The Fatigue of Steel and Its Recovery.
Part I.

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CONTENTS.

PREFACE.

Since the fatigue of metals was treated systematically by WÖHLER(1) and then by BAUSCHINGER,(2) many researches on this problem have been carried out especially by STANTON,(3) BAIRSTOW,(4) ROSENHAIN,(5) HAIGH,(6) SMITH,(7) JENKIN,(8) STROMEYER,(9) THOMPSON,(10) MOORE,(11) and others. According to these researches, it is said that iron and steel can be repeatedly stressed *ad infinitum* without failure so long as the stress is within the limiting range of stress, while broken after a finite number of repetitions if the stress is more than the named range.

Researches in the past have dealt principally with the determination of the limiting range of stress in machines of various types, the relation between limiting range of stress and tensile test results, the relation between limiting range of stress and temperature rise, the influence of chemical composition, mechanical or thermal treatment upon the limiting range of stress and tensile test results, the mechanism of fatigue phenomena, etc., but not with the recovery from fatigue quantitatively except that a few qualitative data may be referred to.(12)(13)(14)

The features of this paper are the investigation of fatigue followed by physical and chemical phenomena, the recovery condition of fatigued steels, and the nature of fatigue.

CHAPTER I. MATERIAL.

The metarials used in this investigation were received in a rolled condition, principally ¾″ diameter, except ¾″ octagonal in hard Steel, by 20′ 0″, 12′ 0″ and 4′ 0″ long, and all cut into pieces 160 mm. long, provided both end pieces were destined for chemical and thermal analyses.

CHEMICAL COMPOSITION.

The materials used in this investigation are commercial steels the chemical compositions of which are shown in Table 1. The heat treatment chosen here was nearly the same as those adopted in practice.

Table 1. Chemical Composition and Heat Treatment.

Composition. / Material.	C%	Si%	Mn%	P%	S%	Cu%	Ni%	Cr%	Heat Treatment.
Dead Mild Steel.	0.06	0.008	0.46	0.078	0.04	0.02			Annealed.
Mild Steel I.	0.16	0.07	0.48	0.01	0.02	0.08			,,
Mild Steel II.	0.22	0.012	0.66	0.062	0.05	0.28			,,
Semi-Hard Steel.	0.45	0.16	0.53	0.051	0.025				,,
Hard Steel.	0.74	0.47	0.67	0.019	0.020				,,
Semi-Hard Steel.	0.37	0.14	0.45	0.048	0.026				Hardened & Tempered
Nickel Steel.	0.28	0.12	0.51	0.013	0.022		3.29	0.115	,,
Nickel Chrome Steel.	0.36	0.15	0.65	0.014	0.034		3.30	0.71	,,

THERMAL ANALYSIS.

The transformation points and A_2 change of material used were determined by a differential method when the increasing and decreasing rates of temperature were a little more rapid than those in Fig. 1. The results are shown in Table 2.

Table 2. Transformotion Points and A_2 Change.

Material.	C	Ac_1			Ac_2		Ac_3	
		Beg.	Max.	End.	Beg.	Max.	Beg.	Max.
Dead Mild Steel. . .	.06	745	752		790	795	850	865
Mild Steel I. . . .	.16	740	750				805	815
Mild Steel II. . . .	.22	735	745					
Semi-Hard Steel. .	.45	730	742	790				790
Hard Steel.	.74	735	750	770				770
Nickel Steel. . . .	.28	730	735	780				780
Nickel Chrome Steel.	.36	715	730	780				780

Material.	C	Ar_3			Ar_2			Ar_1		
		Beg.	Max.	End.	Beg.	Max.	End.	Beg.	Max.	End.
Dead Mild Steel. . .	.06	885	855	820	770	755	720			
Mild Steel I. . . .	.16		800		760	755		674	668	
Mild Steel II. . . .	.22							670	665	
Semi-Hard Steel. .	.45	720	700					670	660	
Hard Steel.	.74		680					680	653	
Nickel Steel. . . .	.28		730					670	633 600	
Nickel Chrome Steel.	.36		660					660	625 583	520

Remarks: Temperature measured in °C.

HEAT TREATMENT.

Some of the steels in Table 1 were annealed and others were hardened and tempered as seen in the table, To facilitate the denotation of each heat treatment some conventional marks are adopted, they being represented as follows.

Ex. 1. 900—15 SC, 850—30 SC............

meaning that specimens were heated in a lead bath at 900°c, 850°c,......... for 15 minutes, 30 minutes,.........respectively, then cooled as they were until the temperature was lowered to 550°c, when those specimens were taken out of the bath and put into straw ash.

Ex. 2. 1000—80 LC, 850—180 LC, 730—320 LC...........

These treatments are almost the same as the precedent, but in these cases the specimens were left to cool down slowly to room temperature as they were instead of taking them out of the lead bath at 550°C.

Ex. 3. 950—360, 900—15,............

meaning that the specimens were heated in an ordinary electric muffle furnace at 950°C, 900°C,.........for 360 minutes, 15 minutes.........respectively and then cooled slowly.

Ex. 4. 850—30 OQ............

meaning that specimens were heated at 850°C in the lead bath for 30 minutes then quenched in oil.

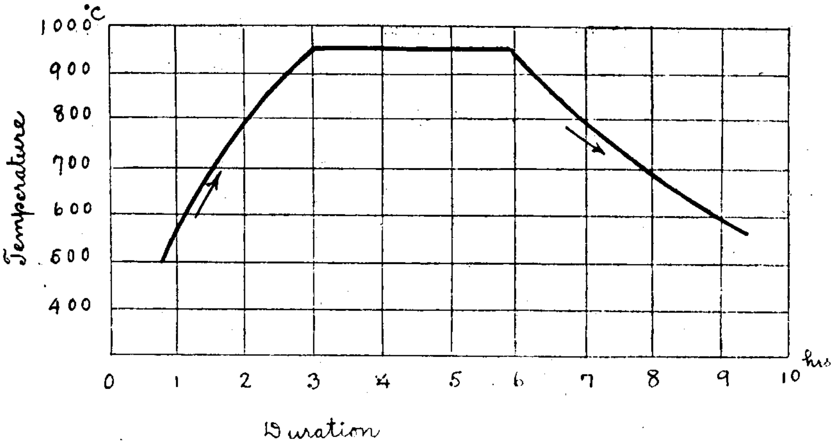
Ex. 5. 650—20 OQ............

meaning that quenched specimens were heated in the lead bath at 650°C for 20 minutes then quenched in oil.

The lead bath furnace mentioned above is so constructed that a steel crucible containing a lead pool, in which about twenty specimens can be placed with ease, is surrounded by a clay tube coiled by nichrome wire which is covered with an asbestos layer of about 120 mm. thickness, and thin zinc plate. When the furnace was heated and the lead in it was melted down, specimens were put in and a suitable weight was lain on to prevent them floating up above the molten lead surface, provided the bath was covered with charcoal or retort carbon powder lest it should be oxidised.

The heating and cooling rates of the bath are shown in Fig. 1.

Fig. 1.



CHAPTER II. TESTING MACHINE, TEST PIECES AND APPARATUS.

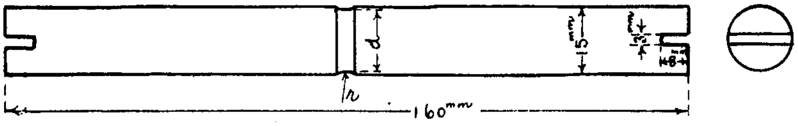
REPEATED SHOCK TESTING MACHINE.

The stress due to repeated shock* was applied to notched specimens in Prof. Matsumura's Repeated Shock Testing MACHINE,(15) the outline of which is reproduced in Fig. 2.

SPECIMENS.

The dimensions of specimens are shown in Fig. 3.

Fig. 3.



The dimensions "d" and "r" in the figure are so determined as to be 14 mm. and 10 mm. in annealed specimens and as 13 mm. and 5 mm. in hardened and tempered ones respectively. Square sectional specimens with notches 0.5 mm. deep on each side, however, were used for special purposes.

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* Blow energy was made constant as 30 kg.-cm, during this experiment, unless specially described

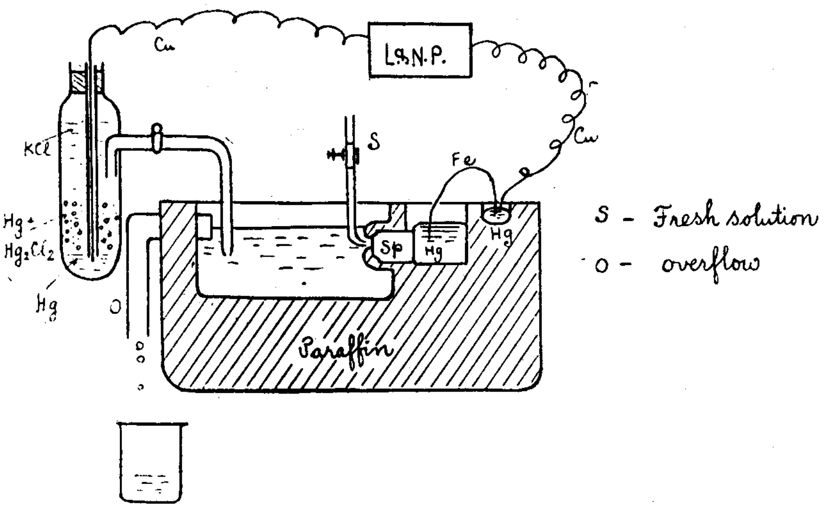
DIFFERENTIAL THERMOCOUPLE.

A hollow specimen for the determination of the transformation points were put into a nickel ring, and one of the hot junctions of a differential thermocouple was inserted in the specimen while the other was placed in the nickel ring itself. Whenever any temperature difference occurred between those two places, the corresponding electro-motive force was generated to be determined by a sensitive galvanometer.

SOLUTION POTENTIAL DETERMINATION.

The solution potentials of differently stressed parts of specimens were determined by Leeds and Northrup's Potentiometer, when a calomel electrode was referred to as being the standard potential. An apparatus used is sketched roughly in Fig. 4.

Fig. 4.



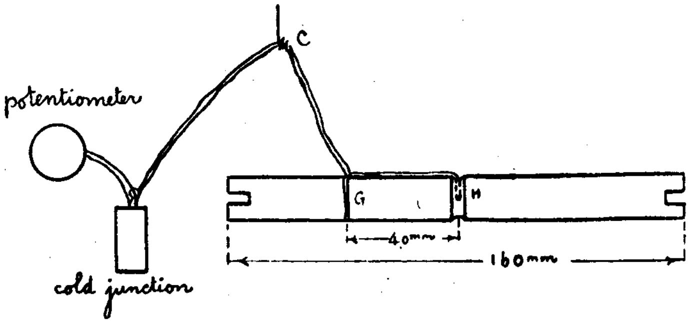
MAGNETOMETER.

Two equiaxial field coils of the same type were placed in the direction of east—west, in the middle of which a horse shoe magnet with small mirror above it was hung by a tiny silk thread. The specimen was put into a tube in one of the coils through which an electric current can be passed. The deflection of the mirror due to magnetic flux induced in the specimen was determined by means of a telescope and scale the distance of which from the mirror was made constant during examination.

THE TEMPERATURE MEASUREMENT OF SPECIMENS WHILE BEING STRUCK.

A hole H reaching the center line of a specimen was made in the notched part, at a distance of 40 mm. from which a circumferential groove G was made as in Fig. 5. A hot junction of a copper–constantan thermocouple was inserted into the hole H, near the hot junction the couple was fastened to the specimen with thin wire to keep the site of the hot junction steady, then the couple was guided along a longitudinal groove to G where the couple was fastened to the specimen with thin wire again, and the remaining part of the couple was supported with a string hung from the ceiling. The other means for this measurement are shown in Fig. 5.

