RECRYSTALLIZATION OF ARMCO IRON AND OBSERVATIONS ON THE WELDABILITY OF STEELS

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RECRYSTALLIZATION OF ARMCO IRON

HISTORY

In the last thirty years there has been considerable interest shown in recrystallization of metals as a result of deformation. This phenomenon may be briefly defined as the tendency of crystals or crystalline aggregates to readjust themselves upon annealing at temperatures below the A_3 range following a deformation of critical amounts.

The study of the various factors which determine the grain size and structure of metals cold-worked and subsequently annealed had its inauguration at least eighty years ago. The attention shown in the last few years has probably come as a direct result of the growing interest in metal single crystals, of the commercial expedience of avoiding and controlling the growth of large crystals with their corresponding effect on mechanical properties in the working and fabrication of metal parts, and of sundry and scientific investigations.

The widespread interest in metal single crystals is readily justified since their characteristics are possibly the fundamental bases for the properties and reactions of polycrystalline aggregates. This is, of course, a highly debatable point since there exists in

the latter structure certain phases and conditions not present in monocrystalline units, such as grain boundary material of either an amorphous or crystalline nature* and analytical impurities such as occluded gases, metalloids, and small percentages of spurious elements.

Of obvious importance to fabrication companies, rolling mills, etc., is the avoidance of large grain structures in the cold-working and fabrication of metals since this property governs the value of their finished product to industry in general.

A brief historical review of past contributions to the field of recrystallization of iron and steel might be in order and is presented below**.

As early as 1858 Nogues(1) noticed the coarse crystalline structure that appeared in platinum wire netting heated for days in a reducing gas flame, and showed that this existed uniformly throughout the cross-section of the material. His explanation was that the high temperature exerted a readjusting influence on the molecular structure of the platinum.

In the next twenty-three years no important contributions were made in this direction until the observations of Kalischer(3) were published. About this time was inaugurated the metallographic examination

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* It is certainly not the intention of this paper to enter upon a discussion, pro or con, of so highly a moot point as whether or not grain boundary material is of an amorphous or crystalline nature. The amorphous cement theory of Rosenhain and Ewen, as so ably presented by Dr. Sauveur in his "Metallography and Heat Treatment of Iron and Steel", has justification in many respects and yet falls very short of presenting a sensible explanation of certain metallurgical phenomena. It does, however, present about the most complete picture of grain boundary behavior as is available at present.

** A chronological bibliography has been compiled and is included in the appendix.

of metal structures by Sorby[2] but not until later[5] did he publish any recrystallization work. Kalischer noted that deformation, as well as temperature of anneal, was an influential factor and made experiments on a wide range of technical metals including iron. In 1883 Ledebur[4] and later others working with iron found that the time of anneal exerted an even greater influence than the temperature. In wrought iron Ledebur noted the production of very coarse crystals in a previously fibered rolled structure, this fact being verified by Sauveur[6] in 1893, Stead[7] in 1898, and much later by Moellendorf and Czochralski[21] in 1913. Stead[7] called attention to a brittleness sometimes referred to as "Stead's Brittleness" in rolled and annealed sheet iron caused by the formation of coarse grains*. In 1915 Chappell[25] published a classic paper on recrystallization taking into account a number of factors such as degree of deformation, temperature and time of anneal, and carbon content, carefully noting the course of recrystallization as a function of increasing temperature and marking the initial appearance of recrystallization. In 1916 a very handy tool for the presentation of recrystallization data was introduced by Czochralski[82] and took the form of a space diagram -- that is, a rectangular coordinate system utilizing grain size, degree of deformation, and annealing temperature**. In 1918 Oberhoffer and Oertel[12] developed a recrystallization diagram for electrolytic iron after the manner of Czochralski and in 1920 Oberhoffer

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* An historical summary of this early work was prepared by Czochralski[82] and may be consulted for further details.

** Such diagrams will be utilized later in this report.

and Jungbluth[45] followed with a similar one for commercial iron*. In this case they found, as did Pomp[33], that the grain size appeared to be a maximum for cold work deformation of the order of 10% reduction in height by rolling, this not being in agreement with the findings for electrolytic iron. It also was found that grain size was dependent on the time of annealing. To them the above appeared as a peculiarity but it is now known that for all metals there is a degree of plastic deformation known as the critical strain, below which no marked grain growth will be manifested at a given temperature and time of anneal. This critical strain and thermal treatment is much lower in electrolytic iron[85] than will be shown later to be the case for Armco iron**.

As a departure from the usual mode of investigation, Hanemann and Lucke[46] followed a new course of research by studying the grain size resulting from annealing after deformation at elevated temperatures. Heretofore all work had been impressed with the metal at room temperature and this new trend gave some very interesting results, being expressed with recrystallization diagrams.

Later work in recrystallization has been carried out in various directions with much attention being given to hot rolling by Hanemann and his co-workers[12]. Single crystals of iron have become scientifically more and more important from a standpoint of magnetic considerations and

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* At about this time Jeffries[84] advanced his theory accounting for grain growth on the basis of a so-called "germinative" temperature at which point adjacent grains coalesce and form larger ones, this critical temperature being effected by rate of heating. For a more complete treatment see reference (85) appendix.

** Armco iron is a very low carbon, commercially pure grade of iron prepared by the American Rolling Mills Company. Electrolytic iron is prepared by electrodeposition and contains a superabundance of hydrogen as a gas.

have led to an investigation of the conditions necessary for their production. Therefore, much work allied with recrystallization has been carried out (44, 52, 57, 60, 68, 73, 74 and 81). Another stimulus has been the question of relation between magnetic properties and grain size and some work in recrystallization has resulted (68, 69, 81), such as that of Moos, Oberhoffer and Oertel[69] who studied recrystallization of transformer steel.

Other scientific problems have called for special studies such as orientation of crystallites produced during deformation and annealing (52, 60, 75), internal stresses in metals (49, 59, 78), the effect of hydrogen on the recrystallization of electrolytic iron (50, 53, 48, 36, 71), peculiarities in the microstructure of ferrite (65, 70), etc. Particular studies have been made on rolled sheet products (54, 66, 75, 76, 77, 79). Ahrell[63] has made a study of cold drawn steel tubing and has expressed his results in the conventional diagram form. It is interesting to note that he found the time of anneal to become more important at the lower degrees of deformation while work by Oberhoffer and Oertel[45] definitely refuted this by their findings that the effect of time was not noticeable on specimens deformed less than 5% but manifested itself for the higher percentages of reduction. Lack of attention to a homogeneous and comparable structure in the starting material used in their work might explain certain of the conflicting results, little weight apparently having been given this property.

REVIEW

Following the above brief history of previous works it might be well if a rather concise summary could be given including a discussion of the principal items in recrystallization rather than a further discussion of separate works.

The temperature of beginning recrystallization is a function of the degree of deformation, the kind of alloying or impurity constituents, rate of heating, grain size contrast and size of grains in starting material. Works by Oberhoffer and Oertel[45] on electrolytic iron and mild steels, Hanemann and Lucke[46] on hot forging 0.06% C steel, Oberhoffer and Jungbluth[38] in cold forging 0.07% C steel, Dr. McAdam,Jr. by cold compression of Armco iron, and Edwards and Yakahama on elongated 0.08% C steel, while not in particular agreement with each other still show the general influence of carbon content and indicate a very definite trend toward a raising of the recrystallization temperature with increasing carbon. Curves presented by Shotsky and Jungbluth[38] representing the critical temperature of 25% nickel steel cold-compressed show that this addition does not seem to raise the recrystallization temperature any more than 0.07% carbon. From work by the above authors on two steels of the following compositions

20% chromium, 7% nickel, and

2.3% chromium, 11% nickel, 2.6% manganese

it appears that the presence of chromium and nickel together seem to produce a considerable elevation of critical temperature amounting to as much as 300° C. These references, in addition to illustrating the effect of alloying constituents also serve to show the effect of temperature and kind of deformation. They show that for any particular temperature of anneal the critical degree of deformation (in the region of smaller deformations) is greater for the hot working than for the cold working. By comparing the curves of Hanemann and Lucke(46) with those of Tafel, Hanemann and Schneider(72) the latter conducting hot rolling experiments on 0.03% carbon steel, shows that it requires a comparatively larger degree of reduction in hot rolling to cause recrystallization at the same temperature as hot forging. All the above works failed to present data for deformations of less than 5% cold reduction. This fact, of course, minimizes its value for comparison with Armco iron but still represents pertinent observations in the field of general recrystallization. Also since many workers maintain that at the temperature of recrystallization the critical strain becomes less as the time of anneal is increased, the above works might seem to be invalid. In all probability, however, the data were determined closely enough to justify the conclusions drawn.

In a discussion of grain size it appears that this property is a function of even more factors than the temperature of recrystallization. The usual grain size produced in electrolytic iron is larger than that in low carbon steels, (45, 46, 72, 35, 63) the former exhibiting grain sizes of the order of 106 x 10^3 square microns and the latter 10 to 50 x 10^3. Armco iron falls between these two values but resembles electrolytic iron more than mild steel in its behavior, the difference probably being due primarily to the inhibiting effect of carbon on grain growth. Alloying agents such as nickel and chromium have a similar effect and give grain

sizes comparable to those of carbon steels, while enormous grain sizes can be obtained in a 4% silicon steel which, according to Moos, Oberhoffer, and Oertel[69] seem to develop grain sizes even larger than electrolytic iron. Depending on the temperature of anneal the grain size of most metals decreases more or less rapidly with increasing degrees of deformation of a large order. It has been found that Armco iron and mild steel exhibit a tendency toward increasingly finer structures at lower deformations than does electrolytic iron, this again, no doubt, being an influence of the carbon content. Large grains may be seen in the latter at reductions as high as 30% for annealing temperatures below A_1, while the former shows a definite grain refinement at 25% (46, 72, 35). Hanemann[46] states that the grain size-deformation curves obtained by hot forging are rectangular hyperbolae but this contention was not verified in later work[72].

For most metals the grain size increases continuously with decreasing degree of deformation (to a critical value) and with increasing annealing temperature. Oberhoffer and Jungbluth[35] state that for commercial iron the maximum grain size occurs for a deformation of 10% reduction in height, this value being substantiated by Pomp[33] and Sherry[29]. This indicates that there is an increase of grain size for deformations slightly above the critical value, the lag undoubtedly being due to impurities. Edwards and Yokahama[84] gave some pertinent information on this point. They found that the grain size of specimens elongated slightly above the critical value increased with annealing temperature up to A_1 and decreased markedly as the temperature approached A_3. They concluded that the presence of impurities makes it impossible to raise the annealing temperature above A_1 without increasing the amount

of a second phase present which offers a barrier to further grain growth.

As mentioned before grain size depends, to some extent, on the time of annealing. Oberhoffer and Oertel[45] concluded from their studies on electrolytic iron that this factor was of minor importance but a specific trend in this direction was noticeable especially for the higher degrees of deformation. According to Ahrell[63] the time of annealing is only important at the beginning of the recrystallization process and even manifests its effect at the lower order of cold work. Aging a steel is held by certain workers to exert an influence on grain size. By allowing mild steel to lie for several months it has been noted that an increase of grain size near the "peak" of the recrystallization diagram takes place.

As another factor operative in recrystallization phenomenon, the effect of initial grain size seems to be a debatable point. The results of Gries and Esser[74] and of Phiel[57] show that this factor is of much importance in producing single crystals by straining and annealing, while Hanemann and his co-workers[46, 72], using hot deformation methods, conclude their results to be independent of grain size. By comparison of extremely coarse grained material such as 4% silicon steel with grain sizes of the order of 9×10^5 square microns, to a specimen exhibiting very fine structure, Oberhoffer, Moos, and Oertel were able to obtain very nearly identical results.

There seems to be a relatively small amount of experimental work available on comparisons of the various types of cold work and in many cases explicit data are not presented to indicate the manner and degree of deformation. The current work is presented, therefore, with as much attention to detail as is consistent with space. It incorporates

considerations of different types and degrees of cold working with careful attention given to thermal manipulation.

PART I

RECRYSTALLIZATION

With reference to the aforementioned recrystallization diagram in which grain size is expressed as a function of the two predominating variables — degree of plastic deformation and temperature of anneal — the temperature is a physically definite quantity and capable of accurate determination. Likewise the grain size, as measured planimetrically or otherwise, can be determined within tolerable limits. Unfortunately, however, the degree of plastic deformation, while easily and accurately expressible in such fundamental terms as percent reduction in height, percent alongation, or percent shear, is not so physically definite. That is, the resultant effect on recrystallization can in no wise be estimated from such values. It is perhaps reasonable to believe that some elusive close relationship exists between the various types of cold work, and it would be highly advantageous if a correlation of the cold-working of each type could be expressed under some common unit which satisfactorily measures the physical effect on recrystallization in each case. While the present work makes no claims whatever to a solution of this relationship, it is, however, intended as a step in this direction.

The three most fundamental types of deformation are shear by torsion,

elongation in tension, and reduction in height by forging or rolling. Accordingly, recrystallization diagrams are herein established for commercially pure iron, using in turn each of these types of cold-work, no consideration being given deformations impressed on the metal while heated to various temperatures. The data will be presented separately in each case and later collectively as a summary consideration.

RECRYSTALLIZATION OF TORSIONALLY STRAINED ARMCO IRON

The chemical analyses of the Armco iron used in the following experiments are as shown below:

C	0.011 to 0.015	S	0.027 to 0.028
Mn	0.00 to 0.012	Cu	0.00 to 0.041
P	0.004 to 0.008	Si	0.004 to 0.008

The stock used was initially in 1" round bars. This material was then sawed into pieces 11" long and turned smooth to a diameter of 15/16 inch. To eliminate the effects of previous history, these specimens were then wrapped in asbestos and heated in a tubular furnace for three hours at 930° C, after which they were furnace cooled.

As a means for measuring the angle of twist, reference lines were scratched very accurately with a lathe tool along the length of the bars and the specimens then fitted into the grips of a torsion testing machine and given a predetermined permanent twist. It was found that the entire bar twisted with great uniformity as evidenced by the straight line curves obtained from a plot of angle of twist against length of bar*. One of the twisted bars was selected and sawed into samples 1/2" thick for further

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* These curves are shown in Figure 1.

heat treatment and examination. The annealing temperatures chosen were 300, 400, 500, 600, 700, 760, 780, 800, 825, 850 and 875° C. To facilitate as rapid heating as possible with a minimum of oxidation, a copper block, with a hole into which the specimens could be quickly dropped, was maintained at the desired temperature in a suitable muffle furnace. Immediately following the proper time of anneal, 3 hours in most cases, the specimen was quickly removed and quenched in water.

Initially all samples were examined microscopically, both on a section perpendicular to the bar axis and on sections including it. After it was evident that the results were the same in both cases, further examination was confined to the normal section. Each sample was examined prior to and immediately after heat treatment and in all cases of marked recrystallization the grain size of the largest crystallites was determined from grain counts between concentric circles drawn upon a visual macrographic view of the whole section. The grain size of the smaller structures was determined from grain counts on photomacrographs.

To study the effect of length of annealing time, a strained specimen was heated 20 minutes at 825° C. A macrograph of the normal section was taken and the specimen was subsequently heated for intervals of time of 20, 40, 90 and 170 minutes showing, upon examination in each case, no material difference in grain size. Considerations of annealing times for as long as 4 days duration will be discussed later. From observations on the small samples cut from the first bar and annealed at the various temperatures designated above, it was found that no recrystallization was manifest at temperatures below 760° C. The data are presented in Table 1 from which representative curves were drawn.

Table 1

SUMMARY OF GRAIN COUNT DATA

Annealing Temp. °C.	Annealing Time Hrs.	Radii mm.	Average Grain Size before Annealing *	Average Grain Size After Annealing
300	3	3	3.5	4.7
		6	4.6	4.9
		9	4.2	6.3
400	3	0	4.7	4.1
		3	4.8	—
		4	—	4.3
		6	4.0	—
		8	—	4.5
		9	4.8	—
		11	—	6.0
500	3	0	4.8	—
		2	—	4.6
		3	4.0	—
		5	—	5.4
		6	4.8	—
		8	—	5.5
		10	4.6	—
		11	—	4.8
600	3	2	4.8	5.2
		5	—	5.9
		6	4.0	—
		8	—	5.4
		10	5.7	—
		11	—	6.6
700	3	2	4.6	5.1
		5	5.4	5.9
		8	5.6	6.7
		11	6.9	7.9
760	3	.5	5.8	—
		2	—	5.8
		5	5.8	—
		7.5	—	8.4
		8	5.5	—
		9.5	—	9.9
		11	5.5	—
		11.5	—	8.7

* Grain sizes given in square microns x 1000.

