"THE EFFECT OF TIME ON ISOTHERMAL DECOMPOSITION OF RETAINED AUSTENITE IN CASE CARBURIZED LOW ALLOY STEELS IN THE RANGE 450° TO 800° FAHRENHEIT"

Thesis for the Degree of M. S.

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Donald Adrian Bergh

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This is to certify that the

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" THE EFFECT OF TIME ON THE ISOTHERMAL
DECOMPOSITION OF RETAINED AUSTENITE
IN CASE CARBURIZED LOW ALLOY STEELS
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Donald Adrian Bergh

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R. L. Sweet
Major professor

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By

Donald Adrian Bergh

Submitted to the School of Graduate Studies of Michigan
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INTRODUCTION

Austenite, so named by Osmond in honor of the late Sir William Roberts-Austen, is a solid solution in which face-centered cubic gamma iron is the solvent and carbon is the solute. (16, 1) The solid solution austenite is formed by heating a steel containing between 0.03% and 1.7% carbon to the austenitizing temperature. This austenitizing temperature is influenced by the alloys added to the steel and varies from 1330°F. for eutectoid steels to 2075°F. for hyper-eutectoid steels. The austenitic range is important because practically all heat treating starts from this solid solution range.

Retained austenite, the austenite remaining at room temperature after rapid cooling, is very detrimental due to its soft and plastic nature when found with hard martensite, which is the rapid transformation product. The subject of retained austenite reached new importance during the war and in recent years has been very carefully studied. (21, 14) The decomposition products have been classified in three general groupings--pearlite, bainite, and martensite. Of the three decomposition products only bainite has received scant attention.

Some of the factors affecting the retention of austenite are as follows:

(1) Carbon content

(2) Quenching rate (quenching media)

(3) Austenitizing temperature

(4) Sub-atmospheric cooling

(5) Cold working

(6) Tempering temperature and time at temperature

(7) Alloy Content

(8) Stress conditions

This retention was first noted in the higher alloy steels--especially those containing high manganese, nickel and chromium. This untransformed product or retained austenite problem has been attacked from many angles. Investigation with a Tukon micro-hardness tester and many types of quantitative analysis have been tried. Some of the study methods used are dilatometric, magnetic (20-25), electrical resistance (24), X-ray (6), specific volume changes, hardness, and a combination photographic point counting and lineal analysis (23).

The first investigators thought that more austenite was retained when the more drastic quenches were used. However Saveur noted nearly twenty years ago that oil quenches seem to give more of the untransformed product (17). Many investigators noted that quenches near the critical cooling rate or those that were just fast enough to yield all martensite gave the largest amounts of the retained austenite.

The suggested explanation for this phenomenon was based primarily on the effect of stresses and stress distribution during quenching. This being a very controversal problem, the ideas presented have been numerous. Since austenite has a greater density than martensite, compressive stress should promote the retention of austenite while tensional stress will promote its decomposition. However all evidence does not support this view; it has been shown that oil quenching leaves more austenite at the center while water quenching retains more on the outside surface. (30) Still Scott reasons that oil quenching allows the martensite to temper while cooling, which allows it to contract and thus sets up compressive and tension stresses. This holds up the austenite transformation. Epstein feels that water quenching sets up sharper temperature gradients giving rise to higher thermal stresses and greater deformations which tend to promote the transformation of austenite. (30)

Early investigators noted that austenite was usually retained with high carbon and alloy content. However X-ray studies by Wever and Engel showed cubic faced-centered austenite in 0.6% carbon. Davenport and Bain reported austenite present at 0.54 percent carbon, while Tamaru and Sekito also using X-rays found evidence of retained austenite at 0.4% carbon. However nearly all investigators reported very minute amounts at these lower percentages and indicated that as carbon percent increases the percent of retained austenite is greater. (30)

Many previous and all the present investigators also found that retained austenite was found in greater amounts when cooled just above the critical cooling rate. Therefore oil quenches always gave more retained austenite than water quenches. When quenches were rapid enough to cause cracking no austenite was retained. This cracking is due to stresses set up upon quenching and when the cracking starts the structures seem to be relieved of their internal stress and all austenite changes to martensite. However this cracking also depends to some extent upon M_s or the starting temperature for the martensite formation. M_s is in turn a function of the alloy content, and does not vary with the austenizing temperature. Higher temperatures for quenching indicate smaller amounts of retained austenite (30-31).

Sub-atmospheric cooling tends to decompose some of the retained austenite. The amount decomposed depends upon the time the specimen was at room temperature, the quenching temperature, and temperature of the subcooling (7-30). Tammann and Scheil found that transformation starts at -20°C. (40°F.) for a 1.7 plain carbon steel and that nothing happens again until the temperature is lowered. Gordon and Cohen indicate that stopping the quench at room temperature seems to stabilize the austenite and that the longer it is held at room temperature the smaller is the amount that transforms on cooling to -310°F. They also have dilatometer, magnetic and specific volume data which indicates this stabilization for approximately three minutes at room temperature. Here again it was indicated by Krivobok and Gensamer that the change of austenite to martensite takes place through the strains which arise. All indicators are that cold working the steel tends to cause decomposition of the retained austenite. Here again the internal stresses are great after deformation (30-7).

In transforming retained austenite, Dowel, Harder, and Van Vleet and Upthegrove (33) state that in most cases the retained austenite decomposes to a martensite which is very similar to martensite before going forward with the transformation. Chevanard and Portevin (34) believed that the austenite decomposed to cementite and an austenite with less carbon; however, more recent data by Antia and Cohen (32) states that austenite decomposes to an acicular transition precipitate (33-32-30). Honda and Nishiyama (32) also showed that with change from tetragonal martensite to a cubic form of martensite there was a definite switch of the position of the carbon atom. However Hagg indicates that a cubic form of martensite is hard to discern with X-ray and Cohen points out β -martensite is harder than the original tetragonal α -martensite. There has been a great deal of discussion about β -martensite and a number of recent investigators wish to refer to this product as cubic ferrite plus cementite. This formation is also accompanied by a transition precipitate which accounts for the darkening of the original martensite (32-33).

The second step of tempering, presumed to be the step where austenite decomposes, occurs at about 450 to 550°F. The decrease in the intensity of austenite diffraction lines in this range seems to verify this point. This decomposition can take place either isothermally or upon heating through this range. The product appears to be somewhat similar to a bainitic structure and shows no curie point until nearly all austenite is decomposed. This would indicate that this product is not a ferrite-cementite mixture. It is more of a bainitic structure. However to call it a secondary martensite product may be off, as 450°-550°F. is well above the formation point of martensite and by now the structure has softened up quite a little. However there are indications of secondary hardening in high alloy steels due to the decomposition of austenite. (32-33)

The third stage in tempering which occupies the range of 550°F to 750°F. is fundamentally the cementite formation range. The microstructure indicates that cementite particles develop and grow out of the decomposition products of austenite and martensite. This would indicate that ferrite and cementite develop over both a period of time and temperature range.

Much of the softening going on around the first and second stages is thought to be due to stress relief, as both are hardening reactions. These facts are borne out by magnetic change in cyclic heating and by checking the magnetic field reading of steels having varying amounts of retained austenite and martensite. Those having the most martensite showed the bigger changes in reading, indicating more stress relief since there is no structual change.

Properties of steels containing retained austenite have not had too much attention; the results usually looked on as unpredictable. However French says that small amounts up to 5% retained austenite did improve the endurance limit and resistance to overstress. He considered the austenite to having a cushioning effect. He also indicated that high carbon manganese and nickel tend to give a structure of nearly all retained austenite (30).

In this paper the primary purpose is to discover how long it takes retained austenite formed in carburized low alloy steels to decompose isothermally in certain temperature ranges and to record these changes in both structure and percent by means of photomicrographs.

EXPERIMENTAL PROCEDURE

Part 1

Determination of Carbon in Case

Five steels were chosen for the experimental work, one plain carbon S.A.E. 1010 and four low alloy steels: S.A.E. 2015, 2340, 3145, and 4640. The analysis of the five steels are as follows:

Table I

		C	Mn	P	S	Cr	Ni	Mo
S.A.E.	1010	0.15	0.55	0.016	0.045			
S.A.E.	2015	0.33	0.54	0.017	0.024	0.33	0.73	
S.A.E.	2340	0.297	0.71	0.011	0.017	0.22	3.42	
S.A.E.	3145	0.40	0.72	0.016	0.020	0.69	1.39	
S.A.E.	4640	0.40	0.65				1.82	0.25

The bars were cut to six inches, center drilled and then turned to the largest possible diameter which would give a taper of no more than 0.001 of an inch from one end to the other. This was checked with taper gages and the lathe was recentered before the operation.

The carburizing was done in a 3.00 inch steel pipe carburizing bomb, using a commercial solid carburizing mixture. The bomb was developed with the idea of checking time and temperature lags. A one-half inch pipe (welded together on the internal side) was in turn welded through one of the ends of the bomb so that a thermocouple could be placed into the center of the bomb and readings taken to check (1) the temperature of the bomb vs the furnace and (2) the time lag that is taken for the bomb to come to temperature. Later a hole was drilled next to the pipe and the thermocouple fastened to the bars to see if the bar temperature and lag were the same as the bomb temperature and lag (see Figure 1).

The analysis of the commercial carburizer may be found in Table 2.

Table 2

Ba CO_3	10—12%
Na_2CO_3	2— 3%
Ca_2CO_3	2— 3%
Coke	25—30%
Charcoals (Type F.S.R.)	Balance

The bars were carburized in groups of two each except for the 4640 bar which was much larger. The bars were carefully placed in the bomb in such a manner as to give an evenly distributed case to all areas. The bomb was sealed and placed in a muffle type furnace which was controlled at 1725-1735°F. The lag in the 3.00 inch bomb was about one hour and the difference of temperature between bar and furnace was about 25°F. for several hours. The cycle of carburizing was about 16 hours with three hours being allowed for heating the furnace to 1725°F. After 13 hours at 1725°F. the furnace was turned off and the bomb allowed to cool to room temperature in the furnace.

The carburized bars were then placed on the lathe centers again and checked for possible warping by use of the dial indicator. If the bars had warped slightly they were aligned again by proper hammering on the lathe centers. The larger bars showed very little warping. After thorough checking by the dial indicator the bars were ready to be machined. The tool was ground with a negative rake to give finer shorter ships, and the bar was thoroughly washed with alcohol and also parts of the lathe, tool rest, and tool. The entire length of the bar was turned except the stud which was used for heat treating and metallographic specimens.

The chips were collected free of oil and dirt in a specially prepared cardboard box. The first cut was 0.002 of an inch and the rest were 0.005 of an inch until the core was reached. Each cutting was placed in a properly labled envelope which was designated both by tool rest travel and by the change of diameter of the bar. Bar diameters were determined by micrometer readings.

The steel chips were analyzed for carbon content in a carbon train (see Figure 2). The carbon train was checked by using Bureau of Standard samples and the results were very good being well within the allowable error of ± 0.03 percent (slide rule error). The steel chips were now analyzed for carbon content in a carbon train. The graph of carbon content vs. distance from edge gives a good indication of the carbon gradient and depth of case.

Part 2

The studs which were all between 0.8 and 1.0 inch long were cut into 0.4-0.5 inch pieces and then quartered across the case. These specimens were now divided into two groups each having an equal number of samples of the five steels. After carefully marking they were heated to 1725°F. throughout, and four samples of each steel quenched into both agitated heated water (120°F.) and agitated heated oil (130°F.). All of the specimens were tempered for 1.5 hours at 400°F., except the S.A.E. 4640 which showed some decomposition at 400°F. However 1.5 hours at 350°F. gave the desired transformation of the tetragonal martensite to a dark etching constitutent in the S.A.E. 4640 steel. The samples were mounted in steel clamps, very carefully rough ground on the emery wheel, the three stages of the belt grinder, and the #400 wet emery paper. Polishing was completed roughly in four steps depending upon the scratches which were present. First after careful cleansing of the clamp and sample in water and alcohol, the lead lap was resurfaced and impregnated with 302½ Buehler lapping compound. The sample was carefully polished until the entire edge near the case was flush with the clamp. Best results were obtained with lead lap when polishing was completed simultaneously with the drying up of the wheel. The lowest possible number of revolutions per minute of the slow speed wheel was used.

The second step involves polishing with #1576 microcloth and #1549 micropolish. The micropolish gives variable results depending upon the quantity of polish on cloth and amount.of knap on cloth. Best results were obtained on these edge polishes by using worn knaps and pasty micropolish before the first etch with 3% nital. However just before the second etch usually about five seconds on the wheel with very little micropolish present gave the best results. To test the validity of the etch, each specimen was polished and etched at least twice with 3% nital before taking the final photomicrograph at 1500 diameters. In order to keep photographing the same area continuously it was necessary to mark the surface with a hardened tool steel scribe, or use tukon hardness tester points with a 20 gram load. At 600°F. and 800°F. tempering treatments it was necessary to start on the lead lap after each tempering interval, thus it was necessary to notch the specimen on the edge of the cases. Photomicrographs of the 5 steels were taken at intervals developed through experience for each tempering range. The first picture was taken in the as-received condition, the second after blackening the tetragonal martensite at 350 deg. F. for 1.5 hours in the lead bath, and the rest at 1, 5, 10, 15, and 20 minute intervals for the 450 deg. F. treatment (see Figure 3). At 600°F. and 800°F. the intervals were much shorter using 30 seconds and of this interval 20-25 seconds were involved in coming to the constant temperature of the lead bath. These times varied depending upon the specimen size and were checked by drilling holes into the sample and placing the thermocouple inside. Alundum cement was placed around the bottom insulation piece and allowed to dry for two days over a steam radiator. Then it was immersed in the lead and the time recorded to reach nine tenths of the lead-bath temperature and the final temperature. It took about 15-17 seconds to reach this first temperature and 5-10 seconds more to reach the lead-bath temperature. After finding the row of marks all pictures were taken in the area of heaviest austenite concentration and at a standard interval from the edge (0.20 mm). The metallograph was set with a constant field and aperture opening to give better time adjustments and similar contrasts.

The method of "Point Counting" was used to determine the quantity of retained austenite present after the individual heat treatments. The method consists of placing a grid on top of the plate and then over exposing the plate to give a good black and white contrast. The next step involves counting the number of intersections of the white and then checking these against counting the black intersections. The value obtained is the number of points per square inch which in turn can be transferred to percent of retained austenite for that particular square inch by a simple formula.

$$\frac{(\text{No of points showing austenite per sq. inch})\ (100\%)}{\text{Total points per sq. inch}}$$

$$= \text{Percent austenite in area}$$

Graphs of temperature vs. log of time were plotted to indicate graphically the positions of different percents of retained austenite at the various temperatures.