Fig. 5.



CURRENT REGULATION.

The temperature of the heating furnace described in Chapter I was almost constant (± 10°C) at night after having attained a certain temperature, unless the supplied voltage changed seriously. The increase or decrease of the voltage, however, might be expected at night when the voltage was abnormal i. e. too low or too high in the evening, then a device was attached to the main circuit. This device was intended, first, to change the current in the magnetising coil for the electro-magnetic core according to the voltage change; secondly to act as relay according to the magnetic change of the core, and, thirdly, to switch the current on or off into a shunt wire of the main circuit for the heating furnace by means of the relay.

CHAPTER III. FRACTURES DUE TO FATIGUE.

The fact that fractures may occur with the appearance of those of brittle materials, where sections of machines or construction parts change abruptly, is frequently met with in practice and is reproduced in text books and periodicals. These fractures are considered to be caused by the repetition of stresses greater than a certain magnitude. The odd numbers 1, 3, 5, 7, 9, 11, 13, and 15 in Fig. 6 show the repeated shock fractures of annealed dead mild steel, mild steel I, mild steel II, semi-hard steel, hard steel, hardened and tempered semi-hard steel, nickel steel and nickel chrome steel respectively, and they may be considered as fatigue fractures.

CHAPTER IV. CORROSION OF FATIGUED STEEL.

SELECTIVE CORROSION.

The fractured surfaces of repeated shock specimens were ground, polished, etched for about half an hour with FRY'S macroscopic and microscopic etching solution,(16) HUMEREY'S,(17) DICKENSON'S,(17) ROSENHAIN'S(17) copper containing salt solutions, or, still better, with cupric chloride solution or HEYN'S solution,(17) and the copper deposited on them washed off. The etched surface thus prepared are reproduced as even numbers 2, 4, 6, 8, 10, 12, 14, and 16 in Fig. 6, showing that the parts which are stressed more than a certain degree are corroded selectively and they correspond to the upper pictures of fractured surfaces marked with old numbers.

A specimen marked 6 in Fig. 6 which was coated electrically with copper, polished, and etched is shown in Fig. 7 the particulars of which are explained in the figure. This was taken from a highly stressed part but a similar figure with much smaller cavities was seen near the neutral axis.

If we compare selective corrosion in specimens which suffered repeated shocks, the Brinell hardness test, and bending, the most severe corrosion is to be seen near the parts remotest from the neutral axis, and the clearest demarcation between low and high stress parts in the specimens of the first kind compared with the other two cases.

SOLUTION POTENTIALS.

The potential of the part near the neutral axis and that of the selectively corroded part in FRY'S macroscopic etching reagent were measured by means of an apparatus shown in Fig. 4. and the results in Table 3.

Table 3.

A			B	C	D	E
Time Since Solution Began to Rinse Specimens.			Potential.		Potential Diff. C—B. v.	Remarks.
			of High Stress Part. v.	of Neutral Part. v.		
hr.	min.	sec.				
0	2	30			0.00794	Material Used = Mild Steel II, - Room Temperature = 16°c.
0	6	0			"	
0	8	0			0.00871	
0	15	0			0.006765	
0	18	0			0.005795	
0	22	0			0.005915	
0	28	0			0.006135	
0	34	0			0.005835	
0	53	0			0.007025	
0	57	0			0.007130	
0	58	0			0.007210	
1	2	0	0.24485	0.25206	"	
1	3	0	0.24627	0.25348	"	
1	5	0	0.24627	0.25348	"	
1	27	0			0.007080	

Next a high stress part and a part near the neutral axis were placed in positions opposite to each other in a paraffin basin into which clear water was poured. When the potential difference between them was zero in this condition a small amount of each reagent in Table 4 was poured into the basin, and the solution agitated and then set still. Such operation was repeated several times and in each period the potential difference was measured. (Table 4.)

Table 4.

Reagents.	Voltage Difference.				Remarks.	
	During Agitation.		While Standing Still.			
	Near Neutral Axis.	High Stress Part.	Near Neutral Axis.	High Stress Part.		
Fry's Macroscopic Etching Solution.	(+) 0.05	(−)	(+) 0.007~0.005	(−)	While standing still after agitation the voltage difference is 0.007~0.005 volt and this condition continued for a long time.	Material used =Mild Steel II, Room Temperature =16°c.
Conc. Hydrochloric Acid.	(+) 0.004~0.005	(−)	(+) 0.002~0	(−)	Voltage difference=0 soon after agitation is stopped.	
Ferrous Sulphate.	(+) 0.003~0.002	(−)	do.	do.	do.	
Ferrous Oxalate.	(+) 0.009~0.005	(−)	do.	do.	do.	
Cupric Chloride.	(−) 0.009 or more	(+)	(+) 0.007	(−)	While standing still the opposite voltage difference to that during agitation period and the former condition (high potential in neutral axis) continued for a long time.	

It might be concluded from these experiments that for revealing selective corrosion such solutions are to be selected that the neutral part shows a high potential for a long time when solutions are set still. From these experiments we find that selective corrosion, at any rate, is due to electrolysis between the differently stressed parts, and we can distinguish the neutral part and highly stressed part by this method.

INELUENCE OF REHEATING UPON SELECTIVE CORROSION.

The broken pieces of a repeated shock specimen were put into the molten lead bath which was so heated previously that when they were put into the bath its temperature would be almost the required one. After keeping them in the bath for a certain time they were taken out, then put into straw ash to cool slowly with the least or no oxidation. When these pieces cooled down the fractured surfaces were ground, polished, then treated with 10% cupric chloride or copper ammonium chloride solution as previously described.

The result is such that the higher the temperature, the fainter the selective corrosion phenomenon, and the longer the time of heating at a certain temperature, the fainter the selective corrosion phenomenon too. If the condition in which the selective corrosion becomes very faint and can be traced only with difficulty is denoted by the mark △⃝ and the logarithmic numbers of the absolute temperature and time (in minutes) in this condition were plotted as ordinates and abscissae respectively, then the locus of mark △⃝ would be nearly a straight line as in Fig. 9. Marks △ and ○ in this figure denote the conditions when selective corrosion is yet to be seen clearly, and when it disappears altogether, respectively.

CHAPTER V. PROCEDURE OF FATIGUE FAILURE.

To pursue the procedure of fatigue failure, the present writer prepared a mild steel specimen of square section for the repeated shock test, polished and etched at the notch part. During the test the writer observed the distortion phenomenon on the latter part with a microscope. After a certain repetition of stress slip bands appeared only in some crystals, and if the repetition of strees were continued further, not only more slip bands appeared in the same crystals but new slip bands appeared in other crystals and in the meantime heavy slippings along the crystal boundaries appeared as black bands, some of which led to incipient cracks at last. If these cracks developed further the stresses concentrated on their bottoms, and the failures did not follow the crystal boundaries but proceeded in the direction to which the previous cracks were turned. (ref. from Fig. 10 to Fig. 12 and from Fig. 13 to Fig. 23—Each figure represents the same place on the specimen.)

Fig. 10.	Etched.	Before Blow.		×80.
„ 11.	„	Blow No.	=11020	do.
„ 12.	„	„ „	=11475	do.
Total Blow No.*			=11510	
Fig. 13.	Etched.	Before Blow.		×150.
„ 14.	„	Blow No.	=400	do.
„ 15.	„	„ „	=1100	do.
„ 16.	„	„ „	=2000	do.
„ 17.	„	„ „	=3100	do.
„ 18.	„	„ „	=4000	do.
„ 19.	„	„ „	=5000	do.
„ 20.	„	„ „	=6000	do.
„ 21.	„	„ „	=7000	do.
„ 22.	„	„ „	=7420	do.
„ 23.	„	„ „	=8003	do.
Where line A A corresponds with A A in Fig. 22.				
Total Blow No.			=8189	

Figs. 24 and 25 are the etched figures of the transverse sections of fatigue and shock fractures respectively, and in the former a crack passes along the crystal boundaries while in the latter a crack traverses in the direction to which the previous crack had turned. Besides there are seen etch bands nearly paralled to the cracks in the latter while no such figures are to be observed in the former. Figs. 26 and 27 are the more magnified figures of Figs. 24 and 25 respectively and the etch bands are only observable along shock failures in Fig. 27.

The fractured surface of mild steel due to repeated shock was ground, polished, then etched deeply with picric acid and the etching solution was replaced very quietly with running water. The specimen dried

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* Total Blow No. (or T. B. N.) means conventionally the number of repeated blows which a specimen endures before failure and this conventional term is used often in this paper.

appeared bright near the neutral axis, while the high stress parts were colored brown due to the fact that there are several microscopic 'sonims' rimmed with brown iron oxides as shown in Fig. 28.

CHAPTER VI. SLIP BAND, SELECTIVE CORROSION, AND BLOW ENERGY.

SLIP BAND VERSUS SELECTIVE CORROSION.

The mild steel specimen of square section was repeatedly struck until failure. When this specimen was treated with copper ammonium chloride solution it was observed that only the parts where the slip bands showed were more corroded selectively than the other parts.

BLOW ENERGY AND SELECTIVE CORROSION.

The mild steel specimens were repeatedly struck with energies of 17.25 and 50 kg.-cm. and broken down after repetitions of 28331 and 4688 blows respectively. One piece of the broken specimen (where the blow energy = 50 kg.-cm.) was cut transversely into small pieces through the planes A, A′, B, B′, C, C′, D, and D′, and another into E, E′, F, F′, G, and G′ (in Fig. 29), and these pieces were corroded selectively like the figures at the top and bottom on the right when treated with copper ammonium chloride solution. The general view of such corrosion may be shown by shading as on the right in the middle figure.

In the other specimen (where blow energy = 17.25 kg.-cm.) similar figures are to be seen on the left. After this experiment it may be concluded that the greater the blow energy the larger the areas corroded selectively.

BLOW ENERGY VERSUS SLIP BANDS.

From the above experiments the greater the blow energy the wider the area where slip bands prevail.

CHAPTER VII. EFFECT OF REPEATED BLOWS AND ANNEALING UPON ELECTRIC RESISTANCE.

Both ends of each specimen were connected with both poles of the electric battery, and the current (I) through the circuit was measured with sensitive galvanometer, and the two points (135 mm. apart) between the two ends were connected with Leeds and Northrup's potentiometer to measure the potential difference (E), then the resistance (R) between these two points was determined by formula $R = E/I$. Then each specimens was struck 10~25 %† of the T. B. N., the resistances were measured again, the specimen as reheat treated 950–180 LC, 900–15 SC and the resistances were measured again as before. The result of many observations is described as follows.

No. of Tests.	Temperature of Specimens.	Resistance		
		Before Blow.	After P. B. N. (10%~25%)	After Reheat Trēatment.
52	20°C	$1237 \times 10^{-7}\,\Omega$	$1245 \times 10^{-7}\,\Omega$	$1240 \times 10^{-7}\,\Omega$

When the specimen was stressed repeatedly the electric resistance increased by a very small amount, though this increment due to repeated stress seemed to be lowered again by the reheat treatment.

CHAPTER VIII. INFLUENCE OF REPEATED BLOWS UPON MAGNETIC PROPERTIES OF STEELS.

The specimen was put into a tube in one of the magnetic field coils, an electric current was passed on and off in the coils, and then a hysterisis curve was obtainable as in Fig. 30. This specimen was struck P. B. N. (about 10 %), then put into the tube in the magnetic coil as before to obtain magnetic hysterisis as shown in Fig. 31.

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† If the specimen was struck certain fraction, for instance 10, 20, or 30%, of the total blow number, it may be conveniently said that the specimen was struck P. B. N. (10, 20 or 30%) and this conventional term is used often in this paper.

Fig. 30.