Table 1 (cont'd)

Annealing Temp. °C.	Annealing Time Hrs.	Radii mm.	Average Grain Size before Annealing *	Average Grain Size after Annealing
780	3	3.5	--	28.1
		4.5	--	27.5
		4.9	10.7	--
		5.5	--	39.0
		6.5	--	48.1
		7.5	--	49.0
800	3	2	6.0	--
		4.3	--	8.0
		5	6.0	--
		5.3	--	723
		5.4	--	684
		6.7	--	254
		8	10.0	34
		9.3	--	17
		10.7	--	16
		11	8.0	--
825	3	1.7	--	17
		2.0	6.0	--
		3.2	--	13
		4.5	--	21
		5.0	7.0	1135
		6.0	--	180
		7.4	--	75
		8.0	8.0	--
		8.9	--	63
		10.0	--	30
		11.0	6.0	--
		11.4	--	17
850	3	2.0	6.0	--
		3.9	7.0	--
		4.3	--	2000
		4.8	--	225
		5.0	6.0	--
		7.8	--	47
		8.0	8.0	--
		10.8	9.0	19
875	3	1.6	--	9
		2.0	11	--
		3.9	--	220
		4.4	--	1570
		5.0	10	--
		5.9	--	133

* Grain sizes given in square microns x 1000.

Table 1 (cont'd)

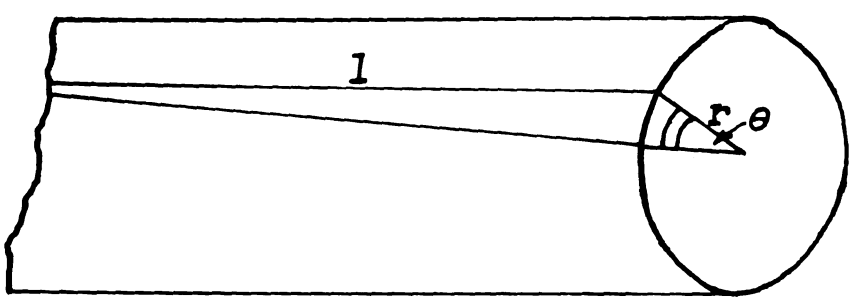
Annealing Temp. °C.	Annealing Time Hrs.	Radii mm.	Average Grain Size before Annealing *	Average Grain Size after Annealing
		7.9	--	52
		8.0	10	--
		9.2	--	30
		10.5	--	19
		11.0	10	--
		11.5	--	21

Critical Radii of Recrystallization --

Temperature, °C -	Below 760	760	780	800	825	850	875
Radii, mm.-------	None	10	8	4.5	4.1	4.0	2.8

From the proper weighting of these curves, i.e., finding the center of gravity of the area included between the abscissa and the lines, the data for the recrystallization diagram were calculated.

The proof of the formula showing how unit shear varies with radius from center of bar is presented below.



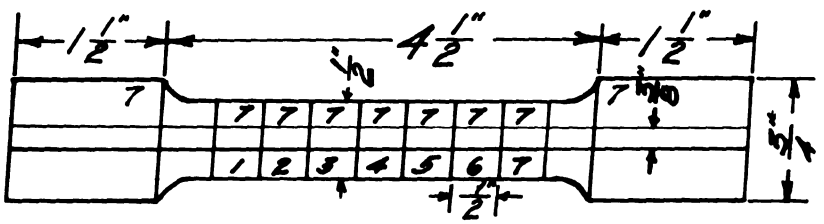
Unit shearing deformation (γ) = tan θ, where
θ = angular displacement due to shear,
r = radius to critical area,
l = length of twisted section.

tan θ = r (θ/l) and since
θ and l are constant,
tan θ, or unit shear is proportional to r.

* Grain sizes given in square microns x 1000.

RECRYSTALLIZATION OF TENSIONALLY STRAINED ARMCO IRON

The chemistry of the material used was as given previously for the torsionally strained specimens. The bars were machined as indicated below.



The bars were wrapped in copper foil and an additional layer of asbestos paper. Since the material in the stock condition showed a non-uniform grain structure, coarse grains being interspersed through the finer grained matrix, it was heated back and forth through A_3 for about 45 minutes, this treatment producing a fairly uniform structure.

By means of the dividing screw of a lathe, reference lines were scratched around the bars at one-half inch distances apart for measuring the amount and uniformity of elongation. Elongations amounting to approximately 2, 4, 5, 6, 8, 10, 16 and 20 percent were impressed on successive bars and the amount and constancy measured by means of a comparator.

The elongation was found to be uniform but the division of the material for heat treatment was carried out according to a definite system as indicated below, such that any discrepancies or peculiarities might be noted. The samples marked "G" were reserved for the comparison of cold work stages. All other samples were heat treated as indicated in the table below:

Sample	Annealing Temperature	Time
E	875° C.	1-1/2 hours
F	825° C.	2-1/2 hours
H	780° C.	2-1/2 hours
D	760° C.	2-1/2 hours
I	700° C.	2-1/2 hours

Grain sizes were measured on the cross-section of each sample, four values being taken at equal intervals across the diameter. In many cases where coarse grains were present many small grains manifested themselves at the boundaries of the former. Grain counts which considered these very small units proved to give no true hint of the size of the more predominant larger ones. Grain counts were also made ignoring these small units.

After grain counts were computed, photomacrographs were taken of the cross-sections of the annealed samples, the purpose being to get a series of representative annealing structures in tensionally strained iron and to study the base effect of the superimposed deformation of punch-marking.

SUMMARY OF GRAIN COUNT DATA

The data obtained were drawn as a series of isothermal curves from which the space diagram was constructed for comparison with the torsion deformation results. The difficulty of making a satisfactory grain count on the specimens because of the presence of numerous fine grains at the grain boundaries necessitated, as previously mentioned, a separate grain count in which the grains of comparatively small cross-sections were not counted. For the samples annealed at 875° C this procedure was not required but for lower temperatures it was quite necessary in order to show what the size of the largest grains produced by the mechanico-thermal treatment really was. The curves corresponding to each annealing temperature except 875° C were modified and this form used for calculating and plotting the space diagram.

An inspection of the photomacrographs showed that the above procedure was justified in arriving at a representative grain size for a particular heat treatment. These also showed the effect of punch-marking the specimens upon resultant recrystallization structures, this effect varying from sample to sample. Some pictures showed no signs of any effect while others indicated a very pronounced one. This spurious cold working seemed to exhibit its greatest effects in the ranges of critical elongation values.

The space diagram was constructed from critical values more or less

arbitrarily chosen as the mean value of two deformations between which a marked change in grain size occurred at a certain annealing temperature. A very careful survey of photomacrographs was made in all cases to determine these points when the structure passed from the worked to the non-worked state.

All photomacrographs of unrelieved structures indicated cold work in the form of wavy lines running through the grains. Whether this was a manifestation of alpha veining or slip along crystallographic planes was not ascertained.

Pertinent points gathered from observations of specimens annealed at indicated temperatures are presented below.

875° C.

(1) Samples deformed up to 4 percent showed a cold-worked structure.

(2) 5 percent deformation showed cold work in region influenced by punch-marks and an annealing structure in the remainder of the cross-section.

(3) 6 percent and greater elongation produced cold-worked structures exhibiting the clusters of fine grains at the boundaries of larger ones, these giving the aforementioned trouble in representative estimations.

825° C.

(1) Much of the same results as presented for the 875° C anneal were observed except that,

(2) For the higher degrees of deformation the smaller grains were not so numerous.

780° C.

(1) Elongations up to 5 percent gave cold-worked structures, and

(2) 6 percent deformation even gave a dubious result.

(3) 8 percent deformation gave a very pronounced indication of recrystallization.

(4) At about 9 percent and beyond the various elongations produced a flaky structure with the number of small grains becoming consistently lower as the cold-working was increased, and almost disappearing entirely at 16 and 20 percent with an apparently homogeneous polyhedral structure.

760° C and 700° C

(1) As would be expected, little difference was noted in the general structural trends from the specimens annealed at 780° C.

The results of the above inspection regarding the critical strain corresponding to each annealing temperature have been summarized in the table below and compared with estimates made from grain size data and from an inspection of photomacrographs of the complete sections. The agreement is close enough but there always remains the possibility that the values obtained from an inspection of the photomacrographs are slightly high because of a misinterpretation of the appearance of sections. That is, what may seem to be a cold-worked structure may in reality be an initial grain decomposition preceding recrystallization. This possibility was borne in mind throughout the above inspection but the structures accepted as completely recrystallized were those in which no trace of either cold work or the alternative possibility, incipient grain decomposition, could be seen.

Table 2

SUMMARY OF GRAIN COUNT DATA

Annealing Temperature:	% Elongation 1.1	3.46	4.72	6.14	7.83	8.63	15.93	19.90
700° C	4.42	5.60	6.51	3.31	5.56	4.19	5.05	6.30
760° C	3.56	3.50	4.25	5.34	10.13	8.91	4.23	5.80
760° C*	--	--	--	--	38.00	27.07	--	--
780° C	3.37	5.83	5.35	5.46	52.80	7.30	5.18	6.96
780° C*	--	--	--	10.24	--	47.9	--	--
825° C	3.94	3.90	43.04	54.35	47.65	15.42	4.10	5.48
825° C*	--	--	219.20	108.50	--	35.71	--	--
875° C	3.72	4.76	139.40	100.70	55.00	46.90	5.12	5.71
875° C*	--	--	--	--	--	--	--	--

Critical Reductions Corresponding to the Annealing Temperature.

Annealing Temperature:	875	825	780	760	700
Critical Reduction	4%	4%	6.2%	7%	--

* Grain counts made neglecting the relatively small grains.
Grain size given in square microns x 1000.

Returning to the phenomenon of small grains coexisting with large ones, and selectively appearing at the grain boundaries of the latter, it remains for future research to establish the true physical or mechanical reason for same. In an effort to theorize, it might be suggested that this was a result of insufficient annealing time, or that the original grain structure was of an order of incipient grain size contrast to promote uneven cold working from grain to grain during deformation. However, in contradiction to these theories rests the following points:

(1) It was found in the previous work on torsionally strained pieces that above 800° C the time of annealing beyond one half-hour was superfluous, complete recrystallization being insured within this period. Such has been found to be the case by other experimenters as mentioned in the previous history and reference summary.

(2) The structure of the original unworked iron exhibited no marked grain size contrast. To be sure the structure was not perfectly polyhedral but was as much so as is ever evidenced in iron samples. That the difference was incipient and defied resolution is possible, of course.

It still remains probable that an investigation of the literature and pertinent experimental research in regard to alpha veining phenomenon may shed some light on this point.

RECRYSTALLIZATION OF COMPRESSIONALLY STRAINED ARMCO IRON

Round bar stock of one inch diameter was machined to a square cross-section. This was wrapped in several thicknesses of copper foil and introduced into an electric furnace at about 870° C, being heated and cooled several times through A_3, as in previous work. The upper temperature was 923° C and the lower 875° C. After one and one-half hours of this intermittent temperature fluctuation, the material was finally furnace cooled.

Even this treatment failed to produce an equiaxed and homogeneous structure. As a result the iron was held at 923° C for two hours for the purpose of causing growth of the fine grains through transformation and thus equalize out the grain size contrast. Excessive grain growth appeared in spots and on treatment similar to that initially employed, a structure not entirely uniform but acceptable was attained.

The surface of the bars was by now disturbed to such an extent that a light regrinding was necessary to get parallel surfaces for an accurate estimation of percentage reduction in rolling.

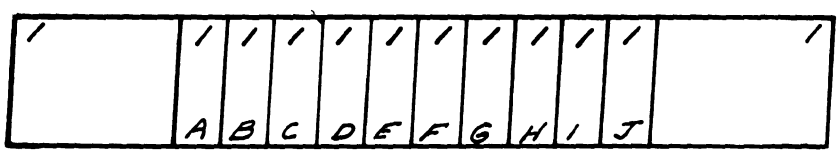
The samples were all cold rolled to the desired degree by several passes through twelve inch diameter rolls. The work was started with the smallest desired reduction and subsequent pieces were rolled on their first pass to the final required thickness of the previous sample, and were finished by two to six more passes through the rolls. The more drastically

worked pieces were thus rolled down in the more severe steps. Micrometer readings were taken at several spots on the specimen to determine the thickness of the samples at the various steps before and after rolling, and an average value taken to compute the actual percent reduction of the bars. The initial thickness of all bars was 0.56 inches. The table below serves to indicate how nearly the desired degrees of cold work were realized.

Percentage Reduction of the Samples

Expected % :	1	2	3	4	6	8	10	15	30
Obtained % :	0.70	1.74	2.98	4.15	5.99	8.02	10.05	14.71	29.82

After rolling, the bars were sectioned as indicated below by means of a slow band saw and kept cool with an air blast.



Samples were heat treated according to the table below.

Sample	Annealing Temperature	Time
A (all bars)	875	3 hours
B (all bars)	850	3 hours
C (all bars)	825	3 hours

D (all bars)	800	3 hours
E (all bars)	780	3 hours
F (all bars)	760	4 hours
J (all bars)	Not annealed	—

The samples were again wrapped in copper foil and introduced into the furnace maintained at the stated temperature. After three hours (in most cases) the samples were removed and air cooled. Each sample was cut across the direction of the bar at a position half-way between the original cut ends of the sample, these interior surfaces being used for micro-examination.

Photomacrographs were taken of each of the series J samples and used in the determination of grain size, but for all other specimens grain size counts were made on the ground glass of the metallographic camera. All pieces were carefully examined, however, over their entire section to note any peculiar features. Occasionally large grains would appear in isolated places on the sample or in groups in certain regions of the section.

To measure the sizes of these large grains they were traced on the camera back and their areas determined planimetrically. As in the case of tensionally deformed Armco iron several small grains were again evident at the grain boundaries. No consideration was given these small areas in the final structural analyses and only the sizes of the largest grains were found. Grain size measurements were made with extreme care and it is believed that representative values were obtained. The grain size and structure data for these experiments are somewhat more involved than in the torsionally and tensionally strained specimens. The data are arranged

below to give not only the exact grain size values determined at the centers of the sections but also structural peculiarities and sizes of large grains.

Table 3

GRAIN SIZE DATA OBTAINED FROM ROLLED AND ANNEALED ARMCO IRON SAMPLES.

Annealing Temperature	Percentage Reduction	Grain Size at center ($\mu^2 \times 10^{-3}$)	Remarks	Sizes of largest grains ($\mu^2 \times 10^{-3}$)
875°	0.70	19.76	Unrecrystallized.	
"	1.74	21.54	Unrecrystallized.	
"	2.98	17.64	Large grains appear near surface.	
"	4.15	20.08	Large grains appear near surface.	
"	5.99	21.57	Large grains in surface. Center still unrecrystallized.	606
"	8.02	37.10	Large grains form in center. Corners remain unrecrystallized.	303
"	10.05	31.57	"	136
"	14.71	23.16	Structure uniform.	
"	29.81	15.93	Fine grain.	
850°	0.70	18.57	Unrecrystallized.	
"	1.74	21.26	Unrecrystallized.	
"	2.98	18.96	Large grains appear near surface.	68
"	4.15	19.31	Large grains on surface and sides.	134
"	5.99	18.11	"	
"	8.02	40.31	Large grains form in center.	107
"	10.05	35.28	Uniform recrystallization structure.	140
"	14.71	21.38	Fairly uniform.	
"	29,81	12.76	Fine grain.	
825°	0.70	21.09	Unrecrystallized.	
"	1.74	25.75	Unrecrystallized.	
"	2.98	27.31	Unrecrystallized.	
"	4.15	22.56	Unrecrystallized.	
"	5.99	25.38	Large grains appear on surface and sides.	
"	8.02	83.80	Large grains on whole section except in corners.	428
"	10.05	49.07	"	140
"	14.71	24.08	Complete recrystallization.	
"	29.81	13.01	Fine grains.	