FIGURE 1

The apparatus used for the carburizing of the steels

KEY

A- 3" pipe

B- Furnace

C- Potentiometer

D- Internally welded 1/2 " pipe

E- Bench

FIGURE 2

The apparatus use for the carbon determinations

KEY

A- Oxygen supply tank

B- Gas pressure regulator

C- Combustion furnace

D- Oxygen washing bottle (conc. H_2SO_4)

E- Ascarite tube (CO_2 removal)

F- Combustion tube

G- Zinc pellets

H- CO_2 and O_2 washing bottle (conc. H_2SO_4 and Cr O_3)

I- CO_2 and O_2 washing bottle (conc. H_2SO_4)

J- Ascarite weighing bottle

K- Balancing Bottle

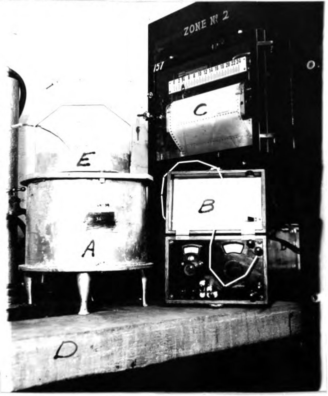
L- Bench

M- Alundum and ascarite bottle

N- Nickle boats

FIGURE 3

The apparatus used for tempering steels



KEY

A- Furnace (lead bath)

B- Manually controlled potentiometer

C- Brown automatic potentiometer

D- Bench

E- Cover

EXPERIMENTAL RESULTS

The experimental results were divided into two major divisions:

Part 1

(a) Carbon gradient data for carburized SAE 1010, 2015, 2340, 3145, and 4640

(b) Graphs of the data for the five steels listed

Part 2

(a) Photomicrographs of listed steels at 1500 diameters

(b) Isothermal decomposition data for the various steels

(c) Graphs of the isothermal decomposition data

Table 3

Data of Carbon Gradient in Carburized

SAE 1010 Steel

Cut No.	Feed Readings In Inches *	Sample Wt. Grams	Grams Wt. CO_2	% Carbon
1	.130 - .135	0.6	0.0289	1.345
2	.140	0.6	0.0257	1.165
3	.145	0.7	0.0253	1.03
4	.150	0.7	0.0280	1.08
5	.155	0.7	0.0242	0.940
6	.60	0.7	0.0218	0.845
7	.165	0.7	0.0185	0.722
8	.170	1.5	0.0199	0.362
9	.175	1.5	0.0265	0.482
10	.180	1.5	0.0178	0.323
11	.185	1.5	0.0105	0.296

* All readings were checked with a micrometer.

Table 4

Data of Carbon Gradient in Carburized

SAE 2015 Steel

Cut No.	Reading of Micrometer In Inches *	Sample Wt. Grams	Wt. CO_2 Grams	% Carbon
1	.577 - .566	1	0.0444	1.195
2	.557	1	0.0362	0.986
3	.549	1	0.0360	0.978
4	.539	1	0.0329	0.895
5	.530	1	0.0305	0.829
6	.523	1	0.0288	0.783
7	.511	1	0.0262	0.713
8	.502	1	0.0232	0.632
9	.495	1	0.0229	0.621
10	.486	1	0.0205	0.558
11	.480	1	0.0166	0.452

* Diameter Change Of Bar

Table 5

Data of Carbon Gradient in Carburized

SAE 3145 Steel

Cut No.	Reading of Micrometer In Inches *	Sample Wt. Grams	Wt. CO_2 Grams	% Carbon
1	.688 - .681	1	0.0548	1.49
2	.664	1	0.0401	1.09
3	.653	1	0.0391	1.063
4	.644	1	0.0360	0.978
5	.640	1	0.0324	0.882
6	.629	1	0.0318	0.865
7	.621	1	0.0287	0.782
8	.612	1	0.0259	0.704
9	.604	1	0.0246	0.669
10	.597	1	0.0222	0.604
11	.589	1	0.0205	0.557
12	.579	1	0.184	0.501

* Diameter Change In Bar

Table 6

Data of Carbon Gradient In Carburized

SAE 2340 Steel

Cut No.	Reading of Micrometer In Inches *	Sample Wt. Grams	Wt. CO_2 Grams	% Carbon
1	.580 - .570	0.7	0.0298	1.160
2	.560	0.7	0.0340	1.320
3	.550	1	0.0426	1.060
4	.540	1	0.0357	0.961
5	.530	1	0.0255	0.694
6	.521	1	0.0253	0.688
7	.511	1	0.0244	0.664
8	.502	1	0.0218	0.594
9	.491	1	0.0172	0.467
10	.480	1	0.0170	0.462
11	.470	1	0.0160	0.435
12	.460	1	0.0147	0.40
13	.450	1	0.0110	0.30

* Diameter Change in Bar

Table 7

Data of Carbon Gradient In Carburized

SAE 4640 Steel

Cut No.	Reading of Micrometer In Inches *	Sample Wt. Grams	Wt. CO_2 Grams	% Carbon
1	1.011 - .969**	1	0.0339	0.924
2	.966	1	0.0327	0.891
3	.956	1	0.0246	0.670
4	.946	1	0.0196	0.534
5	.937	1	0.0193	0.525
6	.927	1	0.0156	0.425

* Diameter Change In Bar

** Bumped Head of Tool in Traverse

FIGURE 4
GRAPH OF CARBON GRADIENT
IN CARBURIZED SAE 1010 STEEL

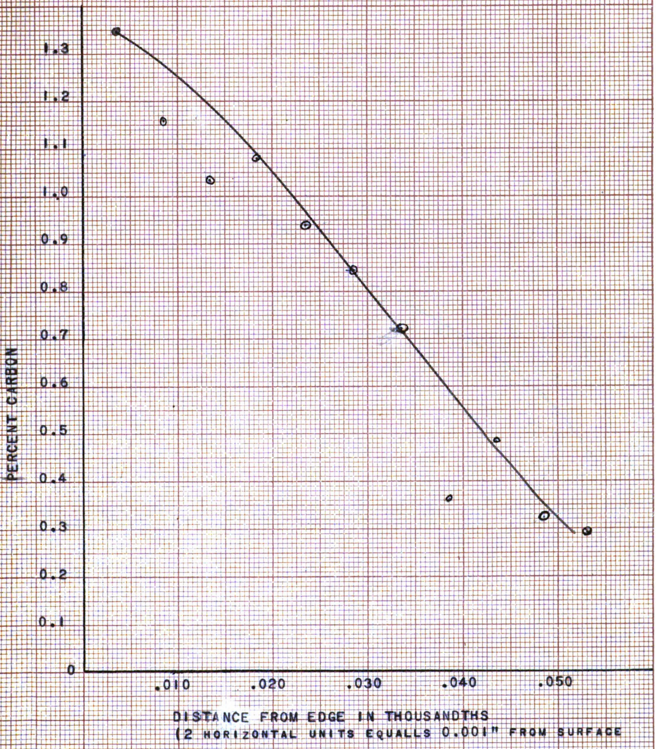
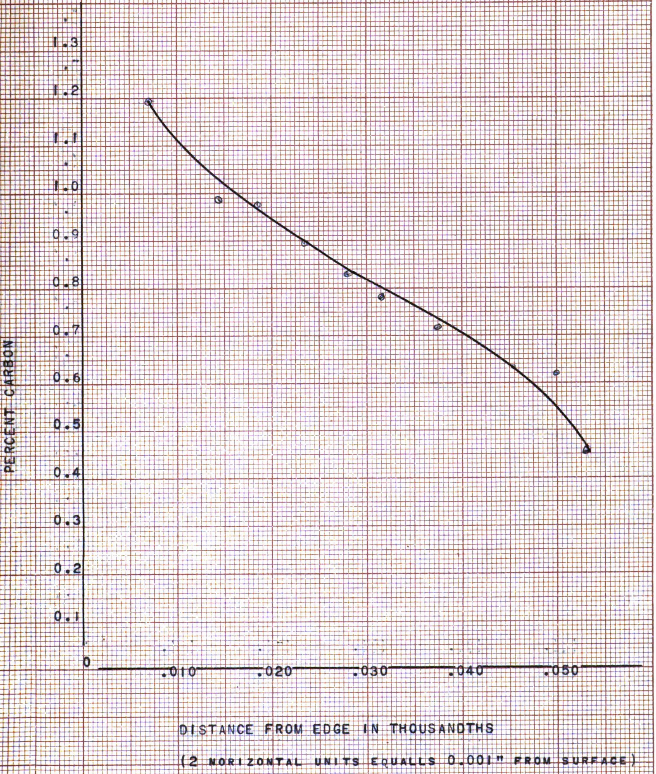


FIGURE 5

GRAPH OF CARBON GRADIENT
IN CARBURIZED SAE 2015 STEEL



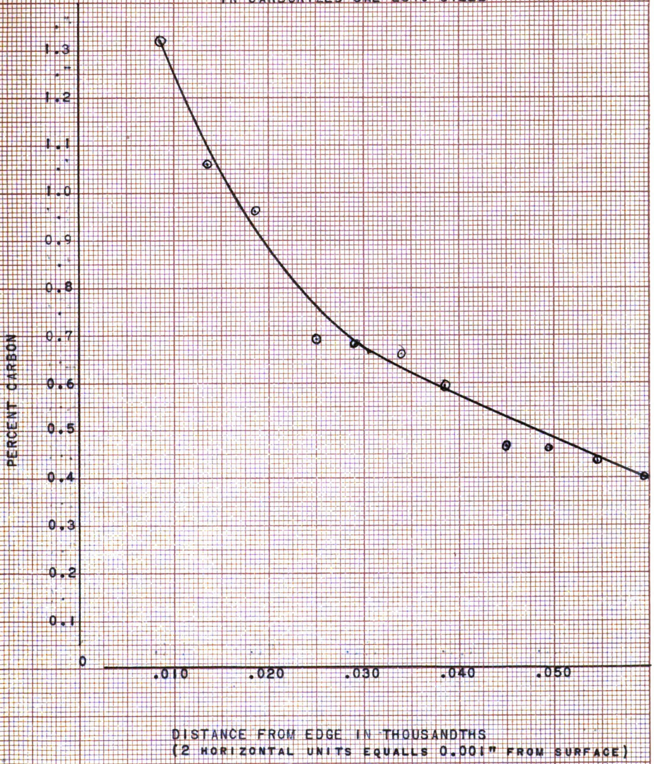


FIGURE 6

GRAPH OF CARBON GRADIENT
IN CARBURIZED SAE 2340 STEEL

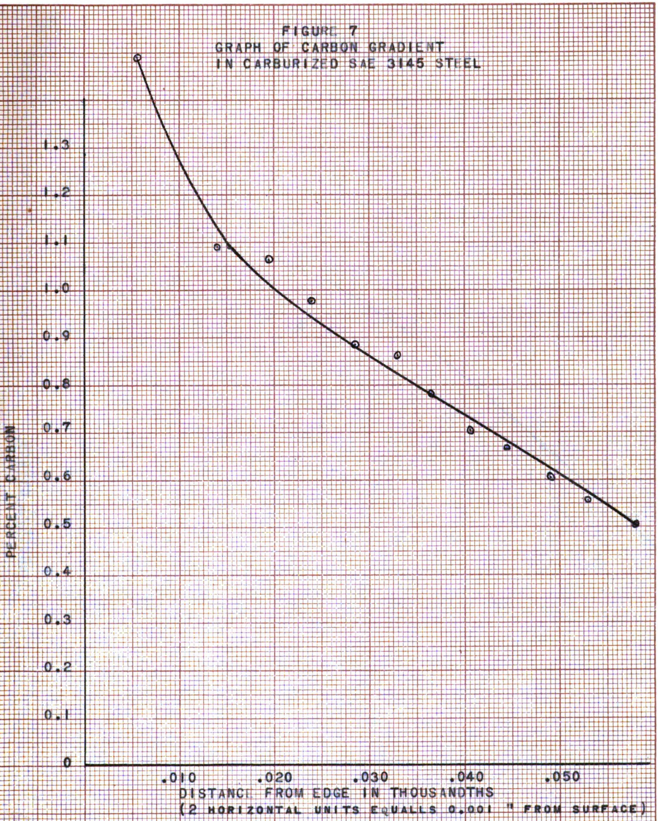
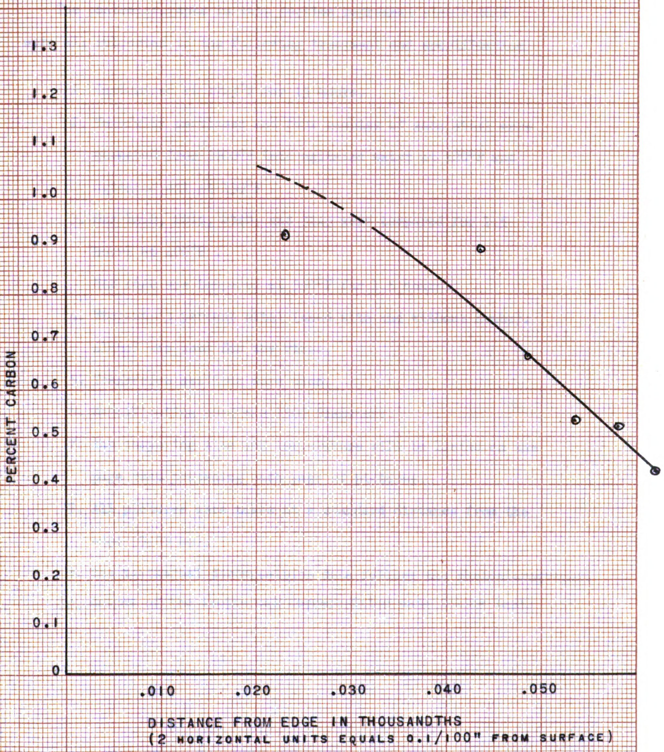


FIGURE 7
GRAPH OF CARBON GRADIENT
IN CARBURIZED SAE 3145 STEEL

FIGURE 8
GRAPH OF CARBON GRADIENT
IN CARBURIZED SAE 4640 STEEL



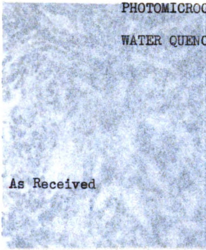
PART II

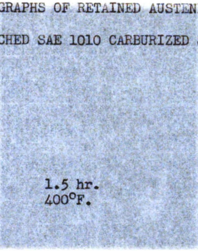
The photomicrogaphs in this section represent steels that were all subjected to the following treatment and specification

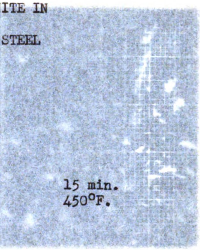
1. Carburized at 1725°F for 13 hours.
2. Carefully sectioned and four samples of each steel were quenched from 1700°F into agitated water at 120°F and agitated oil at 130°F .
3. SAE 1010, 2015, 2340, and 3145 were tempered for 1.5 hours at 400°F .

   SAE 4640 was tempered at 350°F for 1.5 hours.
4. Etchant- 3 percent nital (used with and without swabs). Alchol was used for the rinse.
5. Transverse sections were used.
6. Magnification used was 1500 diameters.
7. The tempering time and temperature will be listed on the page just preceding each page of pictures.
8. All pictures were taken at a standard distance from the edge (0.20 mm).
9. The isothermal decomposition data follows the photomicrographs.
10. Graphs of the isothermal decomposition data follow last.

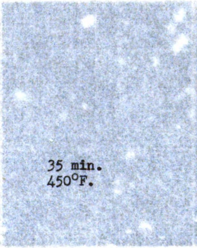
PHOTOMICROGRAPHS OF RETAINED AUSTENITE IN WATER QUENCHED SAE 1010 CARBURIZED STEEL


As Received


1.5 hr.
400°F.

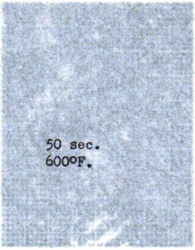

15 min.
450°F.

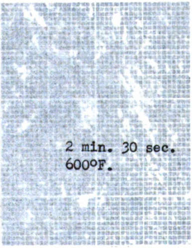
35 min.
450°F.

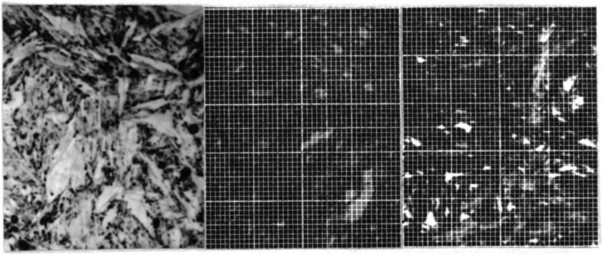

35 min.
450°F.