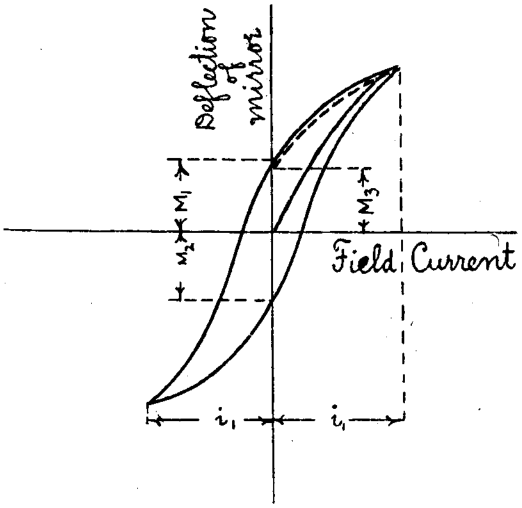
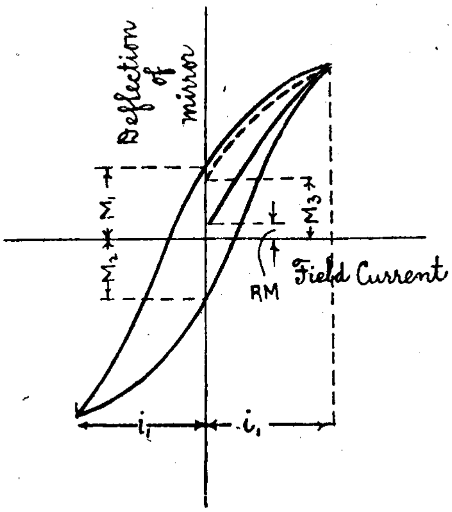


Fig. 31.



Every time the specimen was struck P. B. N. (about 10 %) the magnetic measurement was carried out, $M_1 M_2 M_3$ in these figures are remnant magnetisms, while RM is also a remaining magnetism after this has been magnetised as in Fig. 30 and then struck P. B. N. (about 10 %).

In this experiment the values of RM/M_1 are about 8, 50, 60 and 90 % in annealed carbon steel (C=.74), hardened carbon steel (C=.45 %), hardened and tempered nickel chrome steel and hardened nickel chrome steel respectively, and if magnetisation and repetition of blows were operated alternately over and over again; the values of $M_1 M_2 M_3$ and RM diminished in time for a certain period after which these values did not decrease but sometimes rather increased very slightly. The cause of this tendency might be explained by the generation of incipient cracks.

CHAPTER IX. TENSILE PROPERTIES OF FATIGUED MATERAL.

Specimens of annealed mild steel I (d=14 mm., r=10 mm. in Fig. 3) were struck repeatedly 50, 70, 80, and 85 % of the total blow numbers, and machined into tension test pieces whose parallel parts are 12 mm. diameter by 80 mm. long, and at the same time unstruck specimens of the same material were also machined.

The test piece was mounted in Olsen's wire testing machine and a load applied by means of a screw. While Marten's extensometer set for a 50 mm. gauge length was attached to the test piece, the machine was set then in motion so that readings of the load and extension were then able to be recorded for successive loadings of 2.25 kg./mm.² until the yielding point was reached. After the extensometer was then removed, the test pieces were pulled until fracture occurred. The total breaking strength, elongation and contraction of area were measured, the elastic stage was then plotted to scale, using stresses in kg./mm.² as ordinates and extensions $\frac{\Delta l}{l}$ as abscissae (Fig. 32 and accompanying table). Notwithstanding the fact that the test pieces from unstruck specimens were broken in the middle, those from the struck ones were broken at one end of each parallel part the middle portion of which was strengthened(13) by stress repetition due to blows.

CHAPTER X. INCIPIENT CRACKS.

When the specimen is struck repeatedly slipping takes place in the boundaries of crystals, and in the crystals themselves in notched parts, and the dislocation of the boundaries between slags and steel is observed if the former exist in steel. Eventually cavities occur after a certain number of repetitions of blows where the atomic forces can scarcely exert themselves, that is, steel in a healthy condition changes itself through fatigued condition into a broken one when incipient cracks appear.

DETERMINATION OF THE INSTANT WHEN INCIPIENT CRACKS APPEAR.

The writer adopted conveniently the following two means to determine the instant when incipient cracks occur.

1. Temperature Rise of the Specimen.

If the specimen prepared as in Fig. 5 was struck repeatedly, its temperature in the notch rose rapidly at first, became constant, rose again but very slightly, and rose rapidly at last when the specimen was broken asunder. The period where the constant temperature range changed itself into the range of slight temperature rise was caused by incipient cracks. One example for the mild steel specimens is illustrated in Fig. 33.

2. Impregnation of Cinnabar Stamp Ink.

The specimen was struck P. B. N. (e. g. 40 %), taken out of the machine, the notch was coated with cinnabar stamp ink to allow it to soak into the crack if present, the excess was wiped off and the specimen was struck again and again until failure. According as the ink was observed in the fracture or not the crack was considered to be present or not when the specimen was coated with the ink. Several applications of these methods could determine the exact period when the incipient crack occurred.

The results of the determination of the instant when incipient cracks appear, and the relation between these and other physical properties are shown in Tables 5, and 6 (also in Fig. 34) respectively.

Table 5.

Material.	Heat Treatment.	Dimensions of Specimen.	Measurement of Temperature Rise.		Coating with Stamp Ink.		Remark.
			No. of Experiments.	$\frac{\text{I.B.N.}}{\text{T.B.N.}}\times 100$ % (Mean Values)	No. of Experiments.	$\frac{\text{I.B.N.}}{\text{T.B.N.}}\times 100$ % (Mean Values)	
Dead Mild Steel. . .	Annealed	† d=14mm., r=10mm. in Fig. 3.	1	65	2	57	*I.B.N.=Blow no. to cause incipient crack in the specimen. T. B. N. (defined previously.)
Mild Steel I. . . .			2	59	4	56	
Semi-Hard Steel. . .			2	45	2	52	
Hard Steel.			2	63	2	66	
Semi-Hard Steel. . .	Hardened and Tempered.	‡ d=13mm., r=5mm in Fig. 3.			4	25	
Nickel Steel.					8	27	
Nickel Chrome Steel.					3	33	

† Blow Energy=30 kg.-cm.
‡ Blow Energy=25 kg.-cm.

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*I.B.N.=Blow number to cause incipient crack in the specimen and this term is used often in this paper.

Table 6.

Material.	C%	Heat Treatment.	Dimensions of Specimen.	Brinell Hardness.	$\frac{\text{I.B.N.}}{\text{T.B.N.}}\times 100\%$ (Mean Values.)	Mean.	
						I.B.N.	T.B.N.
Dead Mild Steel. . . .	.06	Annealed.	† d=14mm., r=10mm. in Fig. 3.	94	57	4200	7408
Mild Steel I.	.16			94	56	4400	7884
Mild Steel II.	.22			100			8883
Semi-Hard Steel.	.45				50	5500	11000
do.	.50			150			10959
Hard Steel.	.74			220	65	5900	9062
Semi-Hard Steel. . . .	.37	Hardened and Tempered.	‡ d=13mm., r=5mm. in Fig. 3.	180	25	1200	4657
Nickel Steel.	.28			220	27	1600	5827
Nickel Chrome Steel. . .	.36			254	33	2300	7032

† Blow Energy=30 kg.-cm.
‡ Blow Energy=25 kg.-cm.

Remark—Comparatively high Brinell No. in dead mild steel is due to the segregation in it.

Nickel chrome steel in Table 2 heat treated as in Table 7 were treated similarly as in Table 6 and the results obtained are shown in Table 7 and Fig. 35.

Table 7.

Heat Treatment.		Mean Blow Number.		$\frac{\text{I.B.N.}}{\text{T.B.N.}}\times 100\%$ (Mean Values.)	Remark.
Hardening.	Tempering.	I. B. N.	T. B. N.		
850-30 OQ		17000	19517	86	Specimen :— d=13mm., r=5mm. in Fig. 3. Blow Energy =30 kg.-cm..
do.	205-24	17000	21909	78	
do.	330-20 OQ	18000	23918	75	
do.	378-20 OQ	16500	23288	71	
do.	447-20 OQ	9670	17806	54	
do.	502-20 OQ	5960	12334	48	
do.	547-20 OQ	3900	8830	44	
do.	601-20 OQ	2300	6603	35	
do.	650-20 OQ	1500	4926	31	
850-30 SC		1900	3856	50	

CHAPTER XI. RECOVERY OF STEEL FROM FATIGUE.

A. MATERIAL.

The chemical compositions, transformation points, etc., were shown in CHAPTER I and the heat treatment, dimensions of specimens, blow energies, mean total blow numbers of the specimens of each kind before and after various ' reheat treatments ', explanations of which are made with examples in the next section, are shown in Table 8.

Table 8.

A	B	C	D	E	F	G
Material.	Dimensions of Test Piece.	Heat Treatment.		Blow Energy kg.-cm.	Mean.	
		Before.	After.		T.B.N.	T.B.N. after Reheat Treatment.
		Specimens Machined to Required Dimensions.				
Dead Mild Steel. . .	d=14mm., r=10mm. in Fig. 3.	950-360 900-15		30	6770	7408
Mild Steel I. . . .					7476	7884
Mild Steel II. . . .					8151	8883
Semi-Hard Steel. . .		850-180	850-30SC		10959°	10959
Hard Steel.					9062°	9062
Semi.Hard Steel. . .	d=13mm., r=5mm. in Fig. 3.		850-30OQ 650-20OQ	25	4657°	4657
Nickel Steel.					5827°	5827
Nickel Chrom Steel.					7032°	7032

Remark :—It was determined from the data not described here that total blow numbers marked o (column F) are almost equal to those after reheat treatment and therefore the values in column G can be assumed equal to those in column F.

B. RECOVERY HEAT TREATMENT AND DEGREE OF RECOVERY.

After the mean value of total blow numbers (T.B.N.) was determined in each kind of steel the specimens were struck P.B.N. (e.g. 15, 22.5 and

30%) and then they (a) were reheat treated with the specimens (b) which had not been struck previously. The ratio of total blow numbers of the specimens (a) to those of the specimens (b) may be deemed as the measure of recovery from fatigue and called recovery degree. The reheat treatment was such as 1000–90 LC., 900–15 SC; 730–320 LC, 850–30 SC; 850–180 LC, 850–30 OQ 650–20 OQ; and those marked LC were performed to let the steel recover from fatigue, and this may be called recovery heat treatment. The others, however, were made to get steels with the same structure throughout the examination and these are 900–15 SC for dead mild steel and mild steel, 850–30 SC for semi-hard steel and hard steel, and 850–30 OQ 650–20 OQ for steels to be hardened and tempered.

C. PRELIMINARY EXAMINATION.

a. Finish Machining of Notch versus T.B.N.

The more the notch of the specimen was finished smoothly the higher the values of the total blow numbers and the constancy of the numbers were obtained.

b. Intermittent Rest of Blow versus T.B.N.

Even if the specimen was given rest for one day or two after they had been struck a certain fraction of the T.B.N., and struck again uutil breakage the sum of the blow numbers in such two stages was equal to the total blow numbers when no rest was allowed. So it may be said that there is no recovery after a rest of one or two days.

c. Fatigue versus Grain Growth.

When dead mild steel specimens were broken through the repetition of blows, each of their broken pieces was heat treated 650–60; 760–60; 850–60; 900–60; 920–60 SC; 940–60; 960–30 SC; 960–60 SC; 1030–30 respectively, and the fractures were ground, polished, then etched with 10% nitric acid dissolved in alcohol to reveal crystalline structures. In the first five examples of these treatments the abnormal growth of grains was observed, but in the other examples a few crystals microscopically grown after 940–60, also a few crystals less grown after 960–30 SC, and no abnormal growth at all after 960–60 SC, and 1030–30. were observed.

