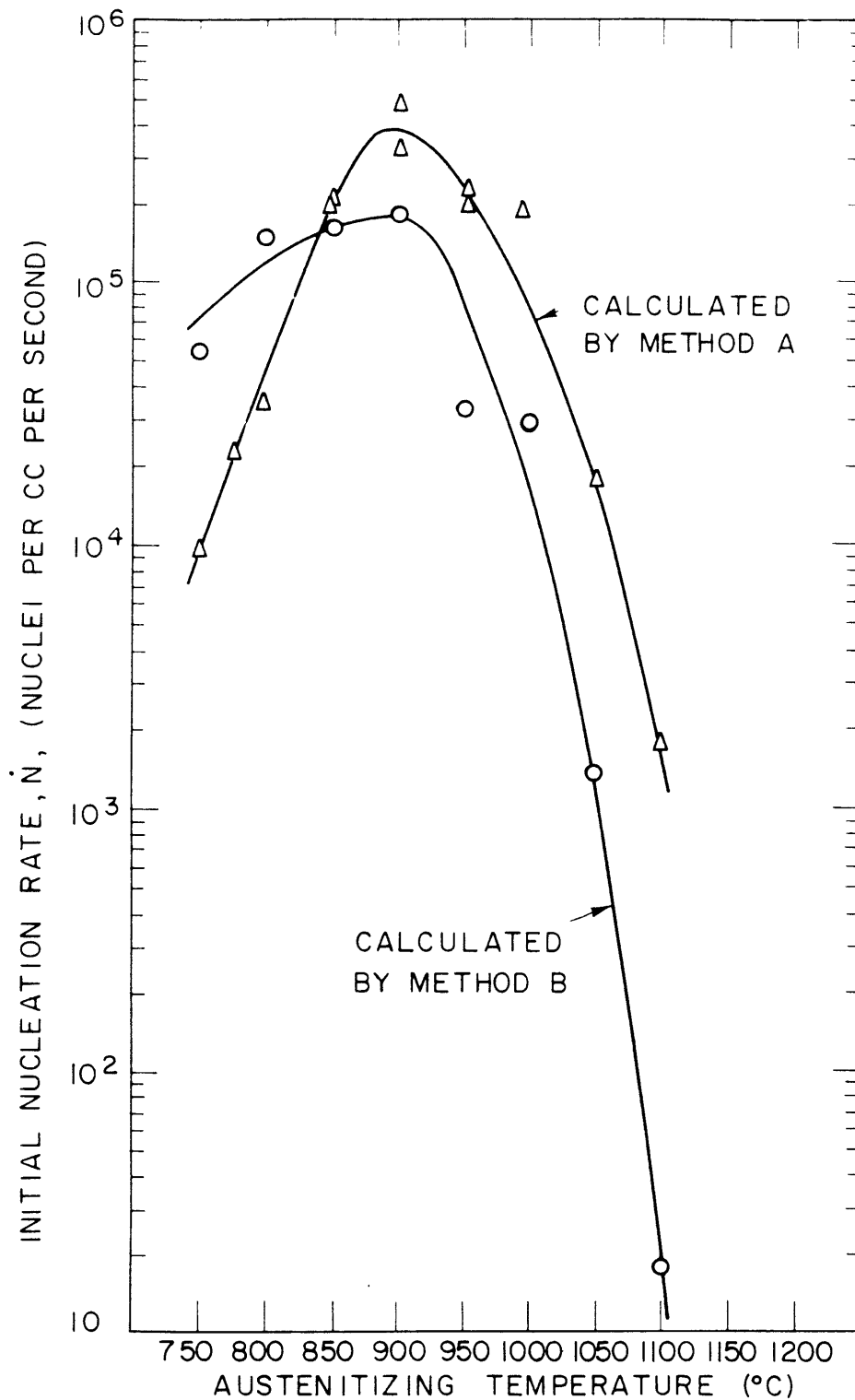


FIGURE 3 INITIAL NUCLEATION RATE AT -140°C , AS A FUNCTION OF AUSTENITIZING TEMPERATURE

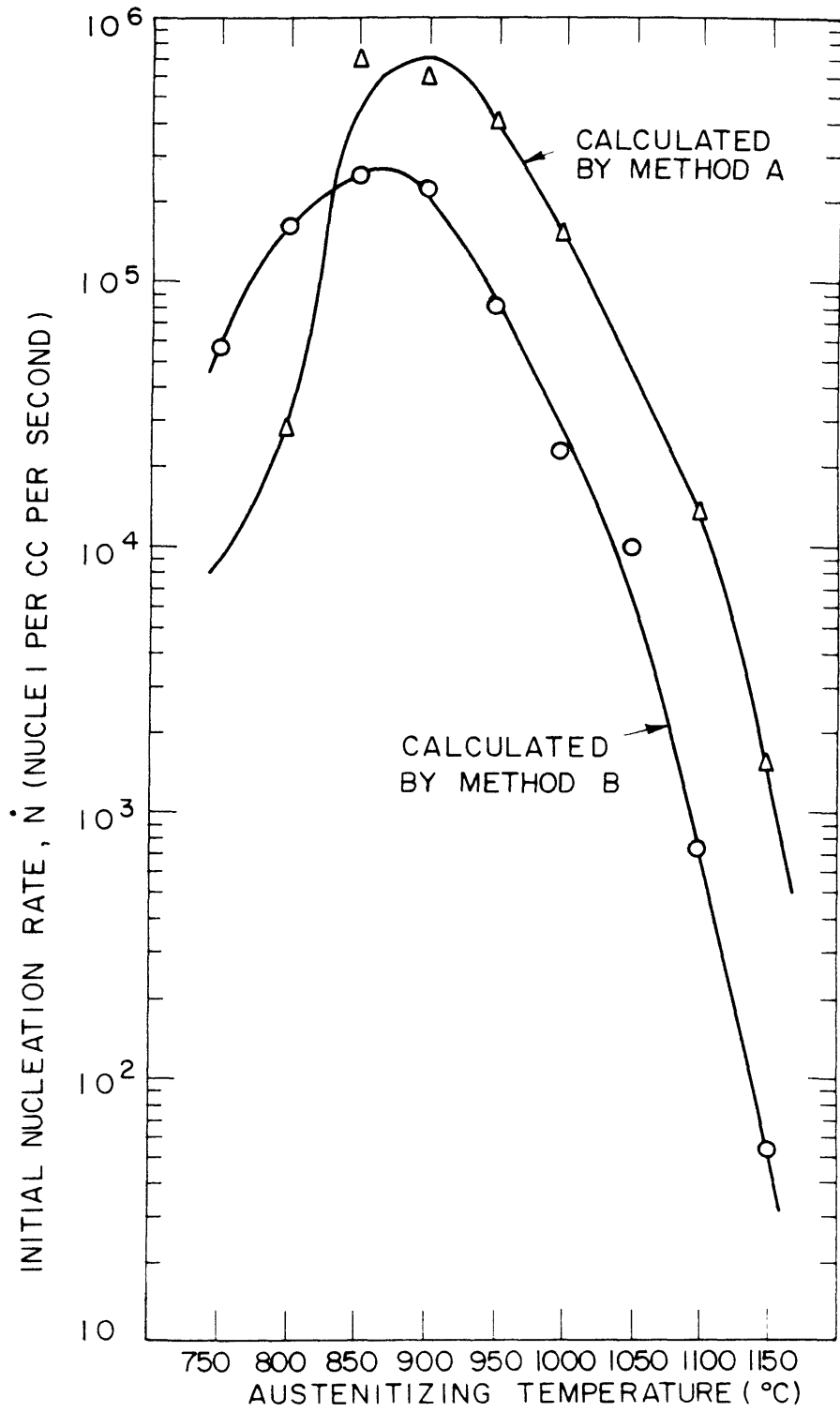


FIGURE 4 INITIAL NUCLEATION RATE AT -125°C , AS A FUNCTION OF AUSTENITIZING TEMPERATURE

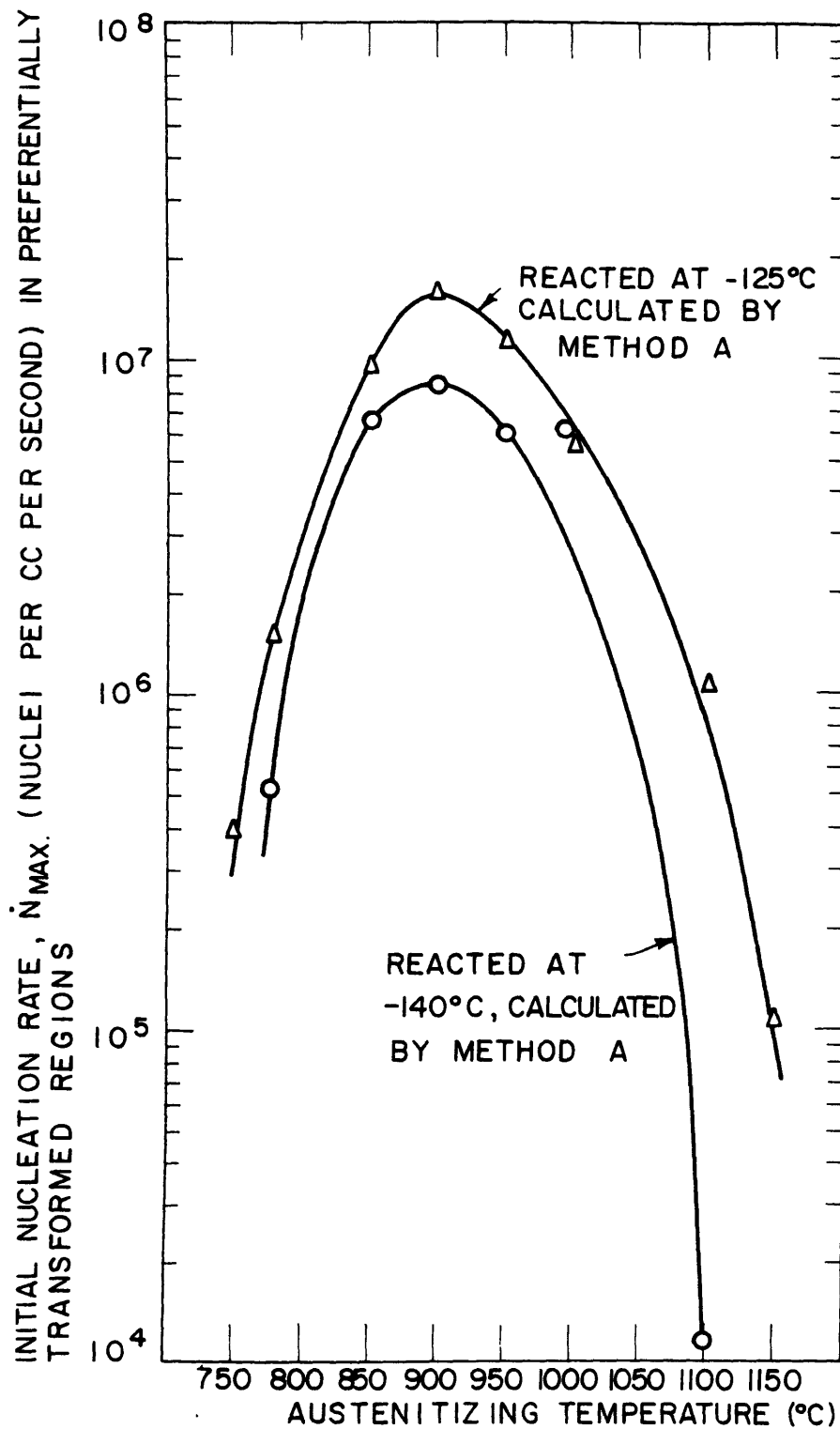


FIGURE 5 INITIAL NUCLEATION RATE IN PREFERENTIALLY TRANSFORMED REGIONS AT INDICATED TEMPERATURES, AS A FUNCTION OF AUSTENITIZING TEMPERATURE

section of the specimens. Usually, the martensite formed initially down the center of the sample, in the region of residual tensile stresses due to cooling. This was in accordance with the observation of Shih et al.⁽⁴⁾ who demonstrated that the tensile stresses set up in the central region of the specimen during cooling tended to promote the martensite formation there.