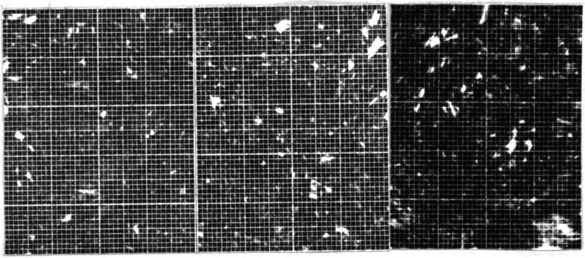

95 min.
450°F.

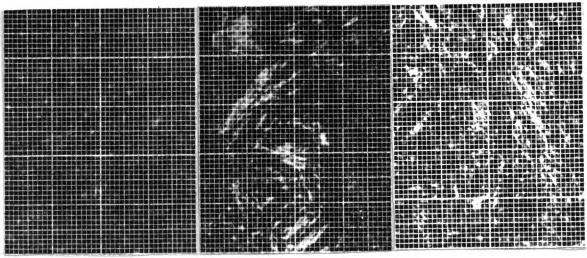
145 min.
450°F.

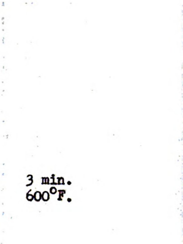

50 sec.
600°F.


2 min. 30 sec.
600°F.

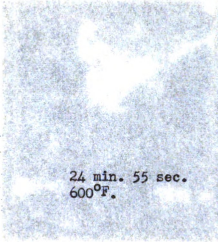




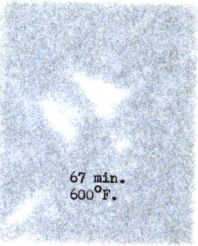




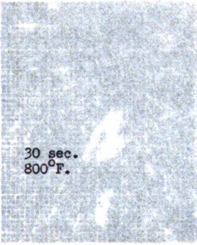
3 min.
600°F.



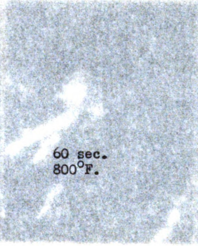
24 min. 55 sec.
600°F.



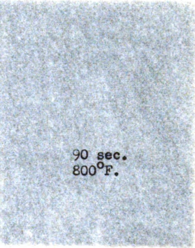
67 min.
600°F.



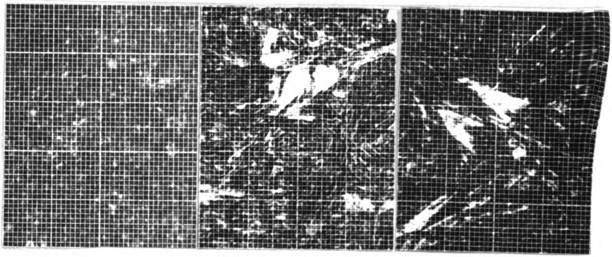
30 sec.
800°F.

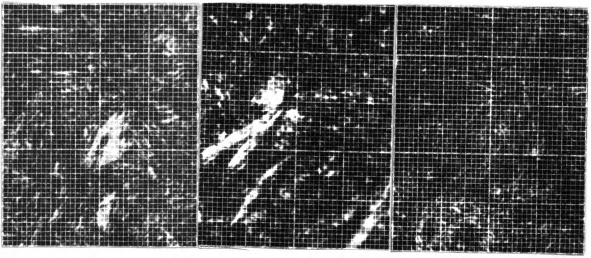


60 sec.
800°F.

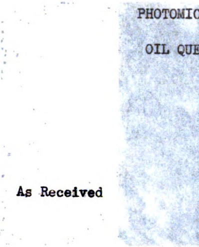


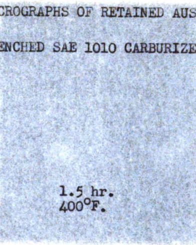
90 sec.
800°F.

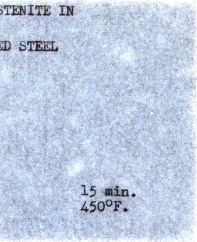


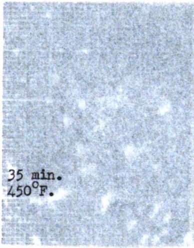


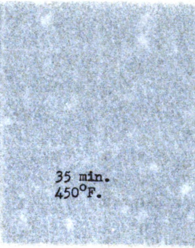
PHOTOMICROGRAPHS OF RETAINED AUSTENITE IN OIL QUENCHED SAE 1010 CARBURIZED STEEL

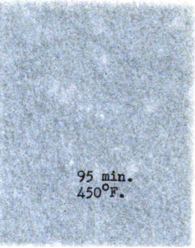

As Received

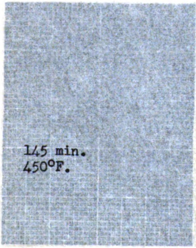

1.5 hr.
400°F.

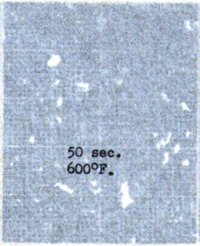

15 min.
450°F.

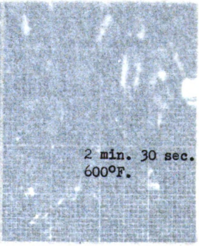

35 min.
450°F.

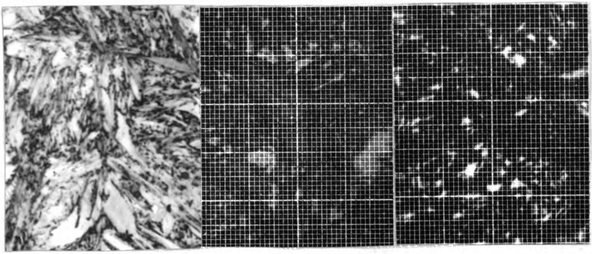

35 min.
450°F.

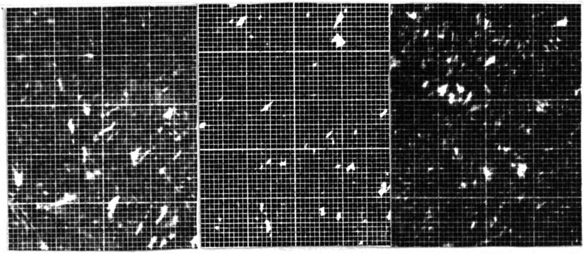

95 min.
450°F.

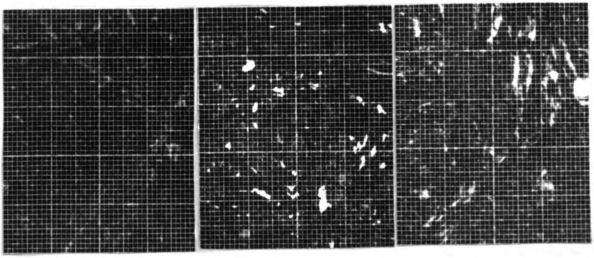

145 min.
450°F.


50 sec.
600°F.


2 min. 30 sec.
600°F.







3 min. 30 sec.
600°F.

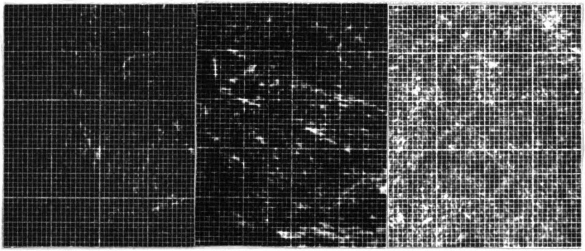
24 min. 55 sec.
600°F.

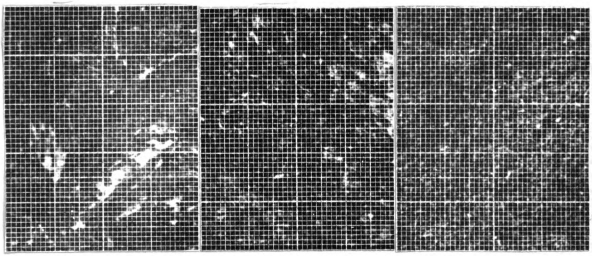
67 min.
600°F.

30 sec.
800°F.

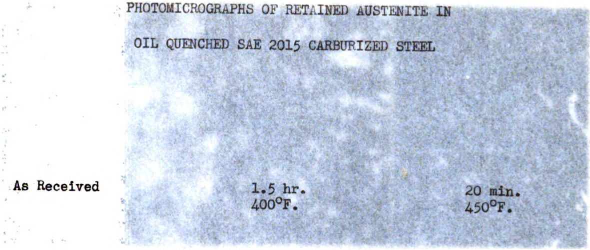
60 sec.
800°F.

90 sec.
800°F.





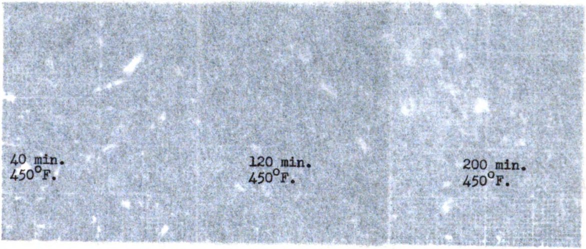
PHOTOMICROGRAPHS OF RETAINED AUSTENITE IN OIL QUENCHED SAE 2015 CARBURIZED STEEL



As Received

1.5 hr.
400°F.

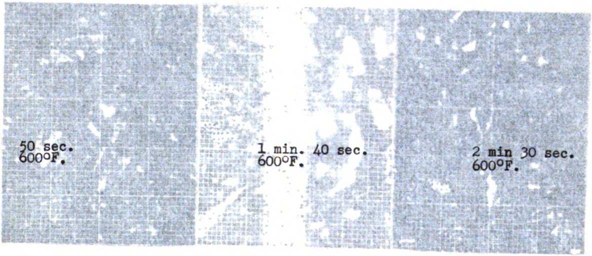
20 min.
450°F.



40 min.
450°F.

120 min.
450°F.

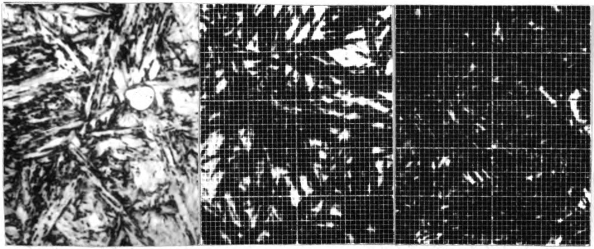
200 min.
450°F.

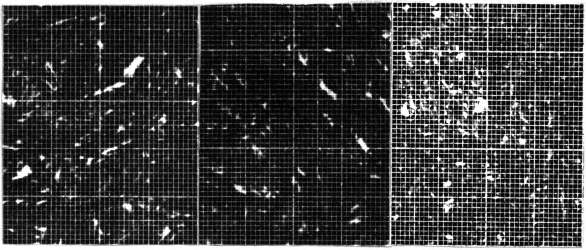


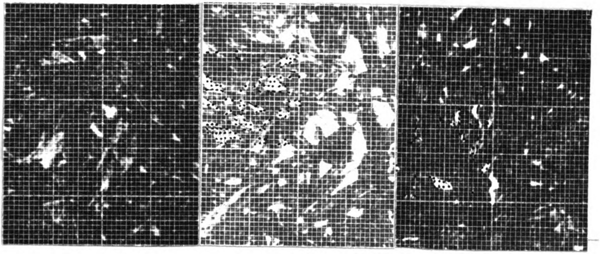
50 sec.
600°F.

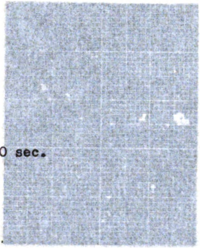
1 min. 40 sec.
600°F.

2 min 30 sec.
600°F.

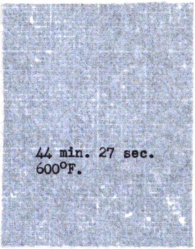




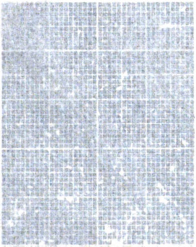




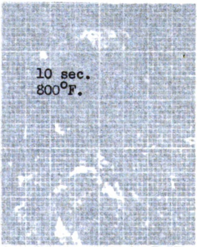
3 min. 20 sec.
600°F.



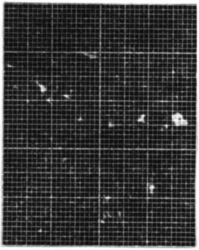
44 min. 27 sec.
600°F.

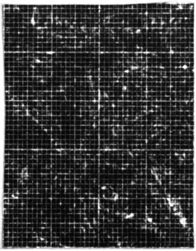


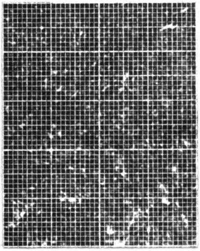
5 sec.
800°F.

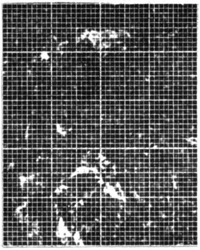


10 sec.
800°F.









PHOTOMICROGRAPHS OF RETAINED AUSTENITE IN WATER QUENCHED SAE 2340 CARBURIZED STEEL

As Received

1.5 hr.
400°F.

20 min.
450°F.

30 min.
450°F.

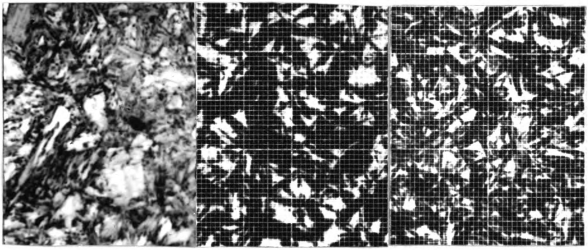
50 min.
450°F.

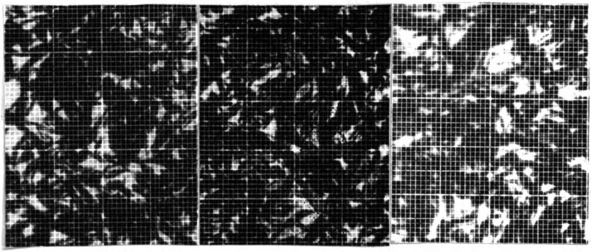
60 min.
450°F.

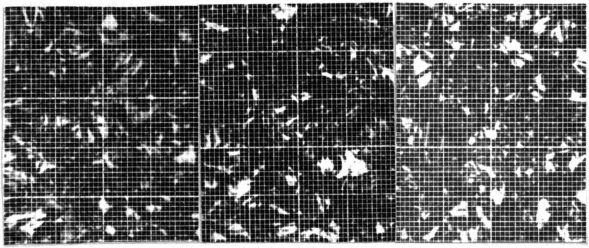
120 min.
450°F.

150 min.
450°F.

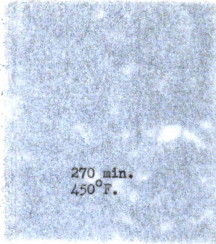
180 min.
450°F.



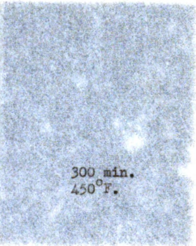




240 min.
450°F.



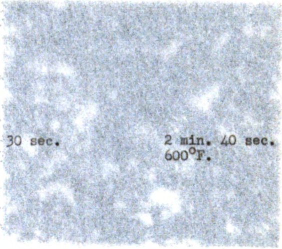
270 min.
450°F.



300 min.
450°F.

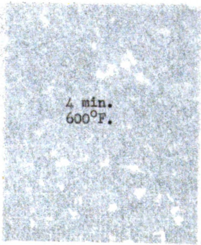
50 sec.
600°F.