In the next examination the broken pieces were treated 870–60 LC, 900–15 SC; 900–60 LC, 900–15 SC; and 920–60 LC, 900–15 SC, then etched as before. The result was that unless the preceding treatment with suffix LC was enough to eliminate the tendency of growth, it is impossible to get a structure without abnormal crystals even after the following heat treatment 900–15 SC. These data are very important to determine the condition in which the recovery of specimens from fatigue can be completed.(18)(19)(20)(21)

d. Shock Fracture of Fatigued Steel versus Reheat Treatment.

A and B in Fig. 36 are fractures of mild steel specimens due to repeated blows. Five specimens of the same steel were repeatedly struck P.B.N. (80 %), and the 1st of those was not heat treated, the 2nd heat treated 900–15 SC, the 3rd 950–180 LC, 900–15 SC; the 4th 950–360 LC, 900–15 SC: and the 5th 950–600 LC, 900–15 SC, and those were broken down at their notches by single blows of a hand hammer as well as the fresh specimen the fractures of which are D, E, F, G, H and C respectively. The segments on the right (from C to H) are sharp notches to break the specimen with a hand hammer, while the segments on the top and bottom are fractures due to shearing in C, brittle fractures due to repeated shocks in D, E, F, and fractures due to shearing again in G. H. That is to say that brittleness caused by repeated application of stress can be eliminated by suitable heat treatment.

e. Can Steel Recover from Fatigue?

A short preliminary experiment was made whether steel could recover from fatigue. Mild steel specimens which had been heat treated 950–180 LC, 900–15 SC; after finish-machining to the required dimensions (d=14mm., r=5mm. in Fig. 3), were determined to have received mean total blow numbers as shown in Table 9 where blow energy was made constant as 30 kg.-cm. Specimens of the same kind were struck P.B.N.

(25, 17, 12.5 and 10%) and reheat treated 950–180 LC, 900–15 SC alternately for six times, and eventually these were struck again and again to break altogether at the seventh repetition, as shown in Table 9. The result shows that the total sum of the P.B.N. i. e. Σ P.B.N. is always greater than the mean total blow number.

Table 9.

No. of Specimens.	T.B.N.	P.B.N.	$\frac{\text{P.B.N.}}{\text{T.B.N.}}$ ×100%	1st P.B.N.	2nd P.B.N.	3rd P.B.N.	4th P.B.N.	5th P.B.N.	6th P.B.N.	7th P.B.N.	Sum of P.B.N. (Σ P.B.N.)	$\frac{\Sigma\text{P.B.N.}}{\text{T.B.N.}}$ ×100%
1	4015											
2	4585											
Mean.	4300											
3		1075	25	1075	1075	1075	1075	1075	1075	1058	7508	165
4				1075	1075	1075	1075	1075	1075	292	6742	
5		720	17	720	724	720	721	720	720	2847	7172	137
6				720	720	720	720	720	720	330	4650	
11	5289											
12	4156											
Mean.	4723											
13		590	12.5	590	590	590	590	590	Fracture. 269		3219	119
14				590	590	590	590	590	590	4524	8066	
15		472	10	472	472	472	472	472	472	2405	5237	132
16				472	472	472	472	472	472	4403	7235	

f. Slip Bands versus Reheat Treatment.

Slip bands appearing in the notched part of mild steel specimens disappeared when the specimens were heated for a certain time at a definite temperature. Figs. 37 and 38 show some of the above examples, Fig. 37 being the microscopic structure with slip bands, while Fig. 38 shows the same place after reheating it at 950°C for two hours in vacuo.

D. RECOVERY LINES AND CURVES FOR GENERAL CONDITION OF RECOVERY.

Each specimen was repeatedly struck P.B.N. (e.g. 15, 20, and 30%) then reheat treated and struck again until breakage to determine the degree of recovery as described in the preceding section. When the logarithmic values of the absolute temperature (in degrees) of the recovery heat treatment were taken as ordinates, and those of time (in mins) as abscissae the points in whose condition the degree of recovery becomes 100% are to be found on and above the straight lines passing through the point corresponding to each melting-point. The value at each point in Fig. 39 to Fig. 46 denotes the mean of two to ten observations. Such straight lines may be called recovery lines.

Besides it may be considered that the fresh specimen does not need to be reheat treated for recovery, or in other words, a recovery line for it will coincide with the ordinate and the specimen with incipient cracks does not recover at all until it may be exposed at its own melting-point, or in other words a recovery line will be a horizontal line passing through its melting-point.

Eventually the relations between the values of $\frac{\text{P.B.N.}}{\text{T.B.N.}} \times 100$ and the inclinations (degree) of recovery lines are shown in Table 10, or if the former may be taken as ordinates and the latter as abscissae, the diagrams in Fig. 47 were obtained which may be called curves for the general condition of recovery, or general recovery curves

Table 10.

Material.	Heat Treatment.	Dimensions of Specimens.	Blow Energy kg.-cm.	$\frac{\text{P.B.N.}}{\text{T.B.N.}}\times 100\%$						$\frac{\text{I.B.N.}}{\text{T.B.N.}}\times 100\%$
				10	15	17	20	22.5	30	
Dead Mild Steel.	Annealed.	d= 14mm., r= 10mm., in Fig. 3.	30		13°			8°	5°	57
Mild Steel I.					20°			13°	10°	56
Mild Steel II.							19°		13°	55
Semi-Hard Steel.					24°		16°		10°	50
Hard Hard Steel.					27°		20°		15°	65
Semi-Hard Steel.	Hardened & Tempered.	d= 13mm. r= 5mm. in Fig. 3.	25	13°	9°					25
Nickel Steel.				13°		9°				27
Nickel Chrome Steel					19°		13°			33

CONCLUSION.

In the scope of these experiments the writer concludes as follows :—

a. Steels are embrittled owing to the repetition of heavier stress than a certain value, become very fragile to shock but recover their own toughness through reheat treatment suitably selected.(22)

b. Resilience of Steels to shock is lowered considerably through the repetition of stress but the tensile properties are not so effected seriously and rather improved in the limit of proportionality and breaking strength.

c. The slipping happens in the crystals themselves and also at their boundaries due to the repetition of the stress, and also slipping and dislocation take place between steel and slag particles if the latter are disseminated in the former.

d. Electric resistance of steel increases very slightly through repetition of the stress but decreases again by reheat treatment.

e. Remnant magnetism of steel was measured after every P.B.N. (10%) and was observed to decrease step by step, but this tendency not only disappeared but also sometimes the opposite tendency appeared after the period when the incipient crack was suspected to occur.

f. The highly stressed portions of the specimen are likely to be more electro-positive than the low stressed part, but this phenomenon disappears if the specimen is suitably reheat treated.

g. After these experiments the boundaries of 'sonims,' other defects, and crystallines themselves are liable to become loose by the repetition of the stress, and cavities are generated where atomic forces have difficulty, or are unable, to exert themselves; and the material is said to be fatigued when some changes in its physical and chemical properties occur.

h. If fatigued steel is reheat treated at certain temperatures, atoms in it can get freedem to approach each other and are bound by atomic forces to recover the condition before being stressed, In these experiments the conditions in which several fatigued steels could be recovered by means of reheat treatment were determined. That is, annealed high carbon steels are able to recover from fatigue much more easily than mild steels whose recovery from fatigue under certain temperatures is likely to be followed by the growth of grains, especially in dead mild steel, to the result that the 'degree of recovery' appears very low. The general tendency of such recovery, however, may be considered thus, that the less the deformation due to repeated stress, the more easily steel can recover from fatigue by the reheat treatment.

FURTHER RESEARCH.

Lastly the writer adds that he is at present carrying out similar experiments with Prof. Ono's Endurance Testing Machine, the results of which will be reported in the near future.

ACKNOWLEDGMENT.

These experiments were carried out in the Technical Department of Kyoto Imperial University under the guidance of Professor D. Saito and Professor T. Matsumura to whom the author's hearty thanks are due. When the solution potential was measured and other measurements carried out valuable suggestions were made by Professor A. Matsubara and others of the University to whem the writer expresses his sincere thanks.

The writer is also very grateful to the Locomotive Manufacturing Co., Ltd., Osaka, and the Kobe Steel Works Ltd., who have generously supplied various materials for these tests and to the Teikoku Gakushiin for donating Baron Fujita's Bounty during the experiments.

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(15) Jour. Inst. Mech. Eng. Tokyo. No. 40.
„ „ „ „ „ No. 52.
(16) FRY's macroscopic etching soln. . $CuCl_2$ 90 g, Conc. HCl 120 cc, H_2O 100 cc.
„ microscopic etching soln. . $CuCl_2$ 5 g, Conc. HCl 40 cc, alcohol 25 cc, H_2O 30 cc.
(St. u. E. 11 u. 18, Aug. 1921).
(17) HUMFREY's solution. . . . . . . Cu Am Chloride 120 g, Conc. HCl. 50 cc, H_2O. 1000 cc.
DICKENSON's solution 1st. soln. Conc. HNO_3 10 cc, H_2O. 90 cc.
2nd soln. Fe_2Cl_6 40 g, $CuCl_2$ 3 g, Conc. HCl 40 cc, H_2O 500 cc.
ROSENHAIN's solutien . . . . . $FeCl_3$ 30 g, conc. HCl 100 cc, $CuCl_2$ 10 g, $SnCl_2$ 1 g, H_2O 1000 cc.
HEYN's solution. . . . . Cu Am Chloride 10 g, H_2O 100 cc.
(Chem. and Met. Eng. Aug. 24. 1921.)
(18) CHAPPEL: Jour. Ir. St. Inst. 1914–I.
(19) KÖRBER: St. u. E. 19. Feb. 1925.
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(22) Present writer. Experiments on Fatigue 1922 in which sound data are reported.

Fig. 2.

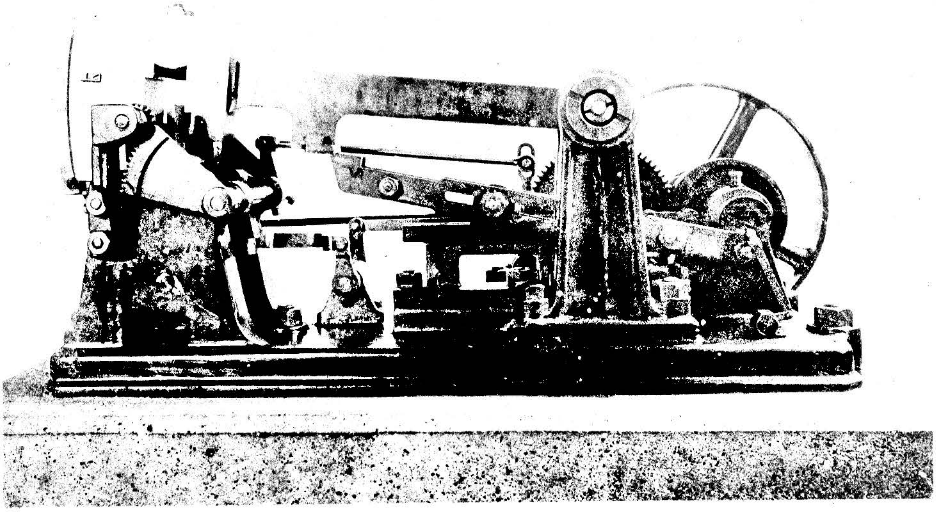
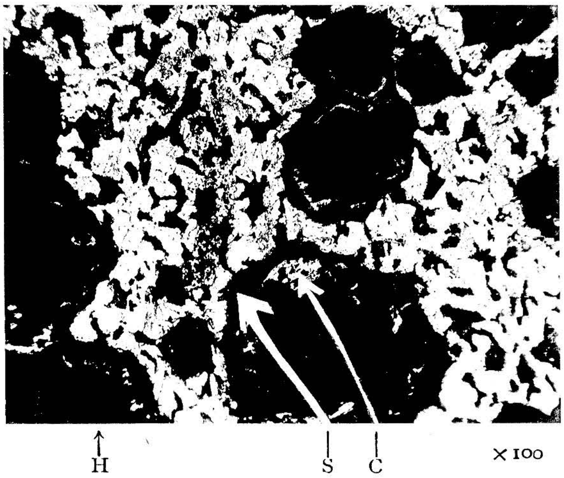


Fig. 7.