In addition to the nonuniformity in the formation of martensite across the section, transformation was nonuniform even along the length of the sample. Doubts naturally arose concerning the homogeneity of composition. However, results obtained to date from electron microanalyzer have not revealed any inhomogeneity of manganese along any direction of the specimen.

V. DISCUSSION OF RESULTS

The U-shaped curve of the incubation period as a function of the austenitizing temperature is similar in form to findings of Morrow⁽⁶⁾ for a transformation temperature of -140°C . This U-shaped behavior can be interpreted with the help of equation (9). Rearranging its terms, we have

$$\tau_i = \frac{0.002}{\dot{N} V} \quad (12)$$

τ_i is thus inversely proportional to the initial nucleation rate and to the volume of each initial martensitic plate. Fig. 6 shows the volume of an initial martensitic plate, calculated from equation (11), as a function of the austenitizing temperature. The volume increases by about four orders of magnitude during the austenitizing temperature range of 750° to 1150°C . On the other hand, the nucleation rate increases slowly with increasing austenitizing temperature up to 900°C , after which it decreases rapidly by four orders of magnitude. Thus, up to an austenitizing temperature between 900° and 950°C , the product $\dot{N} V$ increases, causing the decrease in incubation period. Above this temperature, though the volume of each initial martensitic plate still increases, the nucleation rate decreases much more rapidly causing the product $\dot{N} V$ to decrease which raises the incubation period. Thus, this U-shaped curve of the incubation period versus austenitizing temperature is due to a compromise between the grain size and the