1 min. 30 sec.
600°F.

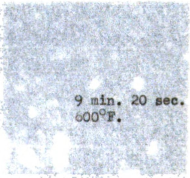


2 min. 40 sec.
600°F.

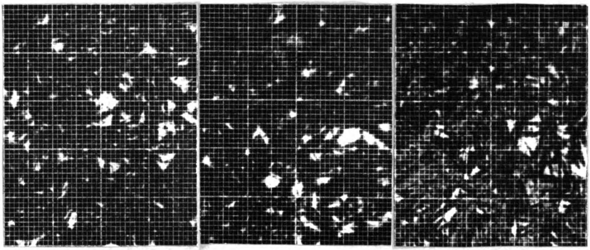
3 min. 10 sec.
600°F.

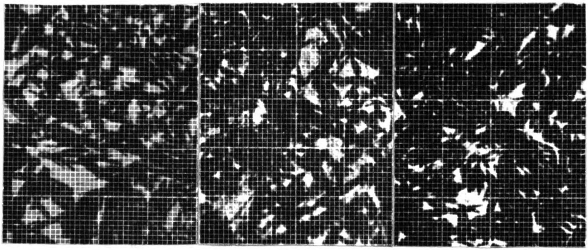


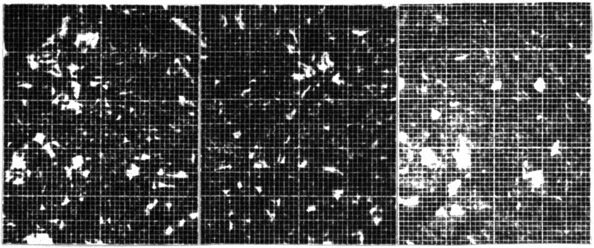
4 min.
600°F.

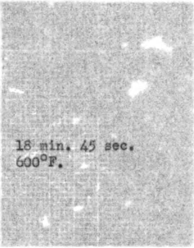


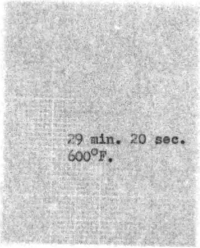
9 min. 20 sec.
600°F.



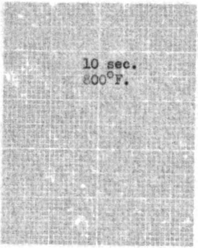


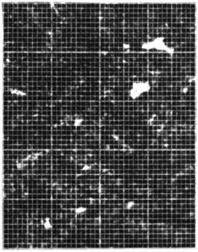


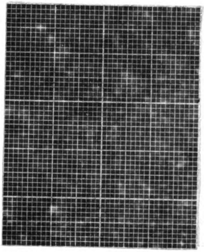

18 min. 45 sec.
600°F.

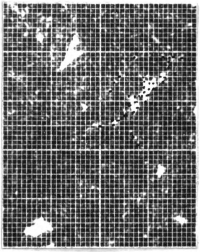

29 min. 20 sec.
600°F.

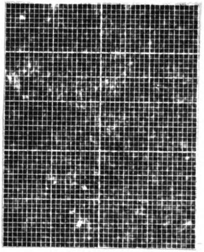

5 sec.
800°F.


10 sec.
800°F.









PHOTOMICROGRAPHS OF RETAINED AUSTENITE IN OIL QUENCHED SAE 4640 CARBURIZED STEEL

As Received

1.5 hr.
350°F.

20 min.
450°F.

40 min.
450°F.

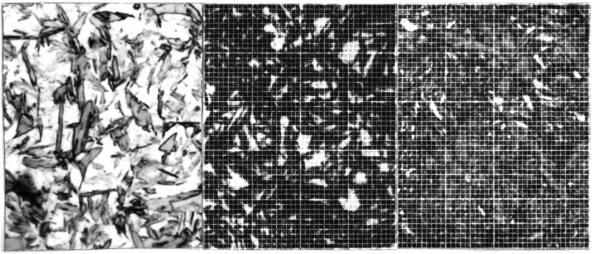
60 min.
450°F.

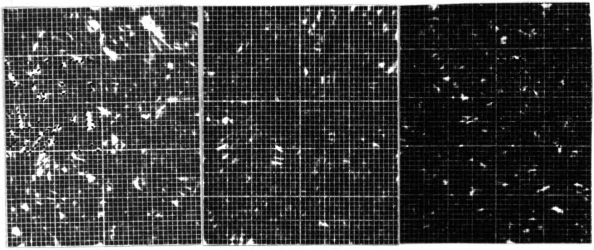
80 min.
450°F.

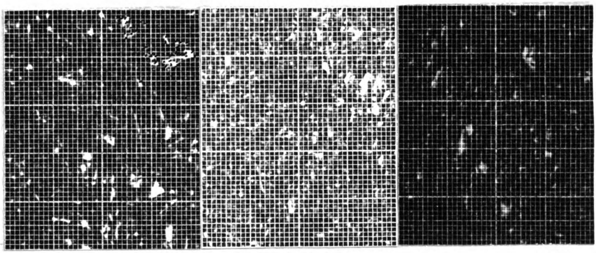
110 min.
450°F.

140 min.
450°F.

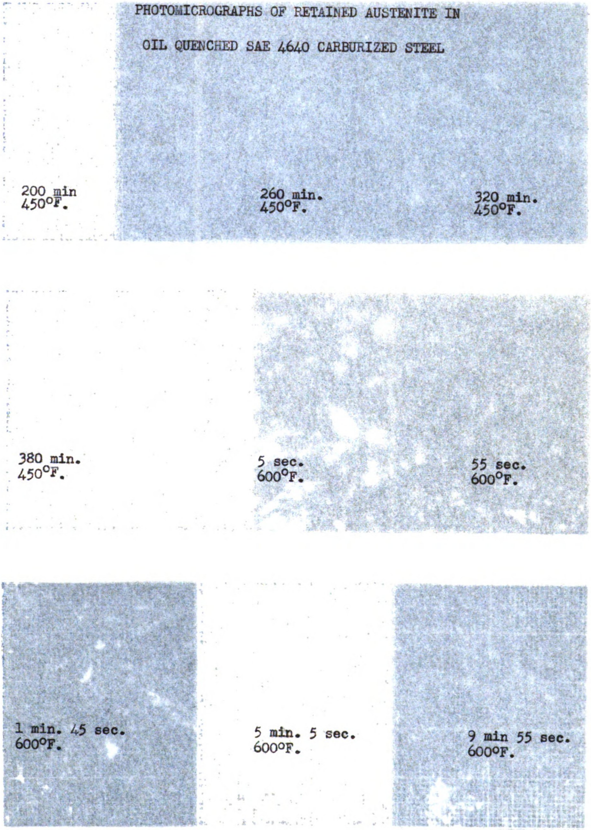
170 min.
450°F.







PHOTOMICROGRAPHS OF RETAINED AUSTENITE IN OIL QUENCHED SAE 4640 CARBURIZED STEEL



200 min
450°F.

260 min.
450°F.

320 min.
450°F.

380 min.
450°F.

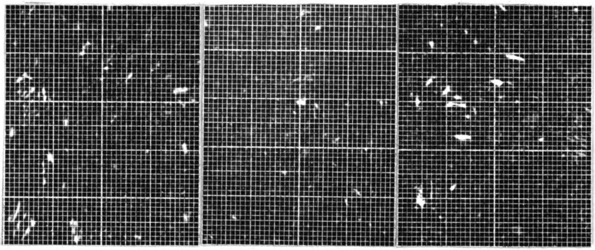
5 sec.
600°F.

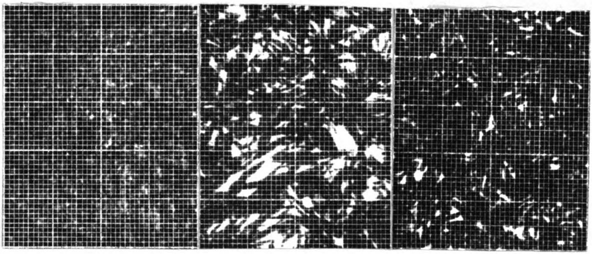
55 sec.
600°F.

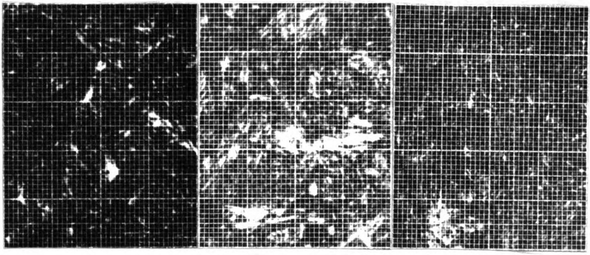
1 min. 45 sec.
600°F.

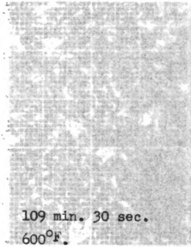
5 min. 5 sec.
600°F.

9 min 55 sec.
600°F.

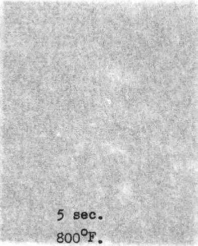




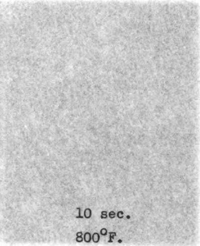




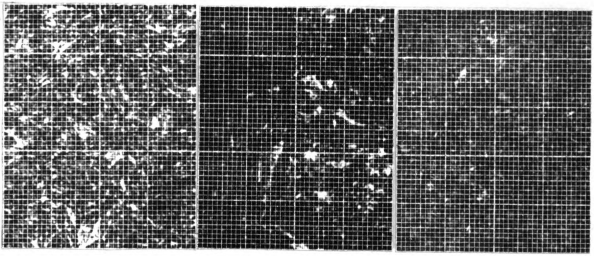
109 min. 30 sec.
600°F.



5 sec.
800°F.



10 sec.
800°F.



PHOTOMICROGRAPHS OF RETAINED AUSTENITE IN OIL QUENCHED SAE 2340 CARBURIZED STEEL

As Received

1.5 hr.
400°F.

20 min.
450°F.

30 min.
450°F.

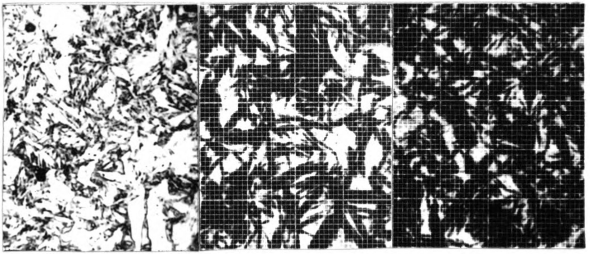
50 min.
450°F.

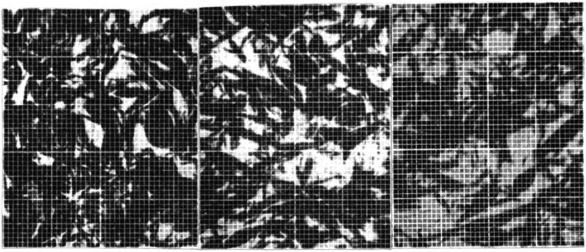
60 min.
450°F.

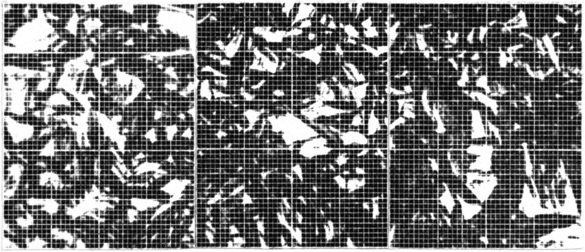
120 min.
450°F.

150 min.
450°F.

180 min.
450°F.







240 min.
450°F.

270 min.
450°F.

300 min.
450°F.

50 sec.
600°F.

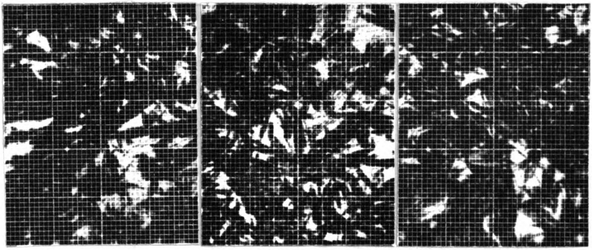
1 min. 30 sec.
600°F.

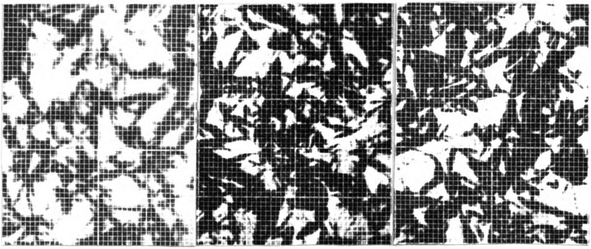
2 min. 40 sec.
600°F.

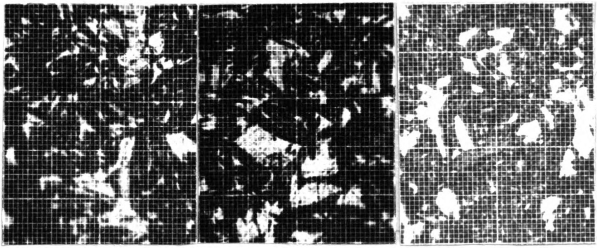
3 min. 10 sec.
600°F.

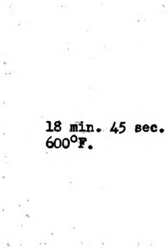
4 min.
600°F.

9 min. 20 sec.
600°F.

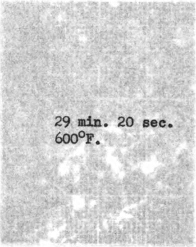




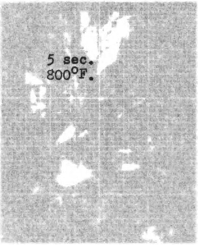




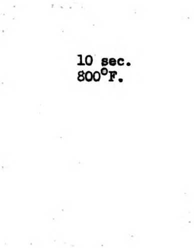
18 min. 45 sec.
600°F.



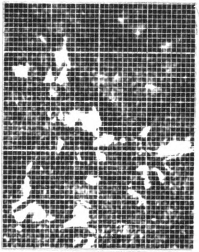
29 min. 20 sec.
600°F.

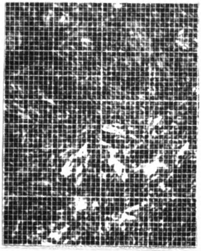


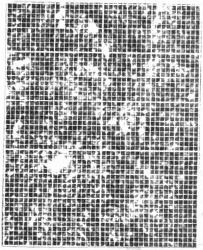
5 sec.
800°F.

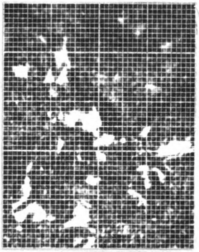


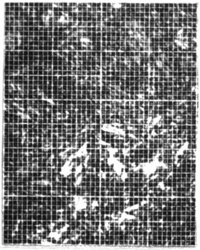
10 sec.
800°F.