White ground—Ferrite, black specks-pearlite,
H—Cavities, C—Deposited Copper,
S—Stained Surface defining the Boundaries of
the Remaining Parts after Corrosion.

Fig. 6.

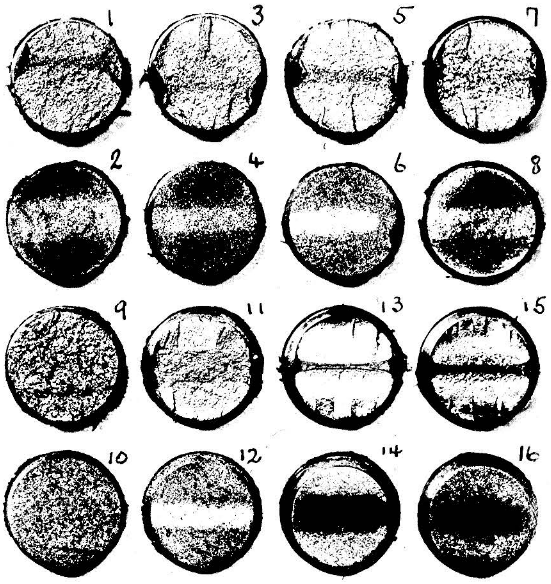
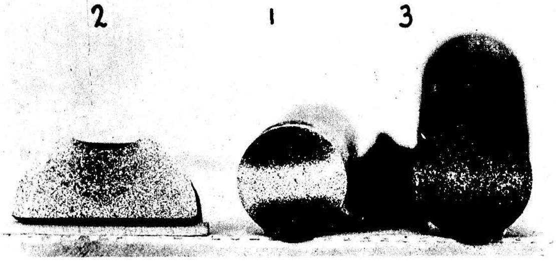
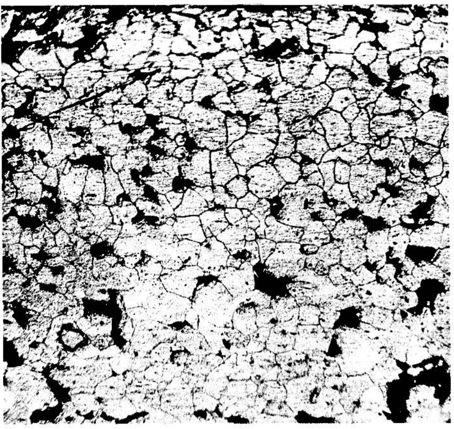


Fig. 8.



1. Repeated Shock Specimen,
2. Brinell Specimen,
3. Bender.

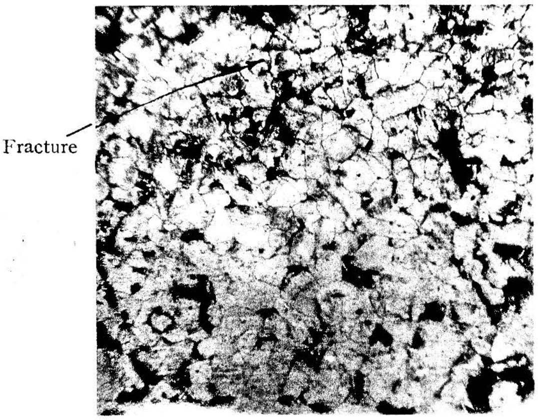
Fig. 10.



Crystal Boundaries where Fracture Took Place after Blow Repetition.

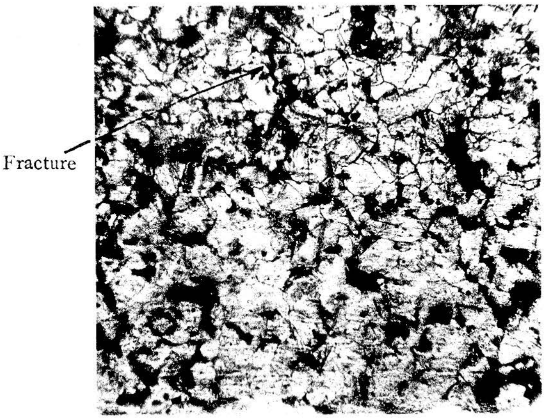
×80

Fig. 11.



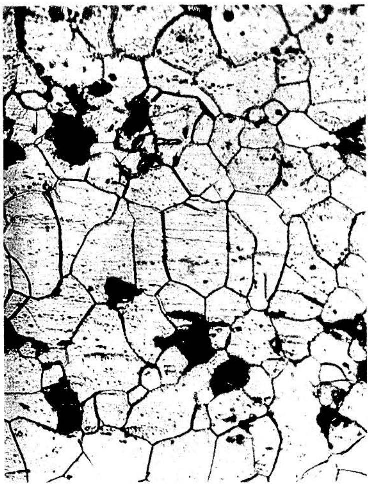
×80

Fig. 12.



×80

Fig. 13.



×150

Fig. 14.

×150

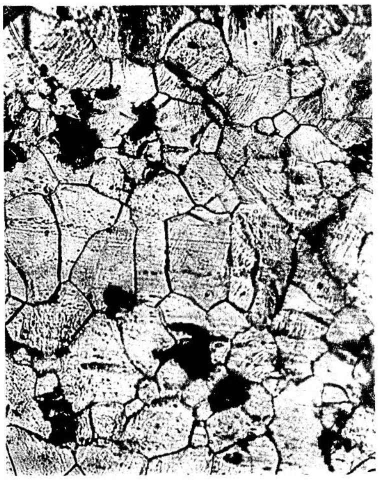
Fig. 15.

×150

Fig. 16.

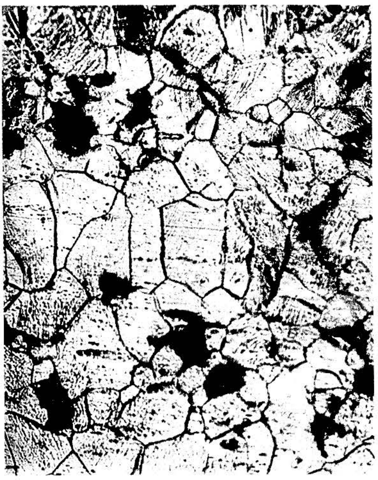
×150

Fig. 17.



×150

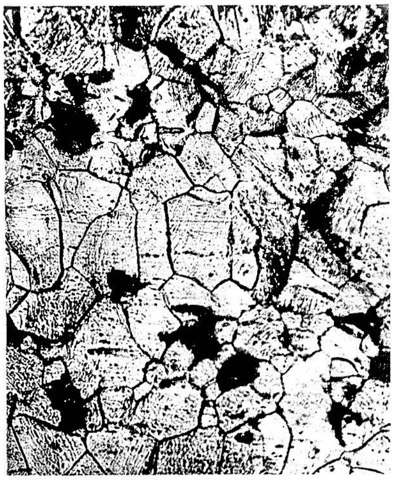
Fig. 18.



×150

PL. III.

Fig. 19.



× 150

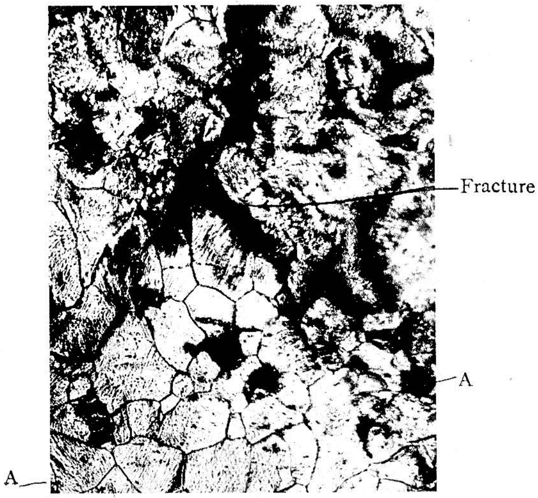
Fig. 20.

× 150

Fig. 21.

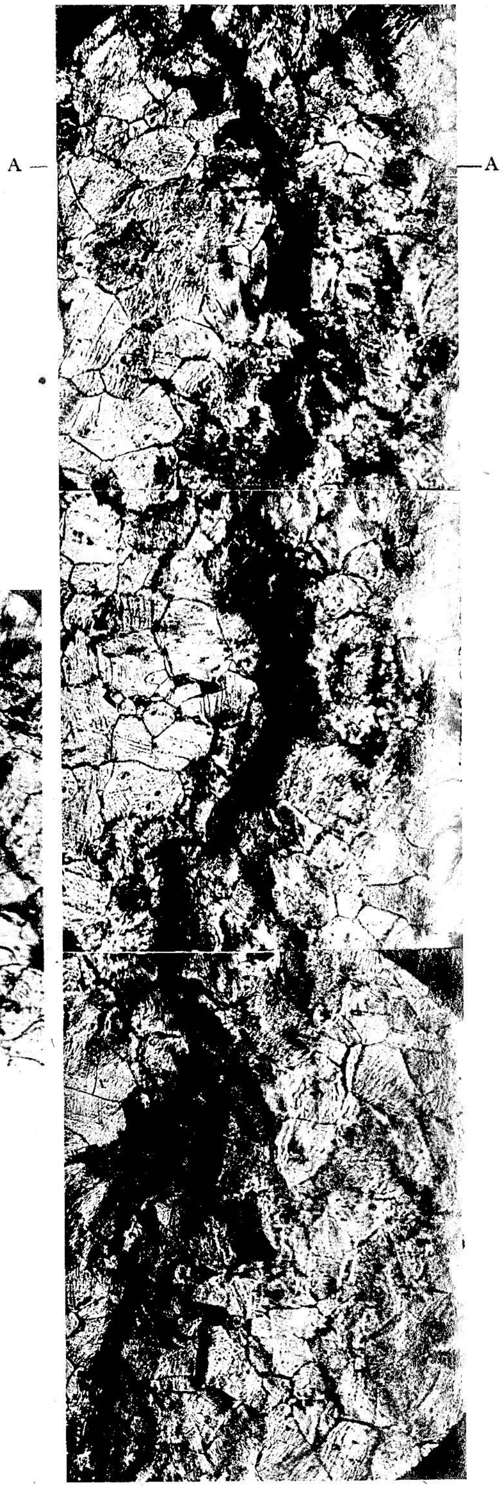
× 150

Fig. 22.



× 150

Fig. 23.



× 150

PL. IV.

Fig. 24

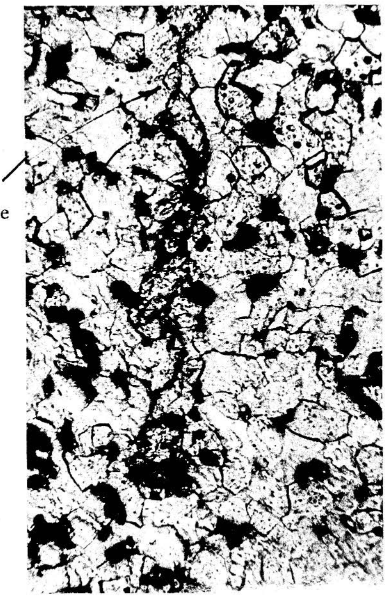


Fig. 25.

Fig. 26.

Fig. 27.

Fig. 28.