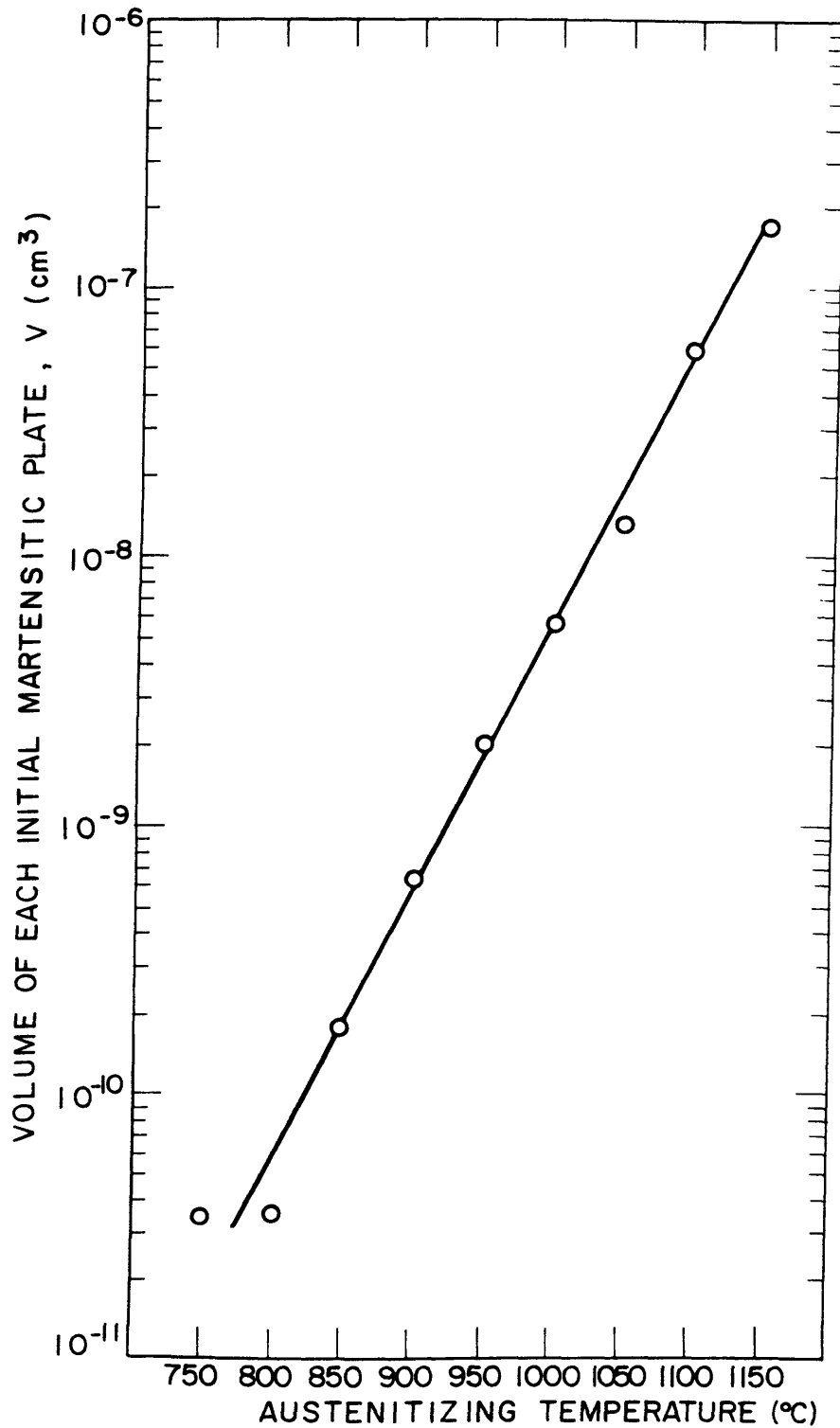


FIGURE 6 VOLUME OF AN INITIAL MARTENSITIC PLATE AS A FUNCTION OF AUSTENITIZING TEMPERATURE

nucleation rate. The grain-size effect is apparently dominant at low austenitizing temperatures while the nucleation-rate effect is the dominant factor at high austenitizing temperatures.

Fig. 2 shows that the incubation period at -125°C is shorter than that at -140° or -115°C . Morrow⁽¹¹⁾ found that -125°C corresponded to the nose of the isothermal transformation-temperature-time curves for this alloy. Therefore, it is expected that the incubation period will be a minimum and the reaction rate a maximum at -125°C . Fig. 5 exhibits clearly that the nucleation rate in the preferentially transformed regions is higher at -125°C than that at -140°C for all austenitizing temperatures. Figures 3 and 4 show generally the similar trends for the average nucleation rate. The nucleation rate at -125°C , calculated by method B, is higher than that at -140°C for the whole austenitizing temperature range, but for the austenitizing temperatures of 750°C and 800°C , the nucleation rate calculated by method A shows the opposite effect, the difference, of course, being small. This discrepancy might arise from the fact that the samples reacted at -140°C , which were used for the nucleation rate measurements, had a larger fraction of martensite formed in them than the samples reacted at -125°C . Method A of the nucleation-rate calculation is sensitive to the fraction of martensite formed, and this can explain the apparent discrepancy. However, it is to be noted that the sensitivity of method A to the fraction transformed is much less than the change in nucleation rate with austenitizing temperature. Thus, this sensitivity

cannot affect the general trend of nucleation rate with austenitizing temperature, though there were small differences in the amount of the martensitic transformation in samples austenitized at different temperatures.

The initial nucleation rate at -125°C , calculated by method B, agrees closely with the value of Shih et al.⁽⁴⁾ for their reaction temperature at -140°C and for similar austenitizing conditions. -140°C corresponds to the nose of the isothermal transformation-temperature-time curve for their alloy and hence it is reasonable to compare their data of -140° with the data of -125°C in the present investigation. Their observed grain size of ASTM numbers 1 to 2 corresponds to an austenitizing treatment at 1100°C in the present investigation. The nucleation rate obtained here is only two times higher than their reported value. However, these values are smaller by a factor of about 10^3 than the Cech and Hollomon⁽³⁾ rates employed in Fisher's⁽⁹⁾ calculation. This can be explained by the fact that in their samples, up to 3 per cent athermal martensite formed on cooling and thus was present at the beginning of the isothermal transformation. Shih et al. have shown conclusively that the reaction rate at the beginning of the strictly isothermal reaction is relatively low, but the rate is a maximum at the beginning in the presence of 1 to 2 per cent prior martensite. Consequently, it is evident that nucleation rates obtained by Fisher's calculations, which predict a maximum initial nucleation rate and which are fitted to Cech and Hollomon data, are not representative of the true initial isothermal nucleation rate.