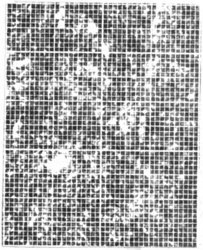




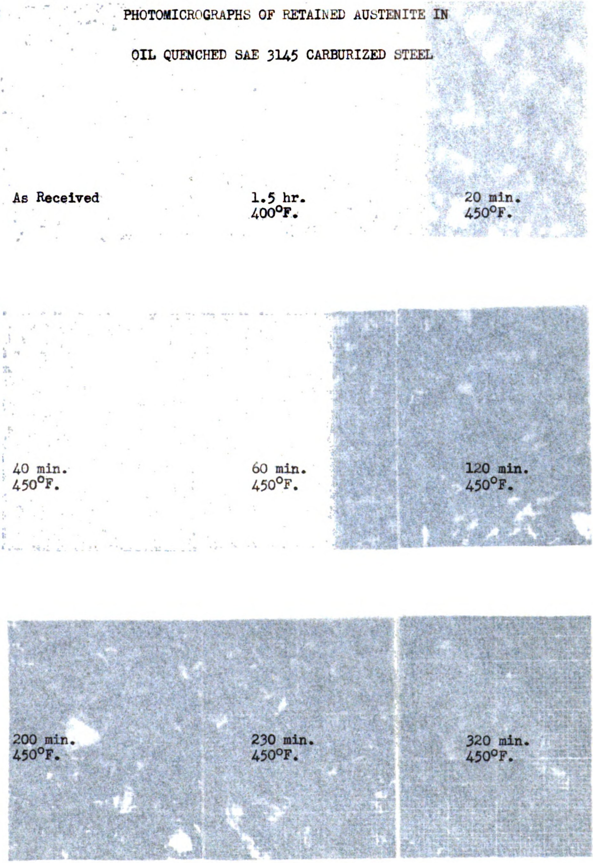








PHOTOMICROGRAPHS OF RETAINED AUSTENITE IN OIL QUENCHED SAE 3145 CARBURIZED STEEL



As Received

1.5 hr.
400°F.

20 min.
450°F.

40 min.
450°F.

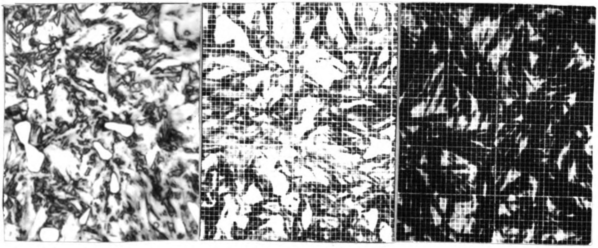
60 min.
450°F.

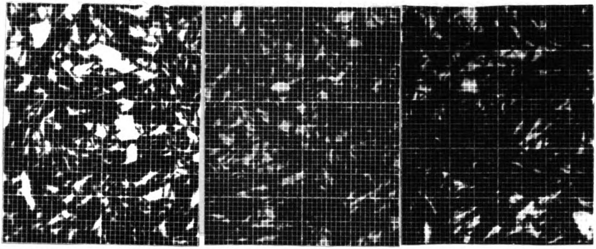
120 min.
450°F.

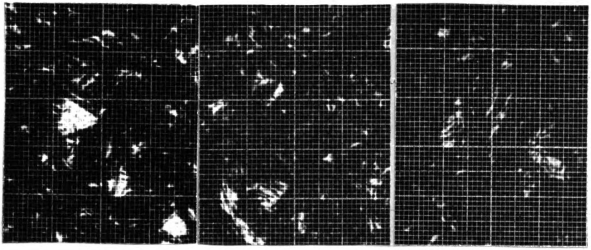
200 min.
450°F.

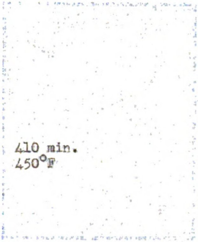
230 min.
450°F.

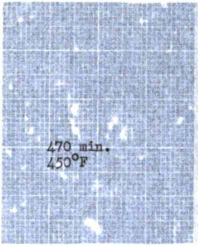
320 min.
450°F.

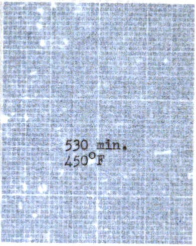




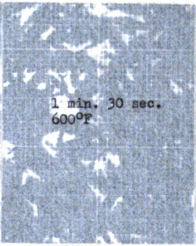


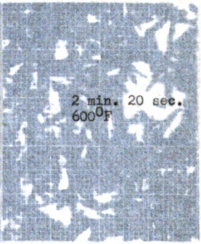

410 min.
450°F

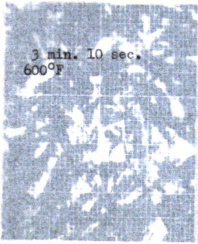

470 min.
450°F

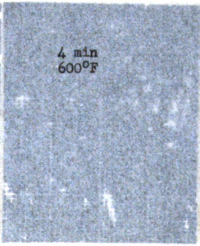

530 min.
450°F

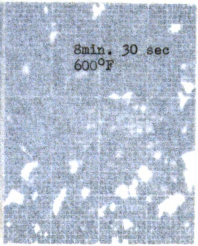

50 sec.
600°F

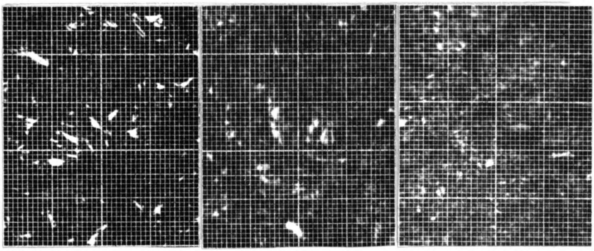

1 min. 30 sec.
600°F

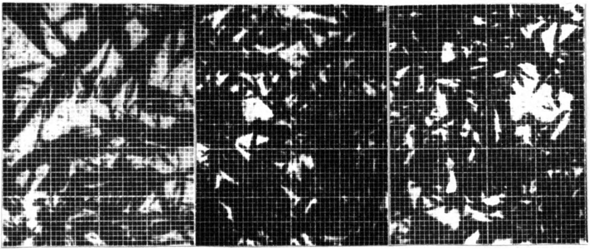

2 min. 20 sec.
600°F

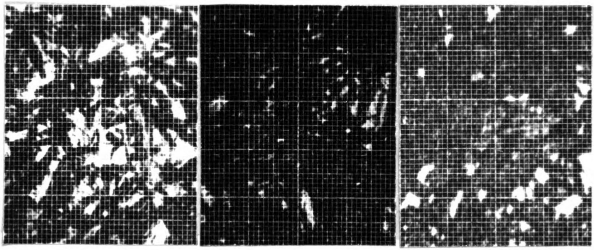

3 min. 10 sec.
600°F

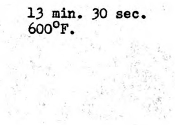

4 min
600°F


8min. 30 sec
600°F

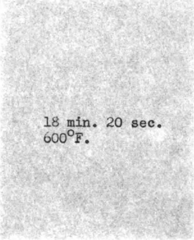






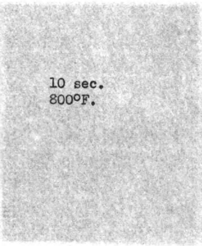


13 min. 30 sec.
600°F.

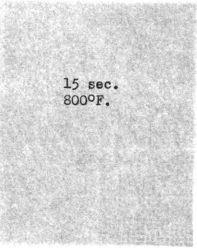


18 min. 20 sec.
600°F.

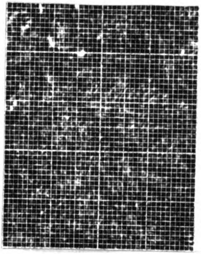
5 Sec.
800°F.

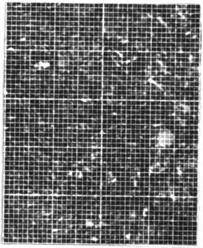


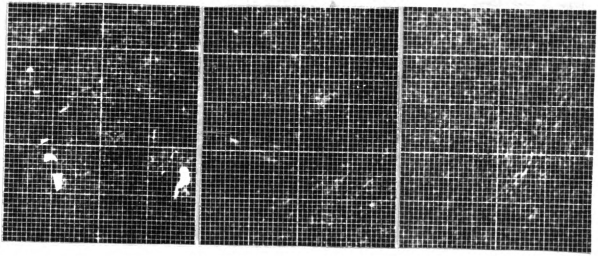
10 sec.
800°F.



15 sec.
800°F.







PHOTOMICROGRAPHS OF RETAINED AUSTENITE IN WATER QUENCHED SAE 2015 CARBURIZED STEEL

As Received

1.5 hr.
400°F.

20 min
450°F.

40 min.
450°F.

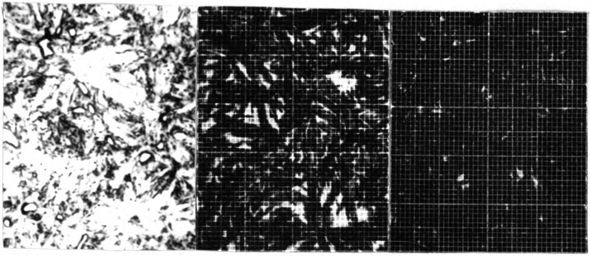
120 min.
450°F.

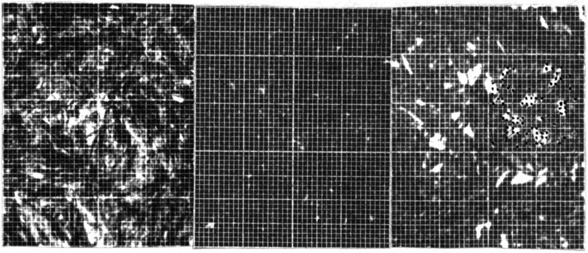
200 min.
450°F.

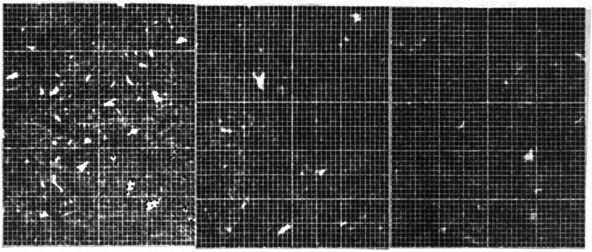
50 sec.
600°F.

1 min. 40 sec.
600°F.

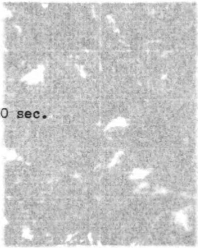
2 min. 30 sec.
600°F.



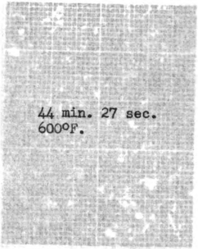




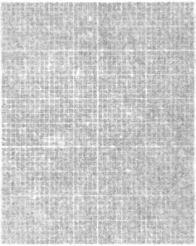
3 min. 20 sec.
600°F.



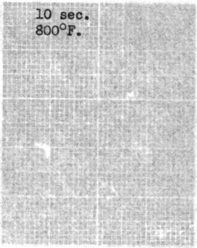
44 min. 27 sec.
600°F.

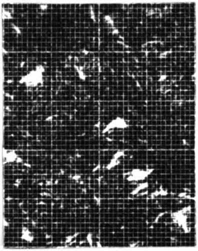


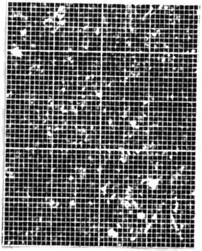
5 sec.
800°F.

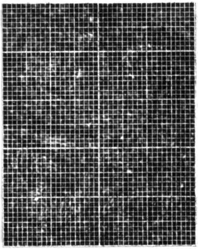


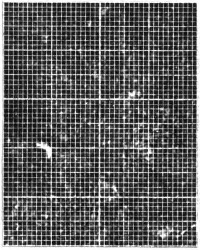
10 sec.
800°F.



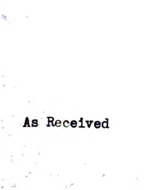


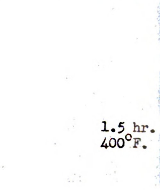


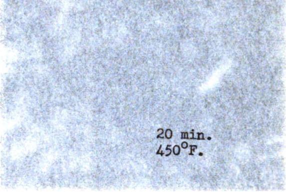


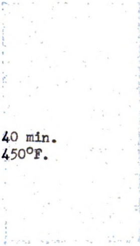


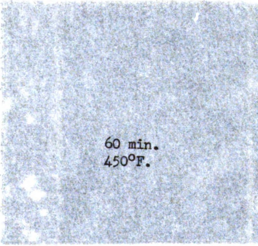
PHOTOMICROGRAPHS OF RETAINED AUSTENITE IN WATER QUENCHED SAE 3145 CARBURIZED STEEL

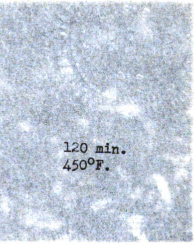

As Received

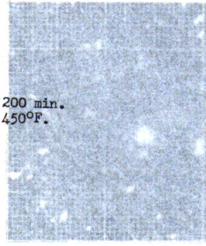

1.5 hr.
400°F.

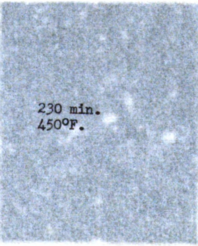

20 min.
450°F.

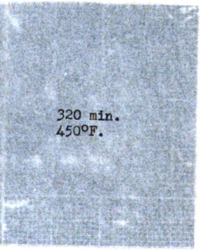

40 min.
450°F.

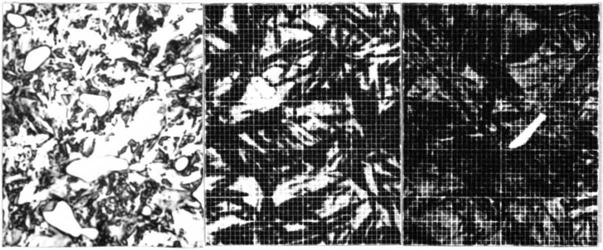

60 min.
450°F.

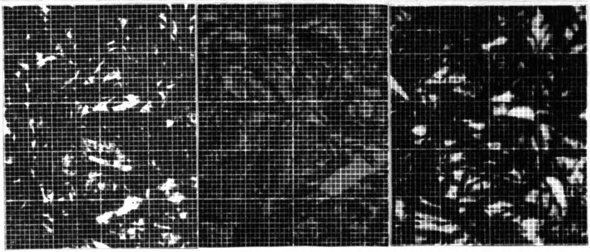

120 min.
450°F.

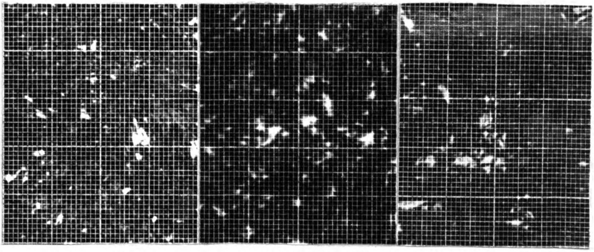

200 min.
450°F.

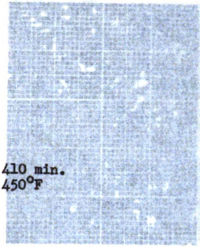

230 min.
450°F.

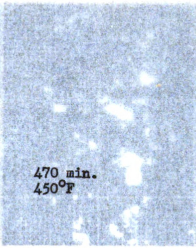

320 min.
450°F.