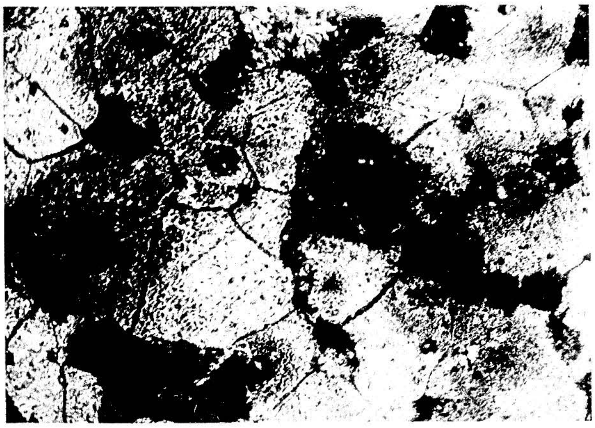


Fig. 36.

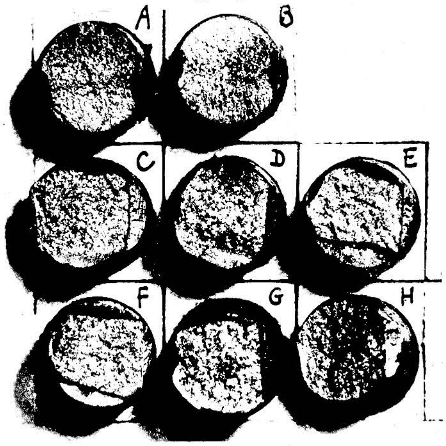
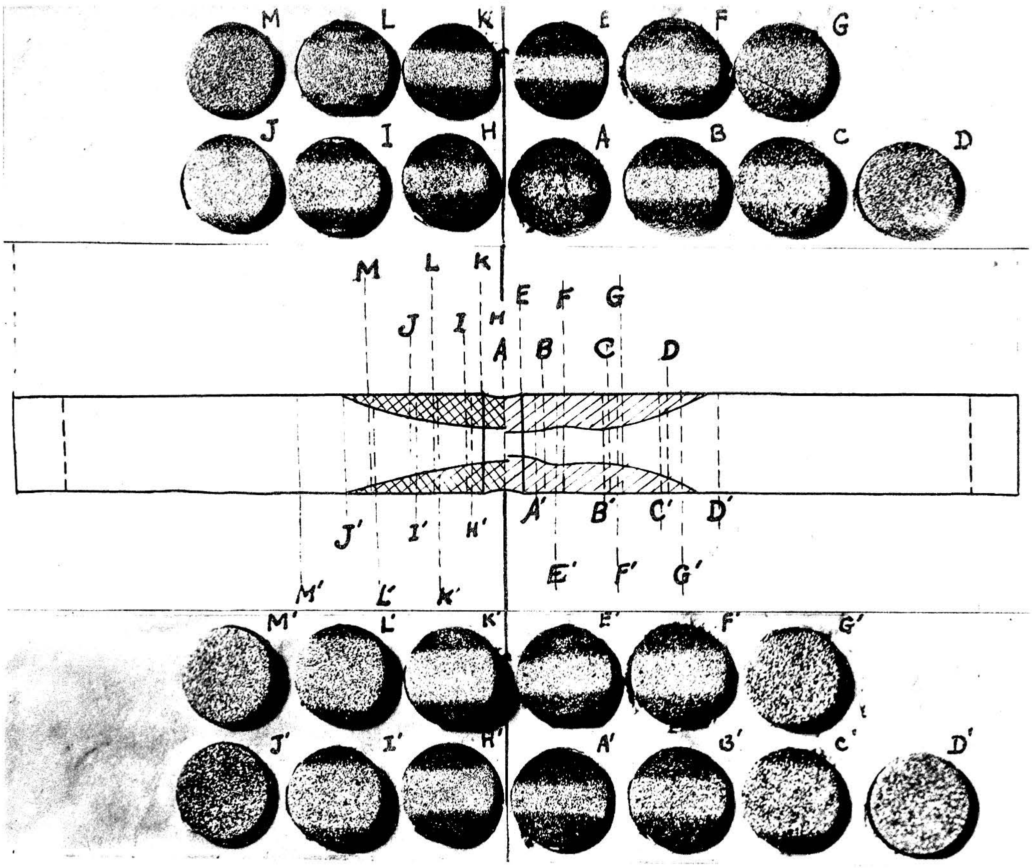


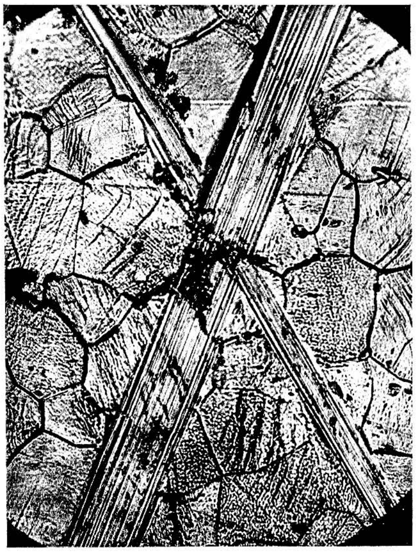
Fig. 29.



Blow Energy = 17.25 kg.-cm.
Total Blow No. = 28331.

Blow Energy = 50 kg.-cm.
Total Blow No. = 4688.

Fig. 37.



×150

Fig. 38.

×150

Fig. 9. Influence of Reheat Treatment upon Selective Corrosion.

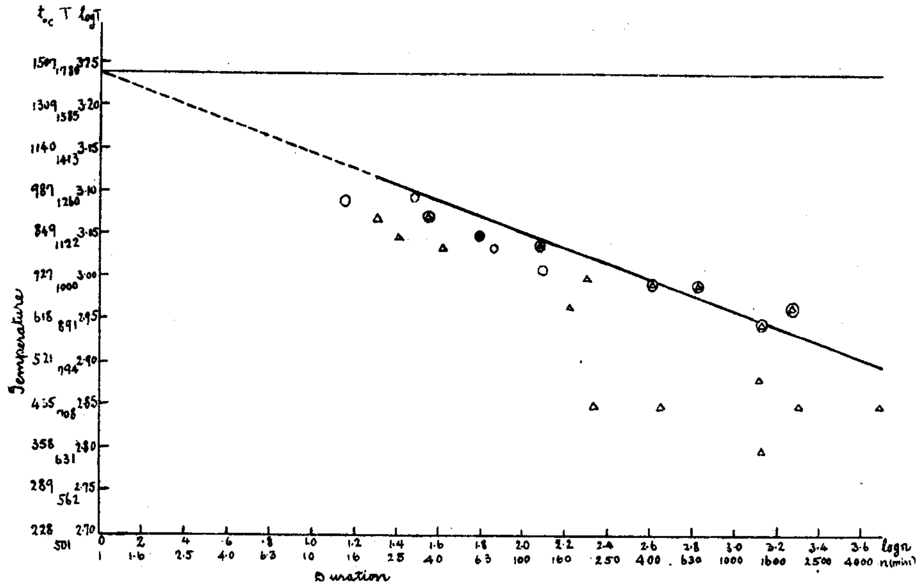
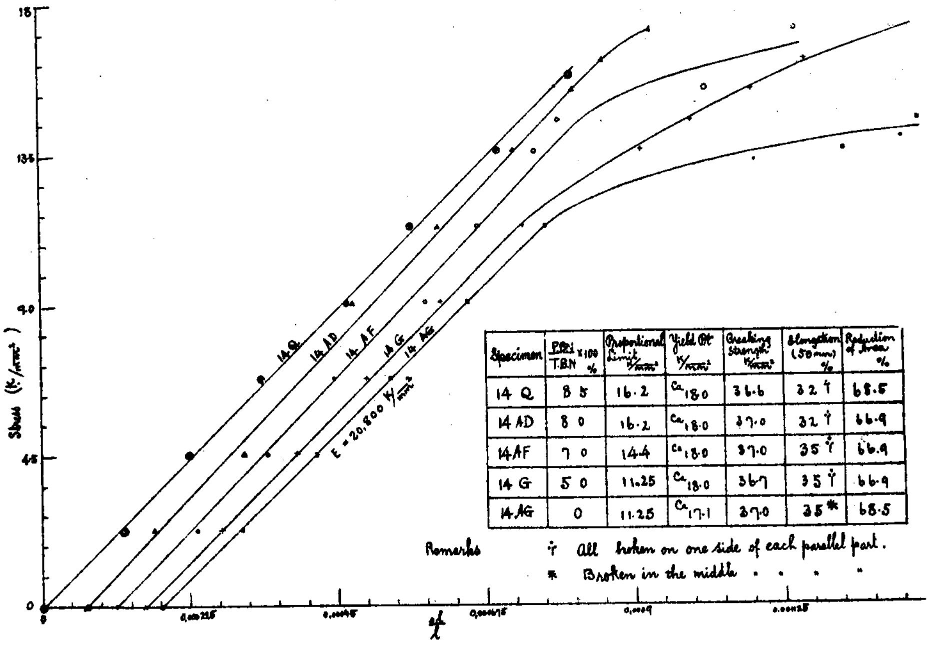


Fig. 32. Fatigue versus Tensile Properties.



Specimen	$\frac{\text{P.B.i}}{\text{T.B.N}}$ x100 %	Proportional Limit K/mm²	Yield Pt K/mm²	Breaking Strength K/mm²	Elongation (50 mm) %	Reduction of Area %
14 Q	8 5	16.2	Ca 18.0	36.6	32 †	68.5
14 AD	8 0	16.2	Ca 18.0	37.0	32 †	66.9
14 AF	7 0	14.4	Ca 18.0	37.0	35 †	66.9
14 G	5 0	11.25	Ca 18.0	36.7	35 †	66.9
14 AG	0	11.25	Ca 17.1	37.0	35 *	68.5

Remarks † All broken on one side of each parallel part.
* Broken in the middle " " " "

Fig. 35. Influence of Tempering Temperature upon I. B. N. & T. B. N. of N_1C_2 Steel.

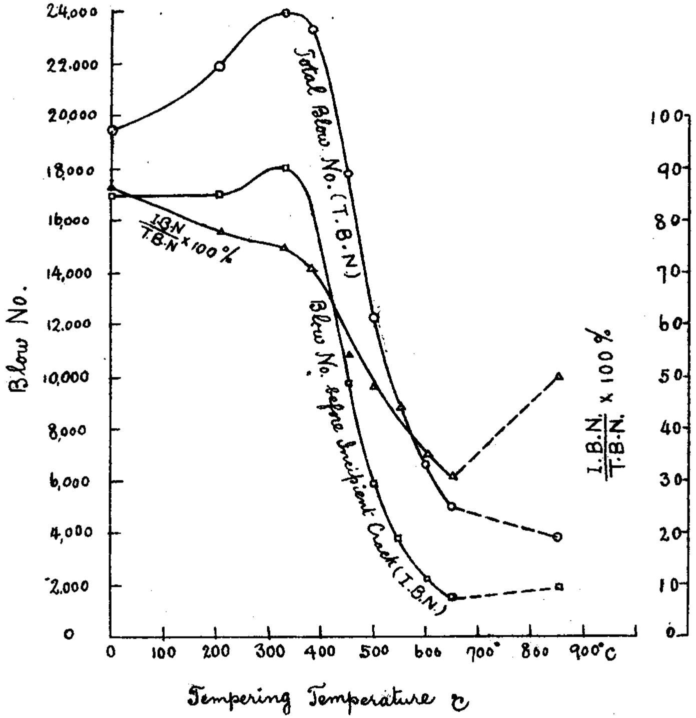
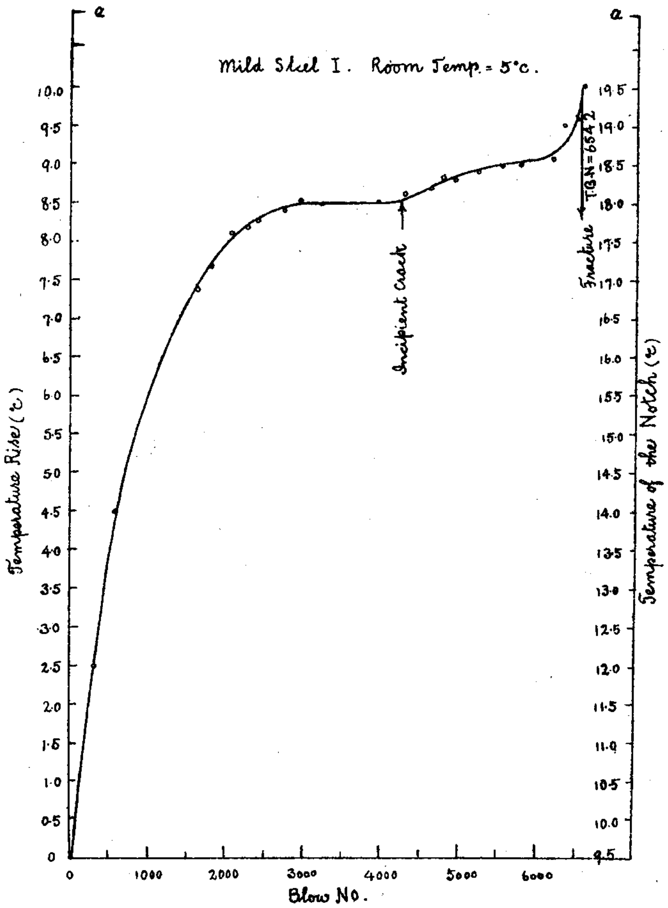


Fig. 33. Blow No. versus Temperature Rise in the Notch.