Nucleation rates calculated by method B are found to be higher than those by method A for low austenitizing temperatures, while the reverse is the case at high austenitizing temperatures. This might result from the assumption employed in calculation of the volume of the initial martensitic plates used in method B. Fig. 6 shows that the calculated volume of an initial martensitic plate is very small at low austenitizing temperatures and very large at high austenitizing temperatures. This volume effect tends to increase the calculated nucleation rate according to method B at low austenitizing temperatures and to decrease it at high temperatures. The volume factor affects the calculations more at high temperatures where the nucleation rates calculated by the two methods differ by two orders of magnitude. Optical microscopic examination has revealed the presence of smaller plates than those limited by grain or twin boundaries in samples austenitized at high temperatures. This is an added factor causing larger discrepancies at high austenitizing temperatures.

Preferentially, transformed regions in the samples represent areas where martensite can form more rapidly than in other regions. It is expected that the initial nucleation rate of the isothermal martensitic transformation in these regions should be higher than the average nucleation rate. This is found to be true for the reaction temperatures, -140° and -125°C for which calculations have been made. The nucleation rates in these preferentially transformed regions are 15 to 100 times larger than the average nucleation rates.

To explain the observed variation of initial nucleation rate with the austenitizing temperature, we refer to the relation proposed by Shih et al. ⁽⁴⁾, according to which the initial nucleation rate is related to the activation energy as follows:

$$\dot{N} = n_i \gamma \exp (-\Delta F_a/RT) \quad (13)$$

where n_i is the number of most-potent embryos per cubic centimeter, γ * is the lattice vibration frequency, ΔF_a is the activation free energy for nucleation, R is the gas constant, and T is the reaction temperature in °K.

For a constant reaction temperature, the factors which can possibly change with the austenitizing treatment of the samples are the number of most-potent embryos and the activation energy for nucleation. Most of the investigators are of opinion that there are some preferred sites for the nucleation of martensite. Kurdjumov and Maksimova ⁽²⁾ have pointed out that martensite nuclei do not originate at random in the matrix, rather they are formed in certain special regions. Shih et al. ⁽⁴⁾ have assumed that there is one most-potent embryo per grain of austenite. On this assumption, they have derived reasonable values for the energies of activation.

If the same assumption is made in the present work as of Shih et al., then the number of most-potent embryos is expected to decrease with increasing austenitizing temperature because the number of austenite grains per unit volume of the alloy decreases. Therefore, the only way to account for any increase in nucleation rate with increasing

* is taken as 10^{13} sec^{-1} .

austenitizing temperature must be on the basis that the activation energy of nucleation decreases with increasing austenitizing temperature. However, the decrease of the nucleation rate at high austenitizing temperatures can be accounted for either by a decrease in number of embryos per unit volume, or an increase in the activation energy for nucleation.

The values of ΔF_a calculated from equation (13) are listed in Tables II and III, for the reaction temperatures of -140° and -125°C respectively. ΔF_a has been calculated from the initial nucleation rates derived by both the methods. The nucleation rates and the numbers of most-potent embryos are also listed in the Tables for various austenitizing temperatures. The derived activation energy values agree closely with those of Shih et al. The temperature dependence of ΔF_a is also closely similar to that found for iron-nickel alloys by Machlin and Cohen⁽⁷⁾.

It is evident from the data listed in Tables II and III that ΔF_a first decreases with increasing austenitizing temperature and then tends to remain essentially constant. This agrees with the analysis presented before. At high austenitizing temperatures (beyond 1000° to 1100°C), the ΔF_a values seem to increase with increasing austenitizing temperature. ΔF_a has been calculated from the nucleation rates obtained by methods A and B. ΔF_a from method B starts to increase at a lower austenitizing temperature than does ΔF_a from method A.

This occurs because of the martensitic-plate volume effect, as discussed before, which tends to lower the nucleation rate (obtained

TABLE II

INITIAL NUCLEATION RATES AND ACTIVATION ENERGIES FOR ISOTHERMAL MARTENSITE FORMATION AT -140°C , FOR VARIOUS AUSTENITIZING TEMPERATURES.