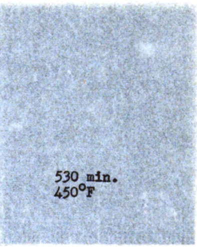


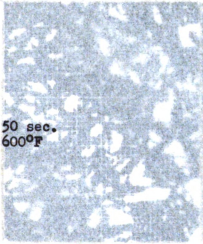


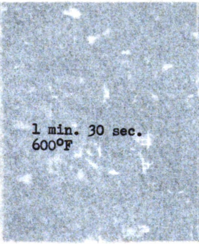


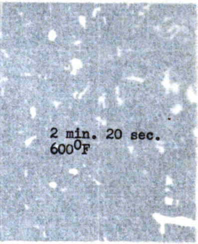

410 min.
450°F

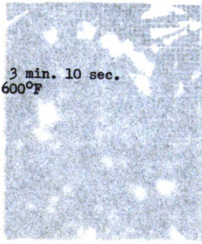

470 min.
450°F


530 min.
450°F

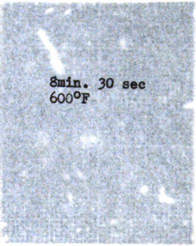

50 sec.
600°F


1 min. 30 sec.
600°F


2 min. 20 sec.
600°F


3 min. 10 sec.
600°F


4 min
600°F


8min. 30 sec
600°F

410 min.
450°F

470 min.
450°F

530 min.
450°F

50 sec.
600°F

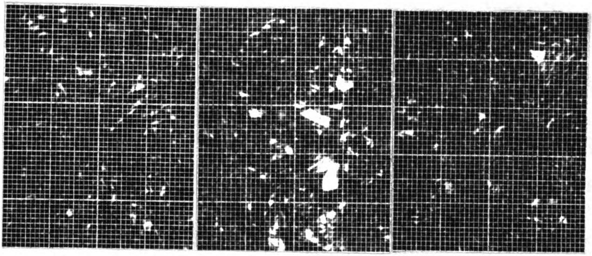
1 min. 30 sec.
600°F

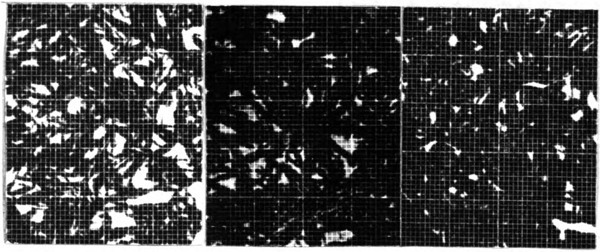
2 min. 20 sec.
600°F

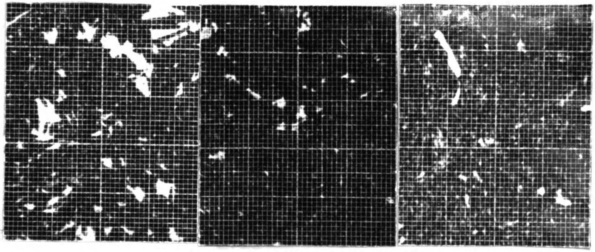
3 min. 10 sec.
600°F

4 min
600°F

8min. 30 sec
600°F







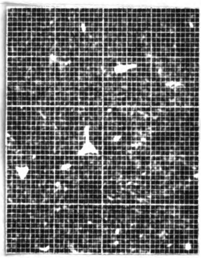
13 min. 30 sec.
600°F.

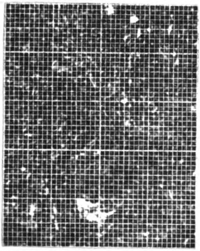
18 min. 20 sec.
600°F.

5 sec.
800°F.

10 sec.
800°F.

15 sec.
800°F.





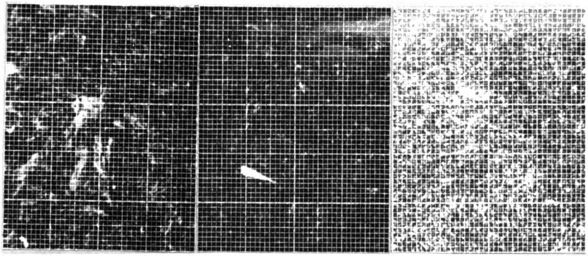


Table 8

Experimental Data For Isothermal Decomposition Of Retained Austenite in Water Quenched SAE 3145 Carburized Steel

Tempering Temperature °Fahrenheitn	Time	Corrected Time	Percent Retained Austenite in Picture	Overall Percent
400	1.5 hr.	---	58%	58%
450	20 min.	---	28%	28%
450	40 min.	---	20%	20%
450	60 min.	---	19%	19%
450	120 min.	---	19%	19%
450	200 min.	---	10%	10%
450	230 min.	---	12%	12%
450	320 min.	---	10%	10%
450	410 min.	---	7-5%	7-5%
450	470 min.	---	11%	3-11%
450	530 min.	---	4-5%	1-5%
600	1 min. 15 sec.	50 sec.	37%	37%
600	2 min. 20 sec.	1 min. 30 sec.	20%	20%
600	3 min. 35 sec.	2 min. 20 sec.	16%	16%
600	4 min. 50 sec.	3 min. 10 sec.	25%	15%
600	6 min. 5 sec.	4 min.	12%	?-12%
600	11 min.	8 min. 30 sec.	10%	10%
600	16 min. 25 sec.	13 min. 30 sec.	2-3%	2-3%
600	21 min 40 sec.	18 min. 20 sec.	1%	1%
800	30 sec.	5 sec.	2-3%	2-3%
800	60 sec.	10 sec.	Doubtful	
800	90 sec	15 sec.	Salt and Pepper Effect	

Table 9

Experimental Data For Isothermal Decomposition

Of Retained Austenite In Water Quenched SAE 2015 Carburized Steel

Tempering Temperature °Fahrenheit	Time	Corrected Time	Percent Retained Austenite in Picture	Overall Percent
400	1.5 hr.	---	29%	29%
450	20 min.	---	10%	10%
450	40 min.	---	10%	10%
450	120 min.	---	3-4%	3-4%
450	200 min.	---	1-?%	1%
600	1min. 15 sec.	50 sec.	19%	19%
600	2 min. 30 sec.	1 min. 40 sec.	5%	5%
600	3 min. 45 sec.	2 min. 30 sec.	1-2%	1-2%
600	5 min.	3 min. 20 sec.	1-2%	1-2%
600	47 min.	44 min. 27 sec.	---	---
800	30 sec.	5 sec.	Little if any	
800	60 sec.	10 sec.	Salt and Pepper Effect	

Table 10

Experimental Data For Isothermal Decomposition Of Retained Austenite In Oil Quenched 3145 Carburized Steel

Temperature ° Fahrenheit	Time	Corrected Time	Percent Retained Austenite in Picture	Overall Percent
400	1.5 hr.	---	48%	48%
450	20 min.	---	37%	37%
450	40 min.	---	36%	36%
450	60 min.	---	20%	20%
450	120 min.	---	17%	17%
450	200 min.	---	16%	16%
450	230 min.	---	12%	12%
450	320 min.	---	12%	12%
450	410 min.	---	13%	8-10%
450	470 min.	---	10%	4-8%
450	530 min.	---	3-5%	1-3%
600	1 min. 15 sec.	50 sec.	37%	37%
600	2 min.20 sec.	1 min. 30 sec.	23%	23%
600	3 min. 35 sec.	2 min. 20 sec.	26%	26%
600	4 min. 50 sec.	3 min. 10 sec.	38%	38%
600	6 min. 5 sec.	4 min.	12%	12%
600	11 min. 20 sec.	8 min. 50 sec.	17%	17%
600	16 min. 25 sec.	13 min. 30 sec.	3-5%	3-5%
600	21 min. 40 sec.	18 min. 20 sec.	1%	1%
800	30 sec.	5 sec.	2-3%	2-3%
800	60 sec.	10 sec.	Some	Some
800	90 sec.	15 sec.	?	?

Table 11

Experimental Data For Isothermal Decomposition Of Retained Austenite In Oil Quenched 2340 Carburized Steel

Temperature ° Fahrenheit	Time	Corrected Time	Percent Retained Austenite in Picture	Overall Percent
400	1½ hr.	---	52%	52%
450	20 min.	---	47%	47%
450	30 min.	---	40%	40%
450	50 min.	---	45%	45%
450	60 min.	---	41%	41%
450	120 min.	---	45%	45%
450	150 min.	---	36%	30%
450	180 min.	---	36%	20%
450	240 min.	---	36%	15%
450	270 min.	---	30%	10%
450	300 min.	---	28%	3-10%
600	1 min. 15 sec.	50 sec.	65%	65%
600	2 min. 20 sec.	1 min. 30 sec.	45%	45%
600	3 min. 55 sec.	2 min. 40 sec.	55%	55%
600	4 min. 50 sec.	3 min. 10 sec.	38%	38%
600	6 min. 5 sec.	4 min.	42%	42%
600	11 min. 20 sec.	9 min. 20 sec.	25%	25%
600	21 min. 40 sec.	18 min. 45 sec.	22%	10%
600	32 min. 40 sec.	29 min. 20 sec.	3-5%	3-5%
800	30 sec.	5 sec.	14%	14%
800	60 sec.	10 sec.	3-5%	?

Table 12

Experimental Data For Isothermal Decomposition Of Retained Austenite in Oil Quenched SAE 4640 Carburized Steel

Tempering Temperature °Fahrenheit	Time	Corrected Time	Percent Retained Austenite in Picture	Overall Percent
350	1.5 hr.	——	39%	39%
450	20 min.	——	16%	16%
450	40 min.	——	17%	17%
450	60 min.	——	9%	9%
450	80 min.	——	7%	7%
450	110 min.	——	5%	5%
450	140 min.	——	5%	3-5%
450	170 min.	——	5%	3-5%
450	200 min.	——	5%	3-5%
450	260 min.	——	5%	3-5%
450	320 min.	——	5%	3-%
450	380 min.	——	Salt and Pepper Effect	
600	30 sec.	5 sec.	29%	29%
600	1 min. 45 sec.	55 sec.	17%	17%
600	3 min.	1 min. 45 sec.	9%	7-9%
600	6 min. 45 sec.	5 min. 5 sec.	17%	7-8%
600	12 min.	9 min. 55 sec.	3-5%	1-2%
600	112 min.	109 min. 30 sec.	Salt and Pepper Effect	
800	30 sec.	5 sec.	5-6%	1-2%
800	60 sec.	10 sec.	Salt and Pepper Effect	

Table 13

Experimental Data For Isothermal Decomposition Of Retained Austenite in Water Quenched SAE 2340 Carburized Steel

Tempering Temperature °Fahrenheit	Time	Corrected Time	Percent retained Austenite in Picture	Overall Percent
400	1.5hr.	---	48%	48%
450	20 min.	---	40%	40%
450	30min.	---	43%	43%
450	50 min.	---	31%	31%
450	60 min.	---	35%	35%
450	120 min.	---	40%	40%
450	150 min.	---	30%	30%
450	180 min.	---	33%	33%
450	240 min.	---	23%	23%
450	270 min.	---	22%	10-12%
450	300 min.	---	3-10%	3-10%
600	1 min. 15 sec.	50 sec.	30%	30%
600	2 min. 20 sec.	1 min. 30 sec.	30%	30%
600	3 min. 35 sec.	2 min. 20 sec.	24%	24%
600	4 min. 50 sec.	3 min. 10 sec.	25%	25%
600	6 min. 5 sec.	4 min.	13%	13%
600	11 min. 20 sec.	8 min. 50 sec.	22%	3-5%
600	21 min. 40 sec.	18 min. 40 sec.	1-3%	1-3%
600	32 min. 40 sec.	29 min. 20 sec.	1-3%	1-3%
800	30 sec.	5 sec.	10%	10%
800	60 sec.	10 sec.	Trace	Trace

Table 14

Experimental Data for Isothermal Decomposition of Retained Austenite in Oil Quenched SAE 2015 Carburized Steel

Tempering Temperature °Fahrenheit	Time	Corrected Time	Percent Retained Austenite in Picture	Overall Percent
400	1.5 hr.	----	28%	28%
450	20 min.	----	15%	15%
450	40 min.	----	10%	10%
450	120 min.	----	8%	8%
450	200 min.	----	1-3%	1-3%
600	1 min. 15 sec.	50 sec.	30%	30%
600	2 min. 30 sec.	1 min. 40 sec.	14%	14%
600	3 min. 45 sec.	2 min. 30 sec.	13%	13%
600	5 min.	3 min. 20 sec.	5%	1-5%
600	47 min.	44 min. 27 sec.	----	----
800	30 sec.	5 sec.	17%	10-17%
800	60 sec.	10 sec.	Salt and Pepper effect	

Table 15

Experimental Data For Isothermal Decomposition Of Retained Austenite in Oil Quenched SAE 1010 Carburized Steel

Tempering Temperature °Fahrenheit	**Time**	Corrected Time	Percent Retained Austenite in Picture	Overall Percent
400	1.5 hr.	—	19%	19%
450	15 min.	—	17%	17%
450	35 min.	—	15%	15%
450	85 min.	—	3-5%	3-5%
450	95 min.	—	3-5%	3-5%
450	145 min.	—	Trace	Trace
600	1 min. 50 sec.	50 sec.	4-5%	4-5%
600	3 min. 45 sec.	2 min. 30 sec.	7-8%	3-5%
600	5 min.	3 min. 20 sec.	?	?
600	27 min.	24 min. 55 sec.	—	—
600	67 min.	—	—	—
800	30 sec.	5 sec.	11%	3-5%
800	60 sec.	10 sec.	Trace	Trace
800	90 sec.	15 sec.	Salt and Pepper Effect	

Table 16

Experimental Data For Isothermal Decomposition Of Retained Austenite In Water Quenched SAE 1010 Carburized Steel

Tempering Temperature °Fahrenheit	Time	Corrected Time	Percent Retained Austenite in Picture	Overall Percent
400	1.5 hr.	---	15%	15%
450	15 min.	---	16%	16%
450	35 min.	---	11%	11%
450	85 min.	---	10%	3-5%
450	95 min.	---	10%	3-5%
450	145 min.	---	1-3%	1%
600	1 min. 15 sec.	50 sec.	5-6%	5-6%
600	3 min 45 sec.	2 min. 30 sec.	3-5%	3-5%
600	5 min.	3 min. 20 sec.	4%	1-4%
600	27 min.	24 min. 55 sec.	1%	1%
600	67 min. 15 sec.	63 min. 42 sec.	Trace	Trace
800	30 sec.	5 sec.	20%	10%
800	60 sec.	10 sec.	Trace	Trace
800	90 sec.	15 sec.	Salt and Pepper Effect	

Table 16

Experimental Data For Isothermal Decomposition Of Retained Austenite In Water Quenched SAE 1010 Carburized Steel

Tempering Temperature °Fahrenheit	Time	Corrected Time	Percent Retained Austenite in Picture	Overall Percent
400	1.5 hr.	----	15%	15%
450	15 min.	----	16%	16%
450	35 min.	----	11%	11%
450	85 min.	----	10%	3-5%
450	95 min.	----	10%	3-5%
450	145 min.	----	1-3%	1%
600	1 min. 15 sec.	50 sec.	5-6%	5-6%
600	3 min 45 sec.	2 min. 30 sec.	3-5%	3-5%
600	5 min.	3 min. 20 sec.	4%	1-4%
600	27 min.	24 min. 55 sec.	1%	1%
600	67 min. 15 sec.	63 min. 42 sec.	Trace	Trace
800	30 sec.	5 sec.	20%	10%
800	60 sec.	10 sec.	Trace	Trace
800	90 sec.	15 sec.	Salt and Pepper Effect	