Table 3 (cont'd)

Annealing Temperature	Percentage Reduction	Grain Size at center ($\lambda^2 \times 10^{-3}$)	Remarks	Sizes of largest grains ($\lambda^2 \times 10^{-3}$)
800°	0.70	23.82	Unrecrystallized.	
"	1.74	19.26	Unrecrystallized.	
"	2.98	25.51	Unrecrystallized.	
"	4.15	17.64	Unrecrystallized.	
"	5.99	23.09	Unrecrystallized.	
"	8.02	23.41	Slightly larger grains in surface.	
"	10.05	33.93	Large and small grains formed except in corners of sections.	110
"	14.71	18.21	Fairly uniform structure.	
"	29.81	9.53	Small grain size.	
780°	0.70	22.10	Unrecrystallized.	
"	1.74	17.49	Unrecrystallized.	
"	2.98	24.52	Unrecrystallized.	
"	4.15	19.62	Unrecrystallized.	
"	5.99	22.04	Unrecrystallized.	
"	8.02	20.82	Unrecrystallized.	
"	10.05	22.43	Slightly larger grain size.	
"	14.71	15.64		
"	29.81	8.61		
760°	0.70	—		
"	1.74	20.37	Unrecrystallized.	
"	2.98	19.46	Unrecrystallized.	
"	4.15	—		
"	5.99	19.28		
"	8.02	—		
"	10.05	17.09	Possibly a slight grain size increase.	
"	14.71	—		
"	29.81	6.37		

Critical Percentages of Deformation as Judged from the Preceding Data.

Annealing Temperature	Critical Reduction for Surface Grains	Critical Reduction for Center of Section
875	2.98	5.99 - 8.02
850	2.98	5.99 - 8.02
825	4.15 - 5.99	5.99 - 8.02
890	8.02	8.02 - 10.05
780	10.05	10.05
760	10.05	10.05 - 14.71

In addition to the annoying small grains, another complication showed up in this rolling phase of the work. The recrystallization structure for the smaller degrees of deformation was non-uniform. It was found that rather small reductions of 3 and 4 percent were sufficient to cause the appearance of very large grains just below the rolling surface of the piece, while as the percentage reductions were increased the large grains began to be formed on the sides of the section as well as just under the surface. With still further increases of deformation, there appeared an inversion of the structure, large grains appearing at the center of the section and relatively small grains at the borders. Deformations of a still higher order promote uniformity of structure over the entire section.

The observed phenomena can no doubt be attributed to non-uniformity in the rolling process, and as a result it will be necessary to follow the paths of past workers and limit considerations and measurements to the center region of the cross-sections. It was thought expedient to use the modified values for grain sizes in the construction of the space diagram, the modification being the elimination of the small grains and planimetric tracings of only the larger ones recorded. This was the plan followed ultimately in establishing values from which the recrystallization diagram for compressionally strained iron were taken.

The critical percentages of reduction necessary for the formation of large grains at the center of the section and also near the surface of the specimen have been tabulated. These values are not sharp and exactly definite since the critical reduction usually occurred between two values used in the experiment but could be estimated fairly close and weighted in

the direction of the more definite macrostructure. These critical values corresponding to the metal near the surface are much lower and more sharply defined than was the case with the center regions. Also this latter region gave values considerably higher than was found for torsionally or tensionally strained Armco iron. However, from past experiments on the recrystallization of hammered Armco iron, values of a more similar order were found, being only slightly greater.

Unfortunately, due to the greater amount of thermal treatment necessary for production of a satisfactory structure in the original material for the rolling experiments, the resulting grain size was at least twice as large as that of the starting material used in the torsion and tension experiments. This probably would not invalidate the results or account for the higher values of critical cold-working in the case of the rolling experiments since the initial grain size of the cold hammered iron mentioned above was comparable to that used for torsion and tension work and yet the results agreed favorably with cold-rolling values.

CONCLUSION

In another part of the thesis it was stated that a summary discussion of the three types of mechanical treatment would be included. It was the author's intention to establish a correlation between the physical effects of the three types of cold work but this relationship has not been satisfactorily worked out, and with an opportunity for more research and literature survey, further definite steps in this direction will be taken. Owing to this fact considerations upon this point will be omitted and space taken only for a brief discussion of the photomacrographs.

Plate 1a shows the effect of temperature and degree of deformation on critically torsion strained Armco iron. Specimens A5, A6 and A7 were heat treated as shown after a cold deformation amounting to 34° twist per inch of bar, or .0235 radians per millimeter. Specimens B5, B6 and B7 received a twist of 22° per inch of bar, or .0154 radians per millimeter. The real value of these macrographs lies in their use for the determination of grain size and radii of critical zones of recrystallization from which the diagrams were constructed. As would be expected the recrystallization area lies nearer the center in the bar given the greater permanent twist. This is very apparent from the formula and actual tests prove these radii to vary in a constant manner with cold deformation.

Plate 2a shows the effect of time on recrystallization and it was found that 3 hours was sufficient for complete grain growth at the higher temperatures. The effect of time at the lower temperatures is clearly shown in plate 3a, increases in annealing time tending to lower the critical cold work values as would be expected. This time factor may vary over a period of at least 4 days as is evident in plate 4a.

Plate 6a serves to illustrate the effect of increasing cold-deformation for tensionally strained iron, while 8a accomplishes the same for compression cold work.

Plates 5a, 7a and 9a present the recrystallization data in diagram form for torsion, tension, and compression. The proper correlation of the values from which these were drawn are to be further considered at a later date with the hope of establishing the aforementioned common expression. It can be seen that the critical deformations in the case of shear lie within an apparently lower range than for the other types. At present Mr. H.F. Kaiser and the author are working on a theory presented by Nadai by means of which it is expected that these values may be brought into line. This theory involves considerations of octohedral shear and appears to be very applicable to this work.

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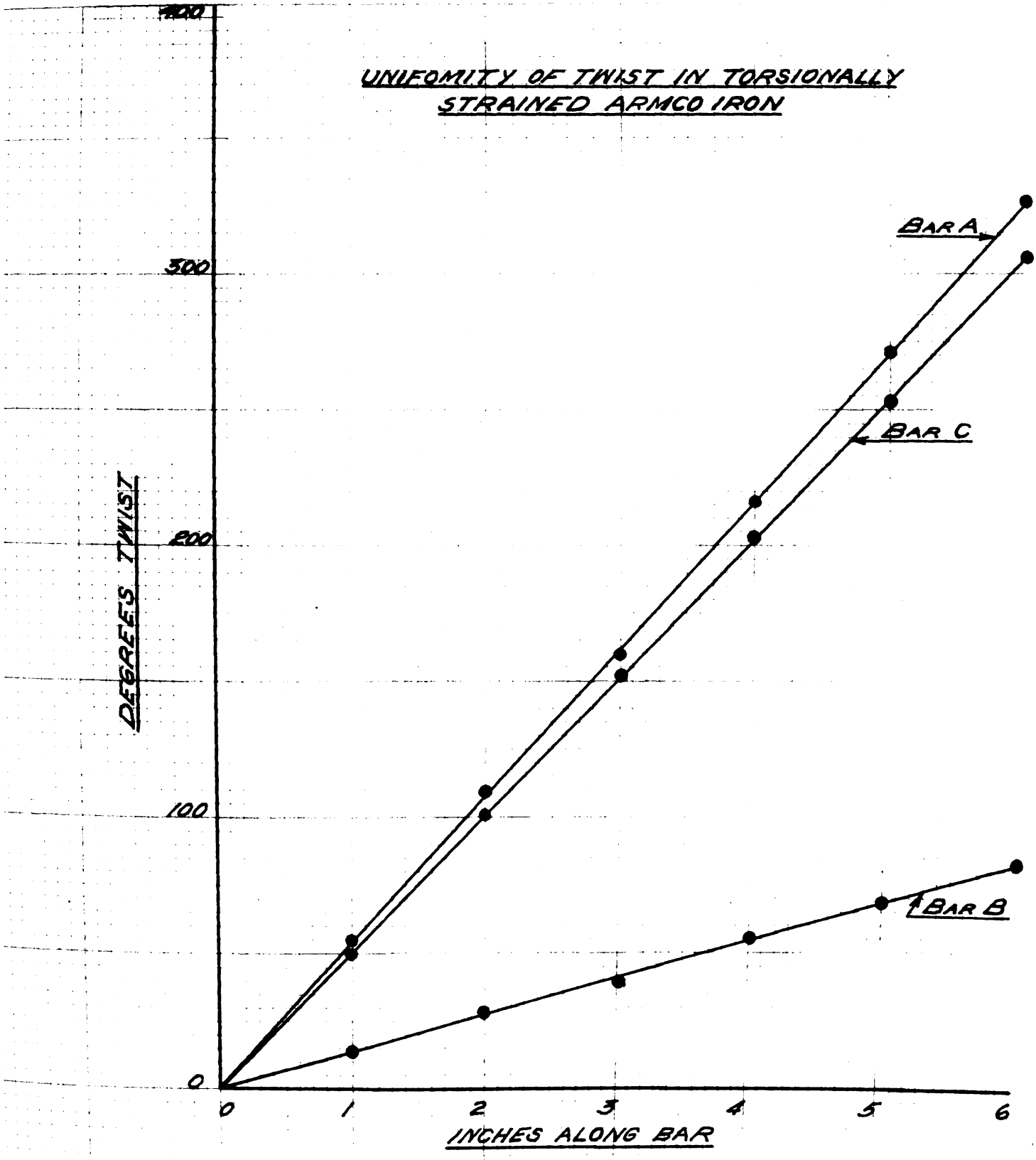

UNIFOMITY OF TWIST IN TORSIONALLY STRAINED ARMCO IRON
400
300
200
100
0
DEGREES TWIST
BAR A
BAR C
BAR B
0
1
2
3
4
5
6
INCHES ALONG BAR

FIGURE 1

PLATE 1a--

Effect of Temperature and Torsional Deformation on Recrystallization

A5 & B5 - Annealed 3 hours at 780°C
A6 & B6 - Annealed 3 hours at 850°C
A7 & B7 - Annealed 3 hours at 800°C

A Series - Twisted 34°/ inch of bar
B Series - Twisted 22°/ inch of bar

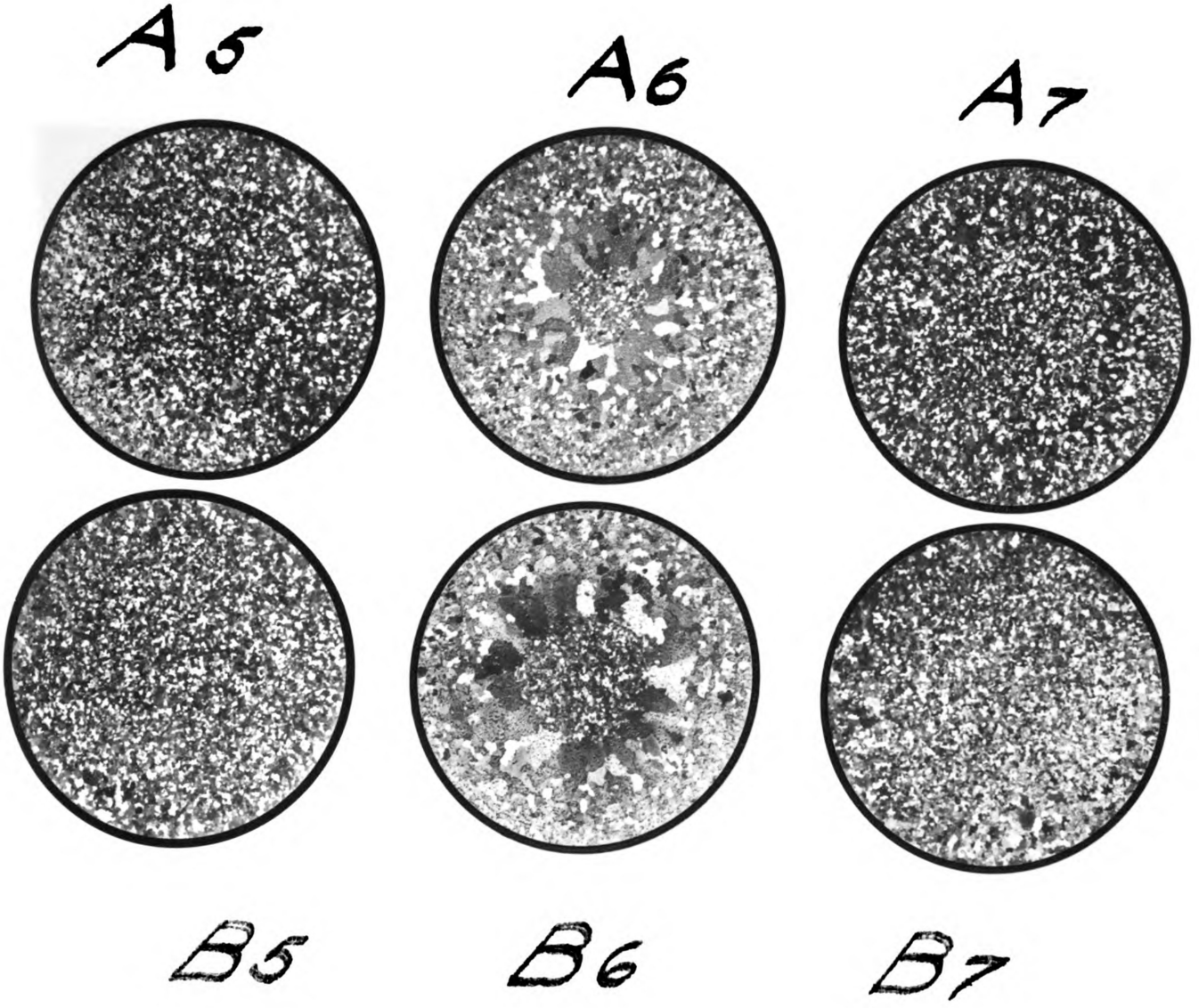
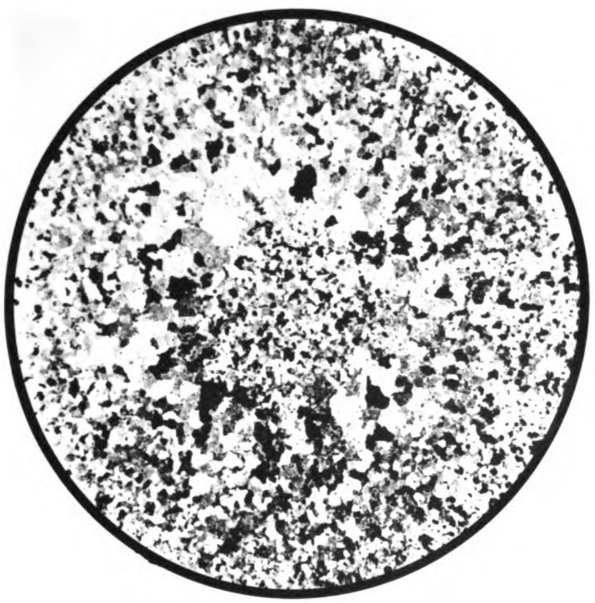