Austenitizing Temperature $^{\circ}\text{C}$	n_i , number of Embryos per cm^3	FOR \dot{N} , CALCULATED BY METHOD A		FOR \dot{N} , CALCULATED BY METHOD B			
		\dot{N} , nuclei per cm^3 per second	F_a/RT	ΔF_a , cal per mole	\dot{N} , nuclei per cm^3 per second	$\Delta F_a/RT$	ΔF_a , cal per mole
750	8.38×10^8	9.58×10^3	41.32	10,940	5.5×10^4	39.57	10,470
800	4.27×10^8	3.53×10^4	39.32	10,410	1.5×10^5	37.88	10,030
850	1.27×10^8	2.09×10^5	36.34	9,620	1.6×10^5	36.62	9,690
900	2.77×10^7	4.90×10^5	33.97	8,990	1.80×10^5	34.98	9,250
950	6.67×10^6	1.95×10^5	33.47	8,860	3.27×10^4	35.27	9,330
1000	1.98×10^6				2.96×10^4	34.15	9,040
1050	3.69×10^5	1.80×10^4	32.96	8,720	1.34×10^3	35.45	9,410
1100	5.85×10^4	1.73×10^3	33.47	8,860	1.79×10^1	38.03	10,090

TABLE III

INITIAL NUCLEATION RATES AND ACTIVATION ENERGIES FOR ISOTHERMAL MARTENSITE
FORMATION AT -125°C , FOR VARIOUS AUSTENITIZING TEMPERATURES.

Austenitizing Temperature $^{\circ}\text{C}$	n_1 , number of Embryos per cm^3	FOR \dot{N} , CALCULATED BY METHOD A		FOR \dot{N} , CALCULATED BY METHOD B	
		\dot{N} , nuclei per cm^3 per second	ΔF_a cal per mole	\dot{N} , nuclei per cm^3 per second	ΔF_a , cal per mole
750	8.38×10^8	8.67×10^3	41.42	5.65×10^4	39.55
800	4.27×10^8	2.77×10^4	39.57	1.59×10^5	37.84
850	1.27×10^8	6.97×10^5	35.14	2.49×10^5	36.18
900	2.77×10^7	6.01×10^5	33.76	2.15×10^5	34.80
950	6.67×10^6	3.93×10^5	32.75	8.17×10^4	34.34
1000	1.98×10^6	1.56×10^5	32.48	2.37×10^4	34.37
1050	3.69×10^5			1.00×10^4	33.55
1100	5.85×10^4	1.37×10^4	31.39	6.38×10^2	34.45
1150	1.36×10^4	1.54×10^3	32.13	5.36×10^1	35.47

by method B) at high austenitizing temperatures. Since it is realized that the assumed model for calculating the volume of an initially formed martensitic plate may not be realistic, especially at high austenitizing temperatures; therefore, from now on, the discussion on the number of embryos and the activation energy for nucleation will be restricted to the values obtained from the nucleation rates calculated by method A.

Even the values of ΔF_a from method A tend to increase slightly above an austenitizing temperature of about 1050° to 1100°C . This, of course, is based on the assumption that one most-potent embryo per grain of austenite is still present. On the other hand, if at such high austenitizing temperatures, embryos begin to anneal out at a still faster rate and their number becomes smaller than the number of grains of austenite per unit volume, then the decrease in n_i itself might explain the decrease in nucleation rate. In that case, ΔF_a could remain constant at the lower level. The number of embryos which could account for the observed nucleation rate at -140°C after the 1100°C austenitizing treatment was calculated on the assumption that ΔF_a was constant at the value corresponding to the 1050°C austenitizing treatment (as listed in Table II). The resulting number of embryos was found to be 3.53×10^4 per cm^3 , which is smaller by a factor of about 2 than the value listed in Table II for the austenitizing temperature of 1100°C .

A similar calculation was made for the austenitizing and reaction temperatures of 1150° and -125°C respectively. The calculated

value of n_i in this case also was found to be smaller by a factor of about 2 than the n_i value listed in Table III for the above austenitizing and reaction temperatures.

It is understandable that the number of embryos should decrease as the austenitizing temperature increases and the rate of annealing out of the embryos might well be higher with increasing austenitizing temperatures. On the other hand, no phenomenon is known which could explain an increase in activation energy for nucleation at the higher austenitizing temperatures. Thus, the above analysis suggests that, of the two possibilities for explaining the decrease of nucleation rate at the highest austenitizing temperatures, a faster rate of annealing out of embryos seems to be more reasonable.

Until now, it has been assumed that even in low austenitizing temperature range there is one most-potent embryo per grain of austenite. This assumption thus accepts a slow rate of annealing out of embryos even at low austenitizing temperatures (750° to 900°C). On the other hand, it might be argued that the number of embryos would remain essentially constant at low austenitizing temperatures up to 850° or 900°C , and starts to decrease only at still higher temperatures. Calculations were made to check the validity of this assumption for both reaction temperatures. In both cases similar results were obtained, but for simplicity only the results for the reaction temperature of -140°C will be described.