FIGURE 9
TABLE 8

ISOTHERMAL TRANSFORMATION DIAGRAM

OF RETAINED AUSTENITE IN WATER QUENCHED SAE 3145 CARBURIZED STEEL

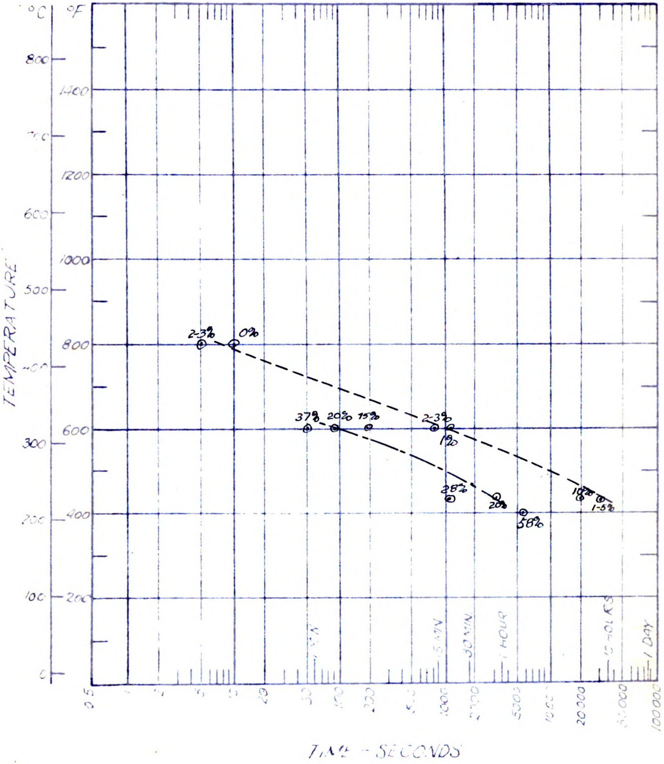


FIGURE 10

TABLE 9

ISOTHERMAL TRANSFORMATION DIAGRAM OF RETAINED AUSTENITE IN WATER QUENCHED SAE 2015 CARBURIZED STEEL

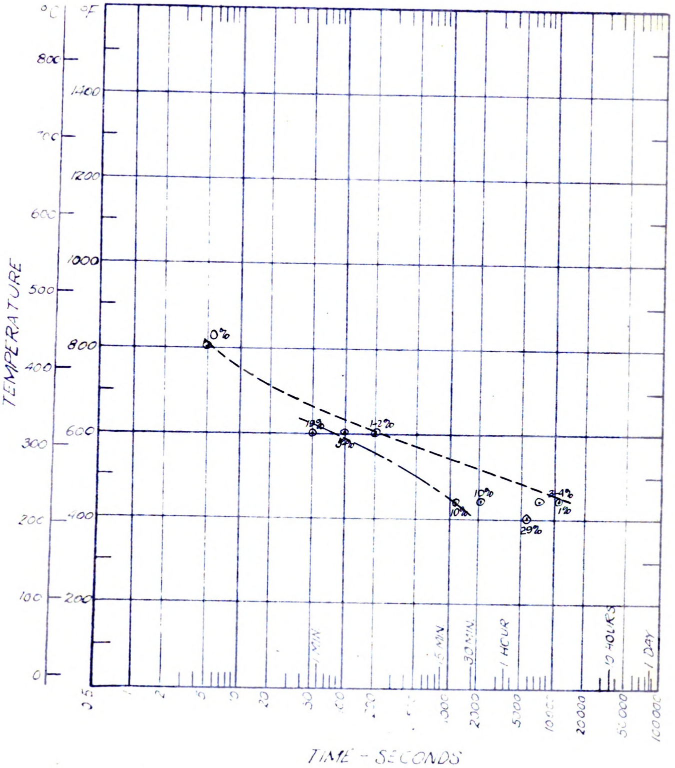


FIGURE 11

TABLE 10

ISOTHERMAL TRANSFORMATION DIAGRAM

OIL QUENCHED 3145 CARBURIZED STEEL

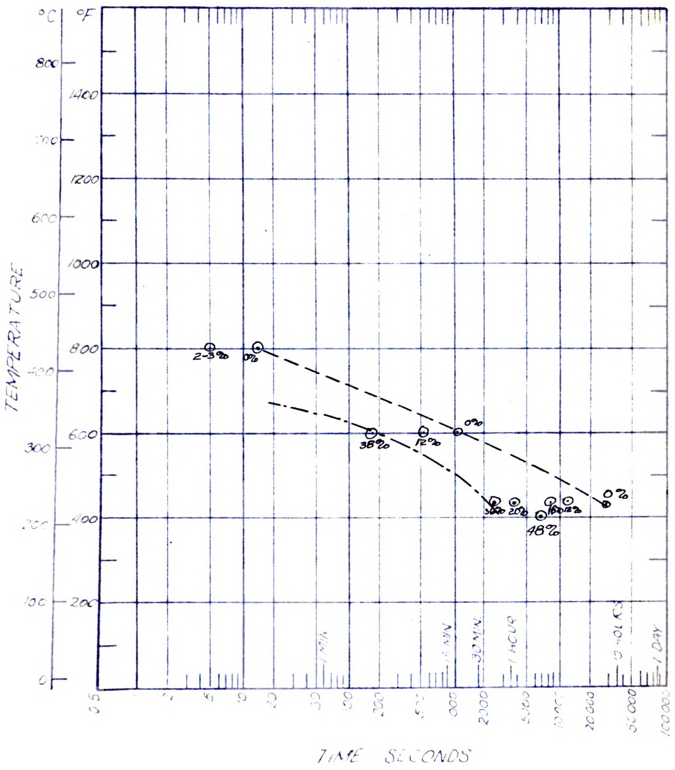


FIGURE 12
TABLE 11

ISOTHERMAL TRANSFORMATION DIAGRAM

OF RETAINED AUSTENITE IN OIL QUENCHED 2340 CARBURIZED STEEL

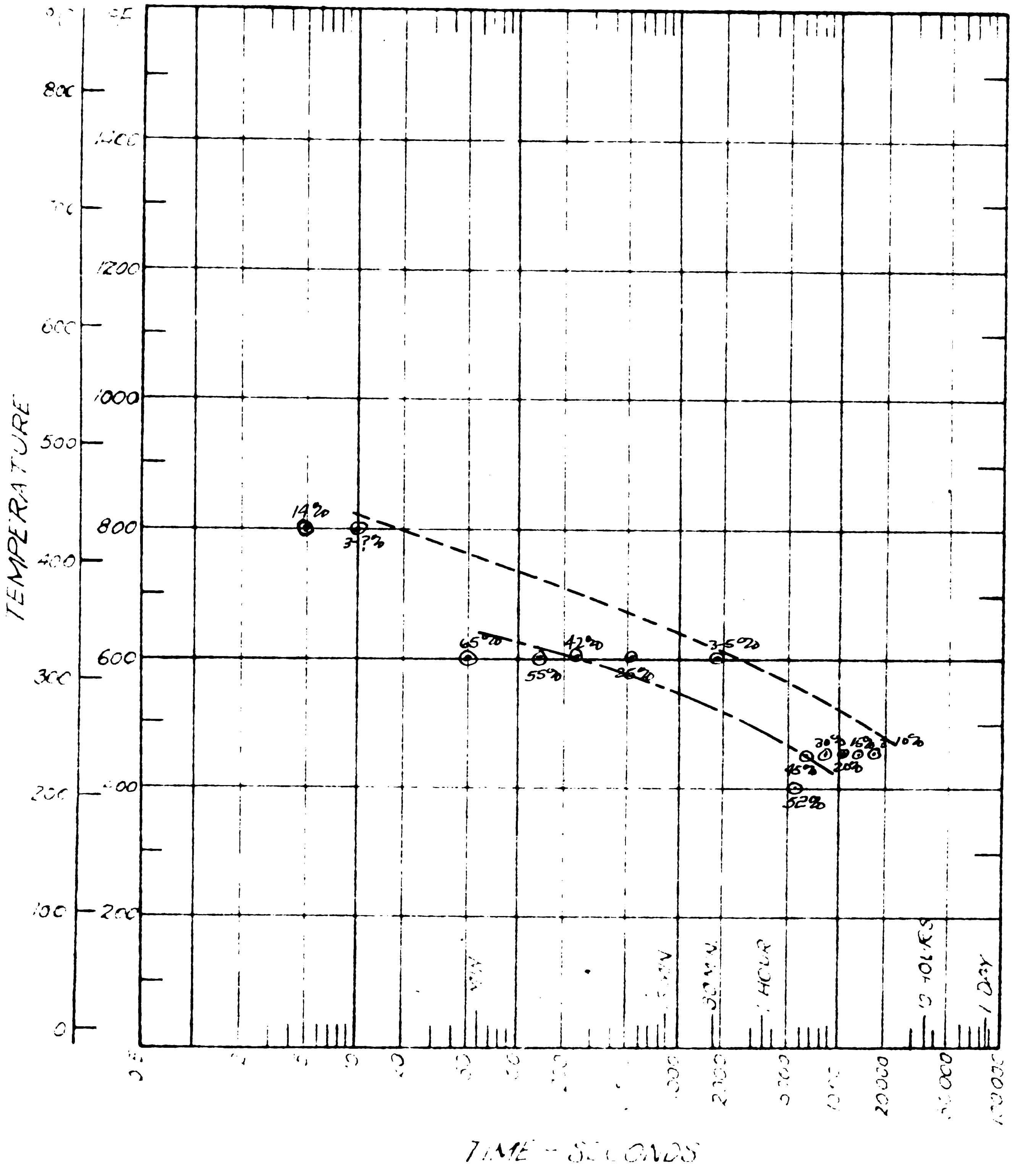


FIGURE 13

TABLE 12

ISOTHERMAL TRANSFORMATION DIAGRAM
OF RETAINED AUSTENITE IN OIL QUENCHED SAE 4640 CARBURIZED STEEL

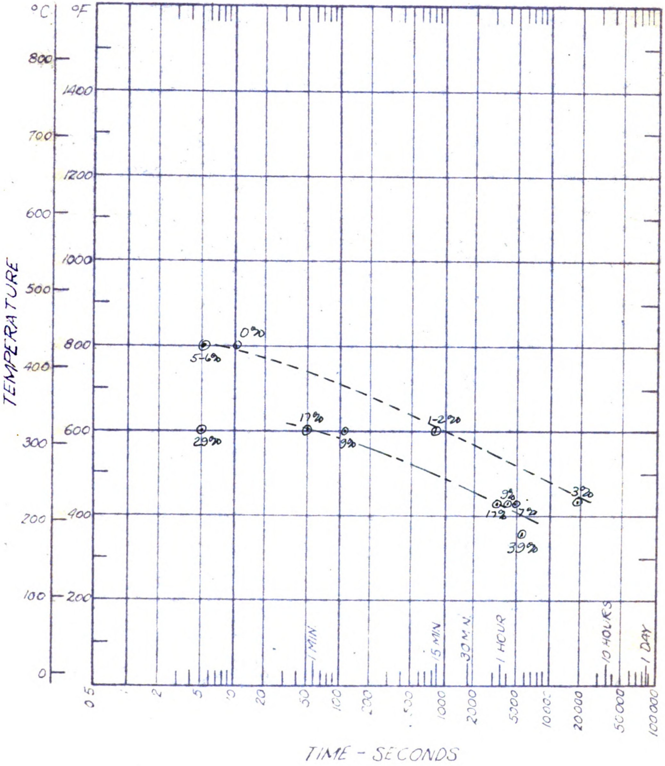


FIGURE 14
TABLE 13

ISOTHERMAL TRANSFORMATION DIAGRAM

OF RETAINED AUSTENITE IN WATER QUENCHED SAE2340 CARBURIZED STEEL

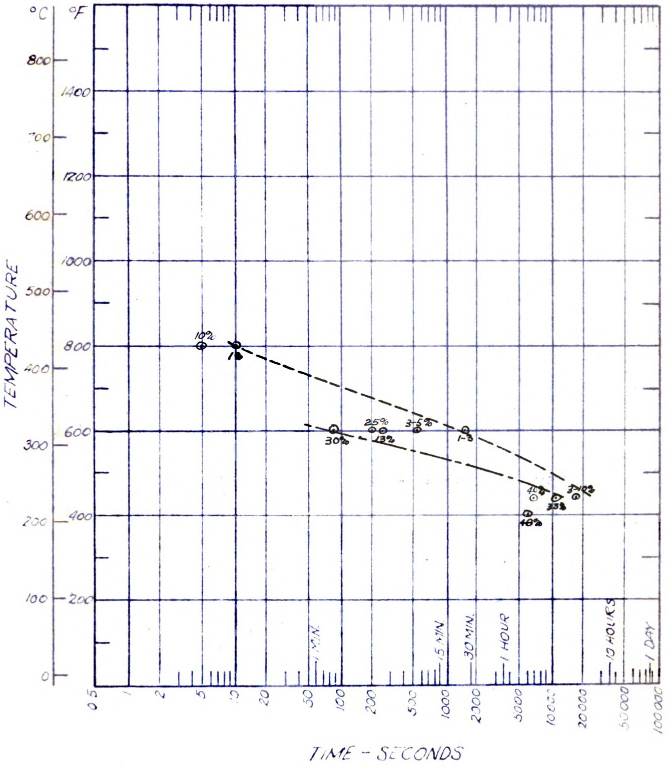


FIGURE 15

TABLE 14

ISOTHERMAL TRANSFORMATION DIAGRAM

OF RETAINED AUSTENITE IN OIL QUENCHED SAE 2015 CARBURIZED STEEL

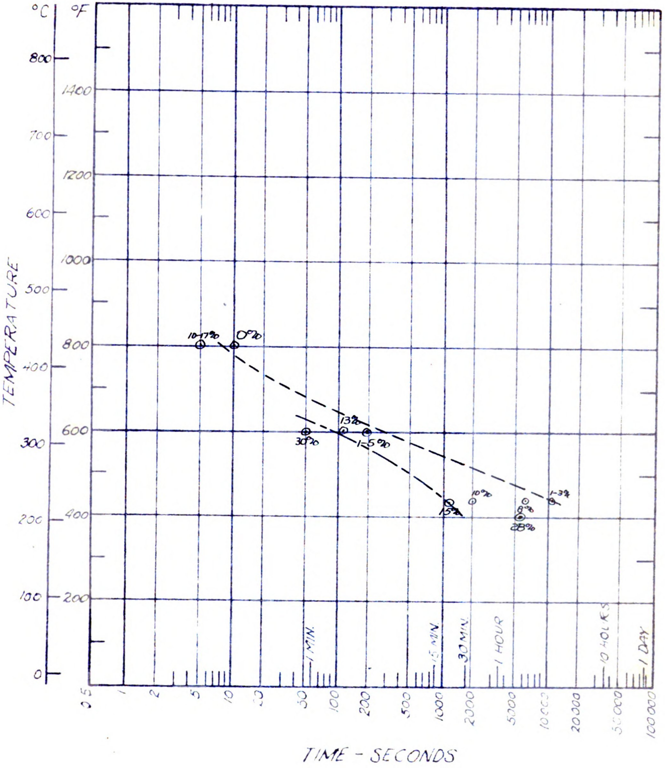


FIGURE 16

TABLE 15

ISOTHERMAL TRANSFORMATION DIAGRAM

OF RETAINED AUSTENITE IN OIL QUENCHED SAE 1010 CARBURIZED STEEL

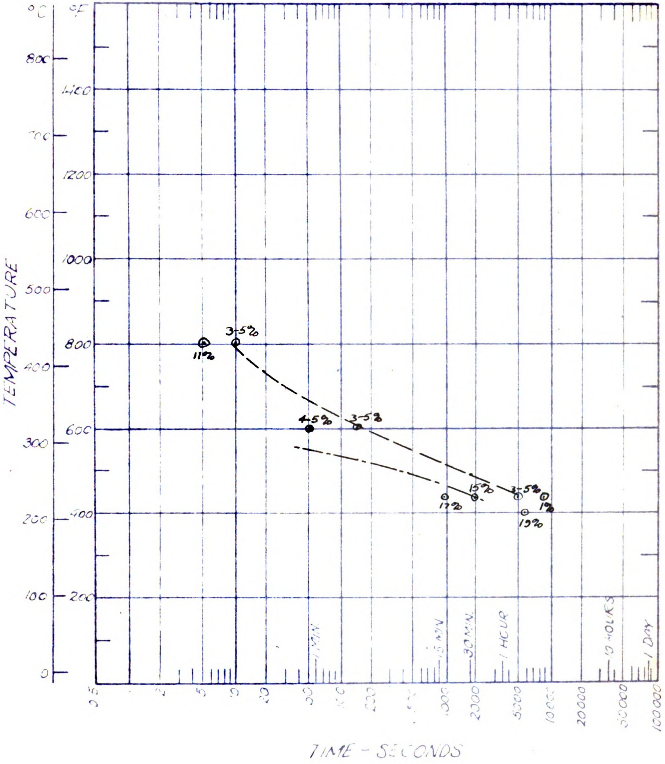
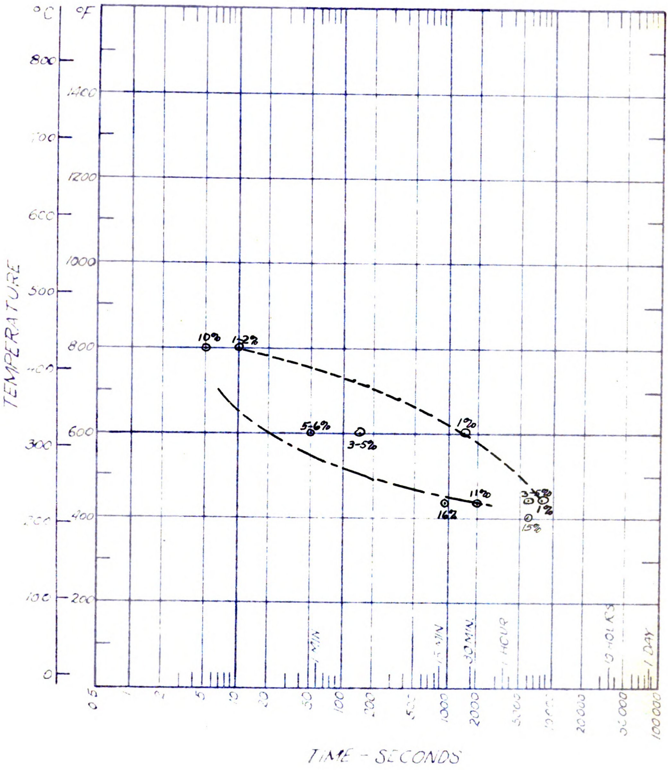


FIGURE 17

TABLE 16

ISOTHERMAL TRANSFORMATION DIAGRAM
OF RETAINED AUSTENITE IN WATER QUENCHED SAE 1010 CARBURIZED STEEL



Discussion

Some of the problems which were encountered have already been discussed lightly in the procedure. Etching in itself was one of the big factors and was seriously affected by the tempering temperature and time. Figure 24 shows a 2015 structure etched short and is contrasted with a 2015 etched long as in figure 25. It is apparent here that the etch needs to be standardized if possible. usually from 5 to 10 seconds was long enough in most cases, but at 600°F it was apparent that the same structure could be etched to three different results. Here again the etching time had to be increased slightly over the time used at 450°F. The above facts would seem to show why everything was double etched before pictures were recorded.

The method of point counting has certain limitations. The person who is taking the pictures is the biggest variable and he must be careful to choose representative sections. If at all possible more accurate results could be obtained if the same area was photographed continuously and more than one picture recorded near that area to give a better average. Also small percentages are hard to count and do not give reliable results. However the method is far above visual estimation and would be very good in structures where the constitutents do not vary. With this in mind it is not hard to see that the variable carbon case present in this problem complicated things no end.

Even though very good checks were obtained on the carbon train the results indicate that there might have been some contamination of some samples. This could be due to a slight amount of oil or other carbonaceous material in the high results while incomplete combustion could account for the low results. however this last factors was held to a minimum by a three hour preheat period with oxygen slowly bubbling through the system and then checked against ASTM standards. One other problem was that of plotting the results. The percent carbon present was over an interval of distance and thus was plotted against the mid point of each cut. This yields a curve which is more representative of the actual carbon gradient.

The plot of the isothermal curves should not be taken as absolutely true as all points were obtained from only one set of results. Even though the same area was apparently photographed over and over in the SAE 1010 steel; the pictures which were recorded gave no indication of likeness. At 1500 diameter one millimeter makes quite a difference in the picture obtained and consequently a change in results.

One of the big factors in doing the experimental work was control of carbon and alloy content of the various steels. Since it was impossible to control any of the alloys except carbon and carbon was only controlled between limits it is difficult to draw valid conclus~~s~~ions.

In all of the steels the amount of retained austenite varied directly with the carbon content and showed fairly homogeneous areas of austenite whenever the percent of carbon present was close to the eutectoid carbon content or higher. At lower percentages it was spotty depending upon alloy segregation and varied in persistence to tempering along these same lines. For instance some of the longer tempering treatments showed groupings of the austenite, where the amount present in the photomicrograph taken was nearly equal to the original structure. This was especially true in SAE 3145 and 2340. The plain carbon steel decomposed faster than the other steels, but did however show areas where the austenite was slow to break up. It seems that as the austenite decomposes (a) the martensite needles develop little warts and grow wider and (b) at the same time there is a divisioning of the austenite present with fine needles developing and slowly spreading out (figure 19, 21, 22). Figure 18 shows the structure just after darkening of the martensite needles and note how sharp and clear they are in contrast to figure 20 where the needles seem to shade and contain a lighter etching area. Figure 19 shows the start of divisioning and it continues on and at about 300 minutes at 450 deg. F. in both SAE 2340 and 3145 the lines have developed into needles and the austenite seems to be quartered away. Now in figure 23 you have the end result of all the different heat treatments which yields nearly a perfect salt and pepper effect for 530 min. at 450°F. for the SAE 3145 carburized steel. To reach this last step in 800°F. tempering it is only a matter of seconds and in 600°F. it takes only a few minutes to yield this similar structure.

Figure 18
2340,
Oil Quenched
1.5 hr. 450°F.

Figure 19
2340,
Oil Quenched
60 min. 450°F.

Figure 20
2340,
Oil Quenched
105 min. 450°F.

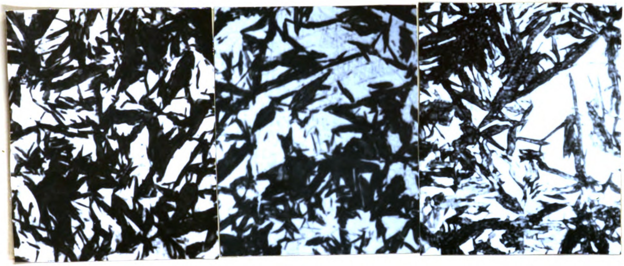
Figure 21
2340,
Oil Quenched
300 min. 450°F.

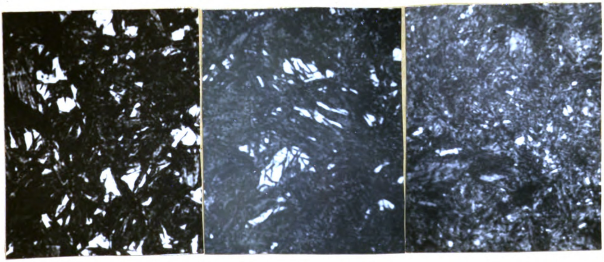
Figure 22
3145,
Oil Quenched
320 min. 450°F.

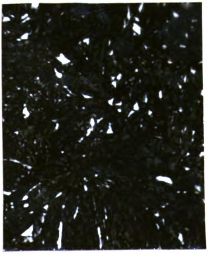
Figure 23
3145,
Oil Quenched
530 min. 450°F.

Figure 24
2015,
Oil Quenched
100 min. 450 °F.

Figure 25
2015,
Oil Quenched
80 min. 450°F.







Time is very important and one second at 800°F. or one minute at 600°F. is as good a retained austenite decomposer as 40 to 60 minutes at 450°F. It should be noted here that just heating through the higher temperature ranges tends to rapidly decompose the retained austenite. Whether this decomposition is a matter of stress relief or carbon movement is beyond the scope of this paper. However either would be possible in the range of temperatures used.