PLATE Ia

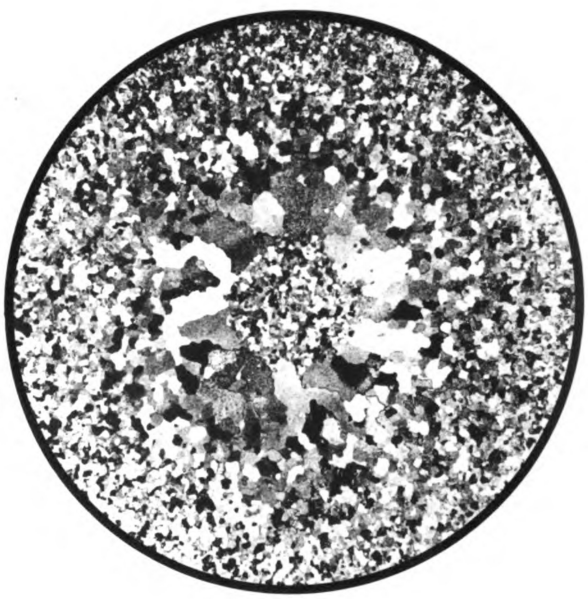
PLATE 2a--

Effect of Time on Recrystallization

A - Annealed 15 Minutes at 875°C
B - Annealed 3 Hours at 875°C



A



B

PLATE 2a

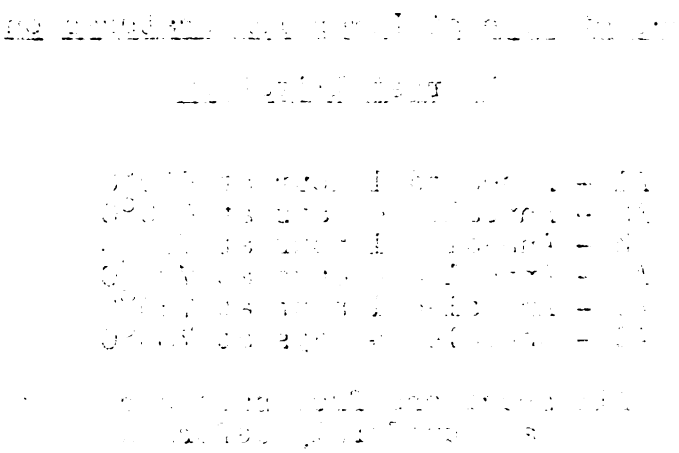


PLATE 3a--

Effect of Time at Lower Temperatures on Recrystallization

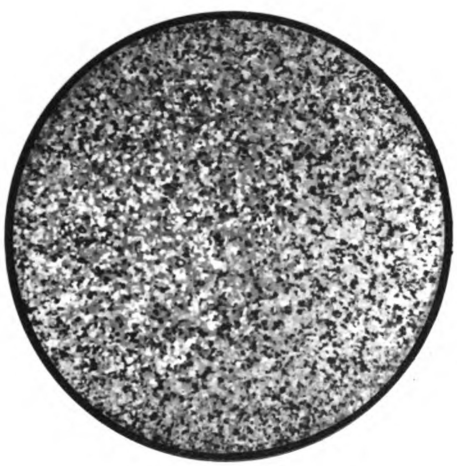
A1 - Annealed 1 hour at 600°C
A2 - Annealed 4 days at 600°C
A3 - Annealed 1 hour at 700°C
A4 - Annealed 4 days at 700°C
A5 - Annealed 1 hour at 780°C
A6 - Annealed 4 days at 780°C

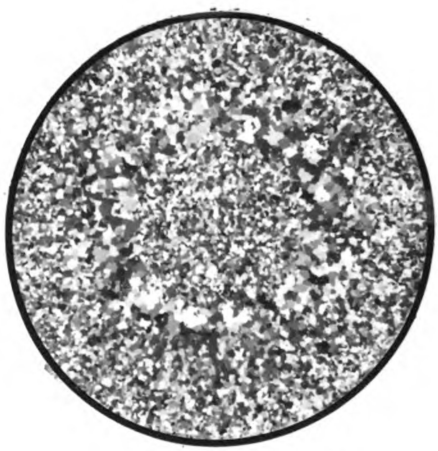
All specimens from same bar
and uniformly deformed

A1

A2

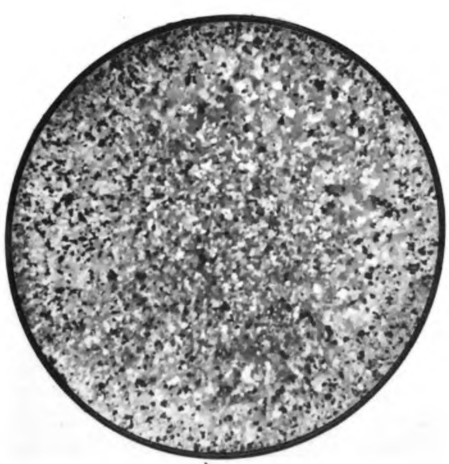
A3

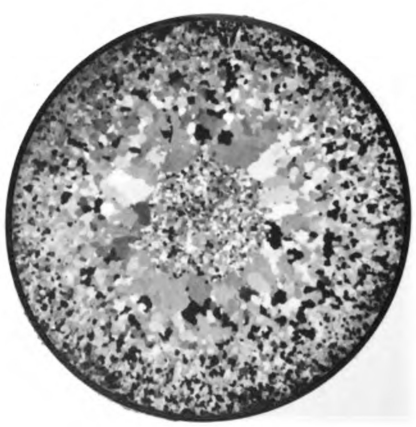




A4

A5





A6

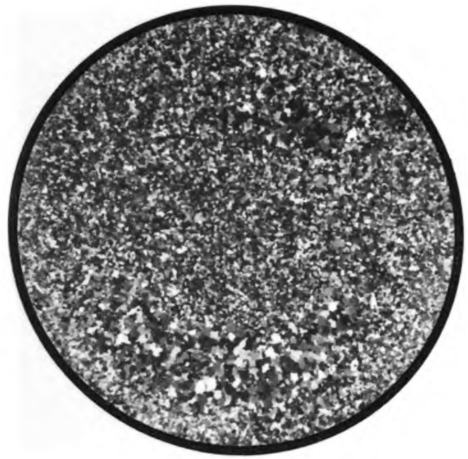
PLATE 3a

PLATE 4a--

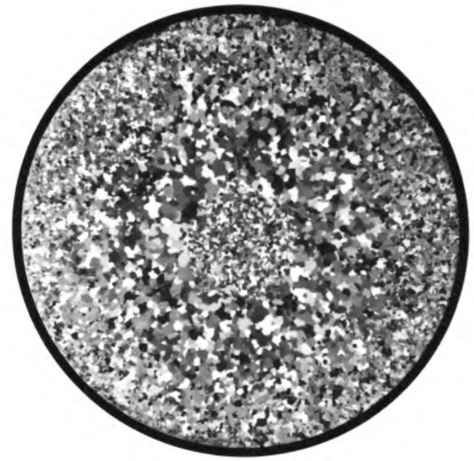
Effect of Temperature on Recrystallization

A1 - Annealed 2 hours at 780°C
A2 - Annealed 2 hours at 875°C
A3 - Annealed 2 hours at 825°C

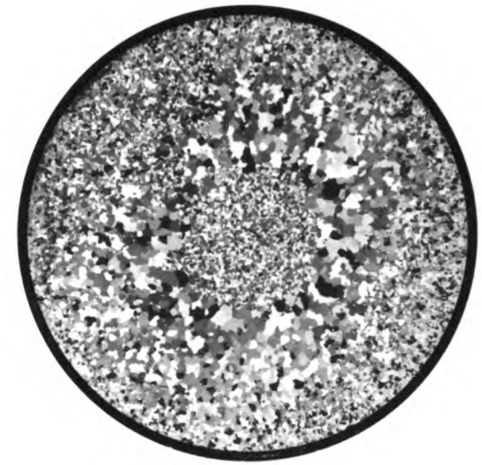
All specimens from same bar
and uniformly deformed



A1



A2



A3

PLATE 4a

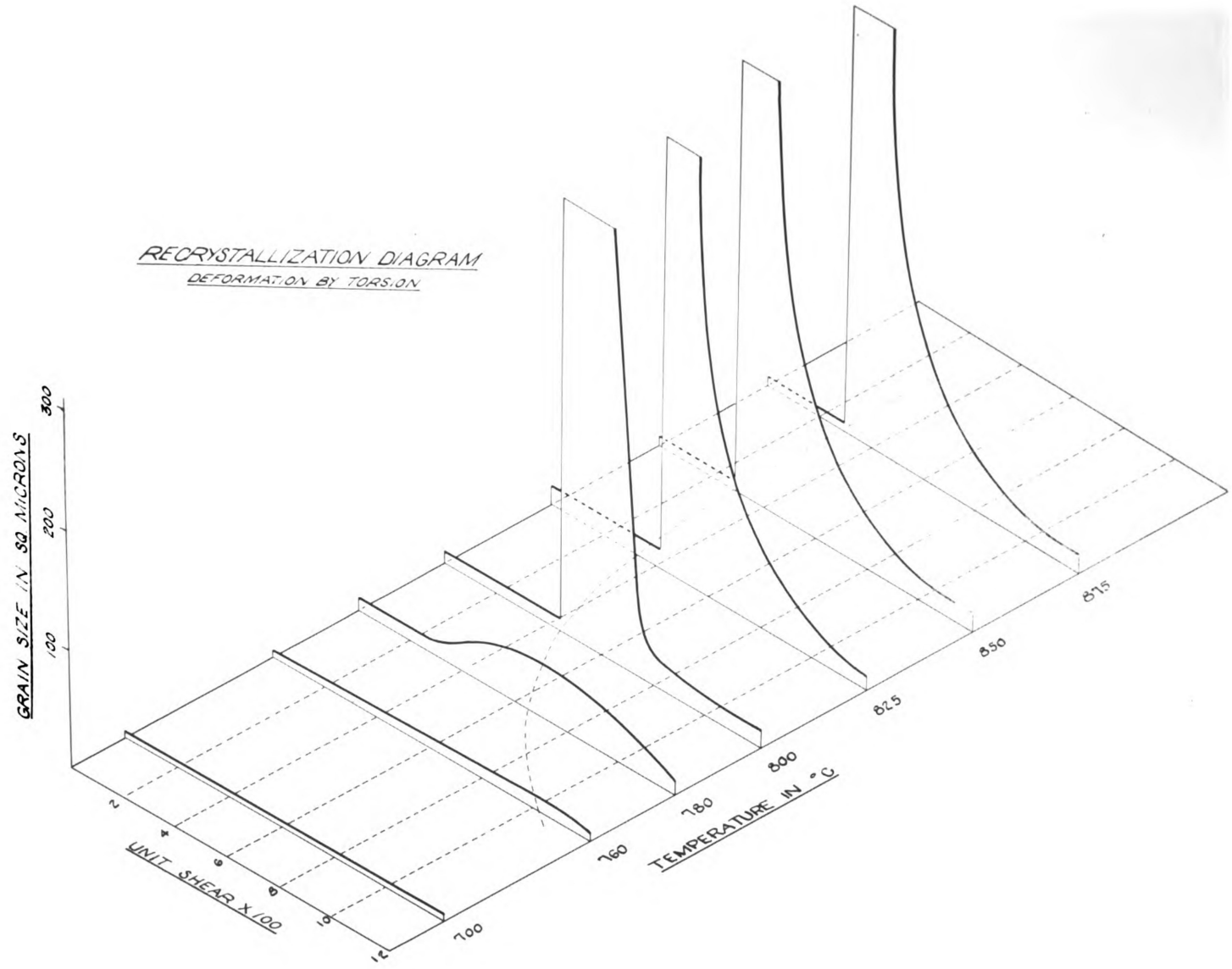

RECRYSTALLIZATION DIAGRAM
DEFORMATION BY TORSION
GRAIN SIZE IN SQ MICRONS
300
200
100
UNIT SHEAR X 100
2
4
6
8
10
12
700
760
780
800
825
850
875
TEMPERATURE IN °C

PLATE 5a

PLATE 6a--

Effect of Tension Deformation on Recrystallization

A1 - Elongation of 1.1%
A2 - Elongation of 3.4%
A3 - Elongation of 4.72%
A4 - Elongation of 6.14%
A5 - Elongation of 7.83%
A6 - Elongation of 8.63%
A7 - Elongation of 15.9%
A8 - Elongation of 19.9%