PL. VII.

Fig. 34. Chemical Composition and Heat Treatment versus Blow No. and B. H.

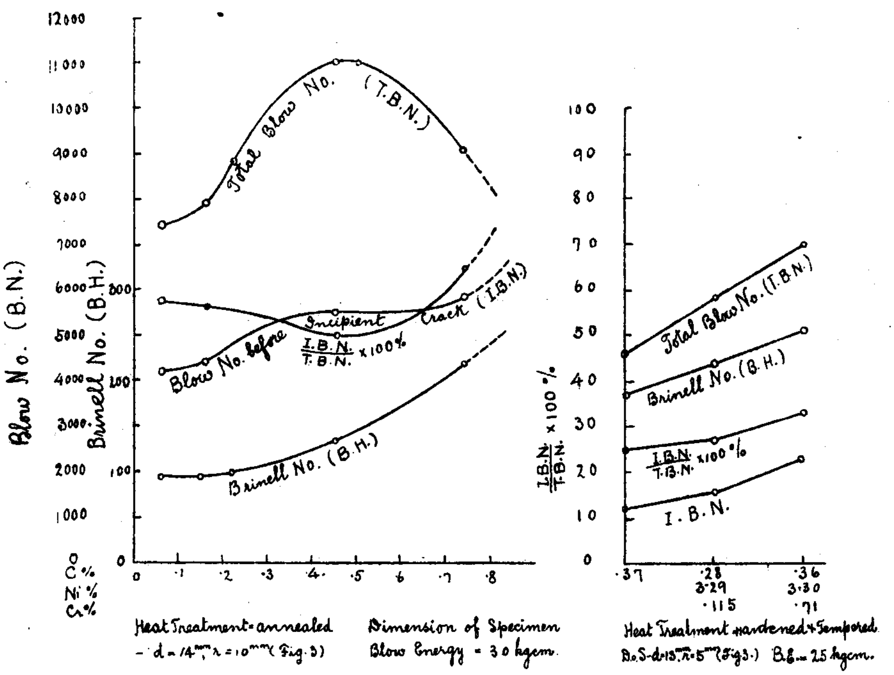


Fig. 39. Temperature and Time of Recovery Heat Treatment versus Recovery Degree.

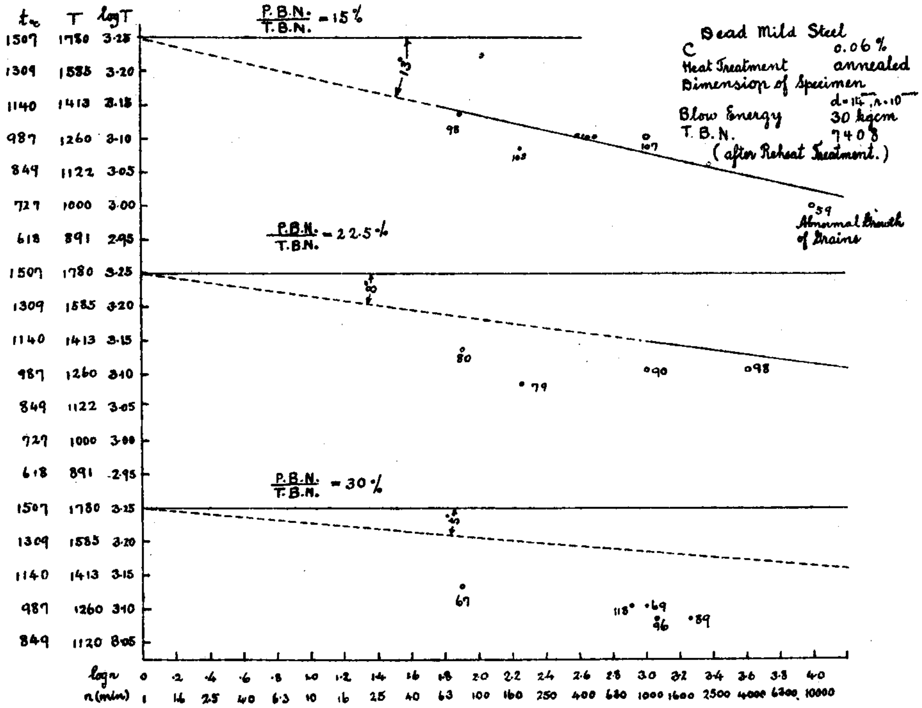


Fig. 40. Temperature and Time of Recovery Heat Treatment versus Recovery Degree.

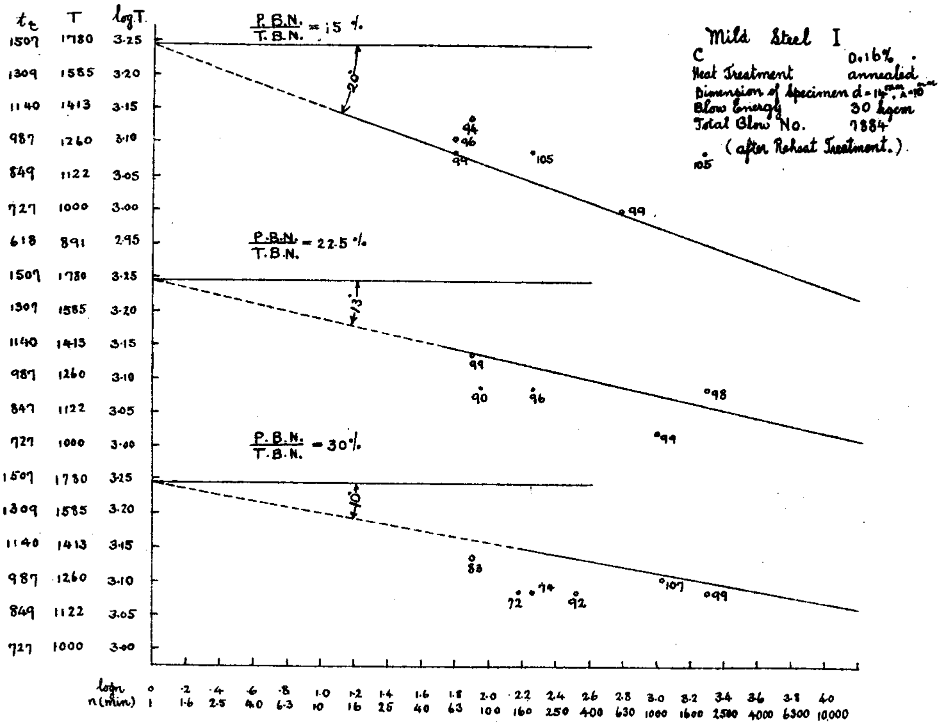


Fig. 41. Temperature and Time of Recovery Heat Treatment versus Recovery Degree.

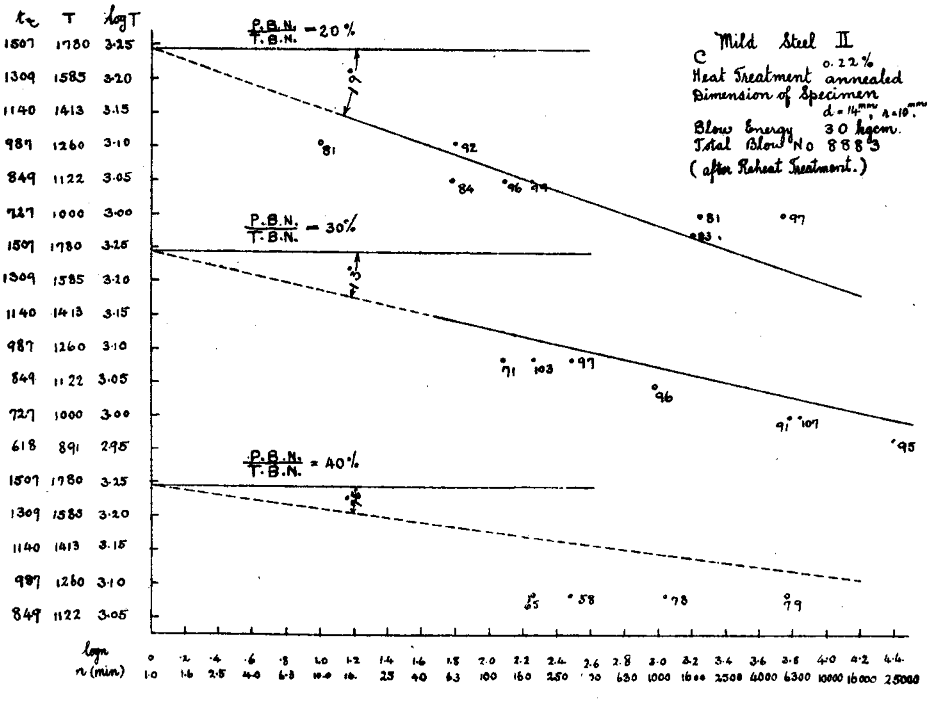


Fig. 42. Temperature and Time of Recovery Heat Treatment versus Recovery Degree.

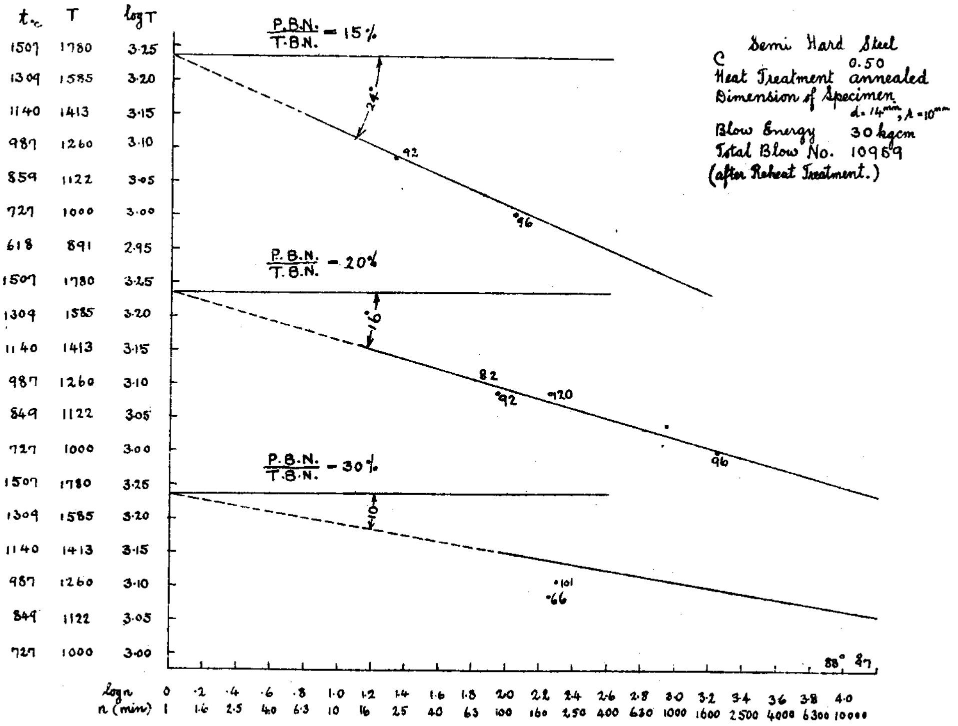


Fig. 43. Temperature and Time of Recovery Heat Treatment versus Recovery Degree.