Perhaps this paper would give further evidence to the support of many old and recent investigators that austenite seems to be sensitive to decomposition at about 450°F. and increases in speed of decomposition for the next 400°. However on interrupted quenching to determine S-curves some investigators found austenite to stablize itself at 800°F. and they developed newer C-curves showing this. Retained austenite indicated none of this stability at ~~7~~800°F. In fact the SAE 2015 and 4640 carburized specimens indicated some decomposition at 400°F. and a lower darkening temperature for the martensite was used.

The 1010 carburized specimens were checked for the effect of the 400° treatment in darkening the α -martensite and indicated no effect whatsoever as the end decompositions came at exactly the same time.

Just why the 2015 and 4640 should be more sensitive to 400°F. is hard to say, unless it be from an alloy standpoint. But then, the 1010 would also be affected in the same way. The 4640 does yield a lower carbon case upon examination and carbon seems to be the most powerful influence present in the alloy field in this problem.

Conclusions

1. The amount of retained austenite varies directly with the carbon content, higher carbon yielding more retained austenite, when the other factors have remained constant.
2. Oil quenched steels give slightly more even distributions of retained austenite. However, the total percentage difference is not great.
3. The three tempering temperatures 450°F., 600°F., and 800°F. all yield the same end result if tempering times are long enough at the lower temperatures.
4. The retained austenite seems to decompose upon going through a range of temperatures as well as decomposing at temperature.
5. High alloy steels retained the most austenite upon quenching.
6. The retained austenite is more persistent in the higher alloy steels.
7. The point counting method can be readily applied and is more accurate than visual estimation.
8. The isothermal diagrams should not be accepted as absolutely true.

Future Work

This problem presents many possibilities for future work:

A. Develop a method to center specimens so that the same area can be photographed continuously.

B. Use smaller specimens so that more accurate estimates can be made of time at temperature for the 600°F. and 800°F. tempering temperature.

C. Use specimens that are carburized all the way through; thus, eliminating the variable case and making the point counting technique more valuable.

D. Treat samples from higher temperature to coarsen structure. This would then allow a smaller magnification, better ability to stay in the same area, and more representative percentages by point counting.

E. Develop a method to give data showing the rate of cooling.

F. Shorten the increments of time in the high temperature treatments.

Selected References

1. Dowdel, R. L. and Harder, O. E., "The Decomposition of the Austenitic Structure in Steels", Transaction for Steel Treating, 1927, Vol. II April, P. 583.

2. Mehl, R. F. and Roberts, G. A., "Mechanism and Rate of Formation of Austenite from Ferrite-Cementite Aggregates: Transactions ASM, Vol. 31, 1943, P. 613.

3. Digges, T. G. and Rosenberg, S. J., "Metallographic Study of Formation of Austenite in .5% Carbon Alloys", Transactions ASM, Vol. 31, 1943.

4. Greninger, A. B. and Troiana, A. R., "Kinetics of Austenite to Martensite Transfer in Steel," Transactions ASM, Vol. 30, 1942.

5. Mehl, R. F. and Roberts, G. A., "Effect of Inhomogeneity in Austenite on Rate of Austenite-Pearlite Reactions in Plain Carbon Steels", Transactions AIME, Vol. 154, 1943.

6. Gardner, F. S., Cohen, M., and Antia, D.P., "Quantitative Determination of Retained Austenite by X-rays", Transactions AIME, Vol. 154, 1943.

7. Gordon, P. and Cohen, M., "Transformation of Retained Austenite in High Speed Steels at Sub-Atmospheric Temperatures", Transactions ASM, Vol. 30, 1942.

8. Lyman, T. and Troiano, A.R., "Influence of C Content upon Transformation in 3% Cr Alloys, Transactions ASM, Vol. 37, 1946.

9. Klier, E.P. and Troiano, A. R., "A_r in Cr Alloy Steels," Tech. Pub. No. 1799, AIME, Metals Tech., Feb. '45.

10. Saveur, A., "Metallography and Heat Treatment of Iron and Steel, 1935, McGraw-Hill Book Company.

11. Austin, J. B. and Ricket, R. L., "Kinetics of Decomposition of Austenite at Constant Temperature", Transactions AIME, Vol. 135, 1939.

12. Savarine, I. M., "Phase Changes in 3.5% Ni Steel in the Ac_1 Region", Transactions AIME, Vol. 135, 1939.

13. Wells, C. and Mehl, R. F., "Rate of Diffusion of Carbon in Austenite," Transactions AIME, Vol. 140, 1940.

14. Greninger, A. B. and Troiano, A. R., "Crystallography of Austenite Decomposition", Transactions AIME, Vol. 145, 1940.

15. Greninger, A. B. and Troiano, A. R., "Mechanism of Martensite Formation", Transactions AIME, Vol. 145, 1940.

16. Gordon, P. and Cohen, M., "Retained Austenite in High Speed Steels, Transactions ASM, Vol. 30, 1942.

17. Mirkin, I. L. and Spektor, A. G., "Transformation of Residual Austenite during Drawing", Metallurgy 12 No. 8, 9-14, 1937 (Russian).

18. Klier, E. P. and Troiano, A. R., "Ar in Cr Steels", Metals Tech., Feb. 1945.

19. Lyman, T. and Troiano, A. R., "Isothermal Transformation of Austenite in One Percent Carbon High Cr Steels", Metals Tech., Feb. 1945.

20. Gordon, P., Cohen, M., Rose, R. S., "The Kinetics of Austenite Decomposition in High Speed Steel, Trans. ASM, Vol. 31, 1943.

21. Smith, G. V., and Mehl, R. F., "Lattice Relationships in Decomposition of Austenite to Pearlite, Bainite and Martensite," Metals Tech., April 1942.

22. Bain, E. C., "Alloying Elements in Steel", ASM, Cleveland, Ohio, 1939.

23. Howard, R. T. and Cohen, M., "Quantitative Metallography by Point-Counting and Lineal Analysis", Metals Tech., August 1947.

24. Rote, C. B., Truckenmiller, W. C., and Wood, W. P., "Electrical Resistance Method for Determining of Isothermal Austenite Transformation", ASM Preprint #46, Oct. 20, 1941.

25. Zimeskal, O. and Cohen, M., "Simultaneous Measurements of Magnetic and Dilatometrical Change, Rev. Sci. Instruments, Vol. 13, 1942.

26. Flectcher, S. G. and Cohen, M., "The Effect of Carbon on Tempering of Steel," Transactions ASM, 1944.

27. Davenport, E. S. and Bain, E. C., "Transformation of Austenite at Constant Sub-Critical Temperatures", Transactions AIME, I and S Division, 1930.

28. Davenport, E. S., "Isothermal Transformation in Steel", Transactions ASM, Vol. 27, 1939.

29. Allen, N. P., Pfeil, L. B., and Griffths, W. T., "The Determination of the Transformation Characteristic of Alloy Steel", British Iron and Steel Institute, Sp. Report, No. 24, 1939, p. 369-390.

30. Epstein, Samuel, "The Alloys of Iron and Carbon", Vol. I, 1936 Ed. McGraw-Hill Book Company.

31. Zmeskal, O. and Cohen, M., "The Tempering of Two High-Carbon, High-Chromium Steels", Transactions ASM, 1943, Vol. 31.

32. Antia, D. P., Fletcher, S. G., and Cohen, M., "Structural Changes during the Tempering of High-Carbon Steel", ASM, Vol. 32, 1944.

33. Van Vleet, H. S. and Upthegrove, C., "Decomposition of Austenite", Metal Progress, 1930, Vol. 18, October, p. 68-70.

34. Chevanard, P., Portevin, A., "Mechanism of Tempering Martensite", Comptes Rendus 191, 1059-62, 1930.