Annealed 3 hours at 875°C

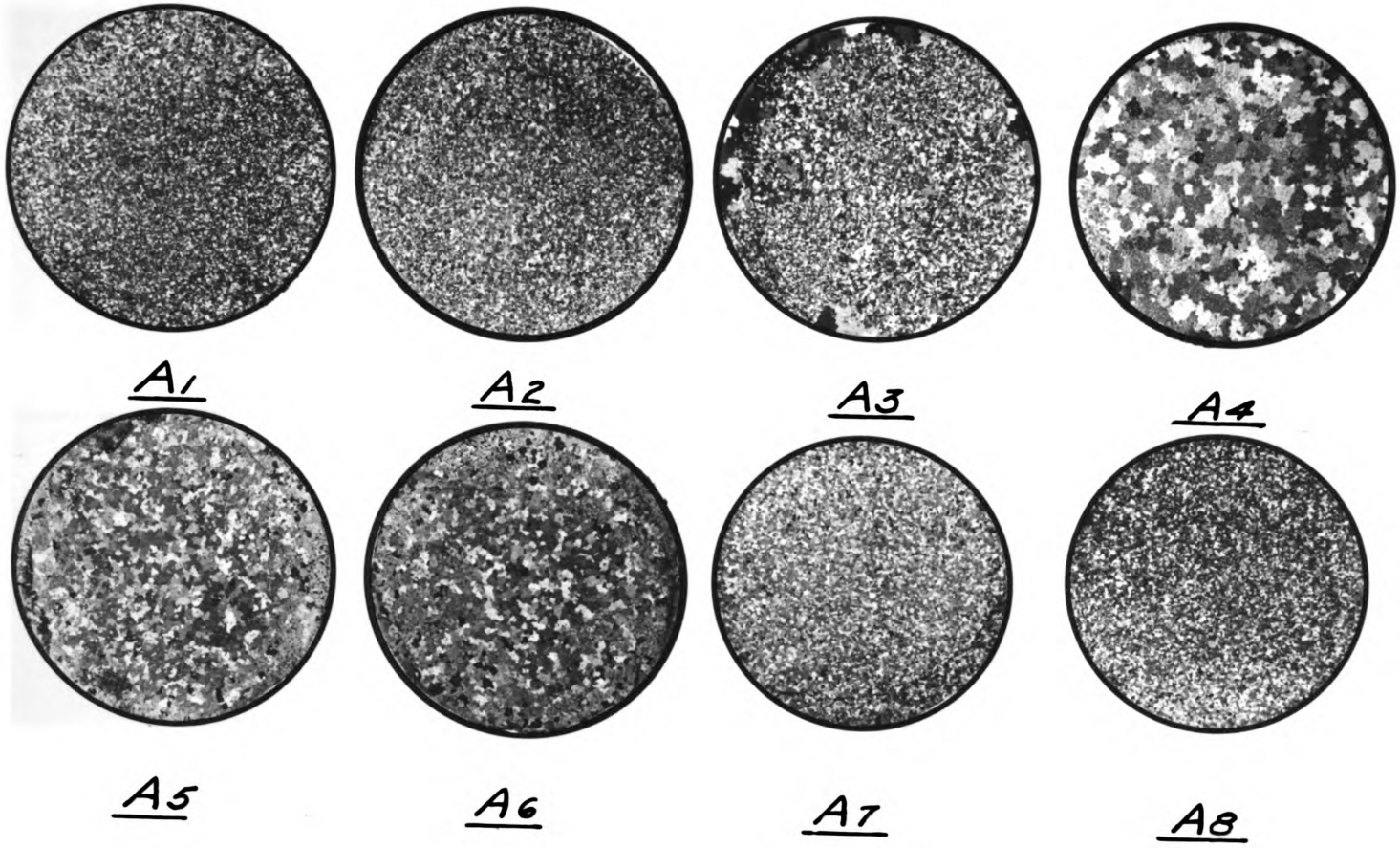


PLATE 6a

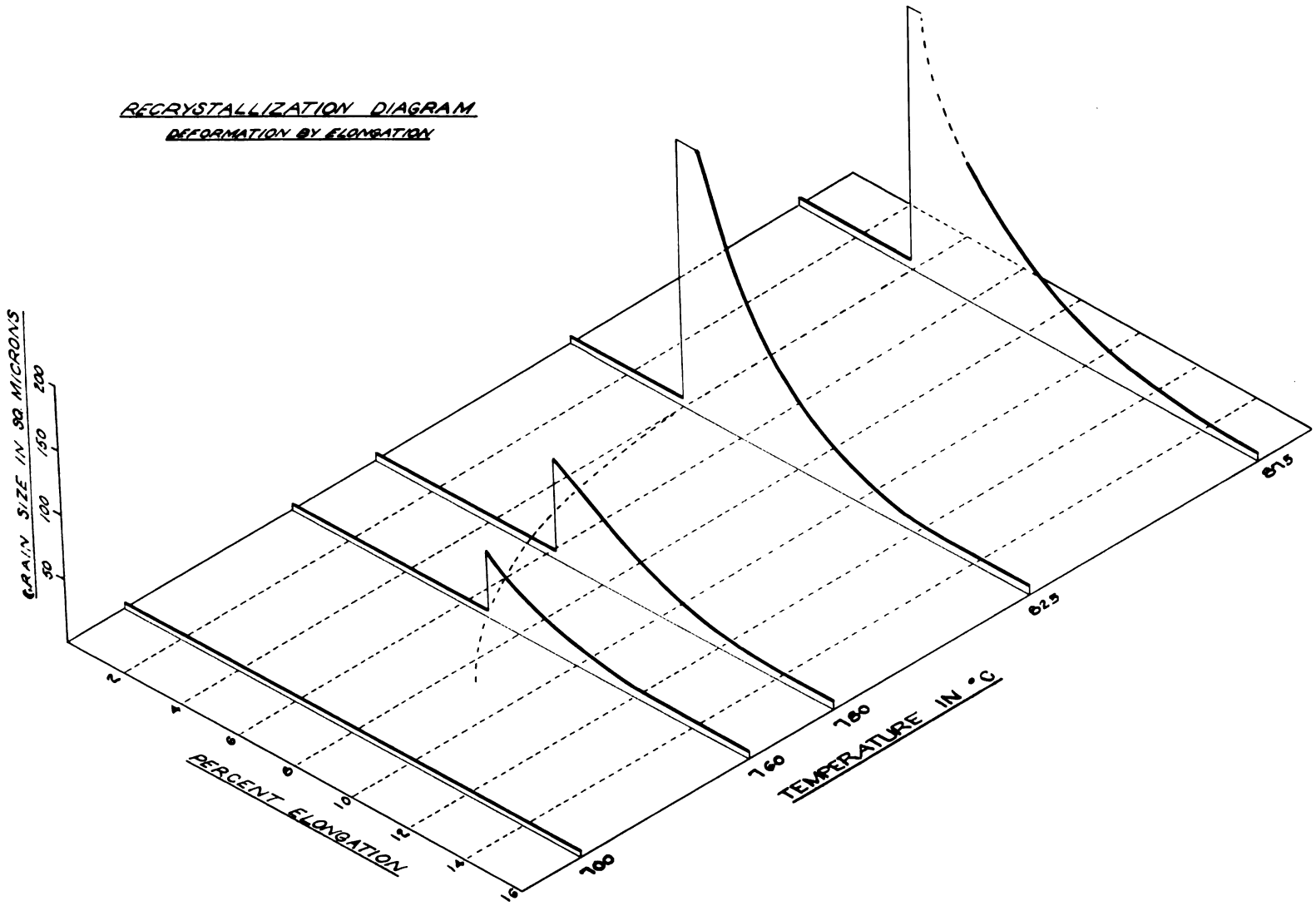

RECRYSTALLIZATION DIAGRAM
DEFORMATION BY ELONGATION
GRAIN SIZE IN SQ MICRONS
50
100
150
200
2
4
6
8
10
12
14
16
PERCENT ELONGATION
700
760
780
825
875
TEMPERATURE IN °C

PLATE 7a

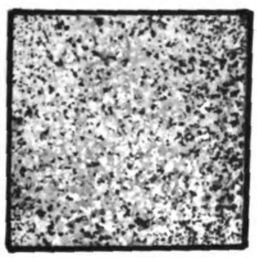
PLATE 8a--

Effect of Compression Deformation on Recrystallization

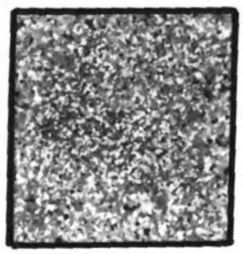
A1 - Cold Rolling of 0.70%
2 - Cold Rolling of 1.74%
3 - Cold Rolling of 2.98%
4 - Cold Rolling of 4.15%
5 - Cold Rolling of 5.99%
6 - Cold Rolling of 8.02%
7 - Cold Rolling of 10.05%
8 - Cold Rolling of 14.71%
9 - Cold Rolling of 29.81%

Annealed 3 hours at 875°C

1



2



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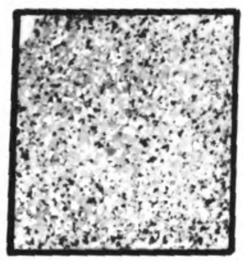

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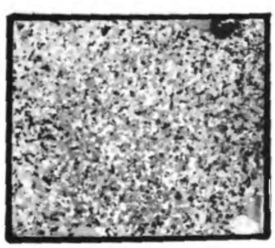

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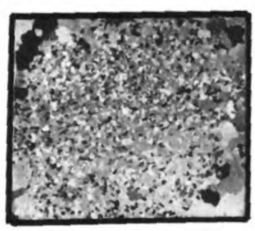

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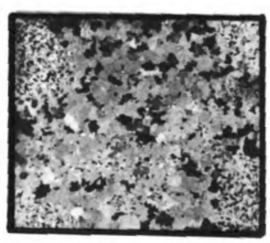

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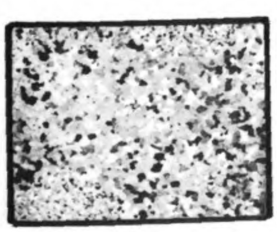

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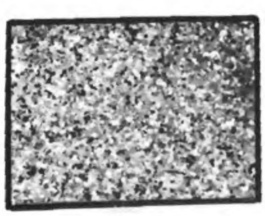


9

PLATE 8a

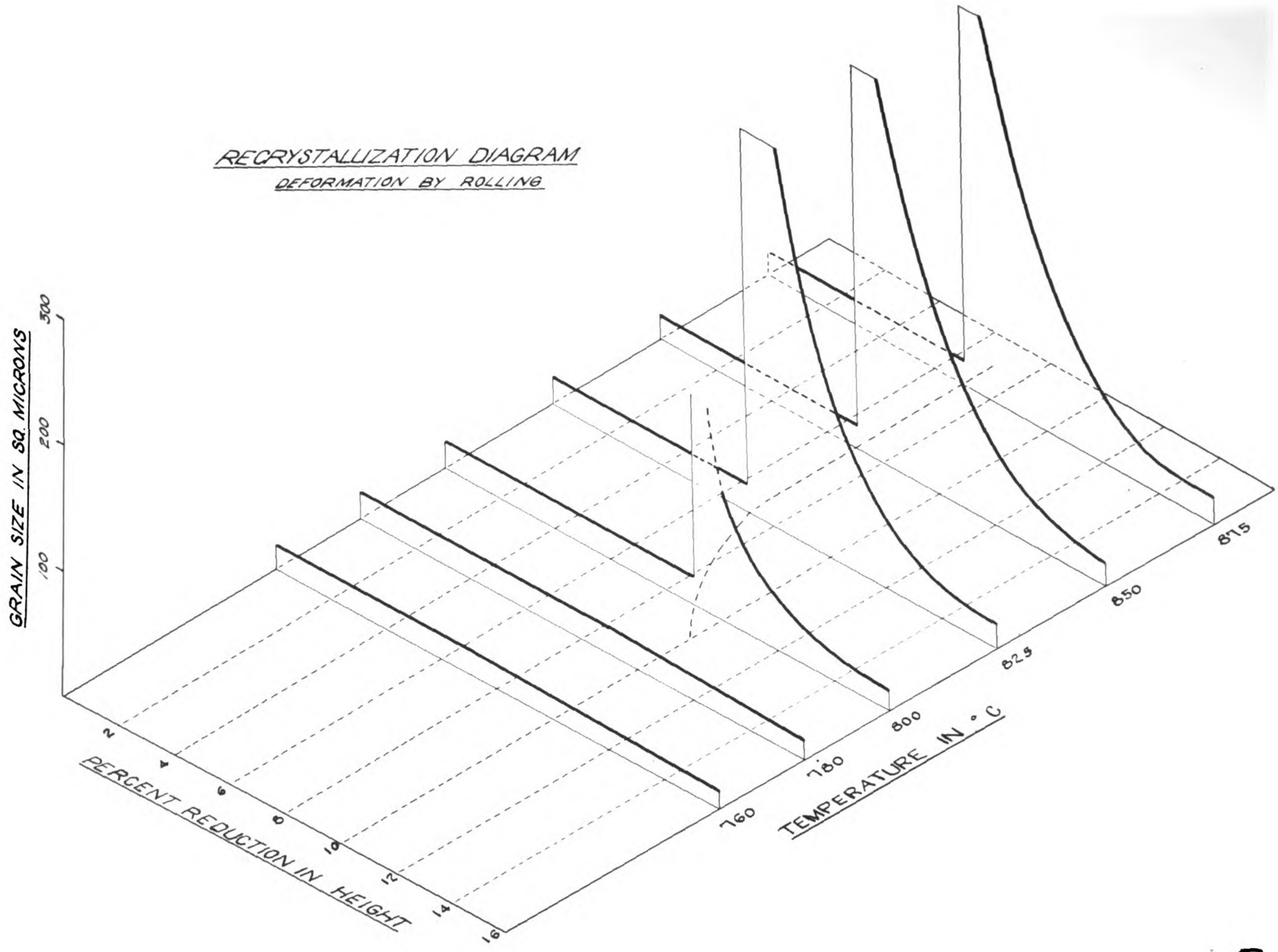

RECRYSTALLIZATION DIAGRAM
DEFORMATION BY ROLLING
GRAIN SIZE IN SQ. MICRONS
100
200
300
PERCENT REDUCTION IN HEIGHT
2
4
6
8
10
12
14
16
TEMPERATURE IN ° C
760
780
800
825
850
875

PLATE 9a

PART II

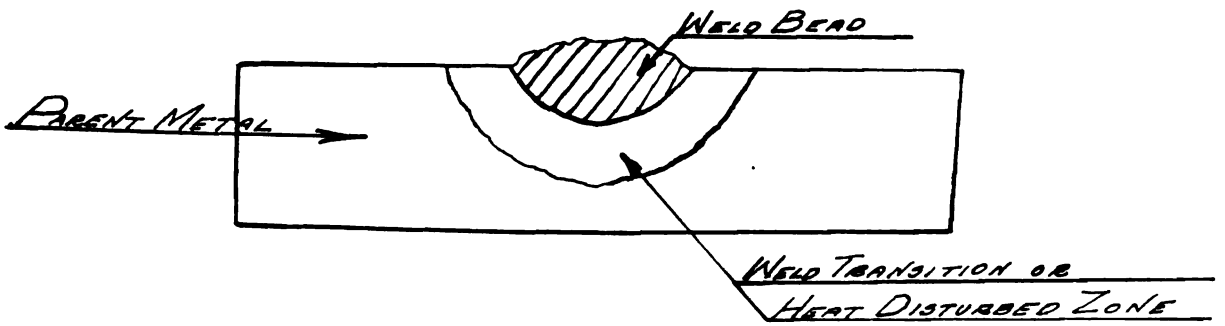
As a supplementary part of the thesis the author thought it might be well to include a certain amount of data and photomicrographs obtained during research on the weldability of iron alloys. A brief history of the problem, together with such of the theory as seems advisable, will also be offered.

The work was done in cooperation with Walter H. Bruckner, now Assistant Metallurgist at the University of Illinois, who at the time was special metallurgist at this Laboratory, and under the direction and supervision of Dr. R.H. Canfield, Superintendent of the Division of Physical Metallurgy and Thermodynamics.

The main aim of the problem was the establishment of a quenching cycle which would accurately duplicate the metal of the transition zone of a weld. This was to be done on a synthetic specimen without an actual weld bead being laid thereon. From preliminary research it had been found by Mr. Bruckner that specimens of the dimension .404" x .207" x 2" were most suitable for the purpose since they could be uniformly heated in 1-1/2 minutes to 1350° C, this temperature being found adequate for obtaining the necessary microstructures.

A diagram showing a welded piece of steel is included below with such nomenclature as to make more clear what is meant by certain terms used hereafter. With reference to this figure a further discussion of

the theories and reasons for the work will be presented.



It can readily be understood that if welding could become universally adaptable it would be an indispensible boon to fabrication concerns and industry in general since a welded joint of comparable strength and wearability with other more ordinary methods of fabrication would often be much desired. It was found, however, that certain metals lent themselves readily to welding with consequent strength, ductility and wearing properties even better than those of the base metal. On the other hand, there appeared many steels which reacted very unsatisfactorily toward welding. The resultant joints often fissured or cracked, were brittle and gave way readily under stresses of even a low order, and in general were certainly not acceptable. It was noticed that breaks and fissuring often occurred in the metal of the heat disturbed, or weld transition zone. It was logical to assume that this took place as a result of embrittlement caused by the brutal treatment received during the laying of the weld bead, and that it no doubt occurred more readily in metals which were extremely sensitive to heat treatments above the critical range of temperatures. The structures resulting in these metals from subjection to intense heat was very often

of a Widmanstaetten nature and thus brittle. The metal in the heat disturbed zone was not burned as proven by a glance at the accompanying photomicrographs but grain sizes were often of an extremely high order as compared to the parent, or undisturbed metal.

As a result of the above observations it was deemed advisable to conduct research along lines that might serve to alleviate this condition of uncertainty. It appeared that the proper lines of attack was the production of a synthetic material which would exhibit structures comparable to those produced in transition zone metal. This procedure was very necessary since enough metal to permit an accurate investigation of the physical and mechanical properties of this critical zone could never be cut from the portion of metal after an actual welding operation. The disturbance is limited to a range less than a quarter inch around the bead in single bead welds using usual welding speeds and base metal of 3/4" or more in thickness.

Plates 1 to 6, inclusive, serve to show photomicrographically the extent of reproducibility of transformation zone microstructures in a synthetic metal by the use of a quenching cycle as explained later*. Wherever typical Widmanstaetten, pearlitic, or martensitic structures, or any combination or decomposition product, were evident in the actual welded plate, duplication was borne out in most cases for the weld-quench specimens. Plates 7 to 11, inclusive, show the effect of variable time in the weld quench test in accordance with the data of Table No. 6. This work was done to investigate the mechanism of the two-stage quench used

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* The synthetic specimens and microstructures will often be referred to as "weld quench specimens" while "welded structures" will be reserved to designate metal of the actual manually welded plate. The weld beads were laid on plates 3" x 6" x 1/2" using 3/16" grade EA, Class 2, heavy coated electrodes and 180-190 amperes, 25-27 volts, at a speed of 6" per minute.

in the weld-quench test and in an effort to either fully substantiate the standard technique in the quenching cycle or to show that some other time factor should be employed.

It is not the purpose of this paper to fully discuss the metallurgical principles and theories behind this work or to present the entire correlated research since that part was done by Mr. Bruckner. The author for the most part was only employed as an aid and the work given herein involves only such as done by him. With this in mind, it will suffice to give only principles as apply fundamentally that a coherent picture may be formulated in the reader's mind and that some meaning may be attached to the photomicrographs.

The establishment of the proper quenching cycle served to evaluate or predict the probable service behavior of rolled steels without being forced to resort to an actual welding operation. The basis, or criterion, of weldability is defined as quench sensitivity since a very drastic quenching action takes place immediately after a weld bead is laid due to the rapid transfer of heat into the large mass of cold parent metal. This, no doubt, was primarily the reason for thinking that a similar welded microstructure could be produced by an artificial quenching of a synthetic material. It is obvious that structures which are sensitive to high temperatures and which possess extreme grain growth susceptibility, would not be the sensible choice if maximum performance under operation was desired.

The photomicrographs included need little more explanation since they serve only the purposes previously mentioned, in some cases indicating very good results while others were less accomodating. The reader is thus left with the task of correlating microstructures with physical properties

as indicated in Table No. 6 if so desired, the paramount reason for including the pictures in the thesis being for comparison of structures of metals of varying compositions together with the methods of producing them. The chemical analyses of the many metals are included in Table No. 1 and are listed as to general type that an idea of microstructure typical of certain classes of steels may be drawn.

Plate No. 12 shows the transformation rate of a material of the composition indicated for item 3. This transformation is only pictured for changes in the first quench at 530° C since reference to the structures shown in Plates 1 to 6 will indicate the ultimate stable microstructure.