The activation energy for nucleation was calculated as a function of austenitizing temperature upto 900°C taking the number of

embryos to remain constant at 8.34×10^8 per cm^3 , corresponding to the austenitizing temperature of 750°C (i.e., one most-potent embryo per grain of austenite). It was further assumed that the activation energy for nucleation would progressively go down with increasing austenitizing temperature beyond 900°C ; in other words, ΔF_a was plotted as a function of austenitizing temperature, up to 900°C , and the curve was extrapolated to 1100°C . The number of embryos which would have to be present after each austenitizing treatment above 900°C (to account for the observed nucleation rates) was then calculated by using equation (13); and by taking the extrapolated values of ΔF_a from the plot as discussed above. The logarithm of the number of embryos, so calculated, was then plotted against the reciprocal of austenitizing temperature. From such a plot an unusually high activation energy of 128 Kcals was obtained for the annealing out of embryos. On the other hand, a more reasonable activation energy of 77 Kcals was obtained for the annealing out of embryos when the number of embryos, listed in Table II (n_i = number of grains of austenite per cm^3), was used in this type of plot. Hence, from the above analysis, it is evident that the assumption of one most-potent embryo per grain of austenite is a reasonable one.

On the basis of these considerations, it may be concluded that the initial nucleation rate increases with austenitizing temperature up to 850° or 900°C because of a progressive decrease in the activation energy for nucleation over this range of austenitizing temperature. At higher austenitizing temperatures, even though the activation

energy for nucleation still decreases (tending to level off only at still higher temperatures), the embryos begin to anneal out at sufficiently faster and faster rate, thus decreasing the nucleation rate.

It is to be noted that recrystallization of the swaged structure occurs even at the lowest austenitizing temperature. Thus, the embryos which have been mentioned throughout are not restricted to cold-worked structures. The relaxation or annealing out of embryos also refers to changes taking place in the austenite after recrystallization has taken place. Previous work⁽⁶⁾ in a similar alloy has shown that the number of most-potent embryos do not change reversibly with austenitizing temperature.

The activation energy for nucleation can decrease with the initial increase in austenitizing temperature if the embryos rearrange themselves into more favorable configurations. As the austenitizing temperature increases, relaxation processes set in, the mobility of defects inherited from the prior swaging process after recrystallization increases, and so more favorable configurations for the most-potent embryos might be created. Manganese is known to reduce the stacking fault energy of iron-nickel alloy, thus promoting the formation of stacking faults during cold working. Therefore, one type of most-potent embryo that can be expected is stacking faults in the austenite, which are left after recrystallization.

The stacking fault is a type of defect which can be expected to anneal out at still higher austenitizing temperatures, in agreement

with the characteristics of the most potent embryos analyzed in this investigation. However, an electron microscopic investigation would be necessary to establish this concept.

V. CONCLUSIONS

1. The incubation period for the isothermal martensitic transformation in iron-nickel-manganese alloy shows a U-shaped behavior as a function of austenitizing temperature. The minimum incubation period occurs in the austenitizing temperature range of 900° to 950°C .
2. The U-shaped behavior of the incubation period versus the austenitizing temperature results from an interplay between a grain size effect, dominant at low austenitizing temperatures, and the annealing out of embryos, dominant at high austenitizing temperatures.
3. For all austenitizing conditions, the incubation period is shorter at -125°C than at -140°C or -115°C . This trend indicates a C-curve behavior for the isothermal nucleation kinetics, as has been reported previously.
4. The initial nucleation rate for the isothermal martensitic transformation increases with increasing austenitizing temperature up to about 850° or 900°C beyond which it decreases rapidly. This trend appears to result from an interplay between relaxation effects (dominant at low austenitizing temperatures) and the annealing out of embryos (dominant at high austenitizing temperatures).

5. The initial nucleation rate in preferentially transformed regions of the specimen increases with increasing austenitizing temperature up to 900°C, beyond which it decreases rapidly. The nucleation rate in these regions is approximately 15 to 100 times faster than the average rate, depending on the concentration of martensitic plates in these regions.
6. Reasonable values for the activation energies of nucleation are obtained on the basis of preferred nucleation sites (one most-potent embryo per grain of austenite). The activation energy so derived, decreases with increasing austenitizing temperature due to relaxation effects, and tends to level off at high austenitizing temperatures due to the annealing out of embryos.

VII. SUGGESTIONS FOR FUTURE WORK

1. Electron microscopic investigation on the untransformed austenite and on partially transformed specimens is necessary to verify the presence of stacking faults or other types of embryos.
2. Nucleation-rate measurements should be made in specimens after double austenitizing treatments (austenitized first at a high and subsequently at low temperatures) to verify the irreversible nature of embryos.
3. Kinetics of isothermal martensitic transformation should be investigated in specimens austenitized at a series of temperatures, below and above the recrystallization temperature of the swaged structure. This will help to illustrate the effect of changes in the configuration of embryos, which control the nucleation kinetics at the low austenitizing temperature range of the present investigation.
4. Nucleation-rate measurements should be made in a series of alloys with increasing manganese content and essentially constant nickel content. This will show the effect of stacking fault density on the nucleation rate of isothermal martensitic transformation in iron-nickel-manganese alloys.

5. Surface-relief effects due to transformation should be investigated on specimens austenitized at low and high temperatures to reveal the difference, if any, in the nature of transformation product. Electron microscopy is also necessary together with the surface-relief experiments for the above purposes.
6. A series of experiments should be undertaken to determine the effects of holding a specimen at room temperature, following austenitizing treatment and prior to subzero transformation. Partial stabilization and thus longer incubation periods may occur if the hold at room temperature is long enough.
7. Length-to-thickness ratios of the initially formed martensitic plates should be measured at a series of austenitizing temperatures to check its assumed linear variation with austenitizing temperature.