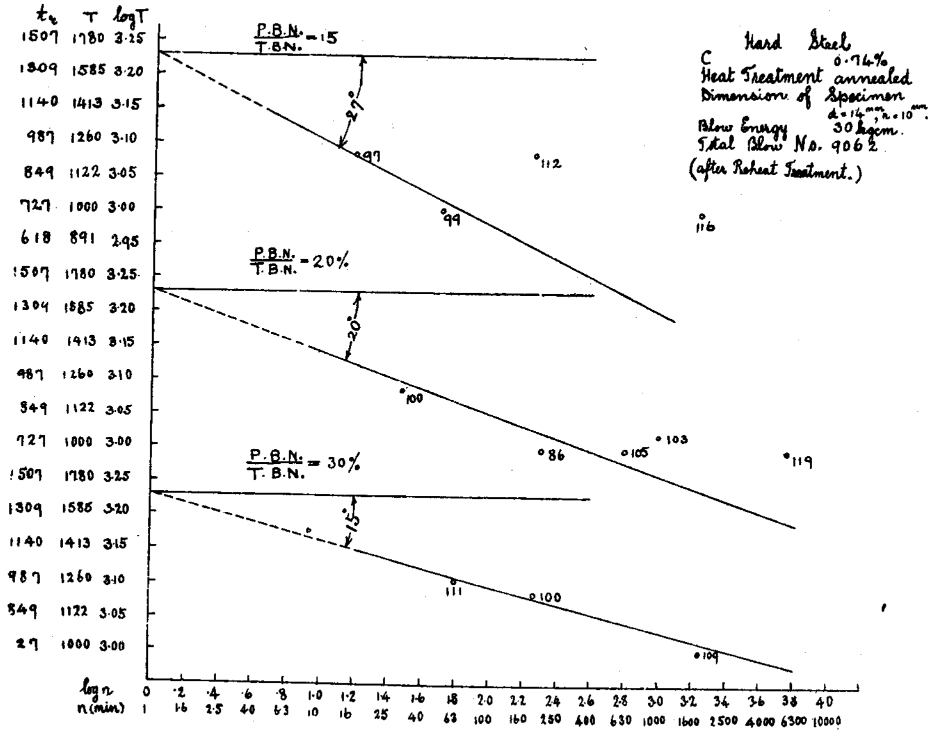


Fig. 44. Temperature and Time of Recovery Heat Treatment versus Recovery Degree.

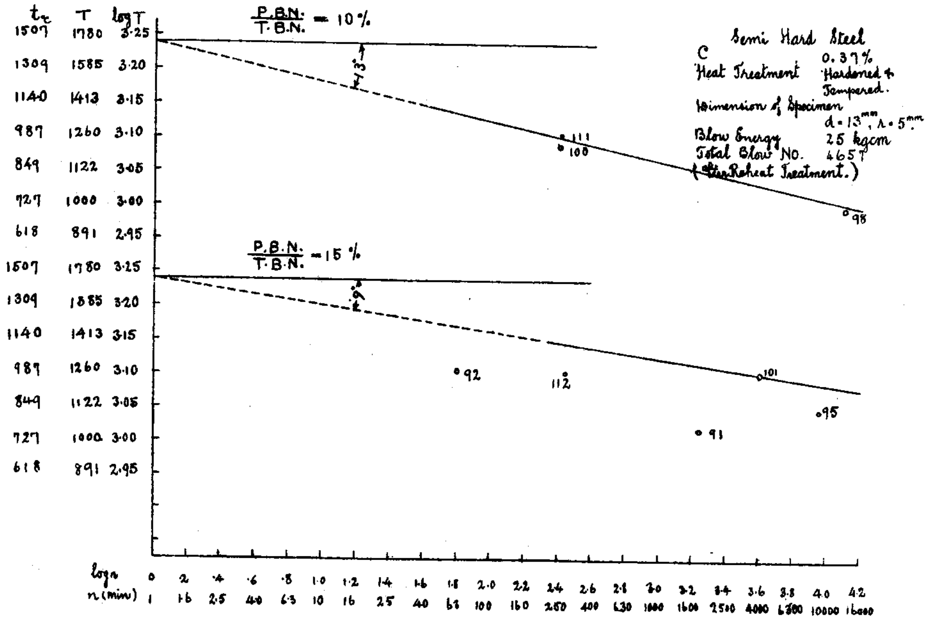


Fig. 45. Temperature and Time of Recovery Heat Treatment versus Recovery Degree.

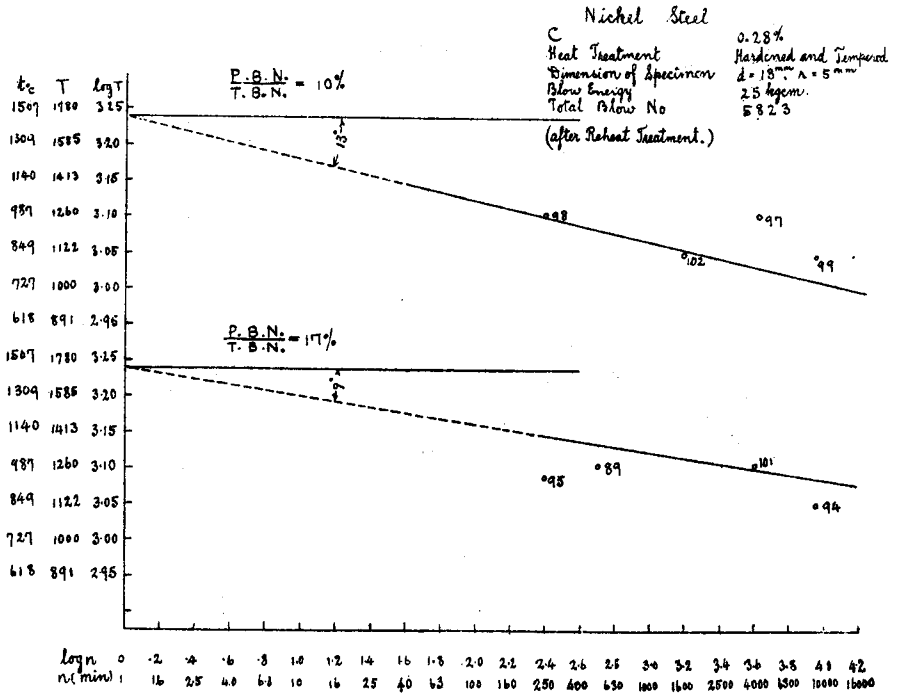
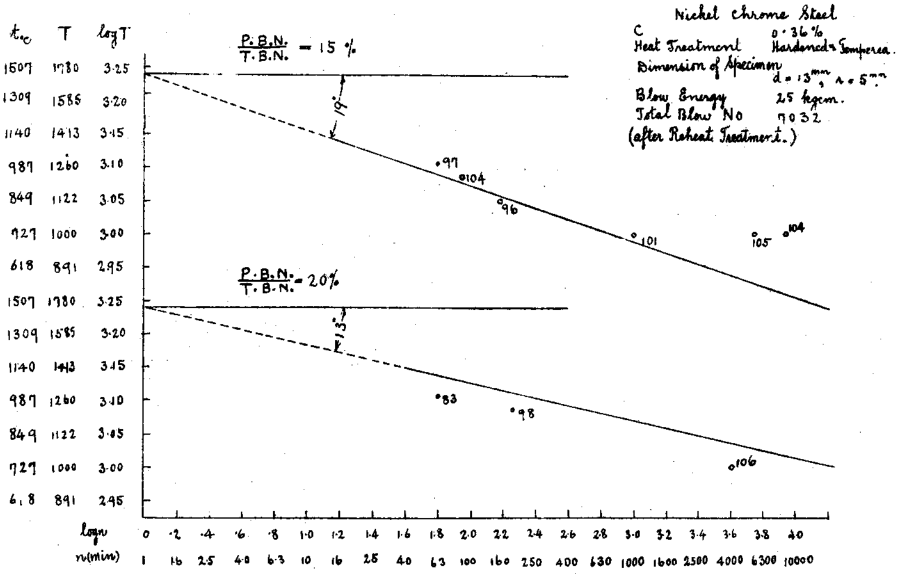


Fig. 46. Temperature and Time of Recovery Heat Treatment versus Recovery Degree.



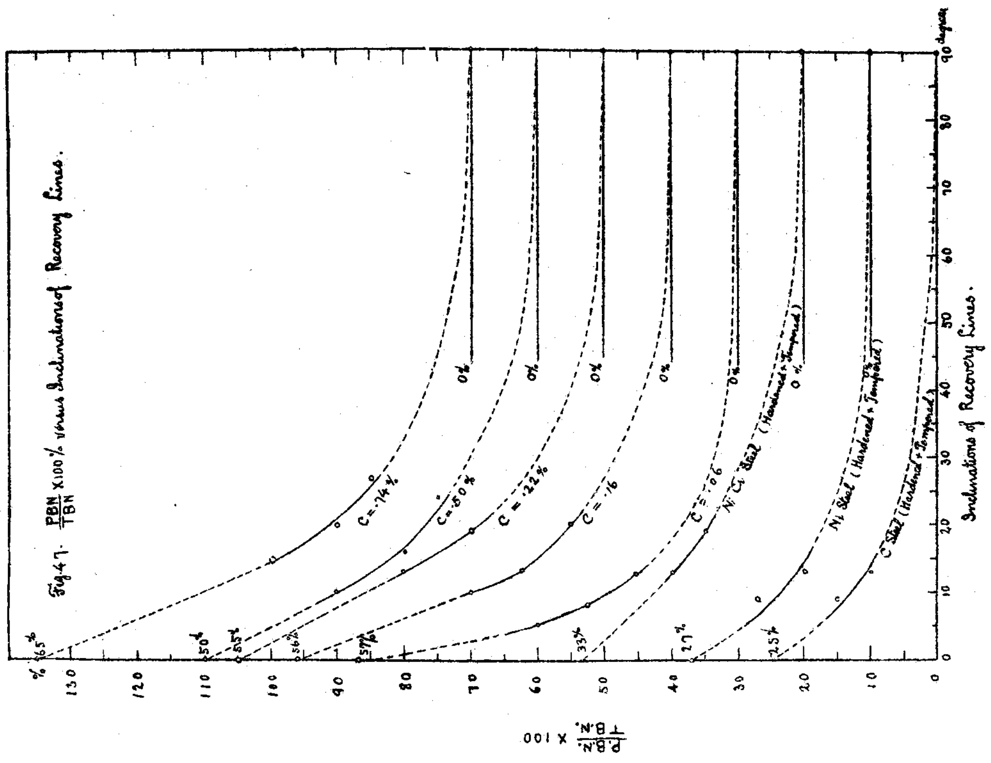


Fig. 47. $\frac{PBN}{TBN}$ x100% versus Inclinations of Recovery Lines.