The polishing technique involved no unusual features and followed the course of ordinary prescribed methods. The etchant was of the composition known as "Vilellas' Etchant" and was found very efficient. The initial structure appearing with the first etch was polished off and a new surface obtained. It has been found a safe rule never to accept the surface of a specimen as it appears after the first etch but to re-polish and re-etch to see if the identical structure returns. It involves a small amount of extra work but is often very much to be desired.

EXPERIMENTAL

Plate 13 shows the manner of assembling the test specimen preparatory to conducting the quenching operation. Figure 18 shows the detailed dimensions of the half-size Charpy samples used, hardness measurements being taken with a Vicker's Brinell machine on these same specimens after they were broken in the Charpy impact tester. The quenching pieces were machined oversize for testing and subsequently finished to the size and shape shown.

The furnace, shown clearly in Plate 14, is of the Hayes-Globar type equipped with a gas atmosphere which was maintained on the carburizing side of neutral to mitigate excess oxidation at the high temperature employed. The cap, coat, asbestos gloves and goggles were used to protect the operator from burns since plunging the hot specimen quickly into molten caustic caused a very liberal spattering. The quenching assembly, consisting of electrical heating pots and Bristol controllers mounted on a portable chassis, was built by the author to facilitate the program. A stop watch was essential for timing accurately the various stages of the cycle, standardized at

(1) 1-1/2 minutes at 1350° C.

(2) 18 seconds at 530° C.

(3) 24 seconds at 310° C.

(4) Specimen air cooled.

The entire cycle was fully established by Mr. Bruckner and that 1-1/2 minutes in the furnace sufficed to thoroughly heat the sample was proven by means of a #40 Pt - Pt, 10% Rh thermocouple placed in a drilled hole in the center of the specimen. Temperatures were read on a Leeds and Northrup potentiometer. The remainder of the cycle was established by trial and error only after a great deal of research. The composition of the bath at 530° C was of a 50-50 mixture of NaOH-KOH, while the other was a plain NaOH bath.

Figures 14, 15 and 16 serve to show the technique of quenching employed, the last being merely an air cooling gesture, practically conducted by laying the rod on, and overhanging, a steel top table so that the piece was suspended fully in air.

The result of work carried out recently shows that steels of chemistry adverse to good welding under ordinary methods can still be satisfactorily welded if proper attention is paid to pre-heating and post-heating conditions. Time has not permitted a thorough investigation of this phase but it is hoped that future investigation may establish this special technique which could easily be applied to small units, and with proper facilities to quite large ones.

The critical sensitivity range of hardness and impact values beyond which steels can be accurately placed in the difficultly welded class has not yet been established pending results of a related research on fully restraining tests, that is, tests of the rigid frame variety, where each of the two parts to be welded with a multiple bead weld are fastened very tightly to a steel bed frame. This causes any excess warpage or shrinkage due to welding to place a great strain on the joint and accelerate any tendencies toward cracking. It thus serves as an indication of the

ductility and strength of the welded joint and indicates what could be expected under practical conditions.

TABLE 1

CHEMICAL ANALYSES AND HISTORY OF MATERIALS INVESTIGATED FOR WELDABILITY

Item	C	Mn	Si	Ni	Cu	Mo	Cr	V	Cb	History
1	.17	.41	.17							)Silicon-killed, hot rolled steels. Carbon series.
2	.25	.43	.20							)
3	.35	.68	.23							)
4	.44	.65	.24							)
5	.21	.38	.003							)Rimmed heat, hot rolled steels.
6	.27	.47	.002							)
9	.24	.48	.23							)Hot rolled steels, Manganese series.
10	.27	.74	.21							)
11	.29	1.06	.25							)
13	.26	.46	.005							)Hot rolled steels, Silicon series.
14	.28	.54	.058							)
15	.25	.43	.20							)
17	.22	.52	.20			.19				)Hot rolled steels-laboratory heats.
20	.24	.46	.001							)Hot rolled, boiler steels.
22	.18	1.40	.21					.12		)Hot rolled, Mu-V steel.
24	.28	.56	.27	3.57						)Hot rolled, Nickel steels,carbon series, 3-1/2% Nickel.
29	.028	.19		2.08						)Hot rolled-nickel ingot iron.
32	.12	.75	.48				.34			)Hot rolled-low alloy welding steel.
33	.11		.19			.51	5.85			)Hot rolled-low chromium steel modified with
34	.065		.22			.51	5.66		.55	)molybdenum.
35	.27	.69	.20	2.31						)Nickel steel-hot rolled.
B	.26	.64	.20							)Grade M hull plate 1-1/2" thick; nickel steel 1-7/8"
36	.27	.69	.21	2.30						)thick. Hot rolled steels for MASS EFFECT tests.

TABLE 6

EFFECT OF VARIABLE TIME IN WELD QUENCH TEST

Time at 1350° C) Quench was 19 sec. at 530° C
) 24 sec. at 310° C

Item	A9 Samples 50 sec. Half Charpy Impact	A9 Samples 50 sec. Vickers Brinell Hardness	Standard Weld Quench Test 1-1/2 minutes Half Charpy Impact	Standard Weld Quench Test 1-1/2 minutes Vickers Brinell Hardness	A10 Samples 2 minutes Half Charpy Impact	A10 Samples 2 minutes Vickers Brinell Hardness
2	16-1/2	160	15	224	9	248
3	22	221	13	260	3	282
17	26-1/2	170	28	221	20	233
18	17	213	25	246	10-1/2	265
19	20	274	20	267	8-1/2	289
22	7-1/2	245	7-1/2	377	6-1/2	410
24	11-1/2	266	2	450	1	536

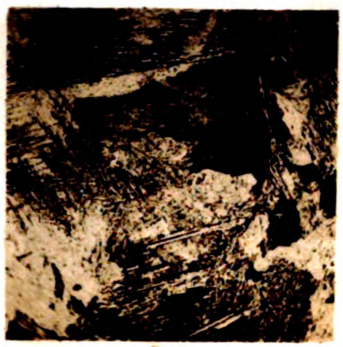
Time in First Quench)1-1/2 min. at 1350° C
)24 sec. in second quench at 310° C

	A11 samples 12 seconds		A12 samples 24 seconds	
2	10	239	13-1/2	237
3	17-1/2	266	15	263
17	23	231	28(L)	220
18	16	281	17-1/2	245
19	14-1/2	323	18	274
22	7-1/2	411	8	362
24	2	487	2	456

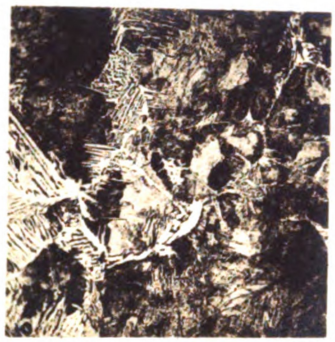
Time in Second Quench)1-1/2 min. at 1350° C
)18 sec. in first quench at 530° C

	A13 samples 12 seconds		A14 samples 36 seconds	
2	13	242	12-1/2	232
3	9	273	9	281
17	27	219	19-1/2	224
18	16-1/2	247	20-1/2	250
19	18	275	17-1/2	281
22	6-1/2	390	6-1/2	389
24	1-1/2	511	2	458