BIBLIOGRAPHY

1. G. V. Kurdjumov and O. P. Maksimova, "Kinetics of Austenite to Martensite Transformation at Low Temperatures," Doklady Akademii Nauk SSSR, 61, No. I, 83 (1948). H. Brucher Translation No. 2187.
2. G. V. Kurdjumov and O. P. Maksimova, "On the Energy of Formation of Martensite Nuclei," Doklady Akademii Nauk SSSR, 73, No. I, 95 (1950). H. Brucher Translation No. 2565.
3. R. E. Cech and J. H. Hollomon, "Rate of Formation of Isothermal Martensite in Fe-Ni-Mn Alloys," Trans. AIME, 197, 685 (1953), Journal of Metals (May 1953).
4. C. H. Shih, B. L. Averbach, and Morris Cohen, "Some Characteristics of the Isothermal Martensitic Transformation," Trans. AIME, 203, 183 (1955), Journal of Metals (Jan. 1955).
5. A. R. Entwisle, "Isothermal Martensite in Iron-Nickel-Manganese Alloys," Unpublished Report of work carried out in the Department of Metallurgy, M.I.T. (1960-61).
6. H. Morrow, "Effect of Austenitizing Treatment on the Isothermal Martensitic Transformation in Iron-Nickel-Manganese Alloys," S. M. Thesis, M.I.T. (1963).
7. E. S. Machlin and Morris Cohen, "Isothermal Mode of Martensitic Transformation," Trans. AIME, 194, 489 (1952), Journal of Metals, (May, 1952).
8. R. B. G. Yeo, "Isothermal Martensite Transformation in Iron-Base Alloys of Low Carbon Content," Trans. AIME, 224, 1222 (1962).
9. J. C. Fisher, "Application of Nucleation Theory to Isothermal Martensite," Acta Metallurgica, I, No. 1, 32 (1953).
10. R. L. Fullman, "Measurement of Particle Sizes in Opaque Bodies," Trans. AIME, 197, 447, (1953).
11. H. Morrow, "Effect of Austenitizing Treatment on the Isothermal Martensitic Transformation in Iron-Nickel-Manganese Alloys," Unpublished work, carried out in the Department of Metallurgy, M.I.T. (1962-63).

APPENDIX

TABLE IV

Incubation periods, time of transformation and the fraction of isothermal martensite formed at different transformation temperatures for various austenitizing treatments.

Sample No.	Austenitizing * Temperature °C	Transformation Temperature °C	Time of Transformation (minutes)	Incubation Period τ_i (minutes)	Per Cent Martensite	
					By Resistivity	By Point Counting
1.	750	-140	29.40	18.00	2.17	1.37
2.	775	-140	13.21	12.00	0.58	0.81
3.	800	-140	7.04	5.00	1.56	1.13
4.	850	-140	1.90	1.25	0.85	1.04
5.	850	-140	2.50	1.35	1.12	1.67
6.	900	-140	0.55	0.30	2.25	1.36
7.	900	-140	0.65	0.55	2.15	1.76
8.	950	-140	1.56	0.44	2.96	2.42
9.	950	-140	0.64	0.50	1.98	1.91
10.	995	-140	0.31	0.20	1.28	0.95
11.	1050	-140	2.35	1.50	3.38	2.95
12.	1100	-140	35.30	32.00	1.25	1.96

* Time of Austenitizing is 1 hour, kept constant throughout.

TABLE IV (CONT.)

Sample No.	Austenitizing * Temperature °C	Transformation Temperature °C	Time of Transformation (minutes)	Incubation Period, τ_i (minutes)	Per cent Martensite	
					By Resistivity	By Point ** Counting
13.	750	-125	17.02	17.00	0.29	0.31
14.	800	-125	6.77	6.25	0.58	0.23
15.	850	-125	1.15	0.75	0.86	1.20
16.	900	-125	0.40	0.25	1.15	1.54
17.	950	-125	0.35	0.20	1.66	1.11
18.	1000	-125	0.48	0.25	1.78	1.23
19.	1050	-125	0.28	0.20	3.01	N.D.
20.	1100	-125	1.02	0.90	1.09	0.70
21.	1150	-125	7.88	3.70	0.79	0.67
22.	750	-115	35.35	28.00	0.84	N.D.
23.	775	-115	27.29	12.00	0.41	N.D.
24.	800	-115	10.00	8.00	0.56	N.D.
25.	850	-115	2.50	2.00	1.38	N.D.
26.	900	-115	0.80	0.60	1.39	N.D.
27.	950	-115	0.82	0.30	2.08	N.D.
28.	1050	-115	0.40	0.30	1.59	N.D.
29.	1100	-115	2.65	2.30	0.66	N.D.
30.	1150	-115	7.93	6.00	0.64	N.D.

* Time of Austenitizing is 1 hour, kept constant throughout.

** N.D. = Not yet determined.