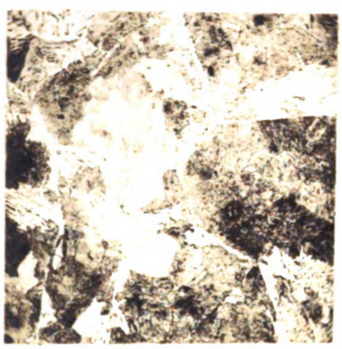
MAGNIFICATION—250 X



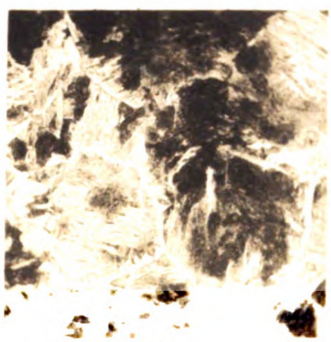
B A



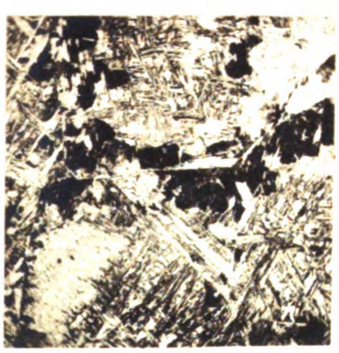
BW3



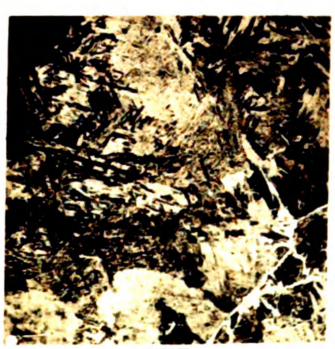
1 A



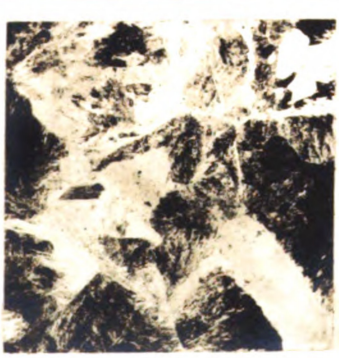
1W3



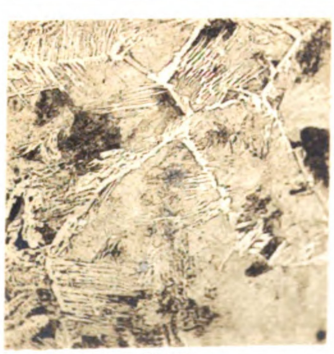
4 A



4W3



5 A



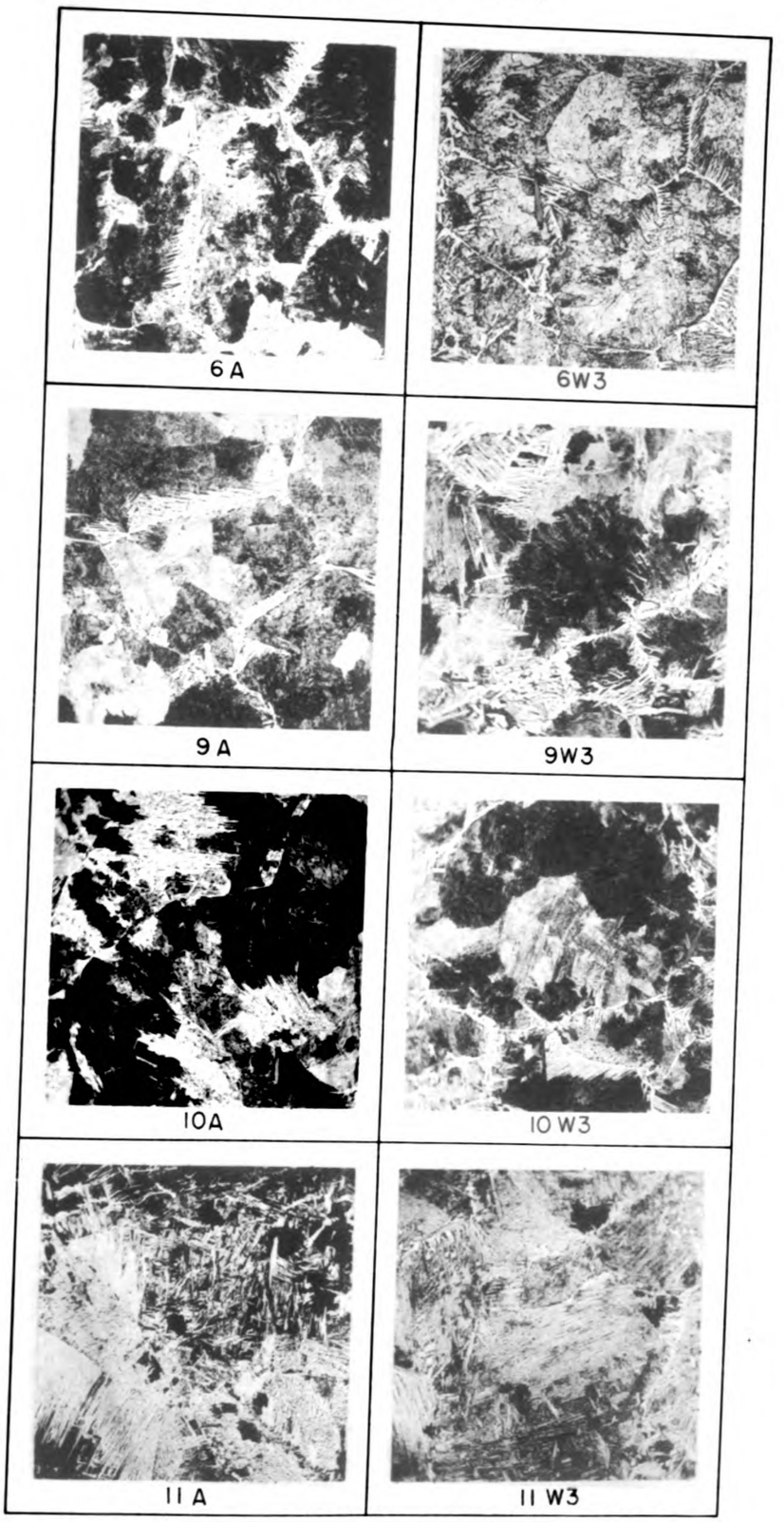
5W3

WELD QUENCH

WELD TRANSITION ZONE

PLATE I

MAGNIFICATION—250X

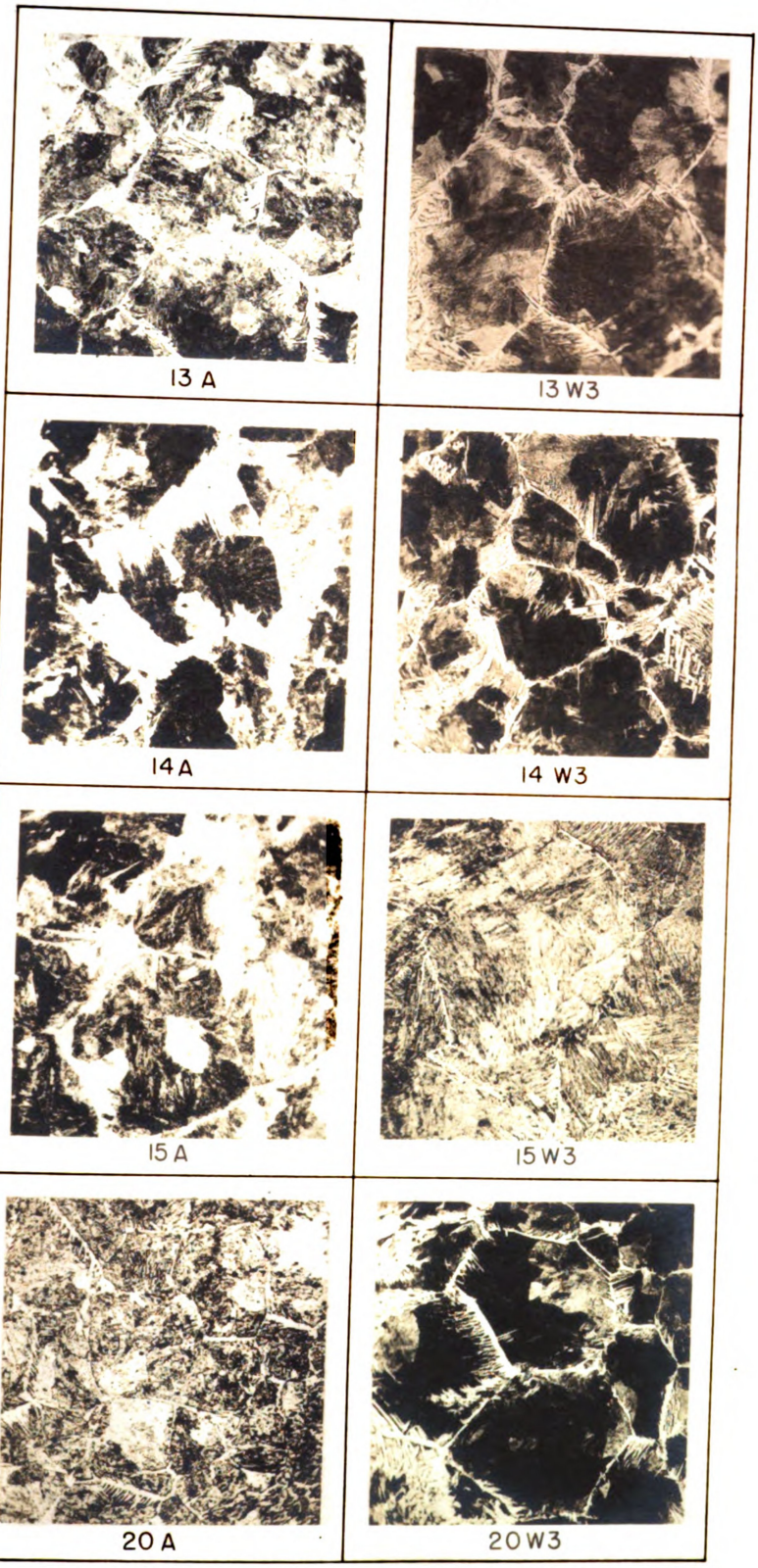


WELD QUENCH

WELD TRANSITION ZONE

PLATE 2

MAGNIFICATION— 250 X

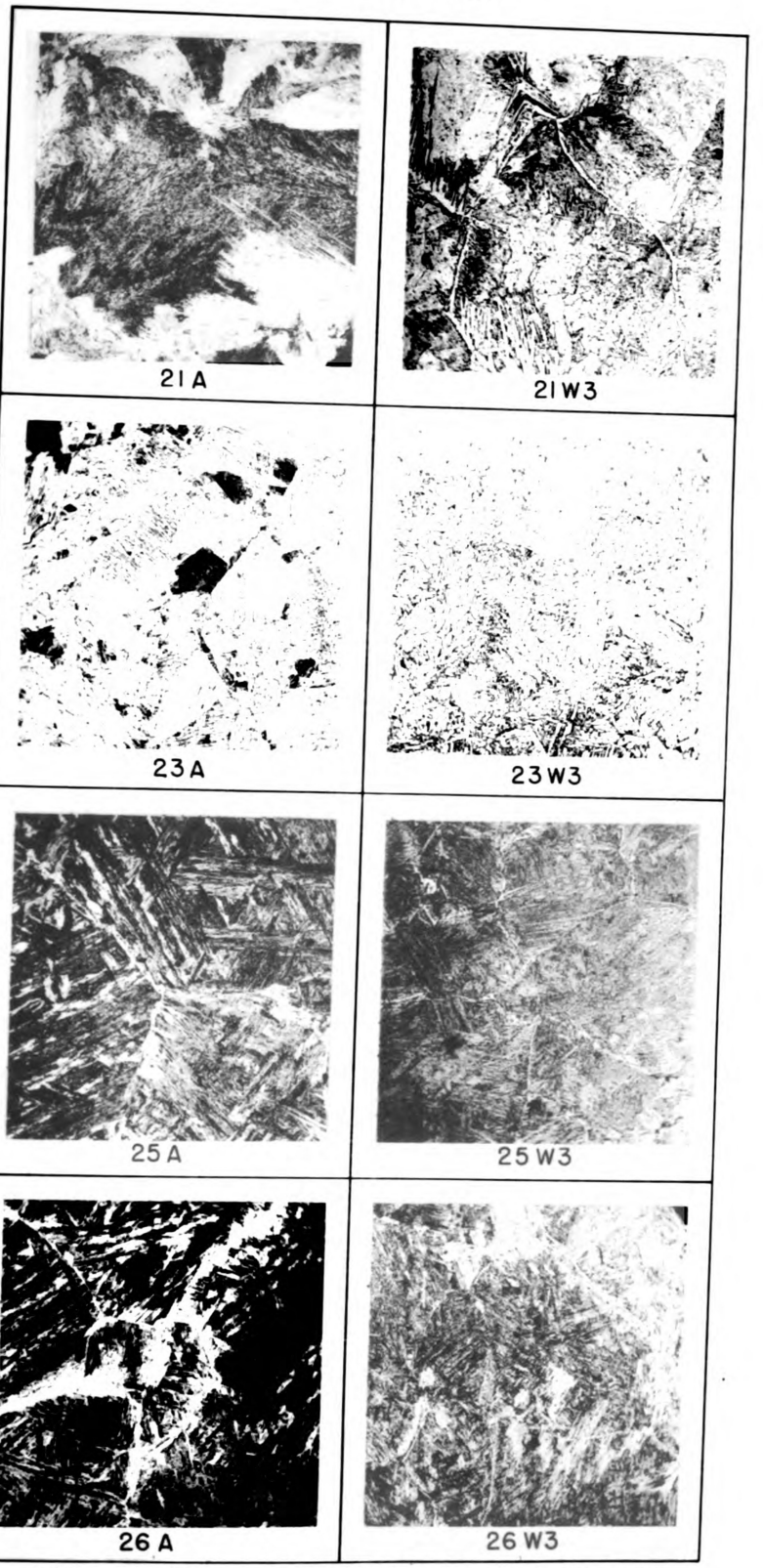


WELD QUENCH

WELD TRANSITION ZONE

PLATE 3

MAGNIFICATION—250 X

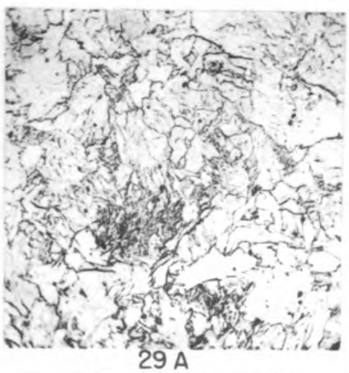


WELD QUENCH

WELD TRANSITION ZONE

PLATE 4

MAGNIFICATION—250 X

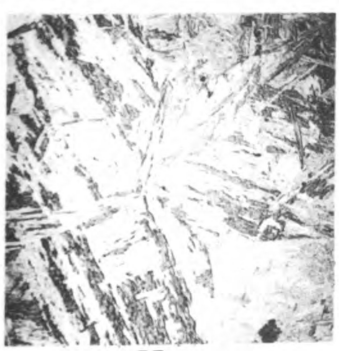


29 A

29 W3

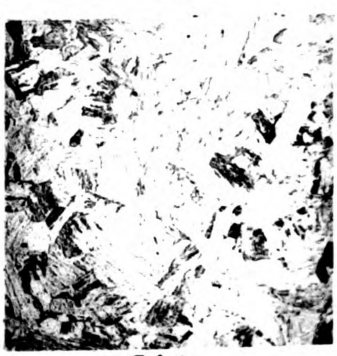
32 A

32 W3

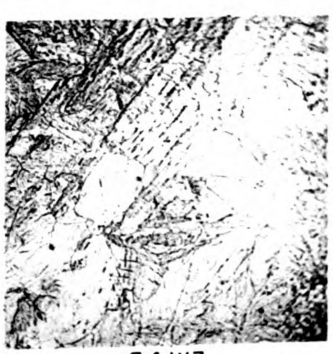


33 A

33 W3



34 A



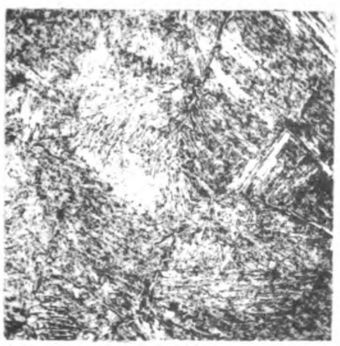
34 W3

WELD QUENCH

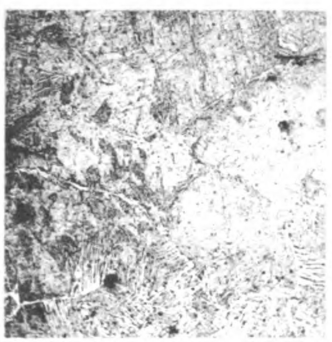
WELD TRANSITION ZONE

PLATE 5

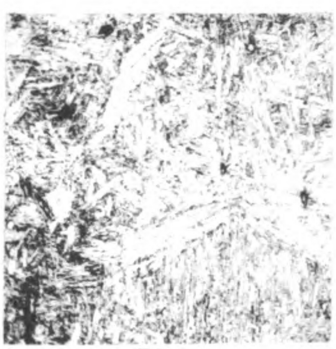
MAGNIFICATION — 250 X



35 A



35 W3



36 A

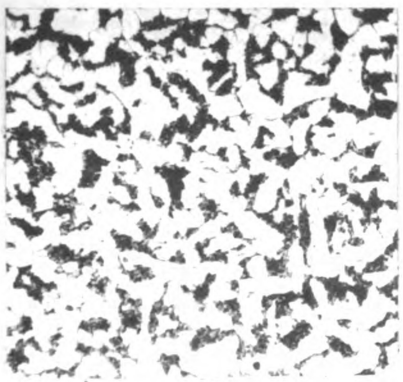
36 W3

WELD QUENCH

WELD TRANSITION ZONE

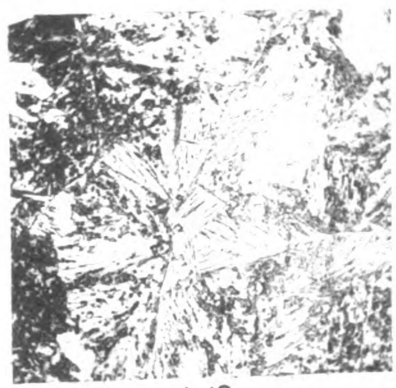
PLATE 6

MAGNIFICATION — 250 X
REFERENCE TABLE NO. 6 – EFFECT OF
VARIABLE TIME IN WELD QUENCH TEST.
ITEM 2


A 9


A 10


A 11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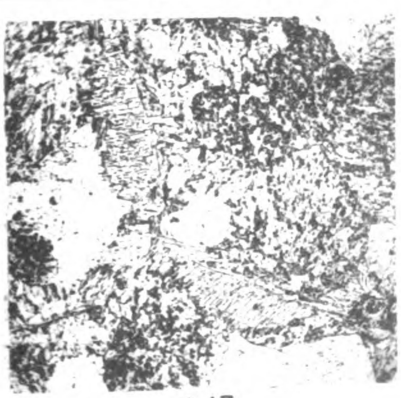
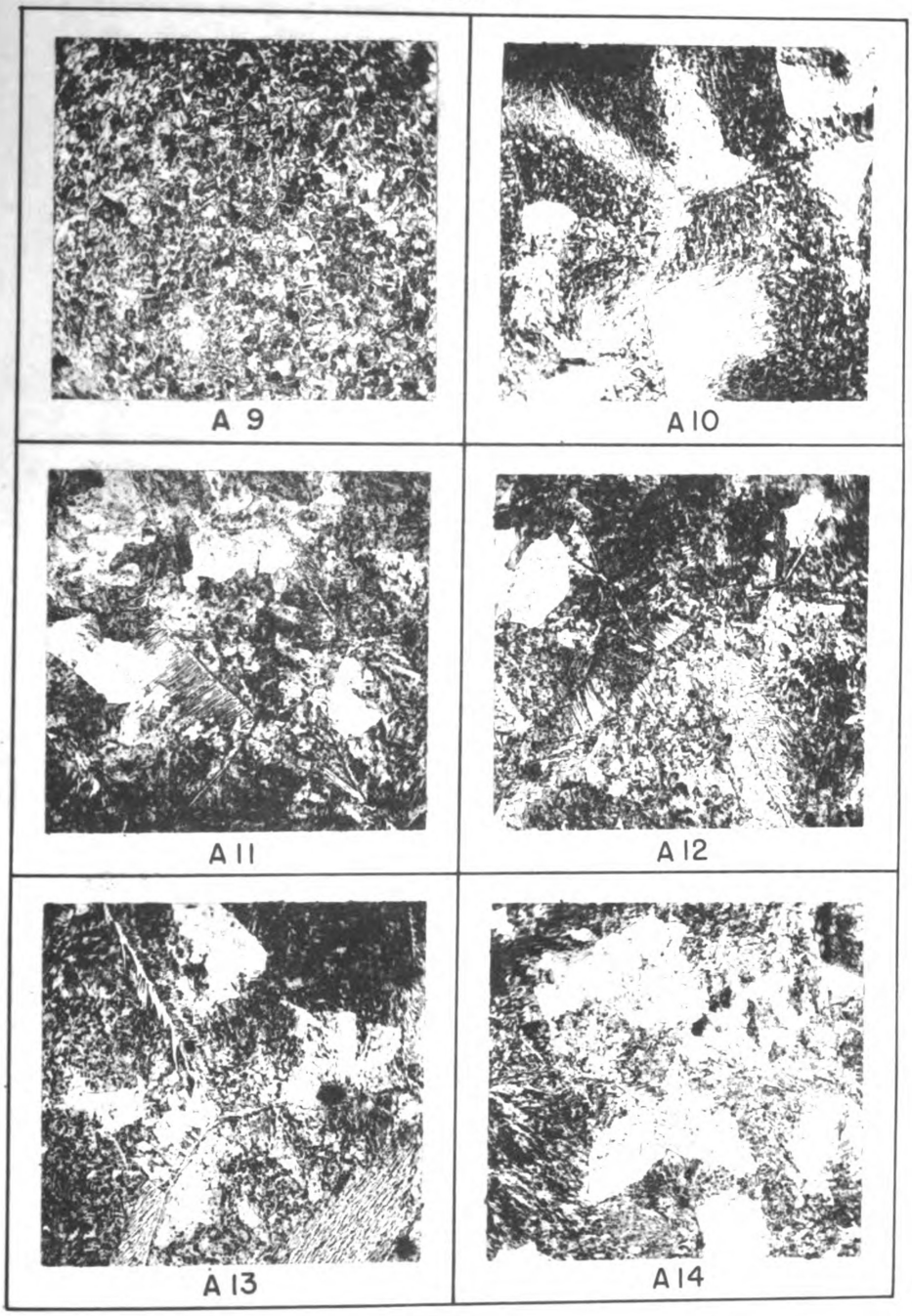

A 13


A 14

PLATE 7

MAGNIFICATION—250 X
REFERENCE TABLE NO. 6—EFFECT OF
VARIABLE TIME IN WELD QUENCH TEST.
ITEM 3



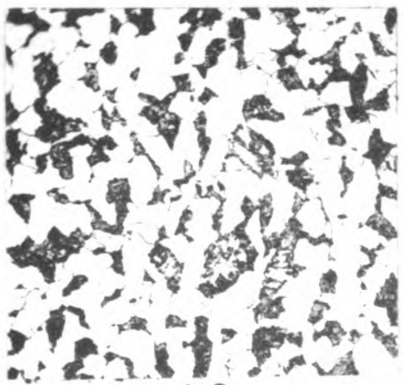
A 9 A 10

A 11 A 12

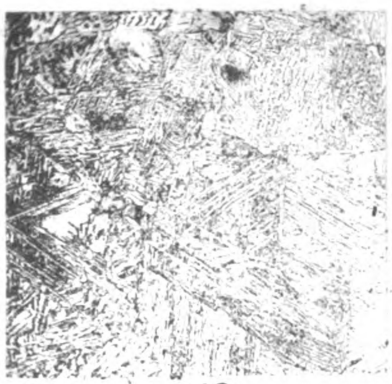
A 13 A 14

PLATE 8

MAGNIFICATION — 250 X
REFERENCE TABLE NO. 6 — EFFECT OF
VARIABLE TIME IN WELD QUENCH TEST.
ITEM 17



A 9



A 10

A 11

A 12

A 13

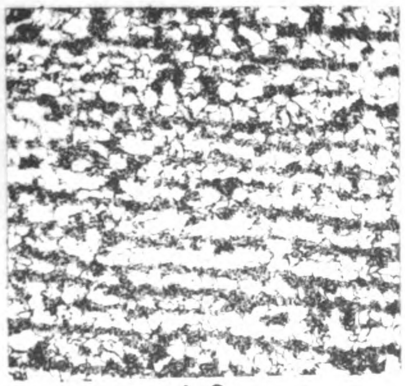
A 14

PLATE 9

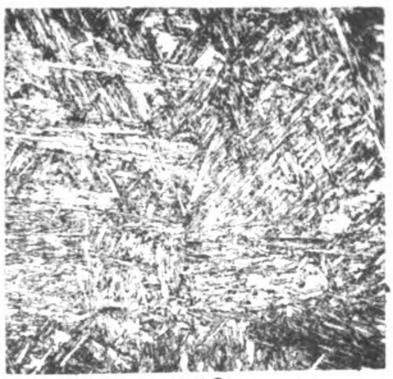
MAGNIFICATION — 250 X

REFERENCE TABLE NO. 6 — EFFECT OF VARIABLE TIME IN WELD QUENCH TEST.

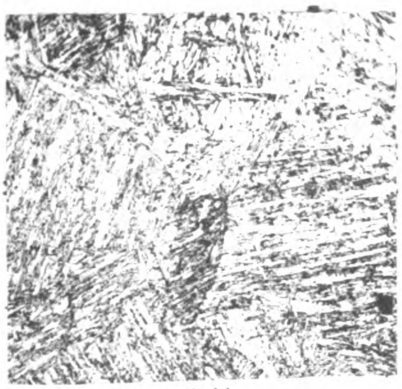
ITEM 22



A 9

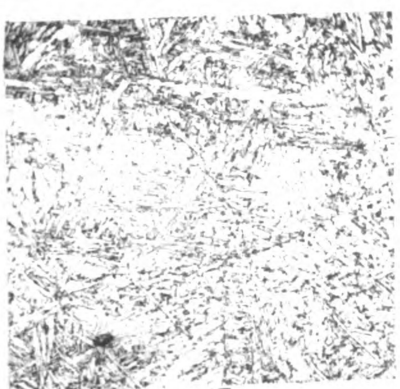


A 10

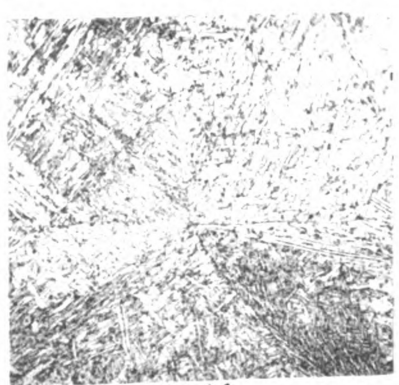


A 11

A 12



A 13



A 14

PLATE 10

MAGNIFICATION—250 X
REFERENCE TABLE NO. 6—EFFECT OF
VARIABLE TIME IN WELD QUENCH TEST.
ITEM 24

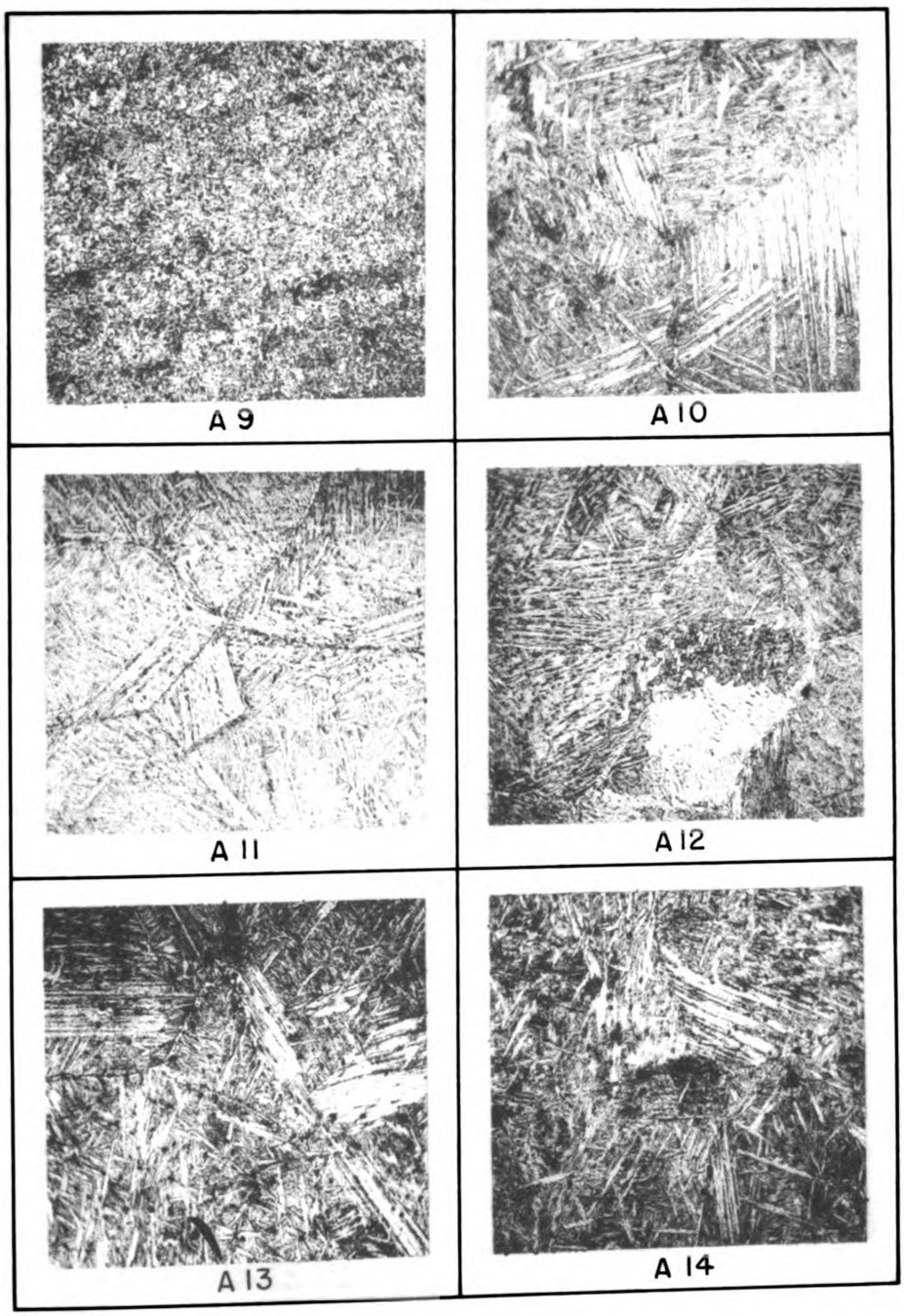
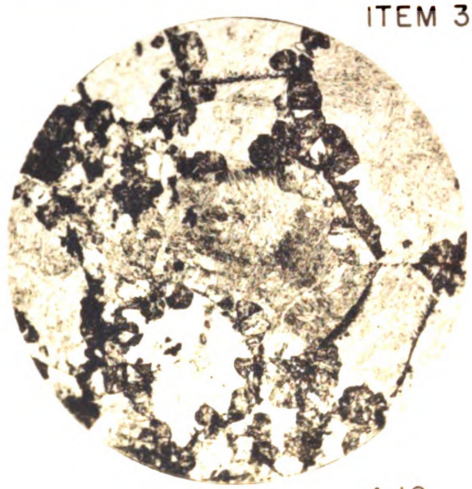


PLATE II

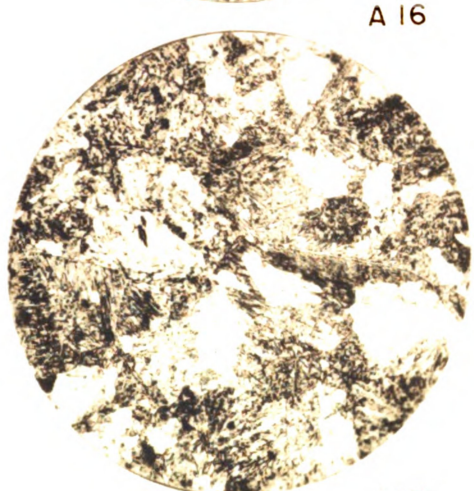
MAGNIFICATION— 150 X

REFERENCE TABLE NO. 7– TRANSFORMATION RATE IN FIRST STAGE OF WELD QUENCH TEST.

ITEM 3



A 16



A 17

A 18

PLATE 12

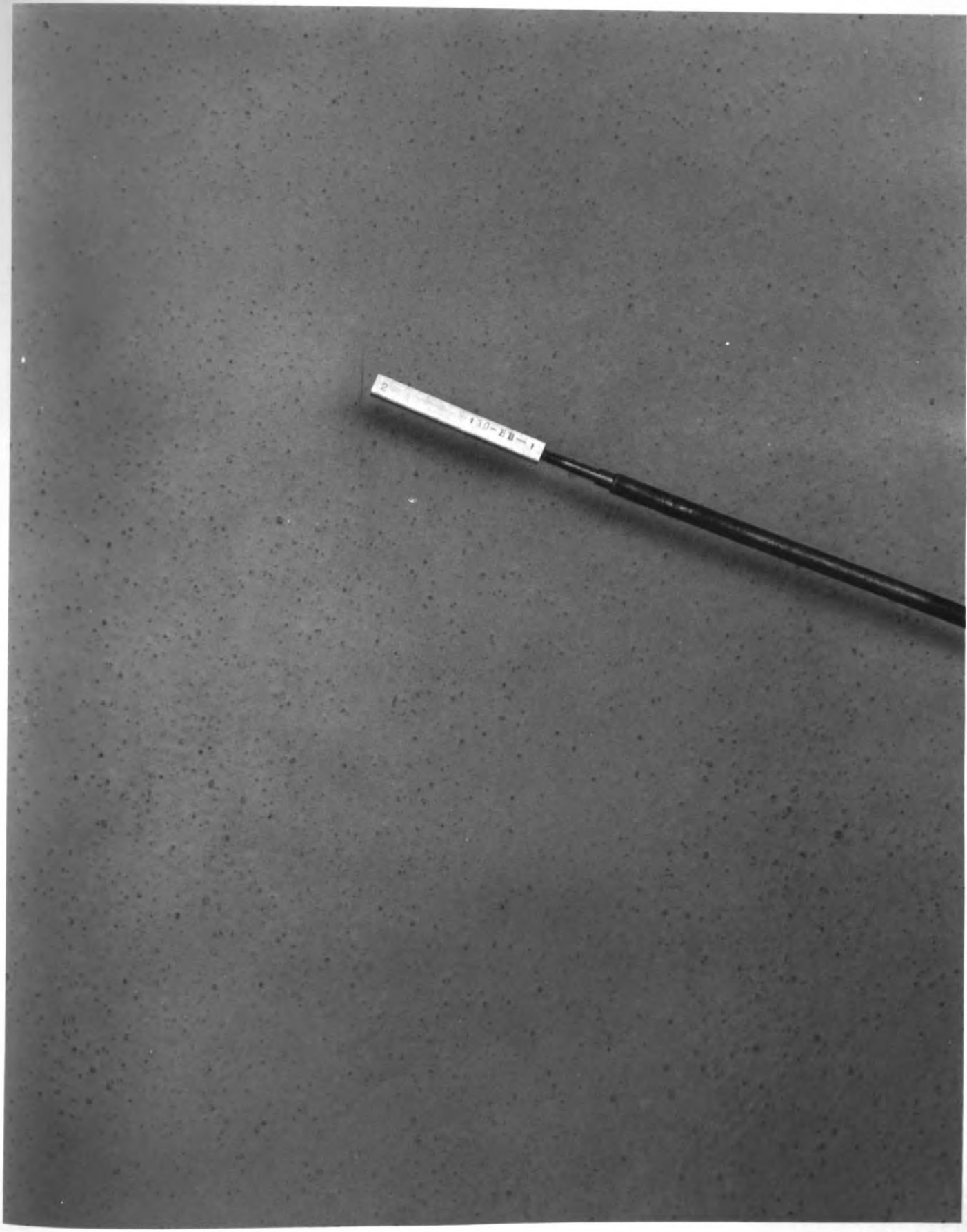


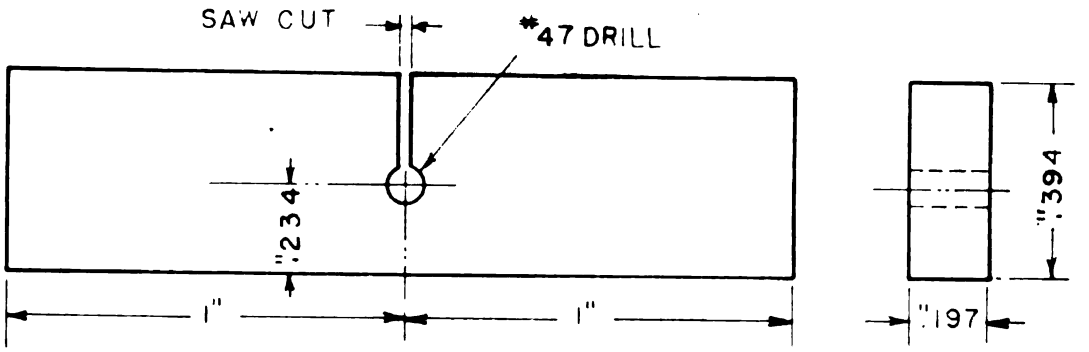
PLATE 13

PLATE 1-

PLATE 16

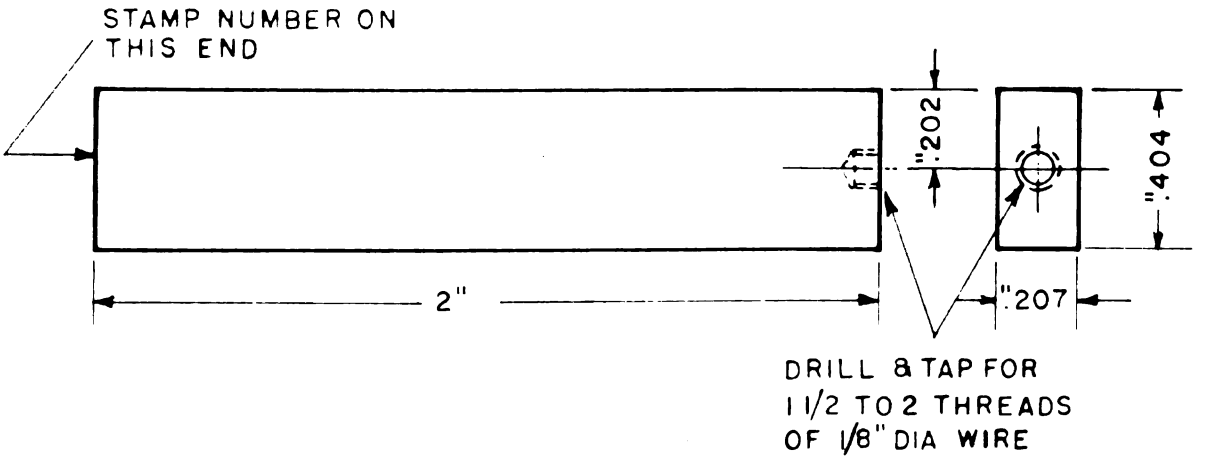
PLATE 17

HALF CHARPY SPECIMEN FOR IMPACT TEST OF "AS RECEIVED" MATERIAL

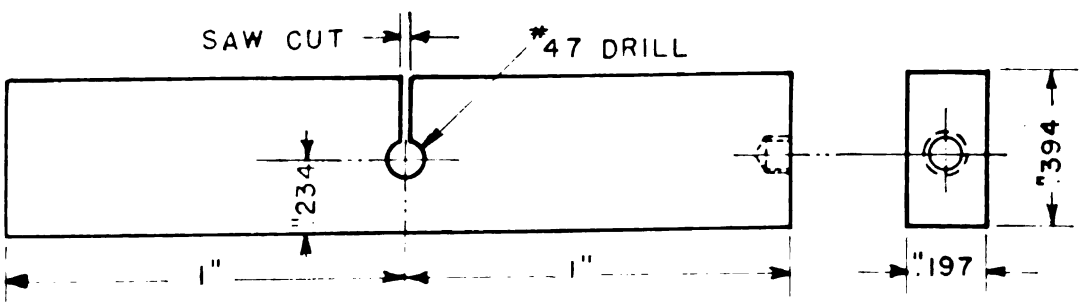


NOTE THAT 2" LENGTH IS IN DIRECTION OF ROLLING AND ".394 WIDTH IS IN DIRECTION OF PLATE THICKNESS

HALF CHARPY SPECIMEN FOR WELD QUENCH TEST BEFORE HEAT TREATMENT



HALF CHARPY SPECIMEN PREPARED FOR IMPACT TEST AFTER WELD QUENCH HEAT TREATMENT



ROOM USE ONLY